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Vanadium-Base Alloys for Fusion Reactor Applications*

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ABSTRACT

Vanadium-base alloys offer potentially significant advantages over other candidate alloys as a structural material for fusion reactor first wall/ blanket applications. Although the data base is more limited than that for the other leading candidate structural materials, viz., austenitic and ferritic steels, vanadium-base alloys exhibit several properties that make them particularly attractive for the fusion reactor environment. This paper presents a review of the structural material requirements a summary of the materials data base for selected vanadium-base alloys, and a comparison of projected performance characteristics compared to other candidate alloys. Also, critical research and development (R&D) needs are defined.

The relatively high thermal conductivity and low thermal expansion coefficient of vanadium-base alloys, which result in lower thermal stresses for a given heat flux compared to most other candidate alloys, should enhance the wall load and lifetime limitations. Since the mechanical strength of vanadium-base alloys is retained at relatively high temperatures, higher operating temperatures are projected for these alloys than for austenitic or ferritic steels. The refractory metals, including vanadium, characteristically exhibit

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good corrosion resistance in purified liquid metals. The vanadium alloys also exhibit favorable neutronic properties which include lower parasitic absorption leading to better tritium breeding performance, lower bulk nuclear heating rates, and lower helium generation rates compared to the steels. Limited data from moderate fluence neutron irradiations (fast breeder reactor) and high-damage level ion irradiations indicate good radiation damage resistance.

Major concerns regarding the use of vanadium-base alloys for fusion reactor applications relate to cost, reactivity with oxygen/air, and the limited data base. The impact of these concerns and potential design solutions are discussed. Because of the corrosion/compatibility considerations, the vanadium alloys offer greater promise for liquid metal breeder concepts than for the solid breeder concepts.

I. Introduction

Selected vanadium-base alloys offer potentially significant advantages over other candidate alloys as a fusion reactor structural material. Although the data base is more limited than that for the other leading candidate structural materials, viz., austenitic and ferritic steels, vanadium-base alloys exhibit several properties that make them particularly attractive for the fusion reactor environment. Moderate fluence fast reactor irradiations and high-damage level ion irradiations have demonstrated an inherent resistance of certain vanadium alloys to void swelling and ductility loss in comparison to most other candidate alloys. Of particular importance in projecting the potential radiation damage resistance of vanadium alloys to fusion reactor conditions is the apparent insensitivity to moderate compositional and microstructural variations. The relatively high thermal conductivity and low thermal expansion coefficient, which result in lower thermal stresses for a given heat flux compared to most other candidate alloys, should enhance the wall load and lifetime limitations. Since the mechanical strength of vanadium alloys is retained at relatively high temperatures, higher operating temperatures are projected for vanadium alloys than for the austenitic or ferritic steels. Vanadium alloys produce the least impact on tritium breeding of the primary candidate alloys and selected vanadium alloys offer the potential for low long term (>30 y) radiation-induced activation.

Major concerns regarding the use of vanadium-base alloys relate primarily to their chemical reactivity with nonmetallic elements such as oxygen and nitrogen; for example, as impurities in liquid metal systems, during accidental exposure to air at high temperature, and contamination during welding or fabrication. Other concerns include the relatively limited materials data base for this alloy system, the limited experience with fabrication and welding, and the material cost.

The V-15Cr-5Ti alloy exhibits many favorable characteristics for the fusion reactor application and, therefore, is currently suggested as a reference alloy for evaluation. Further investigations may provide more optimized alloys with improved performance characteristics. This paper presents a summary of the structural material requirements and an evaluation of vanadium-base alloys for fusion reactor applications. For cases where insufficient data exist for reliable evaluation, projections based on available information are presented. Further effort will be required to verify and more reliably predict the alloy performance for conditions of interest.

II. Structural material requirements and considerations

The first wall/blanket structure of a fusion power reactor must operate for acceptable lifetimes in the severe radiation, thermal, chemical, stress, and electromagnetic environment characteristic of a fusion reactor core. As such, the structural material will have a major impact on both the economics and the safety features of fusion power. Table 1 presents a summary of critical structural material requirements and a qualitative evaluation of selected vanadium base alloys. The performance characteristics for which vanadium base alloys are believed to provide significant advantages compared to other candidate alloys, viz., austenitic and ferritic steels, include: high temperature operation, higher surface heating capability, superior neutronic properties, potentially better radiation damage resistance, and superior corrosion resistance in liquid metals. In addition, the safety analysis conducted as part of the Blanket Comparison and Selection Study (BCSS) [1] indicated some inherent advantages of a vanadium alloy structure. Areas where vanadium base alloys are considered acceptable or the desired performance characteristics can be accommodated by design include: resources, fabrication, welding, and compatibility with hydrogen, air, and water. Based on current data and/or design philosophy, use of vanadium-base alloys with helium coolant does not appear feasible.

Table 1,

III. Candidate alloy selection

The data base for vanadium alloy systems is not sufficient at this time to identify the optimum alloy composition, however, existing data indicate that certain alloys exhibit more favorable characteristics for fusion applications. Numerous scoping alloys were evaluated in the fast breeder cladding program during the 1960's.[2-9] Major efforts were conducted at Argonne National Laboratory, Westinghouse Electric Company and Karlsruhe (KFK), West Germany. The Argonne effort focused on simple solid-solution-strengthened alloys of the vanadium-chromium-titanium system. The Westinghouse effort focused on precipitation strengthened alloys which led to the development of the VANSTAR alloys. The Karlsruhe effort focused predominantly on the V-Cr-Ti and V-Nb-Ti systems with more recent work on the V-Ti-Si system. Much of the data from these programs is summarized in Refs. [10] and [11].

On the basis of the limited data, the second generation V-15Cr-5Ti alloy developed at Argonne appears to exhibit superior characteristics for fusion reactor applications and is, therefore, suggested as the current reference for the vanadium alloy system. General features of this alloy are summarized as follows:

- This is a solid solution strengthened alloy.

- Mechanical properties of the V-Cr-Ti alloys are relatively insensitive to sizable compositional variations, which should decrease the sensitivity to solute segregation by radiation or chemical effects.

- Relatively high concentrations of interstitial impurities (> 5000 appm O, N, C or H) are required to raise the DBTT above room temperature.

- This alloy exhibits superior creep and fatigue properties compared to most other alloys tested.

- Titanium (>1%) substantially improves the resistance to irradiation-induced swelling.

- Titanium improves the fabricability.

- Chromium improves the creep strength and oxidation resistance.

- This alloy exhibits fine-grained weld microstructure.

- Vanadium, chromium, and titanium meet the low activation criteria.[12]

More optimized alloy compositions may evolve from further research and development. Also, variations in thermomechanical treatment may be used to improve selected performance characteristics of this alloy. In the current evaluation the V-15Cr-5Ti alloy is considered representative of a partially optmized vanadium-base alloy. Important characteristics of this alloy are summarized in more detail in the following sections. In many cases it is necessary to compare the properties or predicted performance characteristics of this alloy with the other candidate alloys, viz., austenitic and ferritic steels, to provide a more meaningful evaluation.

IV. Resources/considerations

The resources and availability of vanadium are important considerations for a fusion-reactor structural material since relatively large quantities will be required for a fusion economy. Vanadium is a moderately abundant material in comparison with other transition metals that are typically used for structural alloys. The relative abundance of vanadium is:[13]

- Less than: Al, Fe, Ti, Mn
- Comparable to: Zr, Cr
- Greater than: Ni, Cu, W, Nb, Mo

The largest known resources are located in:[14]

- United States: 20×10^9 kg
- South Africa: 15×10^9 kg
- USSR: 8×10^9 kg
- Canada: 6×10^9 kg

Based on results from the Blanket Comparison and Selection Study,[1] the vanadium needs for 1000 GWe for 40 years (assuming 5 year blanket life and 40 year reactor life with no material recycle) would be approximately 1% of the known resources in the United States.

