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APPENDIX: PROPERTIES OF V-4Cr-4Ti

A.1. INTRODUCTION

The physical, thermal and mechanical properties of V-4Cr-4Ti, including irradiation effects, are included in the ITER Material Properties Handbook (MPH) [1]. Draft 3 of the MPH includes data and correlations for specific heat, thermal conductivity, thermal expansion, thermal diffusivity, ultimate tensile strength, yield strength, uniform elongation, and total elongation. The next draft of the MPH will involve updating some of these properties, as well as adding additional properties. The newer data can be found in the US Contribution 1994 Summary Report on Task T12 for ITER [2], in papers presented at the Seventh International Conference on Fusion Reactor Materials (ICFRM-7 in Obninsk, Russia, Sept. 24-29, 1995) and in the 1995 Fusion Reactor Materials Semiannual Progress Reports.

The U.S. Dept. of Energy Fusion Materials Program has identified V-4wt.%Cr-4wt.%Ti (V-4Cr-4Ti) with 0.01 to 0.1 wt.% Si as a promising structural material for fusion reactor applications. One laboratory heat (30 kg) and one industrial-size heat (500 kg) of this alloy have been produced and characterized. In addition to alloying elements (V, Cr, Ti, Si) and impurities (H, O, C, N, *etc.*), heat treatment plays a very important role in the performance of V-alloys.

The data base for binary (V-Ti, V-Cr) and ternary (V-Cr-Ti) alloys is much more extensive than the data base for V-4Cr-4Ti alone. This extensive data base has been used to develop the current alloy and, for some properties (*e.g.,* thermo-physical, elastic, *etc.*), it can be used directly for the reference properties. However, because heat treatment and impurities can be as important as the base alloying elements, it has sometimes been difficult to isolate the effects of each alloying element. For example, the excellent ductility of the V-4Cr-4Ti (heat BL-47) alloy as compared to a particular heat (BL-63) of V-5Cr-5Ti led some researchers to speculate that the properties are extremely sensitive to the sum of Ti and Cr content. Subsequent work in which the same purity of raw materials and the same heat treatment used to produce the V-4Cr-4Ti alloy was used to produce the V-5Cr-5Ti alloy (heat BL-72) resulted in similar properties for the two alloys. Also, the "optimization" which has led to the selection of V-4Cr-4Ti has been performed from a materials perspective (*e.g.*, very low DBTT and high ductility), rather

than from a design perspective. Therefore, as more experience is gained with alloys in this class and as more interaction takes place among the design engineers and the material scientists, chemistry and heat-treatment modifications will be made to the reference alloy to optimize V-Cr-Ti for design application

The approach used in the following properties summary is to examine the data base for alloys within the compositional range of 4-5 wt.% Cr, 3-5 wt.% Ti and 0.0-0.1 wt.% Si. The particular compositions and heat designations are V-4Cr-4Ti (BL-71, BL-47), V-5Cr-5Ti (BL-72, BL-63) and V-5Cr-3Ti (BL-54). This approach adds some statistical significance to the data base, which is important from a design perspective.

A.2. PHYSICAL PROPERTIES

A.2.1. Density

The room-temperature density of commercially pure vanadium is given in the Metals Handbook [3] as 6,100 kg/m^3. Room temperature densities have also been reported for V-4Cr-4Ti (6,072 kg/m^3) [4] and V-5Cr-5Ti (6,028 kg/m^3) [5]. The recommended density for design studies is 6,050 kg/m^3. The density will decrease with temperature increase and with radiation in a neutron environment (Sec. A.8.6).

A.2.2. Detailed Composition for Activation & Waste-Disposal Analyses

Although developmental work is in progress to define the optimum chemistry and heat treatment for vanadium alloys, it is necessary to specify a composition at this time for design analysis, particularly for activation and waste-disposal analyses. Table A.2-I lists a "reference" composition for such studies. With a few exceptions (*e.g.,* Mo, Nb, Zr), it is based on what has been achieved in the heats produced to date. For impurities which may lead to activation and waste-disposal problems, the anticipated reductions in these impurities are listed.

A.2.3. Melting Temperature

The melting temperature of commercially pure vanadium is given in Ref. [3] as $1900 \pm 25\,^{\circ}$C. This value should be adequate to describe the melting temperature for the alloys of interest.

Table A.2-I.
Recommended Composition (wt/%) for V-4Cr-4Ti
for Activation and Waste-Disposal Studies

Element	Composition	Element	Composition	Element	Composition
V	Balance				
Cr	4.0 ± 0.5	Ti	4.0 ± 0.5	Si	0.05 ± 0.04
H	< 0.0030	B	< 0.0015	C	< 0.0220
N	< 0.0240	O	< 0.0400	Na	< 0.0010
Al	< 0.0200	P	< 0.0030	S	< 0.0025
Cl	< 0.0005	K	< 0.0010	Ca	< 0.0010
Fe	< 0.0250	Ni	< 0.0020	Cu	< 0.0020
As	< 0.0010	Sr	< 0.0060	Zr	< 0.0010
Nb$^{(a)}$	< 0.0010	Mo$^{(a)}$	< 0.0010	Ru	< 0.0010
Hf	< 0.0010	Ta	< 0.0010	W	< 0.0030

(a) These impurity levels can be further reduced if they present problems for activation and waste disposal.

