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## Abstract

Vanadium alloys have been identified as a leading candidate low-activation structural material for fusion first-wall blanket applications. Candidate vanadium alloys exhibit favorable safety and environmental characteristics, good fabricability, high temperature and heat load capability, good compatibility with liquid metals and resistance to irradiation damage. The focus of the vanadium alloy development program has been on the vanadium-chromium-titanium (0-15% Cr, 1-20% Ti) alloy system. Investigations include effects of minor alloy elements such as Si, Al, and Y and substitution of iron for chromium in the ternary alloy. A V-4Cr-4Ti alloy is currently regarded as the reference alloy.

Significant progress has been made in the development of vanadium alloys for fusion applications. Two production-scale heats (500 kg and 1200 kg) of the V-4Cr-4Ti alloys have been produced with controlled levels of impurities. The baseline properties of the 500 kg heat are similar to those of the previous laboratory-scale heats. Additional data have been obtained on baseline tensile and fracture properties. Results obtained on several heats with minor variations in composition indicate high uniform and total elongation of these alloys at temperature from RT to 700°C. Results obtained to date indicate that the V-Cr-Ti alloys are resistant to swelling and embrittlement after exposure to relatively high neutron fluences at temperatures of 400-600°C. The properties are not significantly different when modest amounts of helium are generated during neutron irradiation by the Dynamic Helium Charging Experiment method. However, recent results have indicated that these alloys are susceptible to irradiation embrittlement at lower temperatures. Additional irradiation experiments are in progress to investigate these effects at temperatures of 200-400°C. This paper presents an update on the experimental results on candidate low activation vanadium alloys.

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## 1. Introduction

Vanadium-base alloys have been identified as an attractive high performance first-wall/blanket structural/material for fusion power plant applications[1-6]. Considerable progress has been made on the development of vanadium alloys for the fusion applications even though the effort is only a small fraction of the effort that has been expended on ferritic steels. Results to date from R&D and design studies indicate that vanadium alloys offer a potential for superior performance and long lifetime with favorable safety and environmental features. The most likely application is with liquid metal-cooled systems. The vanadium alloy development program has been focused on the V-Cr-Ti-Si system with an emphasis on compositions in the range V-(0-9)%Cr-(3-6)%Ti-(0-1)%Si (compositions in wt %). An alloy with a composition of V-4Cr-4Ti has been selected as the current reference for the development program. This paper presents a summary of recent progress related to production and fabrication performance limitations, and safety and environmental features. Critical issues that require further investigation and development are identified. Related issues associated with the self-cooled lithium/vanadium blanket concept are presented in a companion paper[7].

## 2. Key Features and Alloy Selection

A considerable data base has been developed which indicates that vanadium alloys provide superior performance compared with other options for the first wall-blanket structure of a magnetic fusion power plant[8-14]. Vanadium alloys will accommodate higher surface heat fluxes and neutron wall loads and can be operated at temperatures to ~ 700°C, which provides for high efficiency energy conversion. The lifetime limits for vanadium alloys in the fusion environment have not been determined; however, this alloy system exhibits several characteristics that should contribute to long lifetime, viz., low transmutation rates, good creep strength and apparent resistance to irradiation-induced swelling. These alloys exhibit high ductility and can be fabricated into sheet, plate and tubing by conventional procedures; however, care must be exercised to avoid oxygen contamination during any elevated temperature processing. Vanadium alloys are weldable. This alloy system exhibits favorable safety and environmental features including low long-term activation and the potential for recycle of this material which will minimize waste management requirements.

The vanadium alloy development program has been focused primarily on compositional variations and variations in processing and thermomechanical treatment (TMT). Investigations have primarily involved V-(0-15)Cr-(0-20)Ti-(0-1)Si (wt%). Concentrations of 3-5% Ti are desirable for swelling resistance and fabricability. Recent investigations of V-(0-9) Cr-(4-5) Ti, which have been conducted to evaluate effects of Cr, indicate that Cr enhances tensile strength, creep strength and compatibility with several environments. However, the higher Cr alloys are more sensitive to embrittlement. Alloys of V-3Ti with variations in Si content have been investigated to determine effects of Si. In addition, Japanese programs have included additions of Al, Si and Y to the V-4Cr-4Ti alloy system and substitution of Fe for Cr (V-Fe-Ti) in similar alloy systems. The Russian program has included V-5Cr-10Ti alloy which provides increased tensile strength. Additional effort is required to evaluate effects of nonmetallic elements oxygen, nitrogen, carbon, and hydrogen. The primary tradeoff for optimal compositions involves strength versus ductility or toughness, the desirable operating temperature limits, and the coolant/breeder system.

## 3. Production and Fabricability

Substantial progress has been made in the scale up of production of vanadium alloys. Early investigations were conducted on alloy heats of about 10-15 kg. More recently a 500 kg heat of V-4Cr-4Ti was produced by Teledyne Wah Chang for the US fusion materials program. Baseline mechanical properties of this alloy are similar to those of the laboratory scale heats. Recently, a 1200 kg heat of V-4Cr-4Ti alloy has been produced by Wah Chang for General Atomics (GA). This heat will be used to fabricate a divertor plate for the DIIID Tokamak at GA[15].

Certain trace elements, particularly niobium and molybdenum, must be maintained at low levels (≤ a few parts per million) to achieve the goal of a low activation material. Detailed analyses indicate that several of the laboratory-scale heats were very low in Nb and Mo, e.g., analyses of the V-9Cr-5Ti alloy indicated 0.4 wppm Nb and 2 wppm Mo. However, the production scale heats, which were produced from available raw materials and with facilities also used for niobium alloy production, contain concentrations of Nb and Mo considerably above the desired levels. Producers believe they can attain the desired trace element impurity levels in vanadium alloys by selection of raw materials and by controlled processing.