Production methods for high-purity vanadium were developed in the 1960's. Although current production is limited, substantial capability exists since facilities currently used for niobium and tantalum production could be converted to vanadium should a large demand arise. The estimated cost of fabricated vanadium alloy (V-15Cr-5Ti) used for the economic analysis in the BCSS was $240/Kg, which is considerably higher than that for the austenitic and ferritic steels.

V. Physical properties

The physical properties of vanadium and selected alloys are reasonably well known. Since most physical properties are not sensitive to moderate compositional variations, data for similar types of alloys are generally regarded as representative of V-15Cr-5Ti. Selected properties considered representative of the reference alloy are summarized in Table 2.[15-19] Similar properties for austenitic (Type 316) and ferritic (HT-9) steels are listed for comparison. The vanadium alloy is characterized by a higher melting temperature and lower density than the steels. Also, vanadium alloys exhibit lower thermal expansion and higher thermal conductivity than the steels. The electrical resistivity is lower than that for the steels and the specific heat is similar to that for Type 316 stainless steel.

Table 2.

VI. High temperature operation

An important advantage of vanadium alloys relative to the steels is the potential for higher temperature operation. Several temperature limiting phenomena correlate with the melting temperature of the structural material. As indicated in Table 2, the melting temperature for the vanadium alloy is over 450°C higher than that for the steels. Since several temperature limiting factors correlate with 0.4 T_m to 0.5 T_m, a temperature advantage of 150-200°C may be expected for the vanadium alloy.

Figure 1 is a plot of the temperature dependence of the ultimate and tensile yield strengths of the V-15Cr-5Ti alloy.[29-22] At temperatures below 500°C the ultimate and yield strengths of V-15Cr-5Ti are comparable to 25%

cold-worked Type 316 stainless steel and normalized and tempered HT-9 ferritic steel. The strength of both steels is considerably enhanced compared to annealed material by the reference thermo-mechanical treatment; e.g., the yield strength of cold-worked austenitic steel is approximately a factor of four greater than for annealed material at 500°C. The data for the V-15Cr-5Ti alloy are for the stress relieved condition. Optimization of the thermomechanical treatment, e.g., strain hardening, could possibly enhance the tensile strength of the vanadium alloy. The most important difference in the tensile properties of the three alloys relate to the temperature at which the tensile strength is substantially decreased; viz., ~500°C for HT-9, ~600°C for 316 SS and ~800°C for V-15Cr-5Ti.

The measured uniform elongation of the V-15Cr-5Ti alloy is ~23% at room temperature and 11-16% at temperatures of 450-800°C.[20-22] The total elongation is ~28% at room temperature and 12-20% at temperatures of 450-800°C. The brittle-ductile transition temperature has not been determined for the V-15Cr-5Ti alloy in either the unirradiated or irradiated condition. The effect of hydrogen, oxygen, carbon, and nitrogen impurities on the brittle-ductile transition temperature (DBTT) for vanadium is shown in Figure 2.[23] Because of the strong chemical affinity of the titanium in the alloy for these impurities and the projected environmental conditions in the fusion energy device, the DBTT for either the unirradiated or irradiated material is not expected to increase above room temperature.

The thermal creep properties of the vanadium alloy are substantially superior to those of the steels. A comparison of the creep properties is best represented by the Larsen-Miller plot in Fig. 3. Again, shown for comparison are data for the austenitic and ferritic steels. Data for three vanadium-base alloys obtained by Gold et al.,[23,24] indicate vastly superior creep properties of the vanadium alloys at higher Larsen-Miller parameters, i.e., higher temperatures and/or longer times. Gold, et al. also obtained superior creep properties for the V-15Cr-5Ti alloy compared to VANSTAR-7 and V-20Ti.

VII. High surface heat flux capability

Because of the favorable physical properties, viz., higher thermal conductivity and melting temperature and lower thermal expansion coefficients compared to the steels, vanadium alloys should accommodate higher thermal heat fluxes than the steels. The calculated thermal stress factor, which is a measure of the allowable heat load, is plotted in Fig. 4 for the three alloys. A higher stress factor indicates higher heat load capability. Majumdar has calculated the allowable design stress limits for the three alloys.[1] These results (Table 3), which include predicted thermal and radiation creep responses for each alloy, indicate higher allowable stresses for V-15Cr-5Ti, particularly at higher temperatures.

Only limited data exist on the fatigue properties of vanadium base alloys. The results of Li [26] plotted in Fig. 5 indicate superior fatigue properties of V-15Cr-5Ti compared to 20% cold-worked Type 316 stainless steel. The better fatigue properties should also enhance the heat flux capability.

Table 3.

VIII. Nuclear properties

Critical neutronic properties for the V-15Cr-5Ti alloy are compared with those for the steels in Table 3. Although these values will vary somewhat with reactor design and blanket composition, the trends remain similar under most conditions. Values given were calculated by Gohar and Jung for the BCSS.[1] The radiation damage rate (dpa = displacement per atom) for all alloys are similar; however, the gas production rates and the nuclear heating rates are lower for the V-15Cr-5Ti alloy compared to both steels. The lower gas production rates may result in reduced radiation damage effects, while the lower nuclear heating rate provides an advantage for first wall applications where thermally induced stresses are limiting. Also, the vanadium alloy provides a modest advantage for tritium breeding (TBR in Table 3).

IX. Corrosion/compatibility

Corrosion/compatibility considerations for fusion reactor applications include liquid metal corrosion, water corrosion, compatibility with impurities in helium, hydrogen interactions, and reactivity with air.

IX.A Liquid metal corrosion

The data base for corrosion of vanadium alloys in liquid metals is very limited. Therefore, the projected corrosion characteristics of vanadium and vanadium base alloys in lithium and Li-Pb are based on (1) very limited experimental data for the systems of interest, (2) reported corrosion data for vanadium alloys in sodium, (3) reported corrosion data for similar refractory-metal alloys, viz., niobium and tantalum alloys in lithium, and (4) reported low solubilities of group V and VI refractory metals in lithium and lead.

The data on corrosion of vanadium alloys in lithium derive primarily from (1) forced-circulation loop tests conducted by Pratt-Whitney and others in the late 50's and early 60's as part of the space power program;[27] (2) capsule tests conducted in the early 1960's at Oak Ridge National Laboratory as part of the high temperature materials program,[28] and (3) forced-circulation loop tests conducted at Argonne National Labortory in the late 70's and early 80's as part of the fusion materials program.[29] The most relevant data related to the current vanadium-lithium blanket concepts is the high temperature results from Pratt-Whitney.[27] Several refractory metals and alloys were tested. Unalloyed vanadium was exposed for 1170 h in a forced circulation loop at a lithium velocity of 4 m/s, maximum temperature of 870°C, and a loop ΔT of 220°C. The reported corrosion indicated for vanadium was "nil", but this is not well defined. Since the lowest corrosion value reported for other alloys in this series of tests is 0.15 mg/cm^2, it seems reasonable to assume that the designation "light" corresponds to <0.1 mg/cm^2 and "nil" probably corresponds to approximately 10^{-2} mg/cm^2 or less. A corrosion rate of 10^{-2} mg/cm^2 in 1000 h corresponds to ~0.1 $mg/m^2 \cdot h$ or ~0.1 μm/y.

The limited capsule tests conducted at Oak Ridge National Laboratory [28] (816°C) confirm the corrosion resistance of vanadium to lithium. Redistribution of nonmetallic elements, e.g., oxygen, was observed in these tests; however, vanadium did not exhibit the severe penetration rate when oxygen was present as was observed for tantalum and niobium.

The forced circulation loop tests at Argonne (600-650°C) further confirmed the corrosion resistance of vanadium and V-15Cr-5Ti alloy in lithium.[29] Very small weight changes in the vanadium samples were observed. The primary focus of these tests was on the redistribution of nonmetallic impurity elements. Scoping tests indicated that the tensile properties of high-purity alloys were not substantially altered after exposures at 600 to 650°C for up to 500 h. However, degradation of the ductility was observed in some less pure alloys after exposure. It was not clear from the limited tests whether the loss of ductility was caused by thermal aging or the lithium environment. The test loop, which was constructed of V-15Cr alloy, was operated for a total of ~30,000 h at a maximum temperature of 600-650°C.