A.2.4. Electrical Resistivity

The room-temperature electrical resistivity of commercially pure vanadium is given in Ref. [3] as 0.248 to 0.260 $\mu\Omega$-m. Touloukian [6] presents data for the variation of resistivity with temperature. Combining the normalized temperature dependence with the room-temperature value of 0.328 $\mu\Omega$-m for V-4Cr-4Ti given by Birzhevoy *et al.* [4] gives the following recommended correlation for electrical resistivity (ρ in $\mu\Omega$-m) as a function of T in °C:

$$\rho \;=\; 0.328 \left[1 + 2.028 \times 10^{-3}(T - 20)\right] . \qquad \text{(A.2-1)}$$

A.3. THERMAL PROPERTIES

The specific heat (C_p in kJ/kg-K), thermal conductivity (k in W/m-K) and mean coefficient of thermal expansion (α_m in 10^{-6}/K) have been measured for V-5Cr-5Ti in the temperature range of room temperature (RT) to 600 °C. They are given in the ITER Material Properties Handbook (MPH) [1] as:

$$C_p = 0.57551 \left[1 - \frac{36.68}{T + 273}\right] , \quad \text{(A.3-1)}$$

$$k = 30.35 \left[1 + 2.835 \times 10^{-4}(T - 20)\right] , \quad \text{(A.3-2)}$$

and

$$\alpha_m = 9.0793 \left(1 + 1.2075 \times 10^{-4}T + 2.2774 \times 10^{-7}T^2 - 2.4013 \times 10^{-10}T^3\right) . \quad \text{(A.3-3)}$$

The thermal property values measured for V-5Cr-5Ti are within 5% of the literature values given for commercially pure vanadium, which suggests that these properties are relatively insensitive to composition in the range considered. Significantly lower values of thermal conductivity (*e.g.,* 23 *vs.* 30 W/m-K at RT) are reported by Birzhevoy *et al.* [4] for V-4Cr-4Ti. However, no details are given by these authors with regard to experimental technique and data points. As their correlation gives values which are inconsistent with values for commercially pure vanadium and other V-Cr-Ti alloys, it is disregarded.

A.4. ELASTIC PROPERTIES

The Young's modulus and the shear modulus for pure vanadium have been measured by Farraro and McLellan [7] using a dynamic technique. The correlation given for Young's modulus (E in GPa) as a function of temperature (T in °C) based on data from RT to 1,627 °C is

$$E = 125.2 \left[1 - 7.69 \times 10^{-5}(T - 20)\right] . \quad \text{(A.4-1)}$$

The correlation given for shear modulus (G in GPa) as a function of temperature, T (in °C) based on data from RT to 677 °C is

$$G = 46.3 \left[1 - 1.82 \times 10^{-4}(T - 20)\right] . \quad \text{(A.4-2)}$$

Simpson [5], using a similar technique, measured $E = 125.6$ GPa and $G = 45.9$ GPa at room temperature for V-5Cr-5Ti which are close to those for pure vanadium. Thus,

these values can be substituted for the 125.2 and 46.3 coefficients in Eqs. (A.4-1) and (A.4-2), respectively, to give a representation of the elastic constants for V-4Cr-4Ti. Birzhevoy *et al.* [4] report E values from room temperature to 600 °C for V-4Cr-4Ti which are about 5% higher than those for pure vanadium. Their G values, however, are 10–20% higher. The effect on Poisson's ratio ($\nu = E/(2G) - 1$) is quite significant. While the pure vanadium equations give a Poisson's ratio which increases from 0.368 to 0.461 as temperature increases from room temperature to 600 °C, the Russian results give a Poisson's ratio which decreases from 0.299 to 0.271. Such differences have a significant impact on the calculated thermal stresses and on the maximum surface heat load which the vanadium alloy can tolerate. Because the elastic constants for V-4Cr-4Ti should be close to the combined results for pure V and V-5Cr-5Ti, the Russian results are disregarded for now, and the recommended elastic constants for V-4Cr-4Ti are

$$E = 125.6 \left[1 - 7.69 \times 10^{-5}(T - 20)\right] , \quad \text{(A.4-3)}$$

$$G = 45.9 \left[1 - 1.82 \times 10^{-4}(T - 20)\right] . \quad \text{(A.4-4)}$$

A.5. TENSILE PROPERTIES OF UNIRRADIATED V-4Cr-4Ti

The tensile properties of V-4Cr-4Ti (lots BL-47 and BL-71) have been reported by Loomis *et al.* [8] and Chung *et al.* [9]. Values for V-5Cr-5Ti (lots BL-63 and BL-72) have been reported by Loomis *et al.* [10], Chung *et al.* [9], Devan, DiStephano, and Hendriks [11], and Natesan and Soppet [12]. Loomis *et al.* [10] have also reported tensile properties for V-5Cr-3Ti.

A.5.1. Ultimate Tensile Strength

Figure A.5-1 shows the data and the best fit correlation for the ultimate tensile strength (UTS) of V-(4-5)Cr-(3-5)Ti alloys. The best fit correlation is designated as S_u (in MPa) and is used to represent the average UTS of V-4Cr-4Ti as a function of temperature (T in °C):

$$S_u = 488 \left(1.0450 - 2.3735 \times 10^{-3}T + 6.2675 \times 10^{-6}T^2 - 4.7504 \times 10^{-9}T^3\right) . \quad \text{(A.5-1)}$$

The form of Eq. (A.5-1) has been chosen for convenience in design analysis. The value in front of the parentheses represents the "average" room temperature UTS. The temperature dependence in parentheses has been normalized to one at room temperature