Procedures for fabrication of plate and sheet forms have been developed and 1-6 mm-thick sheet/plate have been consistently produced for test material without significant contamination during processing. Tubing has been produced but in very limited quantities. Further development and scale up of processes is required. Vanadium alloys have been welded by several methods, viz., gas-tungsten-arc (GTA), electron beam, laser, diffusion, and inertia techniques. Experience on welding is limited and further development is required to optimize weldment properties. Results obtained suggest that contamination can be avoided during welding if precautions are taken. Post-weld heat treatments have been shown to improve weld properties; however, further development is required to define optimum post-weld heat treatment requirements. Practical aspects of component fabrication have been demonstrated by construction of liquid metal test loops. Work is in progress to fabricate a water-cooled divertor plate for the DIIID tokamak at GA[15].

## 4. Performance Limits

Design studies based on available data indicate that fusion power plants with neutron wall loads of $5 MW/m^2$ or higher can be achieved with vanadium/lithium systems. Current data support an operating range of 400-700°C. As shown in Figure 1, the tensile strength of vanadium alloys is relatively insensitive to temperature for the range 300-700°C. Increased strength is obtained by increasing Cr or Ti concentrations. The candidate alloys also exhibit high ductility. The ductile-brittle transmission temperature (DBTT) for the V-4Cr-4Ti alloy determined by 1/3 size Charpy specimens is more than 200°C below room temperature (see Figure 2). These alloys exhibit much higher tensile ductility as indicated by uniform elongations of 10-20% for temperatures up to 700°C (see Figure 3) compared to values for ferritic steels[16]. Results for these alloys indicate that the reduction in area from tensile tests is high (>70% up to 600°C). Recent results show a modest strain rate sensitivity (strain rates of $10^{-4}$-$10^{0}\,s^{-1}$) which is in agreement with previous data on unalloyed vanadium. The vanadium alloys have been shown previously to exhibit high creep strengths to 650-700°C.

Vanadium alloys which contain a few percent titanium have been shown to be highly resistant to radiation-induced swelling. A major issue with vanadium alloys, as with all candidate materials for use in the fusion system environment, relates to the extent of radiation-induced embrittlement. Much of the data on the sensitivity of vanadium alloys to radiation embrittlement have been obtained from tensile tests after exposure in the Fast Flux Test Reactor (FFTF) at temperatures of 425-600°C. The tensile data from these experiments have been revised to correct errors in the previously reported results. The ultimate strengths are unchanged, the yield strengths are slightly increased and both total and uniform elongations are substantially decreased. Revised data for the uniform plastic strain of several vanadium alloys from these tests are plotted in Figure 4 with data for ferritic steel[17]. Most of the eight alloys from these experiments exhibit uniform plastic strains of 2-10% over the range 425-600°C with only a modest dependence on fluence (a few specimens received doses of 87 dpa). Included in Fig. 4 are results from Van Witzenberg [14] for irradiation in the HFR reactor (Petten, Netherlands) at 500, 600, and 700°C to 6 dpa. The results for V-5Ti and V-3Ti-1Si at 500 and 600°C are in agreement with the FFTF results. These results indicate that several vanadium alloys exhibit resistance to radiation embrittlement in the temperature range 425-700°C. Additional results from Charpy impact tests indicate that the ductile-brittle-transition temperatures for these alloys remain far below room temperature after irradiation to ~30 dpa (see Fig. 5).

At temperatures below 400°C the effects of radiation on the ductility of these alloys show considerable variation. Results for several heats of two alloys (V-4Cr-4Ti and V-3Ti-1Si) irradiated to fluences of 4-36 dpa at temperatures of 400°C or less in different reactors (FFTF, EBR-II, HFIR) exhibit severe loss of ductility (uniform elongation < 1%) in some cases and good ductility (>2% uniform elongation) in other cases (see Fig. 6). Further investigations are required to determine whether the embrittlement is due solely to radiation effects or is synergistic with chemical interactions. Additional data on very low fluence irradiations (~0.4 dpa) of V-4Cr-4Ti alloy at temperatures of 110-231°C show severe loss of uniform elongation when tested at room temperature in air (Fig. 7)[18]. Results from these tests also indicate that the DBTT is increased to above room temperature. However, tensile tests conducted in vacuum at room temperature after irradiation of V-4Cr-4Ti to ~30 dpa in FFTF at 425-600°C indicate uniform elongations even higher than those obtained from tests at the irradiation temperature (Fig. 8). These results suggest that vanadium alloys exhibit good radiation damage resistance at temperatures from 400-700°C and that the ductility is retained upon cooling to room temperature.

## 5. Lifetime Limitations

Only limited progress has been made recently on the determination of lifetime limits for vanadium alloys. Earlier studies identified low swelling and lower transmutation rates for He compared to those for other candidate materials as features that would contribute to longer lifetime. A second issue is the characteristic of the V-Cr-Ti system in which transmutation products of these elements consist primary of the same three elements. Therefore, significant composition changes will not occur at high neutron fluences. Previous ion-irradiation investigations indicated good swelling resistance to >200 dpa for vanadium alloys that contain a few percent titanium[19].

