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DEVELOPMENT OF VANADIUM-BASE ALLOYS FOR FUSION FIRST WALL/BLANKET APPLICATIONS*

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DEVELOPMENT OF VANADIUM BASE ALLOYS FOR FUSION FIRST-WALL/BLANKET APPLICATIONS

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Abstract

Vanadium alloys have been identified as a leading candidate material for fusion first-wall/blanket applications. Certain 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 effects. The current focus is on vanadium alloys with (3-5)% Cr and (3-5)% Ti with a V-4Cr-4Ti alloy as the leading candidate.

The available data base indicates that the V-Cr-Ti alloys provide the following advantages:

- These alloys are readily formable and weldable; however, atmospheric contamination must be avoided during welding and high temperature processing.
- The relatively high thermal conductivity and low thermal expansion provide for a high heat load capability.
- These alloys exhibit good high temperature tensile and creep properties which permit high temperature operation.

- V-Cr-Ti alloys exhibit low long-term activation and low radioactive decay heat which provide safety and environmental advantages.

- These alloys are characteristically resistant to liquid metal corrosion.

- Alloys with a few percent titanium are highly resistant to irradiation-induced swelling which provides for the possibility of long lifetime.

- Results obtained to date indicate that the V-4Cr-4Ti alloy is highly resistant to irradiation induced degradation of the mechanical properties.

- Substantial progress has been made in the development of these alloys for the fusion application. Larger heats of the V-4Cr-4Ti alloy have been prepared in the US and Russia. The baseline property data base has been expanded. Recent results indicate that these alloys are resistant to irradiation damage. The irradiation-induced swelling is low, the uniform elongation of alloys irradiated at 400-600°C remains above 8%, and the ductile-brittle transaction temperature of the V-4Cr-4Ti alloy after irradiation remains well below room temperature.

Preliminary results indicate that the crack-growth rates of certain alloys are not highly sensitive to irradiation. Results from the Dynamic Helium Charging Experiment (DHCE) which simulates fusion relevant helium/dpa ratios are similar to results from neutron irradiated material.

This paper presents an overview of the recent results on the development of vanadium alloys for fusion first wall/blanket applications.

* Work supported by the U.S. Department of Energy, Office of Fusion Energy, under contract W-31-109-Eng-38.

1. Introduction

Vanadium alloys have been identified as a leading candidate material for fusion first-wall/blanket structure applications. Certain vanadium alloys exhibit favorable safety and environmental characteristics, good fabricability, potential for high performance and potentially long operating lifetime in a fusion environment. The current focus is on vanadium alloys with (3-5)% Cr and (3-5)% Ti with a V-4Cr-4Ti alloy as the reference composition.

Vanadium alloys have been selected and evaluated in major design studies including the Blanket Comparison and Selection Studies (BCSS) [1], the Tokamak Power Systems Study (TPSS) [2], the TITAN Reversed Field Pinch [3], and the ARIES-II Tokamak design [4]. Vanadium alloys were included in the top rated blanket concepts based on performance, reliability, safety and economics in the BCSS, which considered many combinations of breeder, coolant, and structure. The TPSS was based on a self-cooled lithium blanket with a vanadium alloy structure. This study also included an evaluation of a vanadium alloy structure with a helium-cooled ceramic breeder blanket concept. A vanadium alloy structure was selected for the TITAN design primarily because of the high surface heat load capability. The ARIES design, which placed a high priority on safety and environmental considerations, incorporated a self-cooled lithium blanket with a vanadium alloy structure. In addition, the Report on Environmental, Safety, and Economic Aspects of Magnetic Fusion Energy (ESECOM) identified important safety and environmental advantages of vanadium alloys [5].

Considerable data base has been developed which indicates that vanadium alloys offer superior performance compared to other options for the first-wall/blanket structure of a magnetic fusion power plant. Vanadium alloys can accommodate high first-wall heat loads and can operate at temperatures up to 700-750°C. Vanadium alloys provide favorable safety and environmental features such as low long-term activation, low decay heat and contact dose, and a potential for recycle. These alloys can be rolled into thin sheets, extruded into tubing, and welded by several methods. Existing data indicate that these alloys are highly resistant to irradiation-induced swelling and embrittlement, and are compatible with liquid-metal blankets. They offer a potential for long operating lifetime with subsequent economic and environmental advantages.