Based on analyses conducted as part of the BCSS,[1] the predicted corrosion curve for the V-15Cr-5Ti alloy in lithium is give in Fig. 6. Future work will be required to confirm these predicted corrosion rates. Also, the ability to control nonmetallic elements at acceptable levels in a large heat transport system must be demonstrated.

No data on the corrosion of vanadium alloys in Li-Pb has been reported in the literature. Based on the low solubilities of the group V and VI refractory metals in both lithium and lead, good corrosion resistance for vanadium is predicted. Initial scoping tests at Argonne National Laboratory indicate no measurable corrosion of the V-15Cr-5Ti alloy after 2300 h exposure at ~430°C.[30] Additional tests are currently in progress.

IX.B Water corrosion

It has generally been concluded that vanadium alloys could not be used in pressurized water-cooled systems because of excessive corrosion. An evaluation of recent scoping data concludes that selected vanadium alloys may be acceptable for use in pressurized water. Observed corrosion rates in 288°C water for 500 hours are less than an order of magnitude greater than those typically observed for austenitic stainless steels.[31] The potential for stress corrosion has not been evaluated.

IX.C Gaseous (He) corrosion/compatibility

Both the thermodynamics and kinetics of oxidation processes must be considered in the evaluation of the compatibility of vanadium and vanadium-base alloys in helium with anticipated low impurity concentrations (primarily O_2, H_2O and CO_2). Based on fundamental thermodynamic data, vanadium will oxidize at very low oxygen partial pressures, e.g., $<10^{-40}$ atm at <650°C.[32] Embrittlement by oxygen, which occurs at ~5,000 to 10,000 appm, is predicted at even lower oxygen partial pressures.[23] The potentials for oxidation of vanadium alloys will generally be similar. Since impurity concentrations necessary to maintain these low oxygen partial pressures are not considered attainable in a large helium heat transport system, it does not appear that vanadium could be used in a helium-cooled system unless the oxidation or oxygen penetration rates are sufficiently controlled by kinetic processes.

Oxygen penetration rates calculated from oxygen diffusion data indicate that a significant fraction (~10%) of a 2.0 mm wall would be embrittled in 1 year at temperatures above ~450°C. In reasonable agreement with the calculated results, recent data by Loomis [33] for vanadium alloys exposed to helium with controlled impurity levels (1 ppm H_2O and 1 ppm H_2) indicate penetration rates of ~0.5 mm/y at 550°C. Therefore, use of vanadium-base alloys in "commercial" grade helium does not appear feasible at temperatures of interest (>500°C), unless the oxidation problems can be controlled by hydrogen additions. This does not appear to be an acceptable solution because of the increased potential for hydrogen embrittlement and/or tritium containment problems.

IX.D Hydrogen compatibility

The three primary concerns related to hydrogen compatibility are hydrogen embrittlement, excessive tritium inventory, and tritium permeation. In general, the fundamental data on hydrogen solubility, hydrogen permeability and effects of hydrogen on the ductile-brittle transition temperature of vanadium are reasonably well established. Limited data indicate that the properties of V-15Cr-5Ti do not differ greatly from those of unalloyed vanadium.[29] The solubility of hydrogen in vanadium is given by:[22]

$$S \text{ (at fraction)} = 6.08 \times 10^{-4} \exp \left[\frac{3950}{T}\right]$$

At 1 Pa hydrogen pressure the equilibrium hydrogen concentration in vanadium at 500°C is ~300 wppm. To give perspective, the projected hydrogen pressure in the plasma chamber of a fusion reactor is $\sim 10^{-3}$ Pa and the hydrogen pressure in lithium corresponding to 1 wppm is $<10^{-6}$ Pa.[35] Experimental results have shown that the equilibrium hydrogen concentration in V-15Cr-5Ti is approximately twice that in unalloyed vanadium at 600°C.[29]

Loomis has reported that >5000 appm hydrogen is required to raise the DBTT of vanadium above room temperature.[23] Similar data for the alloys have not been reported.

Hydrogen permeation rates for vanadium are relatively high compared to the steels.[36] Therefore, tritium containment is an important consideration.

IX.E Reactivity with air

Since vanadium will react with air and oxygen at elevated temperatures, a vanadium alloy structure must be protected from air at elevated temperatures. Scoping studies indicate that a short term exposure to with air in the event of an accident is not severe at temperatures below 650°C.[37] The lower oxides, VO, V_2O_3 and VO_2 all melt at ~2000 K; however, the higher oxide, V_2O_5, melts at a relatively low temperature, i.e., 943 K.[32] The possible consequences of formation and melting of this oxide under possible accident conditions is not clear at this time. Piet [37] has reported considerably higher rates of attack of V-15Cr-5Ti with air when the temperature exceeds ~650°C.

X. Radiation damage effects

The primary radiation damage considerations for a fusion reactor structural material relate to dimensional instabilities resulting from swelling or creep, and effects on mechanical properties such as embrittlement or changes in strength. All of these effects may be influenced by displacement damage and/or transmutation reactions. Also, synergistic effects with stress, temperature, chemical environment, etc. may be important. The current data base for vanadium alloys, or even the steels, is inadequate to fully define the material responses to the fusion radiation environment. However, existing data are sufficient to indicate trends and severity of the dominant effects and to define those effects that are likely to be the most important. Since a high flux source with a fusion spectrum is not available, the radiation data base for all alloys is based primarily on fission reactor irradiations and ion irradiations. The V-15Cr-5Ti alloy was originally developed in the fast breeder reactor program. Although this alloy was found to be highly radiation damage resistant, it does not necessarily represent an optimized alloy.

X.A Transmutations

A primary consideration in the effects of radiation for fusion applications compared to fission reactor applications relate to nuclear transmutation effects. The data base for these reactions are reasonably well established. The generation of gaseous products, primarily helium and hydrogen, have received the most attention. As indicated in Table 3, the generation rates for helium and hydrogen in V-15Cr-5Ti are considerably less than those in the steels. If one assumes that the effects of these transmutation products are, to a first order similar for each of the candidate alloys, the lower generation rates inherent in the vanadium alloy would be an advantage. Because of the higher solubility and mobility of hydrogen in vanadium, effects of hydrogen on properties are generally predicted to be of less concern than for the ferritic steels.

The heavy element transmutations, as well as solute segregation, may also be important. The V-15Cr-5Ti alloy exhibits perceived advantages since the transmutation products of the three alloying elements consist almost exclusively of the same three elements; the only other product of significance is a small scandium contribution. In addition, as stated in Section X.D, this ternary alloy system appears to be insensitive to quite substantial compositional variations.