## 6. Safety and Environmental Features

Vanadium alloys exhibit favorable safety and environmental features. The base elements contribute the lowest long-term activities of any of the candidate structural materials being considered. Therefore, the key is the production of alloys with low concentrations of critical trace elements. Although recent production-heats of V-4Cr-4Ti, which have been produced from available raw materials, contain relatively high concentrations of Nb and Mo, laboratory scale heats have been produced with desirable concentrations of Nb and Mo (~ 1wppm). Of particular importance are evaluations which conclude that recycle of vanadium alloys appears feasible[20]. Also, safety and environmental analyses conducted in the US conclude that the V/Li system is one of the most attractive systems.

## 7. R&D Requirements

Although considerable progress has been made on the development of vanadium alloys for fusion applications and the results are generally favorable, continued effort is required to resolve remaining critical issues and to optimize the vanadium alloy system for specific fusion applications. Top priority critical issues include:

- Minimum operating temperature to avoid excessive radiation embrittlement
- Lifetime limits based on radiation damage with relevant helium concentrations
- Optimization of welding procedures
- Development of electrically insulating coatings for lithium systems
- Chemical compatibility with coolant, breeder, plasma, etc.

The primary objective is to define compositional constraints, production and fabrication parameters, and operating limitations for an optimized vanadium alloy system with attractive safety and environmental features.

## 8. Conclusions

Results to date indicate that vanadium alloys exhibit significant advantages, compared to other material options for the structural material for fusion power plant applications, in terms of performance, lifetime, and environmental impact.

Vanadium alloys provide a broad operating temperature range of at least 400-700°C, with a possibility to reduce the 400°C minimum temperature with further development.

Further development is required to optimize the vanadium alloy system and to define overall lifetime and operating limits. The key issues and R&D requirements have been defined.

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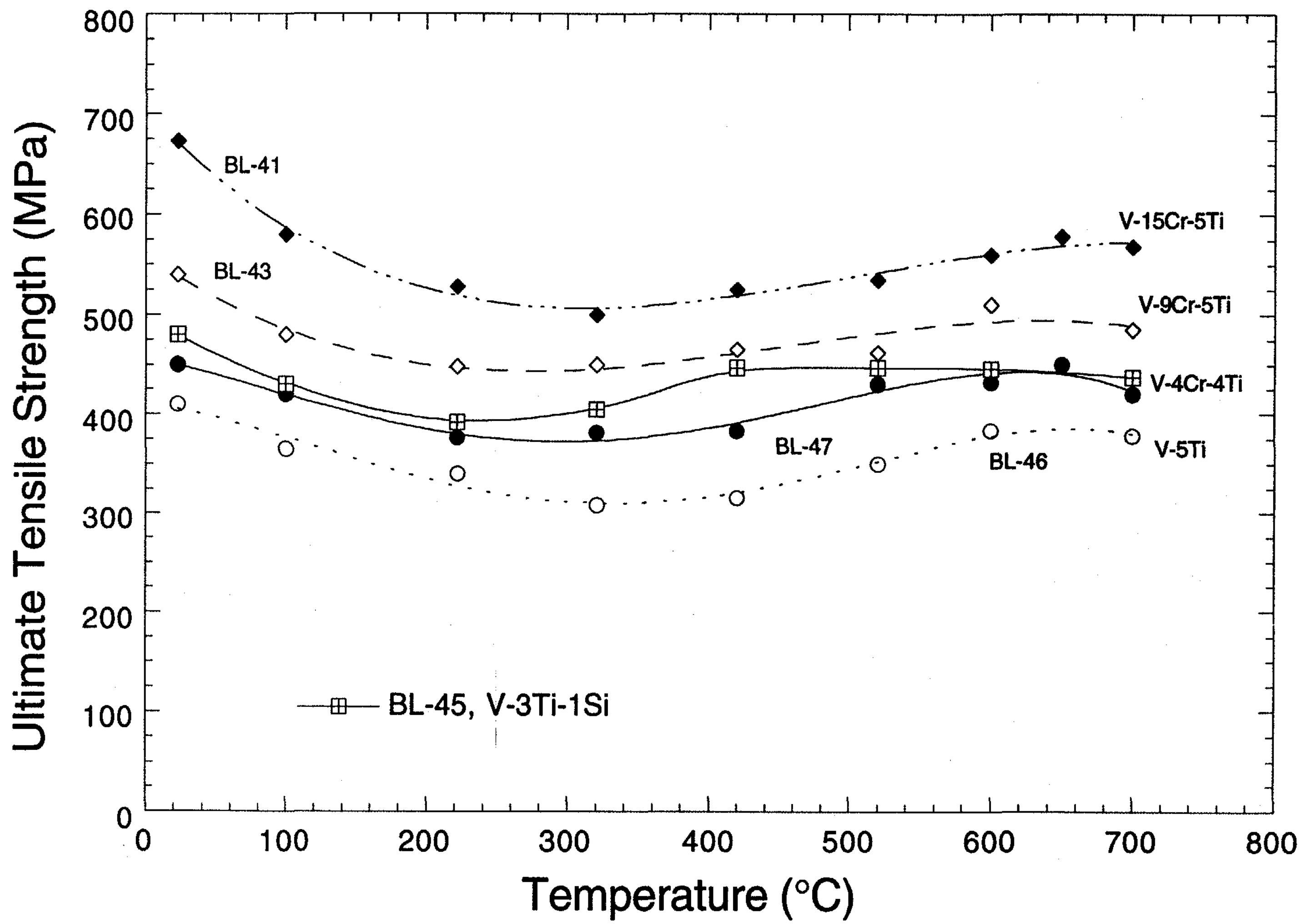