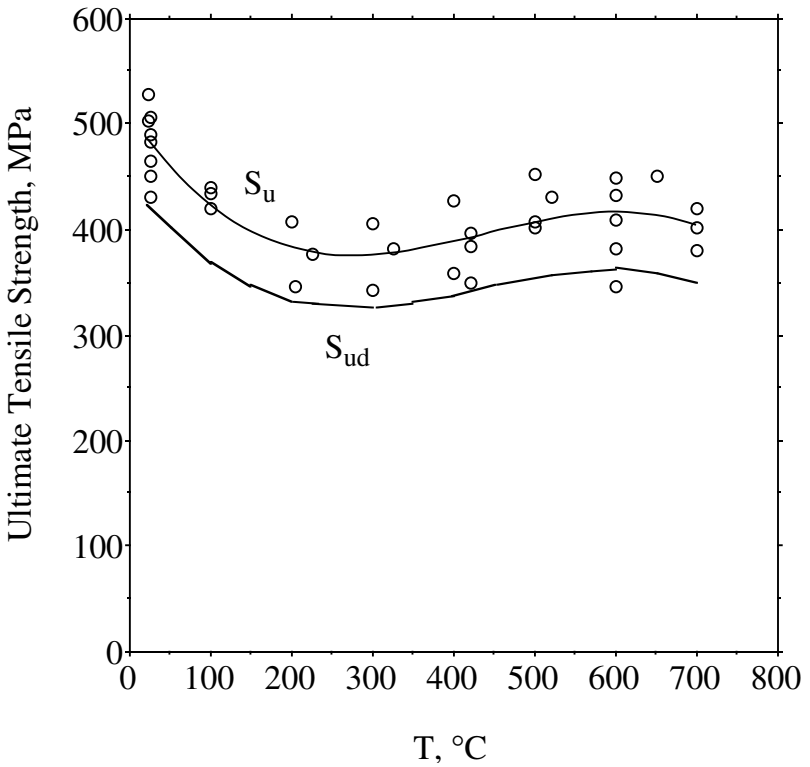

Figure A.5-1. Ultimate tensile strength (UTS) data and best-fit correlation (S_u) for unirradiated vanadium alloys with 4 to 5wt.% Cr, 3 to 5 wt.% Ti and 0.05 ± 0.04 wt.% Si. The best fit correlation is recommended to represent the average UTS for V-4Cr-4Ti. The correlation S_{ud} is recommended for design analysis and for determining the limiting stress intensity (S_m) for average primary membrane stresses.

($T = 20\,^{\circ}\mathrm{C}$). Based on design codes such as the ASME Boiler and Pressure Vessel Code, the "design" correlation is determined by using a factor in front of the normalized temperature dependence which represents the minimum RT data point ($S_{u,min} = 430$ MPa). However, the ASME code assumes a substantial data base for UTS at room temperature. For example, the ratio of average to minimum UTS for 316LN steel is 1.15. Using $S_{u,min} = 488/1.15 = 424$ MPa as a representative value for V-4Cr-4Ti until more room temperature data are obtained, gives the design UTS correlation (S_{ud}) as

$$S_u \;=\; 424\left(1.0450 - 2.3735\times10^{-3}T + 6.2675\times10^{-6}T^2 - 4.7504\times10^{-9}T^3\right)\,. \quad \text{(A.5-2)}$$

Although not required by ASME, Eq. (A.5-2) represents a lower bound to the UTS data from room temperature to 700 °C for all data points except for the 600 °C UTS for V-5Cr-3Ti.

A.5.2. Yield Strength

Figure A.5-2 shows the data and the best fit correlation for the yield strength (YS) of V-(4–5)-Cr(3–5)Ti alloys. The best fit correlation is designated as S_y (in MPa) and is used to represent the average YS of V-4Cr-4Ti as a function of temperature (T in °C):

$$S_y = 402\left(1.0635 - 3.3238\times10^{-3}T + 7.5229\times10^{-6}T^2 - 5.3461\times10^{-9}T^3\right). \quad \text{(A.5-3)}$$

The minimum data point at room temperature is 337 MPa. Again, using the spread in the 316LN data base as a guide, $S_{y,min} = 402/1.25 = 322$ MPa is used until more room temperature data become available. The recommended correlation for the design YS is:

$$S_{yd} = 322\left(1.0635 - 3.3238\times10^{-3}T + 7.5229\times10^{-6}T^2 - 5.3461\times10^{-9}T^3\right). \quad \text{(A.5-4)}$$

Equation (A.5-4) represents a lower bound to the data from room temperature to 700 °C.

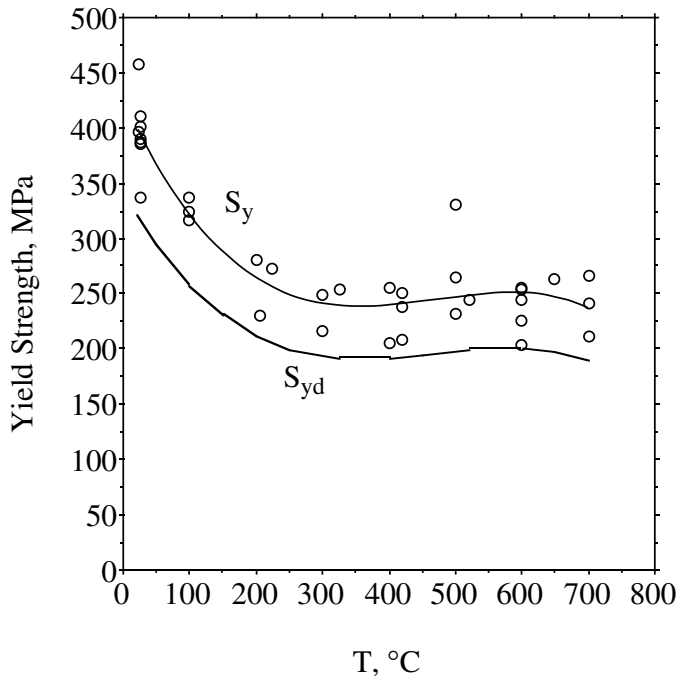

Figure A.5-2. Yield strength (YS) data and best-fit correlation (S_y) for unirradiated vanadium alloys with 4–5 wt.% Cr, 3–5 wt.% Ti and 0.05 ± 0.04 wt.% Si. The best fit correlation is recommended to represent the average YS for V-4Cr-4Ti. The correlation S_{yd} is recommended for design analysis and for determining the limiting stress intensity (S_m) for average primary membrane stresses.