X.B Radiation-induced swelling

The projected swelling response of the V-15Cr-5Ti alloy is based on neutron (fast reactor) and ion irradiation data. Vanadium and vanadium alloys exhibit peak swelling at ~525°C under fast neutron irradiation. Neutron irradiation to ~20 dpa for V-15Cr-5Ti and ~35 dpa for V-20Ti indicated no tendency for swelling. Experiments have shown that titanium concentrations of only a few percent in the alloy greatly suppress swelling compared to unalloyed vanadium.[6] Swelling resistance has been demonstrated in a number of vanadium alloys, including V-15Cr-5Ti and V-15Ti-7.5Cr irradiated to ~425°C and 30 dpa. A few isolated cavities were observed in both alloys after irradiation at 550 and 600°C to a fluence of 30 dpa. The low number density of the voids produced negligible swelling.[22,38]

Resistance of the vanadium-base alloys to swelling has been observed under both single and dual-ion irradiations at high damage levels. Ion irradiations using 3-4 MeV $^{51}V^{+}$ and $^{58}Ni^{++}$ ions on V-15Cr-5Ti over the temperature range of 400 to 720°C at damage levels of up to 250 dpa tend to verify the results obtained from the neutron irradiations at lower neutron damage levels.[38,39] Dual-ion irradiations (3-MeV $^{51}V^{+}$ + degraded 0.83-MeV He^{+} ions, 3 to 50 appm He/dpa or 3-MeV $^{58}Ni^{++}$ + 0.25-MeV He^{+} ions, 9.3 appm He/dpa) of the V-15Cr-5Ti alloy to 125 dpa result in negligible swelling (0.1%) for irradiation temperatures to at least 725°C.[38,39]

Experimental results on the swelling of vanadium and selected vanadium-base alloys are summarized in Fig. 7. Although these data are limited, comparison with swelling data for either PCA or HT-9 steels obtained under similar conditions indicate lower swelling for the V-Cr-Ti alloys. Effects of helium are also projected to be less for the V-Cr-Ti alloys since the helium generation rate is much less than for PCA or HT-9. In addition, Kumar [40] has calculated the theoretical swelling rate for vanadium based on an approach similar to that developed by Wolfer [41]. The calculated maximum swelling rate for vanadium (0.2%/dpa) is slightly lower than that for the ferritic steel. Observed swelling rates for vanadium and V-Cr-Ti alloys [38-41] are significantly less than the maximum calculated rate. Based on this limited data and the comparison with irradiation data for the other alloys, the projected lifetime for swelling of the V-Cr-Ti alloys is >250 dpa.

X.C Radiation creep

The radiation creep properties of the vanadium base alloys have not been measured. One might only project as a first-order approximation that the creep properties may be similar to other body-centered-cubic alloys, e.g., ferritic steels. Further investigations are needed.

X.D Effects of radiation on tensile strength

Only limited information exists on the effect of irradiation on the mechanical properties of the V-15Cr-5Ti alloy. Therefore, the predicted mechanical response of this alloy is based partially on results from other vanadium base alloys, e.g., V-20Ti, Vanstar 7 (V-9Cr-3Fe-1Zr), and other V-Cr-Ti ternaries. Gold and Harrod [11] have summarized most of the earlier data. In most cases the alloys have been stress relieved at temperatures of 900-1100°C prior to irradiation.

Increases in the ultimate and yield strength of several alloys have been observed after neutron irradiation at temperatures ~800°C and fluences of 10^{21} to 6×10^{22} cm^{-2} (0.5 to 30 dpa).[6,9,44,45] For example, the V-15Ti-7.5Cr alloy exhibited ~25% increase in yield stress when tested at 600°C, after irradiation at 600°C to a fluence of $\sim 4 \times 10^{21}$ cm^{-2} (~3 dpa).[43] As shown in Figs. 8 and 9, tensile properties of several ternary alloys, viz., V-2Cr-10Ti, V-5Cr-5Ti, V-5Cr-10Ti and V-15Cr-5Ti, are relatively insensitive to composition over the temperature range of 25-800°C after low fluence neutron irradiations.[9] Strengthening of all four alloys is observed after irradiation.

X.E Effects of radiation on ductility

Loss of ductility caused by radiation hardening, helium embrittlement or increases in the DBTT is a major concern for all alloys, including the vanadium-base alloys. Again, data for the vanadium alloy system are quite sparse; however, results from several investigations have been reported. The data generally indicate that although substantial reductions in ductility (total and uniform elongation) are observed in V-Cr-Ti, V-Ti and V-Cr alloys after irradiation, significant (a few percent) residual ductility is retained. Carlander [44] reported elongations of 8-20% for V-15Ti-7.5Cr at 25-750°C after irradiation to 3 dpa at 600°C. Bohm [9] reported total elongations of 2-3% at temperatures of 25-400°C after irradiation of V-15Cr-5Ti and three other V-Cr-Ti alloys at 100°C to ~1 dpa (Fig. 10). Higher residual ductilities were observed after testing at 400-800°C. Wiffen [46] reported total elongations for the Vanstar-7 alloy of >5% after irradiation at 70, 500 and 700°C to fluences of ~1 dpa and testing at temperatures of 25 to 650°C. Wiffen also reported similar results for V-10Cr after testing at 400 and 650°C. Several investigators [6,22,44,47,48] have reported even higher residual ductilities in V-Ti alloys after irradiation to ~30 dpa, e.g., typical uniform elongation of 5-10% and total elongation of 10-20%. Tanaka [47] has reported results on the effects of helium preinjection (on 90 and 200 appm) on the irradiated (17 dpa) properties of V-20Ti. Uniform elongations of 5, 12, and 3% were observed after irradiation and testing at 400, 575 and 700°C, respectively, with 200 appm He in the alloy. A significant helium effect was observed only at the highest temperature.

More recent irradiations of V-15Cr-5Ti at 375, 550 and 600°C to 5 dpa have indicated severe embrittlement when tested at 25 and 375°C.[45] This embrittlement is tentatively attributed to a high sulfur concentration (>3%), which was observed on the fractured surfaces. Additional investigations on unirradiated material from the same test heat have indicated extensive intergranular fracture with >10% sulfur on the fracture surface.[49] This heat of material also contained a high concentration (~1200 wppm) of oxygen. Intergranular fracture was not observed with higher purity V-15Cr-5Ti (unirradiated) when tested in a similar manner.

In general, the limited data indicate significant reductions in ductility after irradiation and/or testing at temperatures below 400°C. However, the residual elongations are typically similar to or greater than those exhibited by other candidate alloys. At higher temperatures (400 to 750°C, the ductility does not appear to be significantly affected. As for the case of most other alloy systems, data on the effects of helium (and other transmutation products) are even more sparse.

XI. Fabrication/welding of vanadium-base alloys

XI.A Fabrication experience

The fabrication of vanadium and vanadium-base alloys has been carried out on a rather limited basis. The primary working of as-cast ingots is generally accomplished by extrusion or forging at temperatures of 1000 to 1200°C (1832 to 2192°F.[50] The billet is typically encapsulated and sealed by welding in a Type 304 stainless steel container before primary forming in order to avoid interstitial element pickup from the atmosphere. Secondary forming operations, including rolling, swaging, and tube drawing, are usually performed at temperatures of 500°C (932°F) and below, and intermediate vacuum anneals are generally carried out at 800 to 1000°C (1472 to 1832°F), though temperatures as high as 1200°C (2192°F) may be used for some alloys. Tubing, sheet, and/or rod have been fabricated from a number of alloys, including V-20Ti, V-40Ti, V-15Cr, V-15Cr-5Ti, V-15Ti-5Ti, V-15Ti-7.5Ti, VANSTAR-7, VANSTAR-8, and VANSTAR-9, without undue difficulty.[29,50-52]

XI.B Welding of vanadium alloys

In general, the welding characteristics of vanadium and vanadium-base alloys have not been thoroughly investigated, and the parameters for optimum welds have not been defined. However, the limited experience available on the welding of these alloys generally indicates favorable weld characteristics, provided contamination by oxygen and nitrogen is avoided. Consequently, welding must be carried out under high vacuum or in an inert gas environment. To date, vanadium-base alloys have been successfully welded using electron beam welding (EBW) and gas tungsten-arc welding (GTAW), otherwise known as tungsten inert gas (TIG) welding, techniques. Resistance welding of 1.25-mm (0.050 in.)-thick sheet has also been reported.[53]

Among the earliest reported work on the welding of vanadium-base alloys is that of Rajala in 1961,[54] who successfully joined 1.25-mm (0.050 in.)-thick sheet of V-5Ti-20Nb by GTAW in a helium environment. Tensile specimens cut from the weldments failed in the heat-affected zone or the base metal, and no serious degradation in alloy properties as a result of welding was observed.