**Figure 1** **Ultimate tensile strength of several vanadium alloys as a function of temperature**

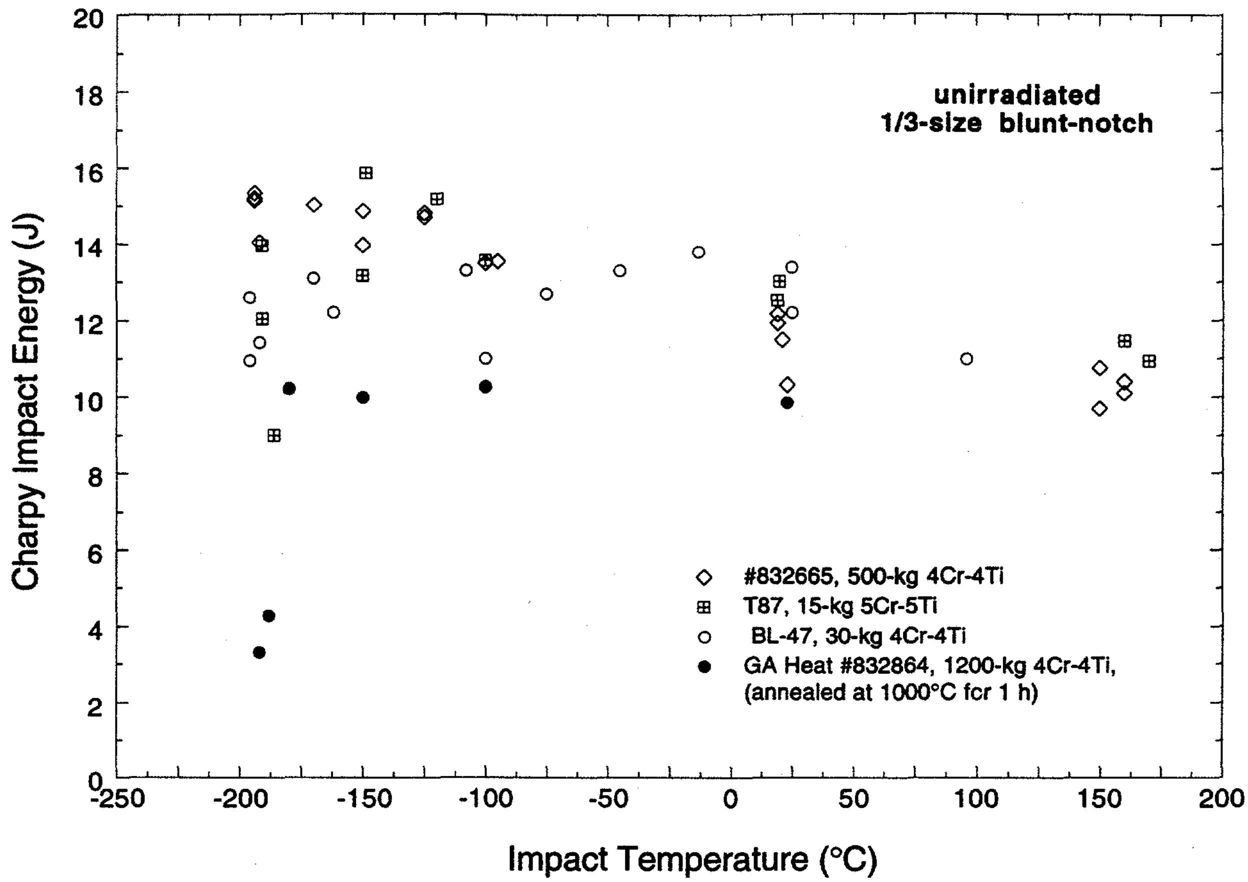


**Fig. 2 Charpy impact energy for four heats of V-(4-5)Cr-(4-5)Cr(4-5)Ti alloys in the solution annealed (unirradiated) condition (1 hr @ 1000°C)**