A.5.3. Uniform Elongation

Figure A.5-3 shows the data and the best fit correlation for the uniform elongation (UE) of V-(4–5)Cr-(3–5)Ti alloys. The best fit correlation is designated as e_u and is used to represent the average UE of V-4Cr-4Ti as a function of temperature (T in °C):

$$\begin{aligned} e_u &= 22.3\% \left(0.9733 + 1.4600 \times 10^{-3} T \right. \\ &\quad \left. -6.2966 \times 10^{-5} T^2 + 5.1635 \times 10^{-9} T^3 \right) . \end{aligned} \tag{A.5-5}$$

The uniform elongation is used to classify materials and to scale certain properties (*e.g.*, fracture toughness) from unirradiated to irradiated conditions. As such, the average values given by Eq. (A.5-5) should be used in the scaling process.

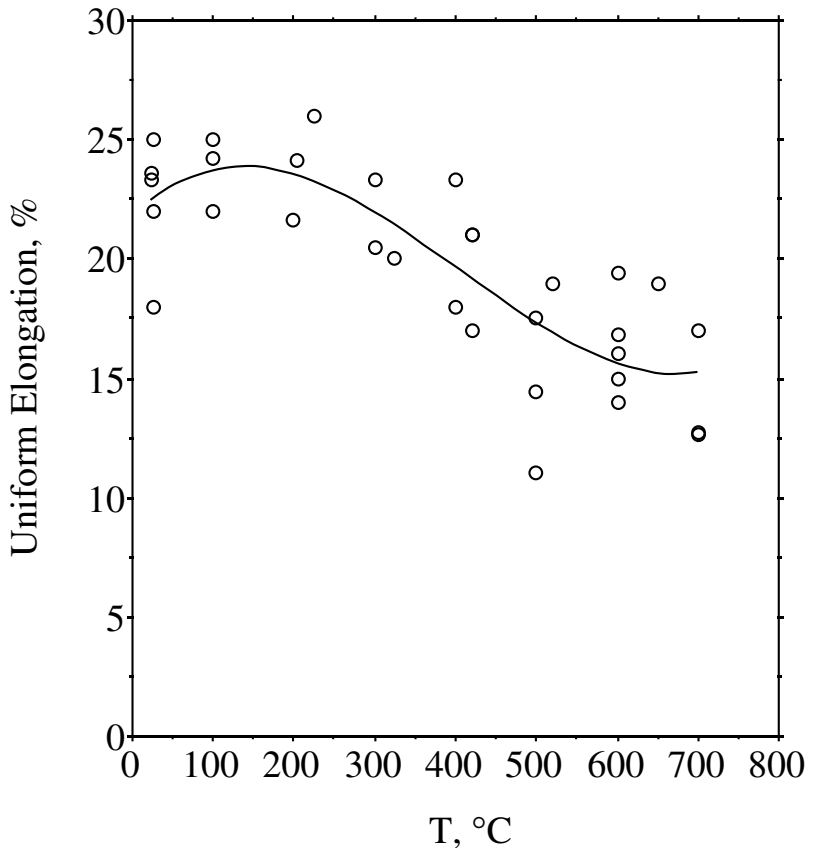

Figure A.5-3. Uniform elongation (UE) data and best-fit correlation for unirradiated vanadium alloys with 4–5 wt.% Cr, 3–5 wt.% Ti and 0.05 ± 0.04 wt.% Si. The best fit correlation is recommended to represent the average UE for V-4Cr-4Ti.

A.5.4. Total Elongation

Figure A.5-4 shows the data and the best fit correlation for the total elongation (TE) of V-(4–5)Cr-(3–5)Ti alloys. The best fit correlation is designated as e_t and is used to represent the average TE of V-4Cr-4Ti as a function of temperature (T in °C):

$$\begin{aligned} e_t &= 30.8\% \left(0.9972 + 1.8008 \times 10^{-4} T \right. \\ &\quad \left. -2.0547 \times 10^{-6} T^2 + 1.4227 \times 10^{-9} T^3 \right) . \end{aligned} \tag{A.5-6}$$

The specifications used to qualify a new lot or heat of a reference material generally include the minimum acceptable RT value of TE. Higher temperature values are generally not used, even for scaling purposes. As such, no e_t correlation with temperature is needed.