The key remaining issues and R&D requirements for vanadium alloys relate to production and joining, chemical compatibility, and effects of the neutron irradiation on the properties. Scale up of industrial capability for production and further weldment development are required. Key issues related to chemical compatibility involve the kinetics of nonmetallic element interactions and the effects of the chemical environment on the fatigue properties. Additional data are needed on the effects of neutron irradiation, including helium and hydrogen transmutations on the mechanical properties of vanadium alloys.

This paper presents an overview of vanadium alloy development for fusion first-wall/blanket applications. The requirements for the ITER application are considerably less severe than those for the DEMO application.

2. Candidate Alloy Selection

The vanadium alloy development program is currently focused on the vanadium-chromium-titanium alloy system. These three elements all exhibit favorable low-activation characteristics. Compositional variations produced by nuclear transmutations for this system are minimal since each element predominantly transmutes to the other two elements. It has been shown for many years that vanadium alloys with a few percent titanium additions are highly resistant to irradiation-induced swelling, thus offering a potential for long operating lifetime in a fusion environment. It has also been shown that a few percent chromium additions significantly improve the tensile and creep strength of vanadium-titanium alloys.

Recent investigations have included compositions (wt %) of V-(0-15)%Cr-(1-20)%Ti(0-1)%Si. Current emphasis is on a reference composition of V-4Cr-4Ti-0.05 Si. A range of compositions are still being investigated to better understand the sensitivity of various properties to small compositional variations. The range of compositions include V-(3-5)Cr-(3-5)Ti-(0.01-0.1)Si. The current focus is on a simple solution anneal thermomechanical treatment (TMT) with an annealing temperature of about 1050°C. However, variations in processing conditions, amount of warm or cold-work, and variations in annealing temperature are being investigated in order to better understand the effects and to optimize the properties for the DEMO applications.

The effects of variations in nonmetallic element concentrations, particularly O, N, C, and H, have also been investigated. Nominal compositions of these elements are (200-400) wppm oxygen, (50-200) wppm nitrogen, (50-200) wppm carbon, and <5 wppm hydrogen.

3. High Performance Characteristics

Vanadium-base alloys exhibit physical properties that are favorable for the fusion first-wall applications. Table 1 lists selected physical properties for the vanadium alloys compared to the austenitic (Type 316) and ferritic/martensitic (HT-9) steels. In addition to the high melting temperature (~500°C higher than the steels), vanadium alloys have a lower coefficient of thermal expansion, a higher thermal conductivity, and a lower elastic modulus; all of which contribute to a higher heat load capability compared to the steels.

Depending on the conditions and criteria, vanadium alloys can accommodate heat loads a factor of 4-7 higher than those of the steels. Figure 1 is a plot of the calculated first-wall heat flux limits based on thermal stress limits for a 5 mm-thick structure [6]. For a common set of criteria, the vanadium alloy provides significant advantages compared to annealed Type 316 austenitic steel over the entire temperature range and at temperatures above 400°C compared to the HT-9 ferritic/martensitic steel.

The high-temperature advantages of vanadium alloys are further illustrated in Figs. 2 and 3. The tensile strength of several vanadium alloys are plotted in Fig. 2 up to 700°C [7]. The tensile strengths of these alloys are relatively insensitive to temperature up to 700°C. The increase in tensile strength with increasing Cr content is also shown for the V-Cr-5Ti system. The high temperature advantage of the vanadium alloys is further illustrated by the creep data plotted in Fig. 3 for several vanadium alloys and steels [8]. The Larsen-Miller parameter, which includes both time and temperature, illustrates the benefits of Cr additions on the creep strength of vanadium alloys as well as the significant creep strength advantage of vanadium alloys compared to both austenitic and ferritic steels. A Larsen-Miller parameter of 21,000 corresponds to a 10,000 hr life at 600°C. The corresponding stress at this parameter is ~400 MPa for V-4Cr-4Ti compared to values of only 120-130 MPa for HT-9 and annealed Type 316 steels.

4. Safety and Environmental Features

The V-Cr-Ti alloys exhibit favorable safety and environmental features; particularly with respect to low long-term activation, low decay heat, and low contact dose. Figure 4 shows the calculated radioactivity as a function of time after shutdown for several metallic elements after exposure to a first-wall fluence of 12.5 MW•y/m^2 [9]. Vanadium exhibits the lowest long-term radioactivity of the elements shown, chromium is next best and titanium is significantly better than most. Silicon and aluminum exhibit lower radioactivity than does vanadium and chromium at times less than 10-20 years. Figure 5 shows results of similar calculations of specific radioactivity for pure alloys of vanadium, a low activation ferritic/martensitic steel, and Type 316 austenitic steel and SiC [10]. Vanadium alloys exhibit lower radioactivity than the steels at all times and lower than SiC at times greater than ~60 years. The effects of impurities must be considered in all cases; however, it appears that relatively pure materials can be obtained. Similar plots (Figs. 6 and 7) for the specific decay heat-generation rate and contact dose also show advantages compared to the steels at all times and compared to SiC at times greater than 5-50 years. The biological hazard potential is an important parameter for accident scenarios. Figure 8 shows the calculated BHP for a vanadium alloy compared to several steels.