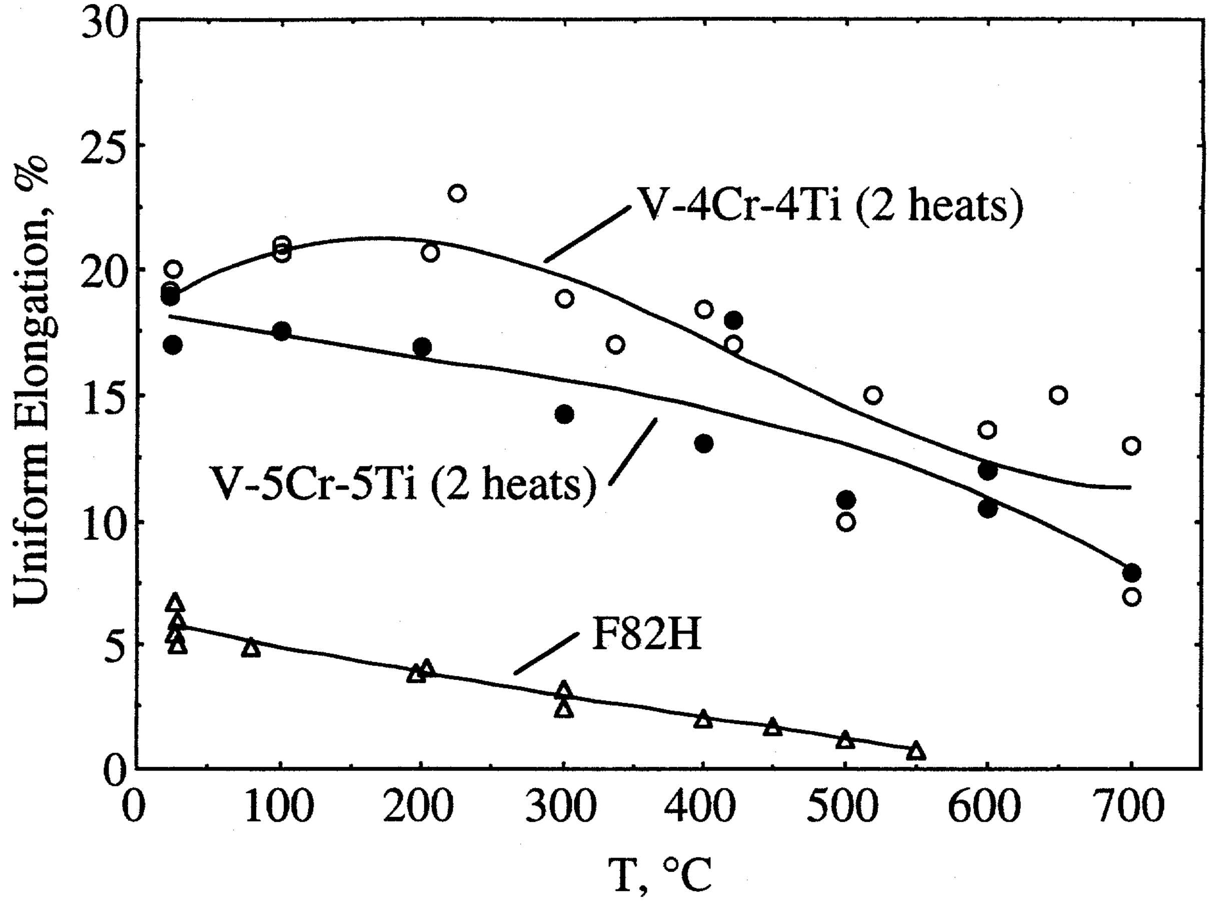


**Figure 3 Uniform elongation of unirradiated V-4Cr-4Ti and V-5Cr-5Ti as compared to ferritic/martensitic F82H in the unirradiated condition.**

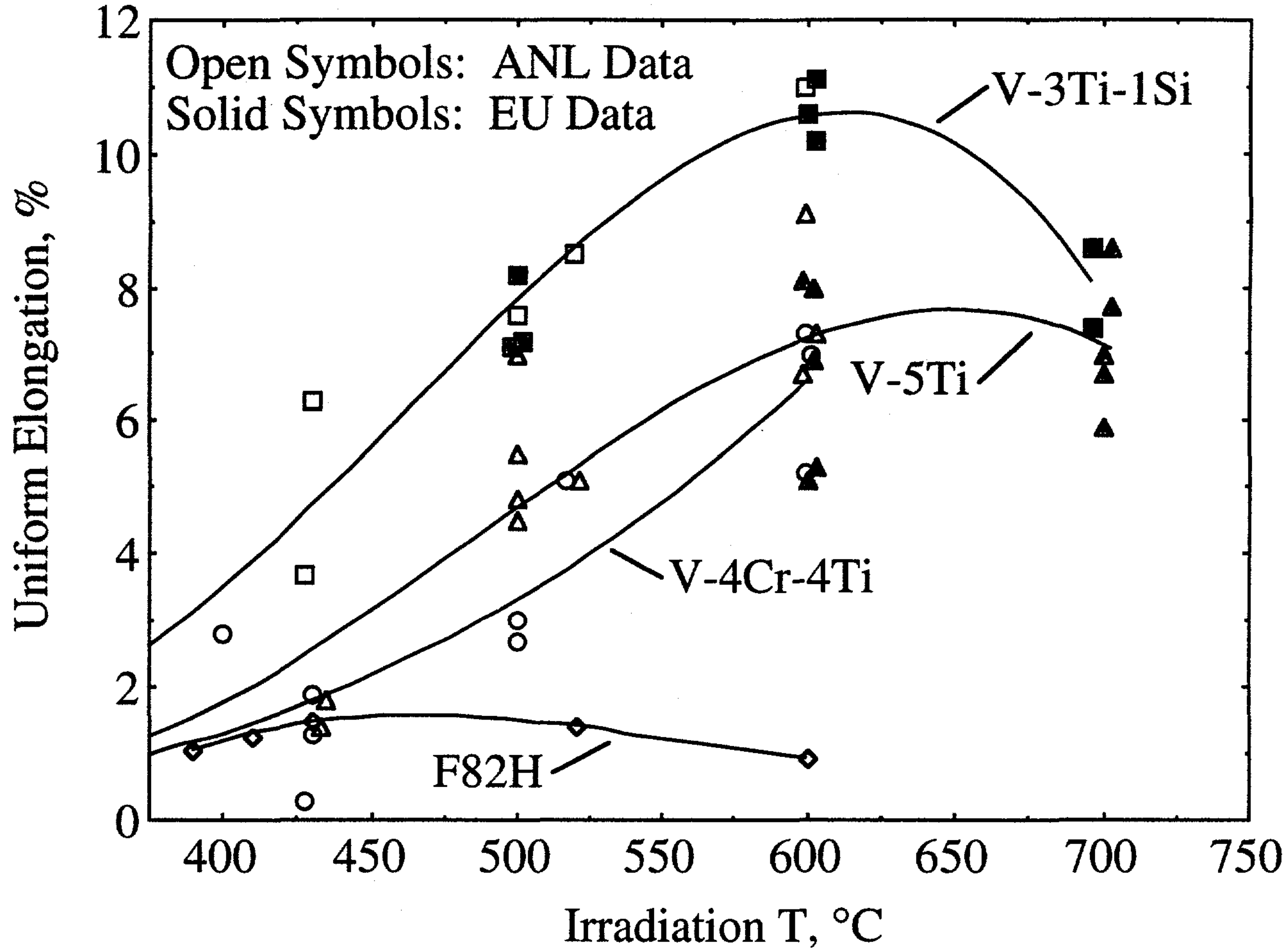


**Figure 4 Uniform elongation of irradiated (6-33 dpa) vanadium alloys compared to irradiated (~36 dpa) F82H (test temperature ≈ irradiation temperature).**