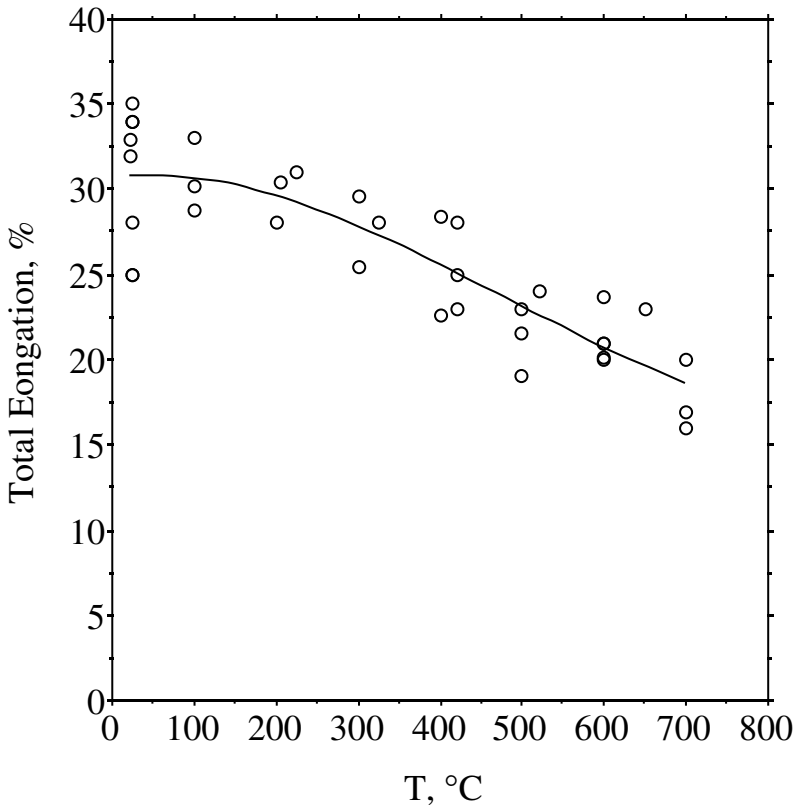

Figure A.5-4. Total elongation (TE) data and best-fit correlation for unirradiated vanadium alloys with 4–5 wt.% Cr, 3–5 wt.% Ti and 0.05 ± 0.04 wt.% Si. The best fit correlation is recommended to represent the average TE for V-4Cr-4Ti.

A.5.5. Reduction in Area

Figure A.5-5 shows the data and the best fit correlation for the reduction in area (RA) of V-(4–5)Cr-(3–5)Ti alloys. The best fit correlation is designated as $-\Delta A/A_o$ and is used to represent the average RA of V-4Cr-4Ti as a function of temperature (T in °C):

$$-\frac{\Delta A}{A_o} = 91.3\% \left(1.0118 - 6.6008 \times 10^{-4} T + 3.5173 \times 10^{-6} T^2 - 5.2599 \times 10^{-9} T^3\right) . \quad \text{(A.5-7)}$$

The reduction in area is generally used to scale low-cycle fatigue data from the unirradiated material state to the irradiated state. Average values given by Eq. (A.5-7) are recommended for such scaling.

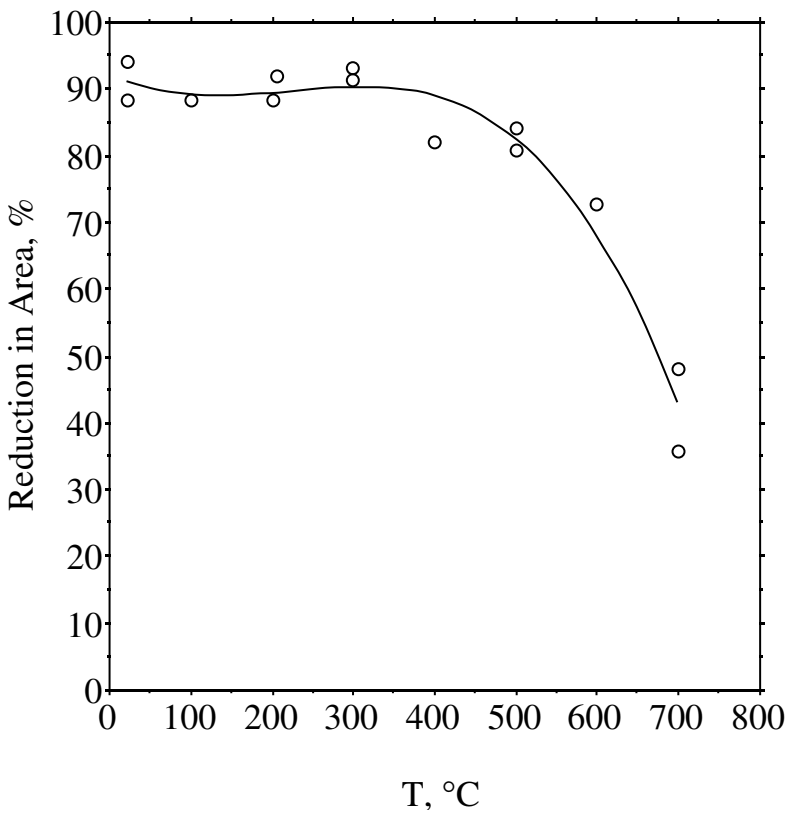

Figure A.5-5. Reduction in area (RA) data and best-fit correlation for unirradiated vanadium alloys with 4–5 wt.% Cr, 3–5 wt.% Ti and 0.05 ± 0.04 wt.% Si. The best fit correlation is recommended to represent the average RA for V-4Cr-4Ti.

A.6. THERMAL CREEP

Chung, Loomis, and Smith [13] have reported secondary thermal creep rates for V-4Cr-4Ti at 600 °C in the high stress range of 320–440 MPa. A reasonably good fit to the data is obtained for the thermal creep rate $d(e_{ct})/dt$ in %/hour as a function of stress S in MPa with

$$d(e_{ct})/dt \;=\; 1.89 \times 10^{-28} S^{9.94} \,. \tag{A.6-1}$$

At the allowable primary membrane stresses of interest (about 100 MPa), secondary thermal creep is insignificant for anticipated lifetimes of a Demo power plant. While it would be interesting to know if this holds true at 700 °C as well, the data base does not permit such extrapolation because creep has been characterized only at one temperature.