In the mid-1960's, several studies were conducted on the welding of vanadium-base alloys for aerospace and nuclear reactor applications. Bill [53] reported good weldability of a V-20Nb-4Ti-1Zr-0.07C alloy using GTAW techniques. Post-weld tensile tests showed the weldments to have strength properties equal to those of the base metal, and only a modest loss of ductility at and near the weld was noted in bend tests. Royster [55] performed both EBW and GTAW welding of V-20Nb and Nb-40V. Sound welds were obtained in both alloys by both techniques, although the V-20Nb alloy exhibited some slight cracking in bend tests.

Three alloys (V-7.5Cr-1.5Ti, V-15Cr-5Ti, and V-15Cr-7.5Ti) were successfully welded by Kramer et al.[51] for two different product forms. End plugs were joined to 6.6-mm (0.26 in.) diameter, 0.38-mm (0.015 in.) wall thickness tubing using GTAW procedures in Ar and He-Ar environments. The same alloys in the form of 1.5-mm (0.059 in.)-thick sheet were welded by EBW. Post-weld tensile tests and metallographic examinations indicated generally good quality welds, even though no serious attempt was made to optimize weld parameters. Similarly, Pollack et al. [56] produced satisfactory welds in unalloyed V and eight different vanadium-base alloys by GTAW. However, most of the alloys showed substantial increases in the bend ductile-to-brittle transition temperature (BDBTT) as welded, an effect apparently associated with the dissolution of interstitial O, N, and C during the welding thermal transient. Post-weld heat treatments reduced the transition temperatures to or below room temperature in all cases.

More recently, Smith et al. [29] successfully welded 12.5 mm (0.50 in.) OD x 1.25 mm (0.050 in.) wall thickness tubes of V-10Cr, V-15Cr, V-15Cr-5Ti, and V-10Ti by GTAW in helium. In addition, the dissimilar metal welds with V-20Ti/V-15Cr and V-15Cr/Type 304 stainless steel were made. Gold and Bajaj [57] have investigated in some detail the ductilities of V-20Ti, V-15Cr-5Ti, and VANSTAR-7 joined by GTAW in argon. While the first two alloys produced satisfactory weldments, VANSTAR-7 exhibited cracking in the fusion zone, suggesting that further optimization of welding parameters is needed. After welding, the V-20Ti had the lowest DBTT and V-15Cr-5Ti the highest. Glenn et al. [58] conducted tensile tests and metallographic examinations on electron beam welds of six different heats of nominally pure vanadium containing various interstitial levels. The effect of interstitial content on strength was significant, but the influence on ductility was less apparent, probably because of variations in grain size.

A number of studies have indicated that vanadium-base alloys can, in general, be welded without undue difficulty using GTAW and EBW procedures. Excessive interstitial element content can lead to weld embrittlement, but with proper precautions most vanadium-base alloys can apparently be welded without the need for post-weld heat treatment. Possible exceptions are some of the more complex alloys such as the VANSTARS. Further investigations are required to determine the sensitivities of alloy composition to weld characteristics and to define the optimum weld procedures and parameters. However, some perspective can be gained about the ability of achieving success by looking at the welding experience that exists for niobium alloys, which are comparable to vanadium in sensitivity for interstitial contamination.

XII. Summary

Although the data base is quite limited, existing data indicate that vanadium-base alloys, in particular the V-15Cr-5Ti alloy, are potentially attractive candidates for fusion reactor first wall blanket applications. Possible advantages compared to other candidate alloys, viz., austenitic and ferritic steels include:

- Higher temperature operation
- Higher surface heat load capability
- Low long-term activation
- Good liquid metal compatibility
- Radiation damage resistance

Critical areas for which projected performance appears acceptable are:

- Resources
- Fabrication/welding
- Hydrogen compatibility
- Compatibility with water

It is questionable whether vanadium alloys could be used in a large helium-cooled system at temperatures of interest because of either oxidation from impurities in helium and/or tritium containment considerations.

Considerable R&D will be required to better define the operating limitations of this alloy system and to optimize the alloys for fusion applications. However, results of this evaluation indicate that vanadium alloys may significantly improve the attractiveness of fusion as an energy source.

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Table 1.
Summary Evaluation of Critical Requirements for Vanadium Alloy Structure (V-Cr-Ti)

Performance Characteristics	Evaluation of Selected Alloys
Resources/Availability	A
Fabricability/Welding	A
Physical Metallurgy/Composition Sensitivity	S, A
High Temperature Operation	S
High Surface Heat Load Capability	S
Neutronic Properties	S
Low Activation	S, A
Radiation Damage Resistance	S, A
Liquid Metal Corrosion Resistance	S
Hydrogen Compatibility	A
Reactivity with Air	A
Compatibility with Water	A
Compatibility with He (impurities)	U

S: Potentially superior to other candidate alloys.
A: Considered acceptable or can be accommodated by design.
U: Considered unacceptable based on current data/design.

Table 2. Selected Physical Properties of Three Reference Alloys

	316 SS	HT-9	VCrTi
Melting Temperature, °C	1400	1420	1890
Density, g/cm^3	8.0	7.8	6.1
Poisson's Ratio	0.27	0.27	0.36
Linear Thermal Expansion, 10^{-6}/K			
400°C	17.6	11.8	10.2
500°C	18.0	12.3	10.3
600°C	18.3	12.6	10.5
Thermal Conductivity, W/m-K			
400°C	19.5	26.8	26.8
500°C	21.0	27.3	28.0
600°C	22.5	27.7	29.5
Electrical Resistivity, μΩ-m			
400°C	1.01	0.91[a]	0.67
500°C	1.06	0.99[a]	0.74
600°C	1.12	1.05[a]	0.81
Specific Heat, J/kg-K			
400°C	560	600	535
500°C	575	680	560
600°C	580	800	575

[a]Data for 410 SS.

Table 3. Properties of Structural Alloys

Candidate Alloys	Austenitic Steel PCA-CW	Ferritic Steel HT-9	Vanadium V-15Cr-5Ti
Physical Properties			
Melting Temp. (°C)	1400	1420	1880
Nuclear Properties[a]			
dpa/MW Y/m^2	11	11	11
appm He/MW Y/m^2	174	130	57
appm H/MW Y/m^2	602	505	240
Heating Rate (W/cm^3)	40	40	25
T-Breeding Ratio[a]	1.23	1.23	1.28
Thermal Stress Factor			
MW/m^2-mm (500°C)	3.2	4.8	9.8
Max. Surf. Heat Flux, MW/m^2 [b]	0.3	0.4	1.8
Design Stress Limit			
S_m (MPa) 500	205	175	220
S_m (MPa) 550	192	160	235
S_{mt} (MPa) (2 × 10^4 h, 100 dpa)			
500	100	155	165
550	85	100	165
700	---	---	165

[a]For lithium blanket.
[b]Idealized flat plate 5 mm thick with 50°C film coefficient, T_{out} = 400°C.