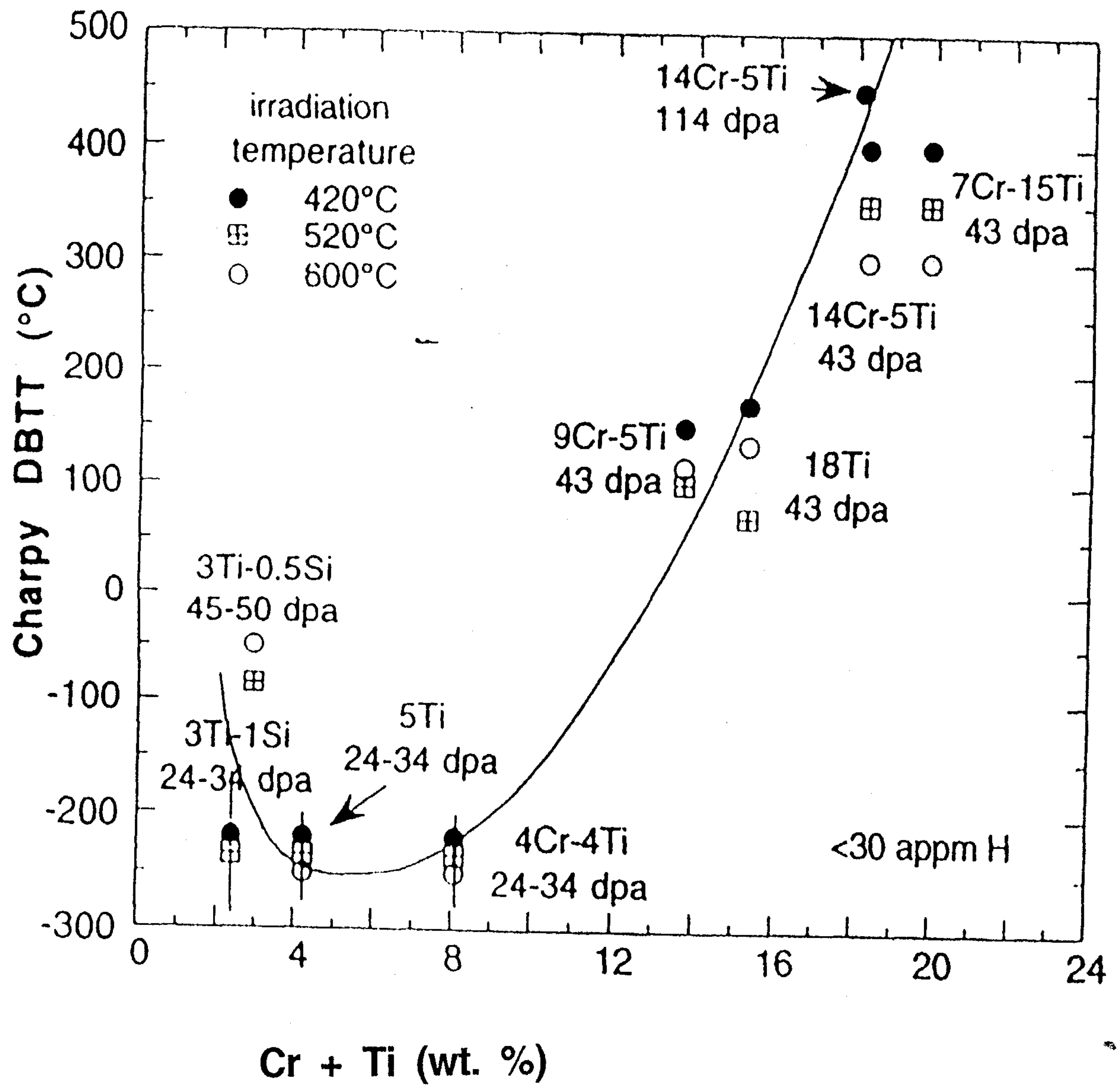


**Figure 5**

**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-TiSi alloys after irradiation.**

## Uniform Elongation, 200-430°C, V-4Cr-4Ti & V-3Ti-1Si

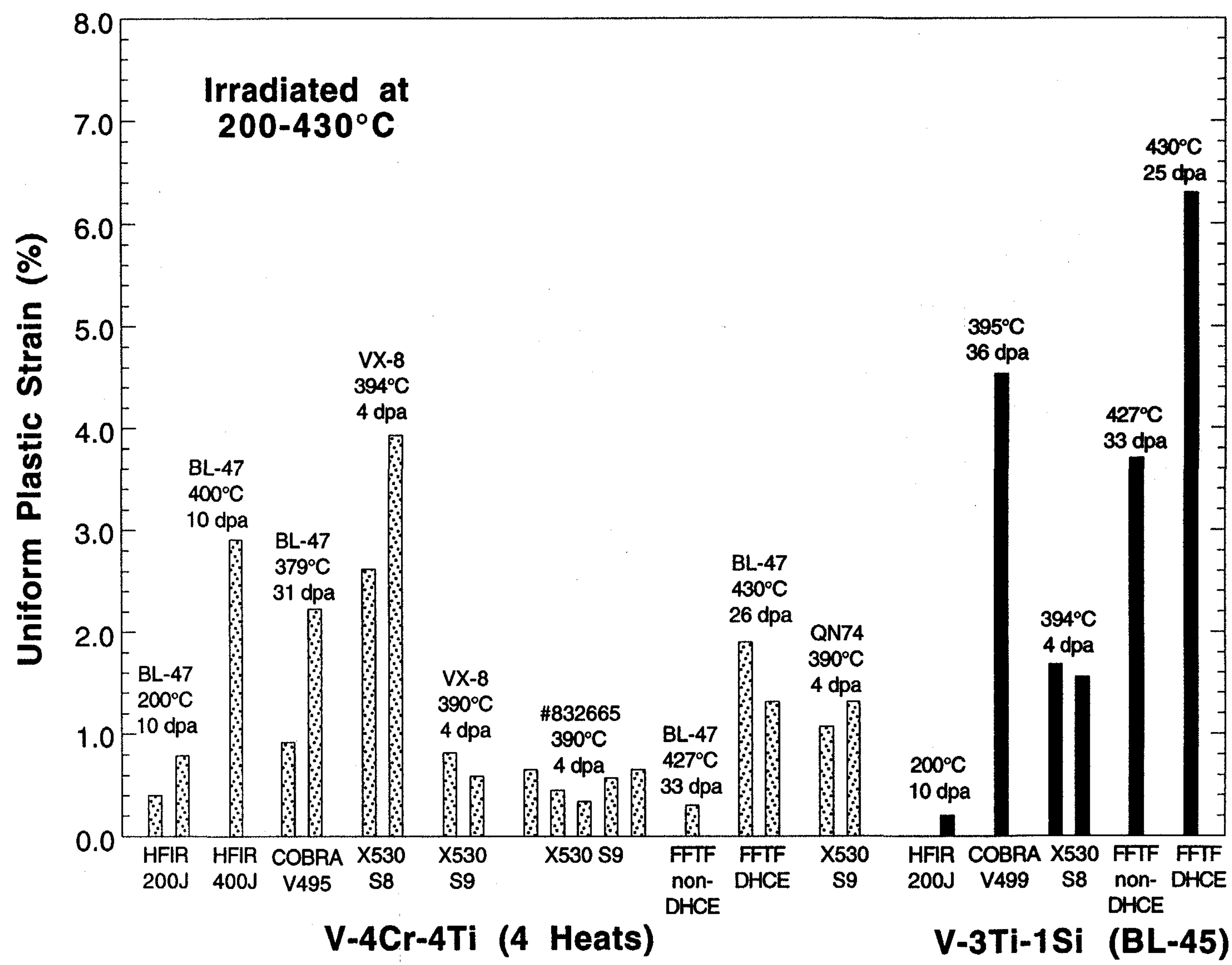