Chung, Loomis, and Smith [13] also present some time-to-rupture data for V-4Cr-4Ti at 600 °C for stresses in the range of 387–420 MPa. While only one temperature is characterized and the stresses are too narrowly grouped in the high stress range, the more extensive data base for V-15Cr-5Ti stress-rupture [14] may be used to guide the development of a correlation. Figure A.6-1 shows the V-15Cr-5Ti data base in terms of stress as a function of the Larsen Miller Parameter P, where P is defined as

$$P \;=\; T\,(20 + \log t_r) \,, \tag{A.6-2}$$

where T is temperature in K and t_r is rupture time in hours. The correlation plotted in Fig. A.6-1 for V-15Cr-5Ti is

$$\log S \;=\; -0.8922 + 0.34967(P/1000) - 0.0087(P/1000)^2 \,. \tag{A.6-3}$$

The data base for the V-15Cr-5Ti used to generate Eq. (A.6-3) includes temperatures in the range of 650–800 °C and stresses in the range of 276–414 MPa. This correlation has been modified to match the few data points for V-4Cr-4Ti to give

$$\log S \;=\; -0.92522 + 0.34967(P/1000) - 0.0087(P/1000)^2 \,. \tag{A.6-4}$$

There is more validity in this approach than there would be in best-fitting the few data points for V-4Cr-4Ti at one temperature. Both Eqs. (A.6-3) and (A.6-4) are limited to the range $P/1000 \geq 20$.

Equation (A.6-4) can be rewritten to express time to rupture as a function of stress at the upper temperature limit of 700 °C to investigate whether thermal creep-rupture

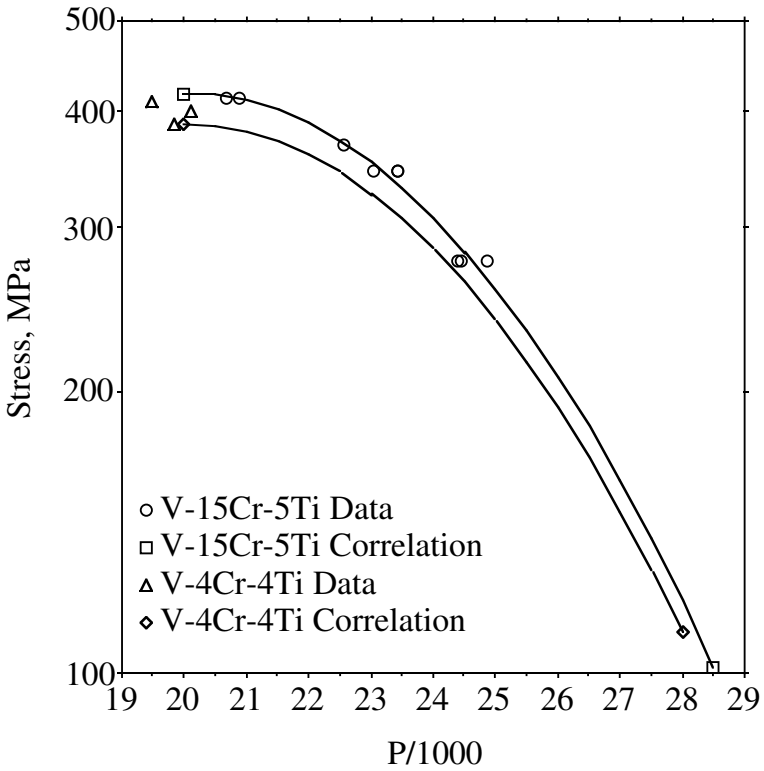

Figure A.6-1. Rupture stress as a function of the Larsen Miller Parameter, P, for V-15Cr-5Ti and V-4Cr-4Ti. The correlation for V-4Cr-4Ti is based on the form of the correlation for V-15Cr-5Ti.

will be lifetime-limiting for Demo operating conditions. Figure A.6-2 shows the results for allowable primary stress as a function of rupture time in effective full power years. At a stress of about 260 MPa, the rupture time is over 20 years. Thus, at stresses on the order of 100 MPa, thermal creep rupture is estimated to be non-lifetime-limiting. Higher temperature ($\geq$600 °C) and lower stress (<387 MPa) creep-rupture data would be needed to validate these predictions.

While the creep-resistance of V-4Cr-4Ti appears to be quite high based on the results presented above, it should be emphasized that there is a high degree of uncertainty in extrapolating creep data to higher temperatures and lower stresses. In particular, the creep mechanism may change (*e.g.,* from matrix creep to grain boundary sliding) which would cause a significant change in the creep rate as a function of stress and stress as a function of time-to-rupture relationships. While the above approach is reasonable given the limited data base, it is more accurate to say that no data are available to suggest that thermal creep will be lifetime-limiting in a Demo design for which $T \leq 700\,^{\circ}\mathrm{C}$.

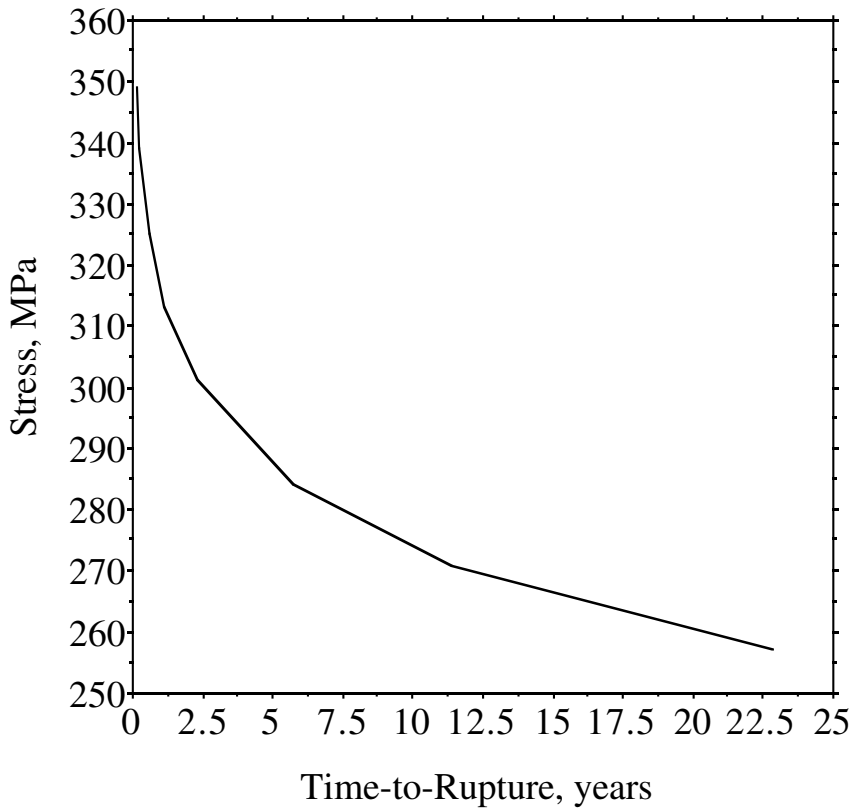

Figure A.6-2. Predicted stress as a function of rupture time for V-4Cr-4Ti at 700 °C based on the Larsen-Miller-Parameter correlation shown in Fig. A.6-1.