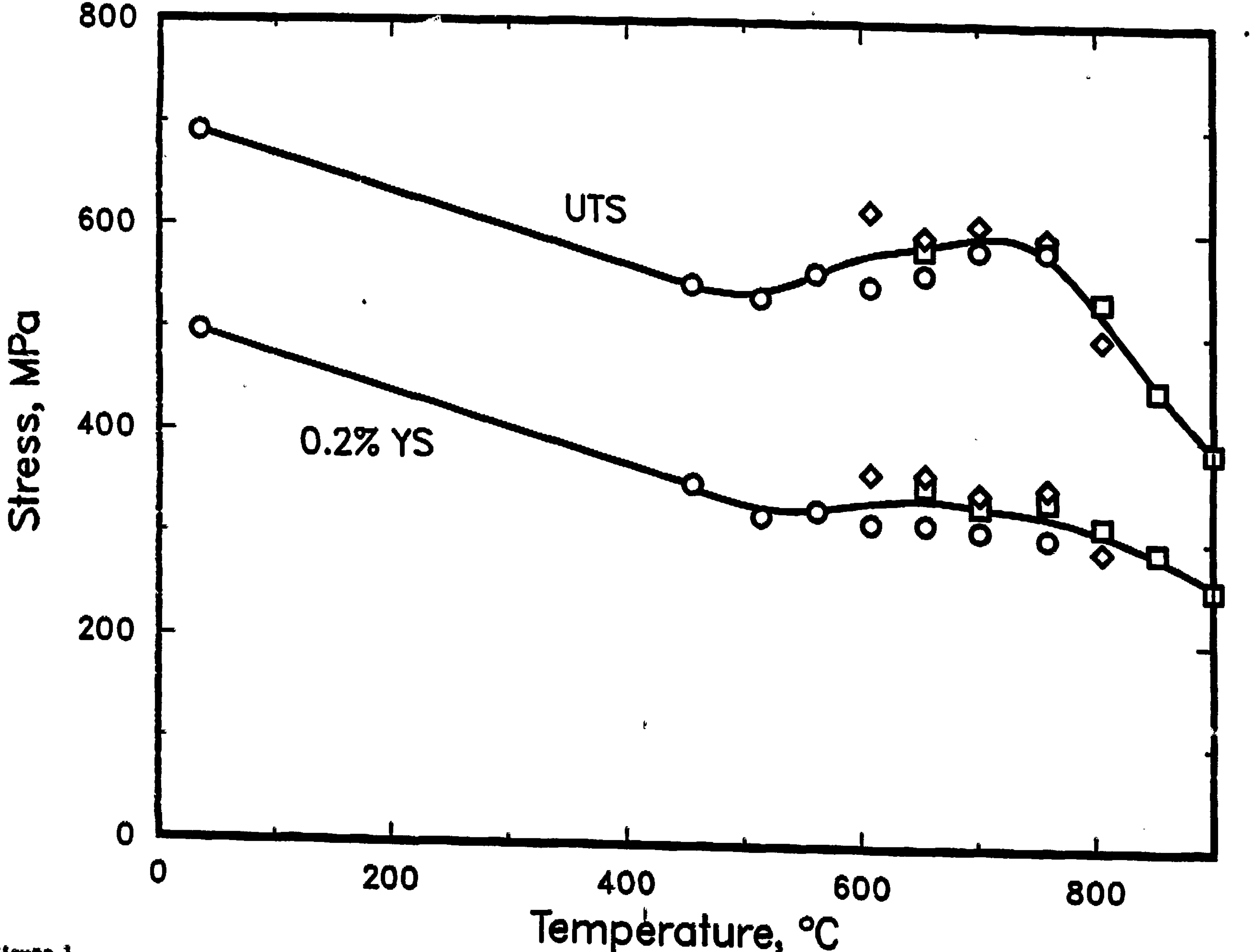
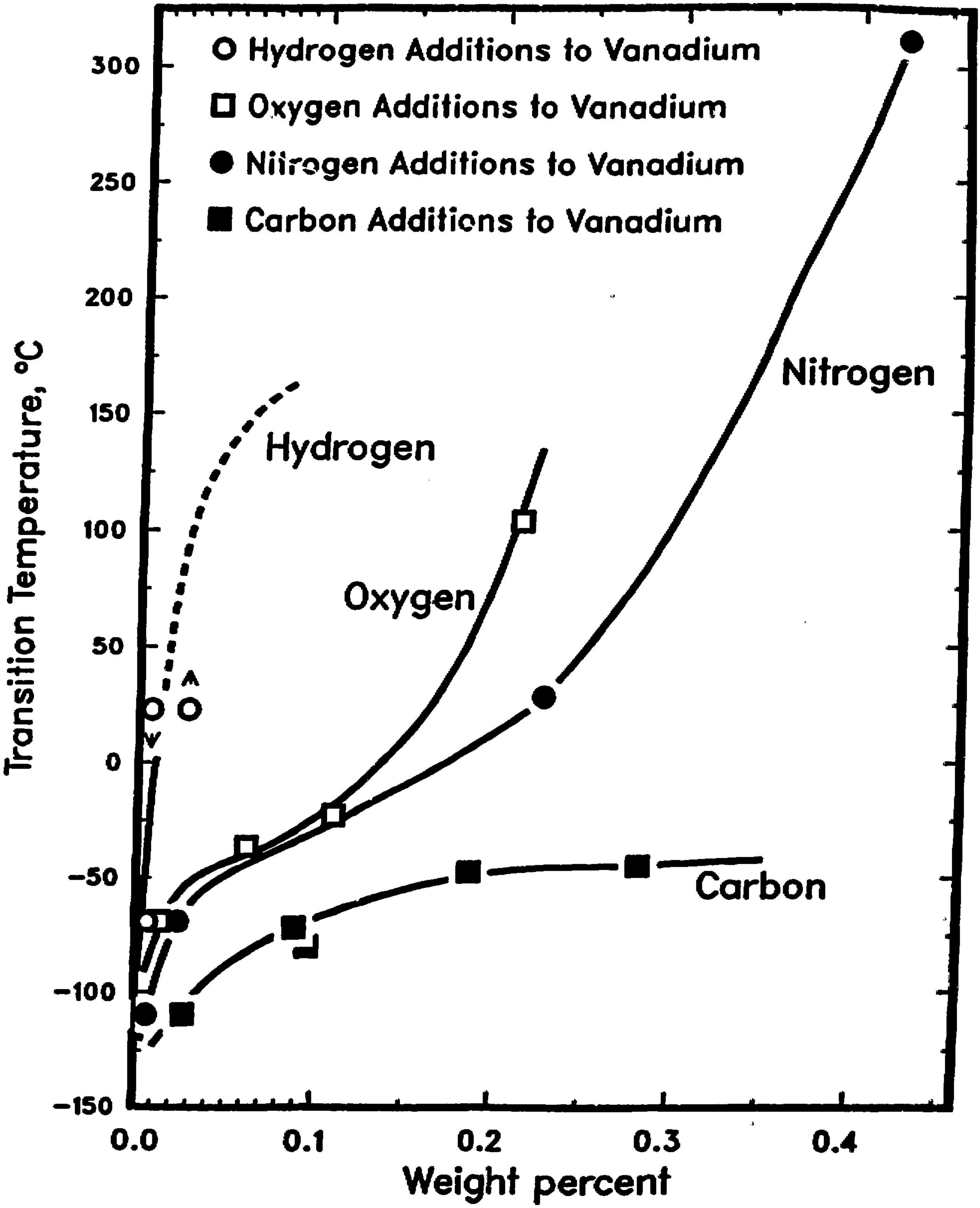
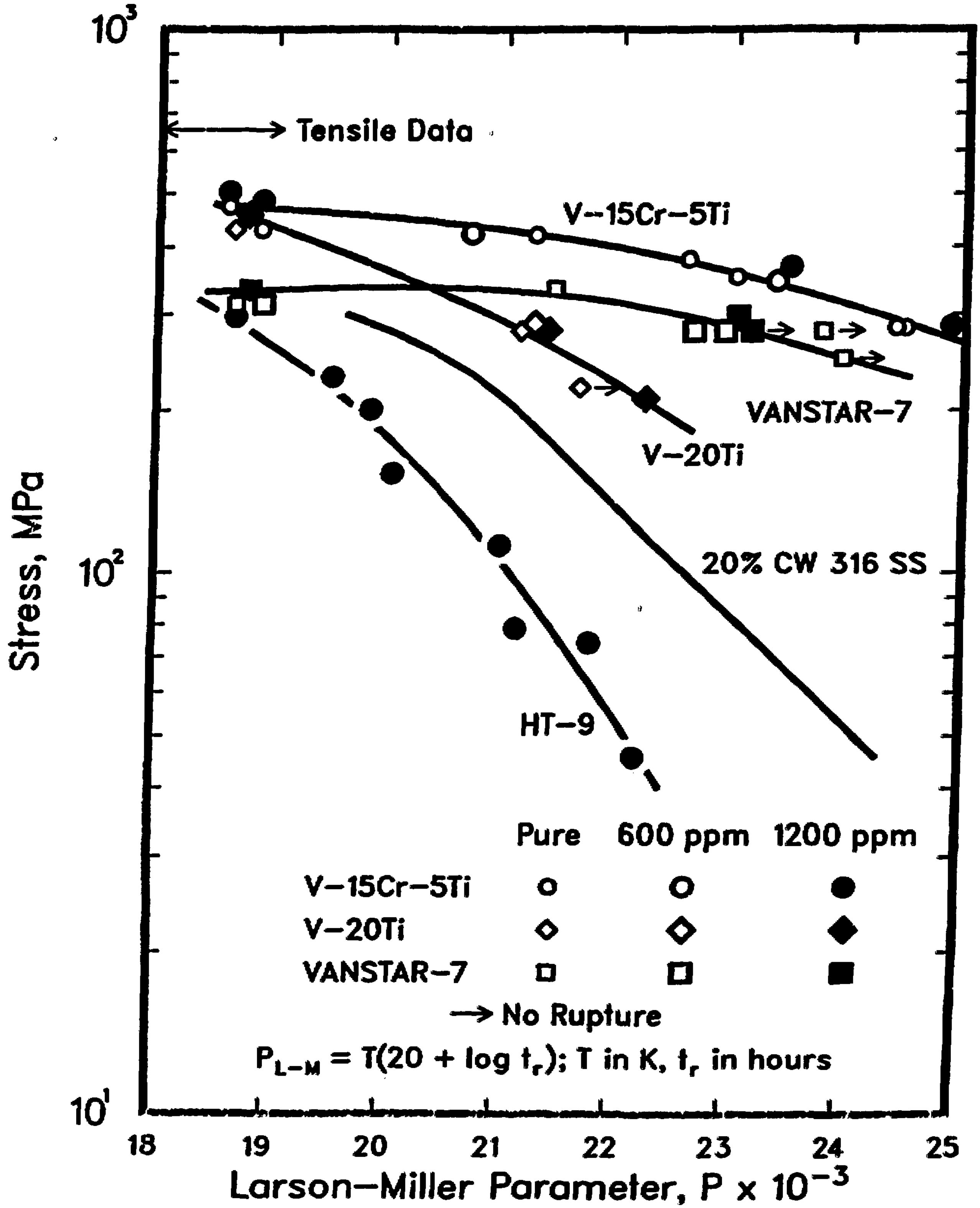