**Fig. 6 Post irradiation uniform plastic strain of vanadium alloys ($T_{irr} \approx T_{test}$)**

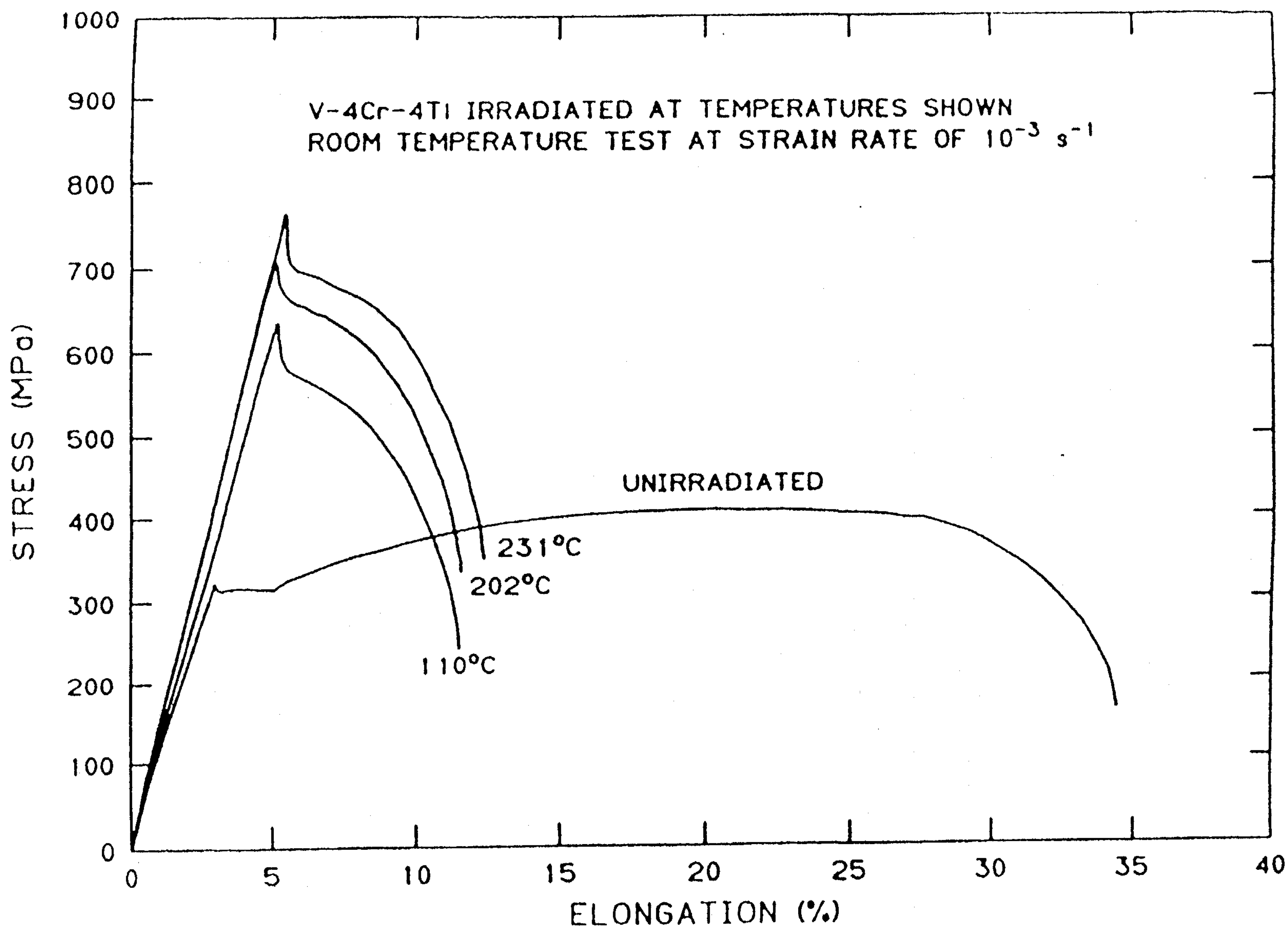


**Fig. 7 Stress-elongation curves measured