A.7. FATIGUE AND FRACTURE TOUGHNESS

A very limited data base is available for the room-temperature fatigue and fracture toughness of heat BL-63 (V-5Cr-5Ti). However, this heat has been shown to have Charpy-test brittle-to-ductile transition temperature (DBTT) far inferior to the newer V-5Cr-5Ti heat (BL-72) and the V-4Cr-4Ti heats. Thus, there is some question as to the relevance of these data. Whether or not the data are relevant, they are too limited in temperature to be useful in design for the temperature range of 200–700 °C. Clearly, well-developed fatigue and fracture toughness data bases are needed for these newer heats of vanadium alloys.

A.8. IRRADIATION EFFECTS

A.8.1. Thermo-physical and Elastic Properties

Irradiation in a fusion neutron environment will generate displacement damage, transmutation helium and transmutation hydrogen in vanadium alloys, as well as other structural materials considered as options for Demo reactors. As long as the volumetric swelling is small, particularly due to helium bubbles, the effects of irradiation on the thermo-physical and elastic properties are anticipated to be negligible.

A.8.2. Tensile Properties

Within the irradiation data base available for V-4Cr-4Ti (400–600 °C, 0–31 dpa, and 0–75 appm He), the changes in tensile properties are as follows: UTS increases by 79% (400–430 °C), 35% (500–520 °C) and 8% (600 °C); YS increases by 162% (400–430 °C), 112% (500–520 °C), and 45% (600 °C); UE decreases to 1.6±1.0% (400–430 °C), 3.6±1.3% (500–520 °C) and 6.5±1.1% (600 °C). For all of these cases, the DBTT remains $\ll$0 °C. The increase in strength should cause no problems in the design. However, the designer should not use this irradiation-strengthening to increase the allowable stresses. Overpower and undercooling events which tend to elevate the structure temperature for brief periods of time may anneal out this hardening. Also, with some materials [*e.g.,* 316L(N)] cycling has been observed to soften the irradiated material.

The decrease in uniform elongation with irradiation is significant for samples irradiated and tested at 400–430 °C. Such low uniform elongation values require the use of special design rules such as those developed for ferritic and austenitic steels which tend to embrittle to even lower UE values at 200–400 °C. They also suggest that more irradiation testing be performed to map out the temperature range, neutron damage level and He concentration at which embrittlement may become a serious design issue. In the interim, it is recommended that T ¿ 430 °C be used as a lower limit temperature for V-4Cr-4Ti alloys.

A.8.3. Fracture Toughness and Fatigue

As mentioned in Sec. A.7, the fracture toughness and fatigue properties of unirradiated V-4Cr-4Ti are not well characterized. The same lack of data exists for irradiated material. However, there are indications from other data that decreased performance

under irradiation is not anticipated for the test conditions described above. The DBTT (based on Charpy impact tests) remains well below 0 °C for irradiated material, as well as unirradiated material, suggesting that the fracture toughness is not degraded by neutron damage up to 34 dpa [16]. The increase in UTS with irradiation should improve the high-cycle fatigue performance. No reduction-in-area data are available for irradiated material, so no conclusions can be drawn at this time about the low-cycle fatigue performance with irradiation.

A.8.4. Embrittlement due to Transmutation H and Injected D/T

Hydrogen embrittlement of vanadium alloys is a potential problem at low temperatures, particularly for vanadium which has a coating at the V/Li interface. For bare V/Li, the lithium coolant has a higher affinity for hydrogen isotopes than does the vanadium. However, the electrical resistance coating may act as a barrier to hydrogen-isotope transport across this interface. The increase in hydrogen with irradiation needs to characterized in order to assess the potential for hydrogen embrittlement being a life- limiting phenomenon. This is an extremely difficult problem analytically because of the uncertainties in surface parameters.

A.8.5. Irradiation Creep

The irradiation creep of V-4Cr-4Ti has been measured recently by Troyanov *et al.* [17] based on torsion loading of a thin-walled tube irradiated in BR-10. The testing temperature was 445 °C and the peak fast flux was 5.8×10^{25} n/m^2 ($\sim$3 dpa). The irradiation creep rate [$d(e_{ci})/dt$, in %/dpa] was found to vary linearly with stress for stresses up to 110–120 MPa. The correlation developed under these conditions for e_{ci} (in %) as a function of stress, S (in MPa) and D (in dpa) is

$$e_{ci} \;=\; 3.3 \times 10^{-2} S\, D\,. \qquad \text{(A.8-1)}$$

The creep rate constant measured for V-4Cr-4Ti is about 50% higher than the one determined for HT-9 [18]. As the irradiation creep rate for the two materials is expected to be of the same order of magnitude, the Troyanov *et al.* [17] results appear to be reasonable. It is recommended that Eq. (A.8-1) be used to represent the irradiation creep of V-4Cr-4Ti at all operating temperatures and neutron damage levels for stresses <120 MPa.