Stress, MPa
800
600
400
200
0
UTS
0.2% YS
0
200
400
600
800
Temperature, °C

Figure 1.



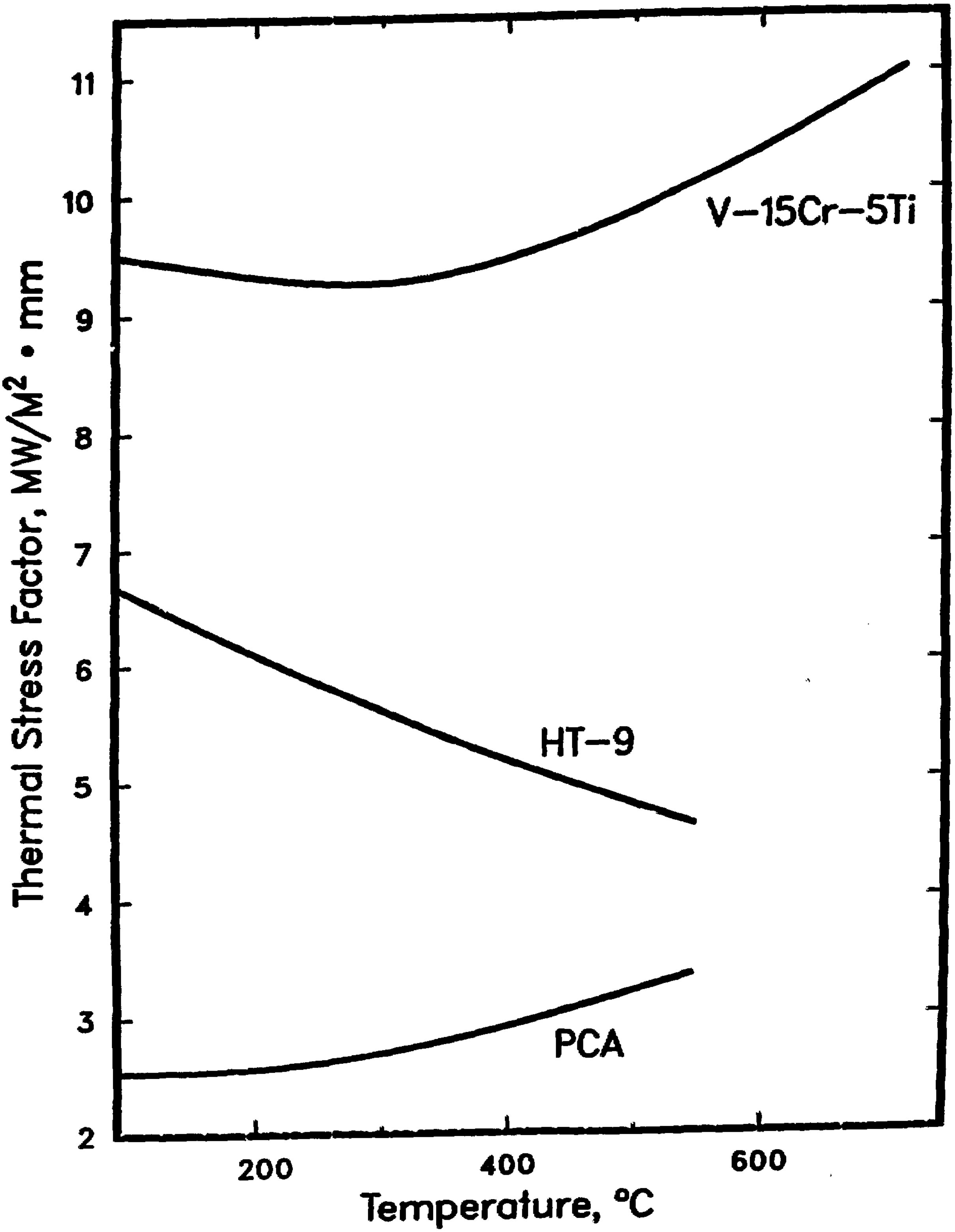
Hydrogen Additions to Vanadium
Oxygen Additions to Vanadium
Nitrogen Additions to Vanadium
Carbon Additions to Vanadium
Hydrogen
Oxygen
Nitrogen
Carbon
Transition Temperature, °C
Weight percent
300
250
200
150
100
50
0
−50
−100
−150
0.0
0.1
0.2
0.3
0.4

Figure 2.



Tensile Data
V-15Cr-5Ti
VANSTAR-7
V-20Ti
20% CW 316 SS
HT-9
Pure
600 ppm
1200 ppm
V-15Cr-5Ti
V-20Ti
VANSTAR-7
No Rupture
P_L-M = T(20 + log t_r); T in K, t_r in hours
Stress, MPa
Larson-Miller Parameter, P x 10^-3

Figure 3.



Thermal Stress Factor, MW/M² • mm
11
10
9
8
7
6
5
4
3
2
200
400
600
Temperature, °C
V–15Cr–5Ti
HT–9
PCA

Figure 4.