at room temperature for V-4Cr-4Ti (832665).**

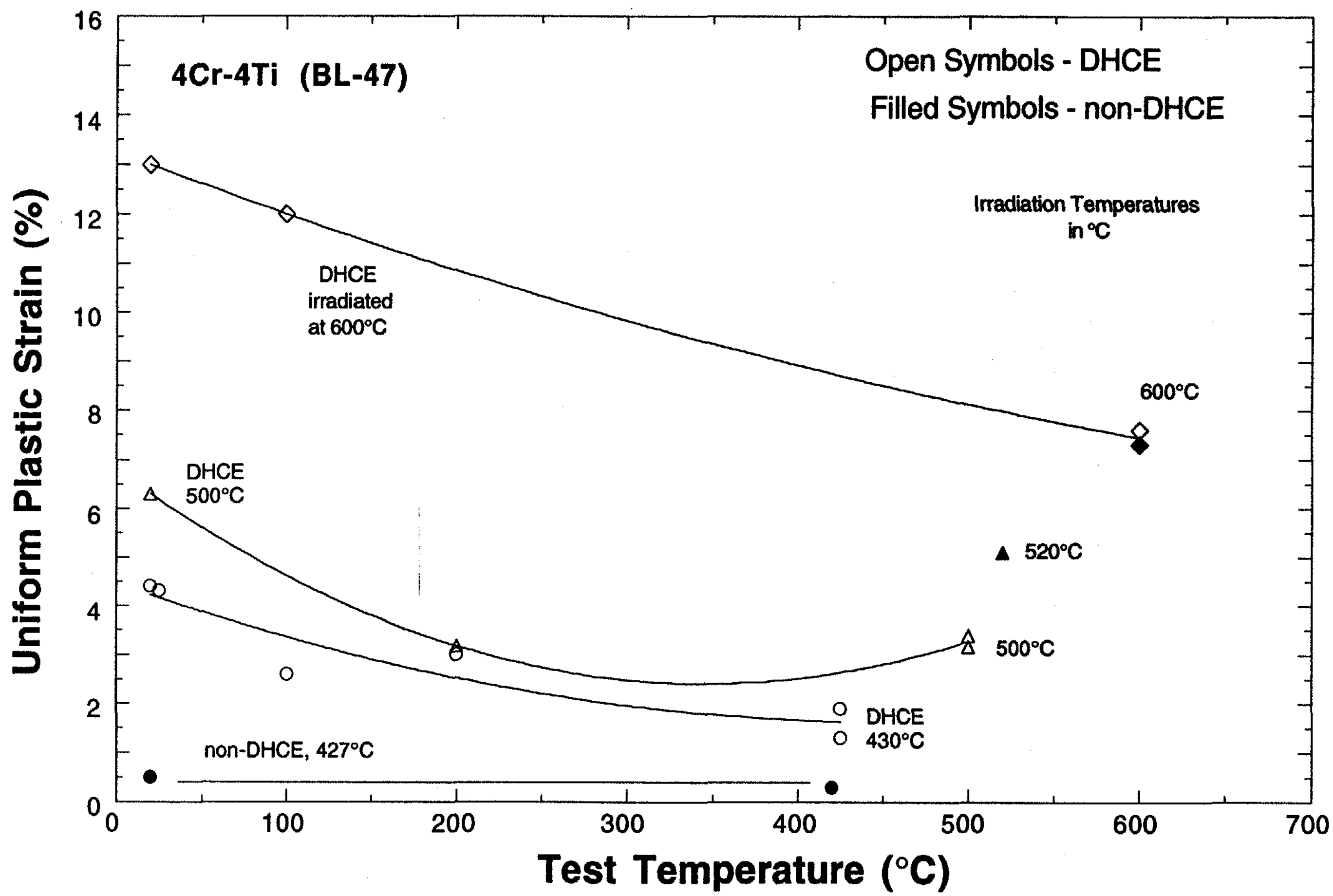


**Fig. 8 Post irradiation uniform plastic strain as a function of test temperature after irradiation at ~430, 500, and 600°C**