A.8.6. Swelling

Based on both neutron and ion irradiation experiments, V-Cr-Ti alloys are the lowest swelling materials of the three classes of alloys considered for fusion first-wall application: vanadium alloys, ferritic/martensitic steels and austenitic stainless steels [19]. Neutron irradiations have been conducted in fast reactors (with negligible He present) up to 114 dpa in the temperature range of 420–600 °C. Ion irradiations have been conducted (with and without He) up to 250 dpa in the temperature range of 400-800 °C. V-15Cr-5Ti showed negligible swelling in these ion irradiations. Of particular interest to fusion first wall applications, swelling was negligible up to 725 °C and 200 dpa for dual-ion irradiations including up to 1500 appm He [20]. Also, no evidence of He bubble coalescence was found in this alloy under these ion irradiations.

The swelling behavior of V-15Cr-5Ti is difficult to characterize as a function of dpa and temperature. In fast neutron irradiations, volumetric swelling values as high as 2.3–2.7% have been recorded at 75–85 dpa. However, with continued irradiation up to 114 dpa, the swelling decreased to values <0.3%. This non-classical swelling behavior is associated with density changes caused by solid-state reactions, rather than by neutron-induced voids and He bubbles [21].

The V-4Cr-4Ti alloy has been irradiated up to 34 dpa with 0–75 appm He in the temperature range of 420–600 °C [22]. The data are shown in Fig. A.8-1, along with data for V-8Cr-6Ti and V-10Cr-5Ti for the same temperature range. The V-4Cr-4Ti data are not at high enough neutron damage levels to allow a design correlation to be determined with reasonable confidence. However, the higher-swelling V-(8–10)Cr-(5–6)Ti alloy data may be used to establish an upper bound swelling curve for design analysis. The design curve shown in Fig. A.8-1 is an upper bound to the V-4Cr-4Ti data base and a reasonable bound to the V-(8–10)Cr-(5–6)Ti data base. It follows the general shape recommended for vanadium alloys. The higher-damage-level V-15Cr-5Ti data (both neutron and ion-irradiation) have been used qualitatively to support low swelling levels at damage levels beyond 85 dpa and temperatures beyond 600 °C. The recommended design correlation shown in Fig. A.8-1 is

$$\frac{\Delta V}{V_o} = 1.9 \left(\frac{D}{D_m}\right)^3 \exp\left[3\left(1 - \frac{D}{D_m}\right)\right] . \qquad \text{(A.8-2)}$$

where $\Delta V/V_o$ is volumetric swelling (in %), D is damage level in dpa, and D_m is 55 dpa.

It is difficult to assess the confidence level associated with Eq. A.8-2 because of the limited data base for V-4Cr-4Ti. There is reasonable confidence that it represents an

upper bound prediction up to 85 dpa and 600 °C based on the neutron irradiation data base for the higher swelling V-(6-8)Cr-(5-6)Ti. It also represents an upper bound to the V-15Cr-5Ti neutron-irradiation data base at 114 dpa and 420 °C. To the extent that ion irradiations simulate neutron irradiations, there is some justification in anticipating that Eq. A.8-2 represents an upper bound prediction for temperatures up to 725 °C, for neutron damage levels up to 200 dpa, and for He levels up to 1500 appm. Until more V-4Cr-4Ti data become available, it is recommended that Eq. A.8-2 be used for fusion demo first-wall and divertor design analysis for the full temperature range of interest (200–700 °C) up to 200 dpa. Beyond that, predictions should be indicated graphically by a dotted line to show extrapolation beyond the data base.

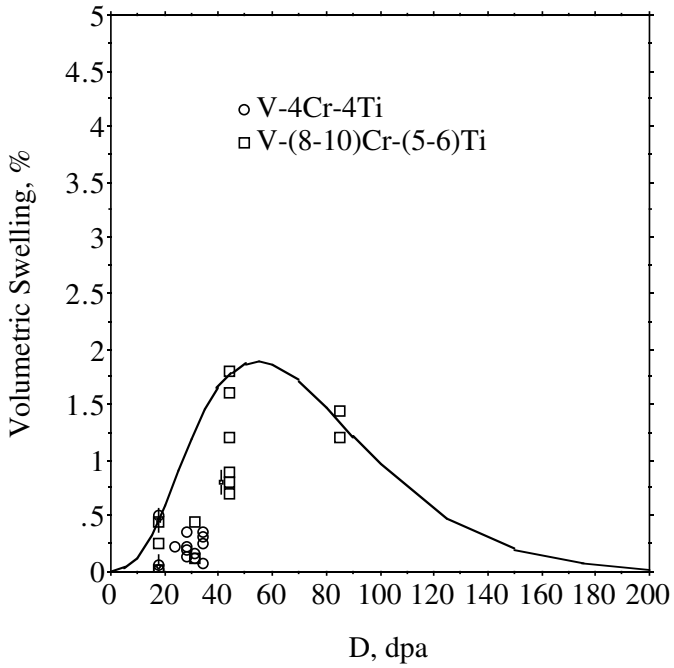

Figure A.8-1. Swelling data for V-4Cr-4Ti and V-(8–10)Cr-(5–6)Ti alloys in the temperature range of 420–600 °C and the helium concentration range of 0–75 appm. The recommended design correlation for V-4Cr-4Ti is indicated by the solid line. The curve is an upper bound to the V-4Cr-4Ti data, a reasonable bounding curve to the higher swelling V-(8–10)Cr-(5–6)Ti alloys, and follows the general shape used to describe V alloy swelling. Data for V-15Cr-5Ti (not shown) which have been used to support low swelling at high neutron damage levels include: near-zero swelling at 114 dpa and 420 °C; negligible swelling for ion irradiations up to 250 dpa and 800 °C; and negligible swelling for dual-ion irradiations up to 200 dpa, 725 °C and 1500 appm He.

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