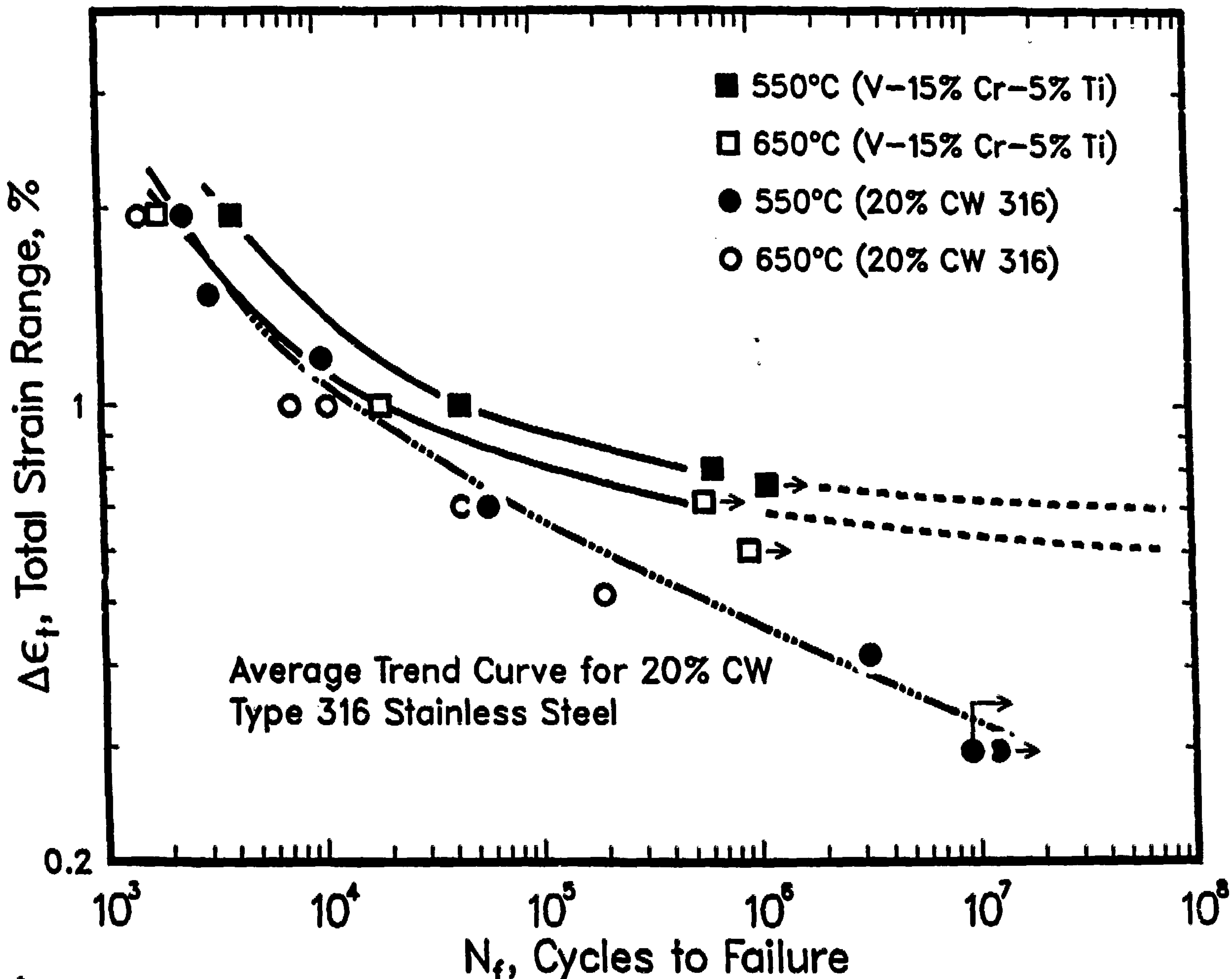
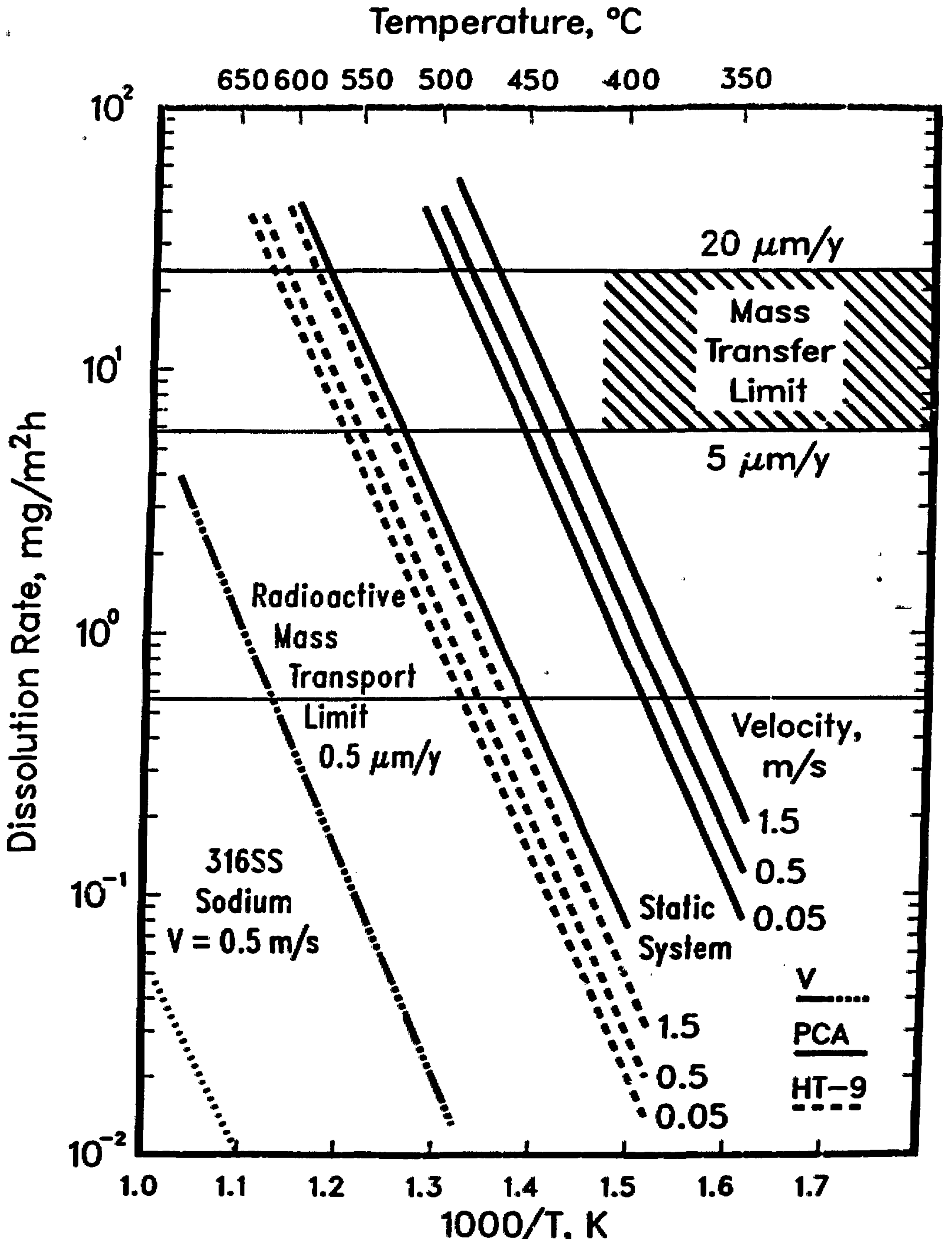

550°C (V–15% Cr–5% Ti)
650°C (V–15% Cr–5% Ti)
550°C (20% CW 316)
650°C (20% CW 316)
Average Trend Curve for 20% CW
Type 316 Stainless Steel
Δε_t, Total Strain Range, %
1
0.2
10^3
10^4
10^5
10^6
10^7
10^8
N_f, Cycles to Failure

Figure 5.



Temperature, °C
650 600 550 500 450 400 350
10^2
10^1
10^0
10^{-1}
10^{-2}
Dissolution Rate, mg/m^2h
20 μm/y
Mass Transfer Limit
5 μm/y
Radioactive Mass Transport Limit 0.5 μm/y
Velocity, m/s
1.5
0.5
0.05
316SS Sodium V = 0.5 m/s
Static System
1.5
0.5
0.05
V
PCA
HT−9
1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7
1000/T, K

Figure 6.