In addition the high melting temperature of vanadium alloys and the relatively low volatility provides advantages in the event of accidental release during thermal transients. One concern for the vanadium alloys is the relatively high-oxidation potential of vanadium alloys. This has been addressed in the design studies by providing an inert atmosphere in the reactor building. This inert environment is generally recommended or required to prevent oxidation of other materials, particularly the candidate plasma facing materials. In addition, the first-wall surface of nearly all fusion reactor designs are protected by a coating of some type.

The potential for recycle of a vanadium alloy structure has also been considered. The conclusions of these studies indicate that recycle is indeed feasible [11]. Further examination of the implications of recycle is recommended.

5. Fabricability of Vanadium Alloys

The vanadium alloys with compositions of interest are highly ductile and readily fabricable. The total elongations of all these alloys from conventional tensile tests at a strain rate $3x10^{-4}$ are in the range of 20-35% from room temperature to 700°C. Figure 9 shows the 25°C ductility of several V-Cr-5Ti alloys as a function of chromium concentration [12]. The uniform elongations are typically about 75% of the total elongation. The vanadium alloys with less than 10% Cr+Ti also exhibit high ductility in high strain rate Charpy impact tests. As shown in Fig. 10, the ductile-brittle transition temperature (DBTT) determined from Charpy impact tests is below liquid-nitrogen temperatures [13] Figure 11 is a plot of the DBTT for several alloys as a function of Cr+Ti concentration [14]. These results are the primary reason that the vanadium alloys with about 4 Cr and 4 Ti are proposed as a reference alloy since embrittlement is considered the key feasibility for all alloy structural materials.

Vanadium alloys with compositions in the range considered are readily fabricable into plate and sheet. Test specimens for these alloys have been fabricated from plate and sheet rolled down to 6-0.5 mm thicknesses. Reductions in thickness as large as 85% between anneals have typically been obtained both in the U.S. and Russia. Although care must be taken to avoid atmospheric contamination during high-temperature processing, procedures have been developed and demonstrated for maintaining high purity. These alloys can also be extruded into rod or tubing. Further development of secondary fabrication on a larger scale is required.

Vanadium and vanadium alloys have been welded by several methods: tungsten inert gas (TIG), electron-beam, and laser weld procedures. Resistance welding also appears feasible. Generally good weld characteristics have been obtained even though complete weld optimization studies have not been conducted. Figure 9 shows that the mechanical properties of several alloy weldments are similar to those of the base metal [12]. Other studies in the U.S. have shown that minimal contamination results from TIG weldments in a glovebox environment [15]. In practice, liquid-metal test loops have been fabricated in the U.S. and Russia by TIG welding [16].

6. Chemical Compatibility

The key compatibility issues for vanadium alloys relate to their chemical reactivity with oxygen, nitrogen, carbon, and hydrogen. These alloys are particularly attractive for liquid-lithium blankets in which these elements, particularly oxygen and hydrogen, can be more easily controlled. Vanadium alloys will tend to oxidize when exposed to oxygen or air. However, this problem can be solved by design. The first-wall/blanket system in most fusion-reactor designs is contained within the vacuum vessel which will protect the vanadium structure from the atmosphere. Even in the event of a vacuum chamber leak, the first wall in nearly all designs is covered by a low-Z (Be, C, etc.) or high-Z (W, Mo material). These coatings or tiles will tend to protect the vanadium, however, since they also are reactive with air, an inert gas is typically proposed for the ex-vessel environment. Although vanadium alloys are not generally proposed for use in an oxidizing environment, the kinetics of oxidation of these alloys are quite moderate at temperatures below about 450°C. Figure 12 shows the kinetics of oxidation of a V-5Cr-5Ti alloy in air as a function of temperature [17]. The kinetics of nitridation are even slower than those for oxidation. Oxidation and atmospheric contamination problems can be solved by design.

Vanadium alloys are compatible with the hydrogen pressure characteristic of the plasma chamber viz., 10^{-1}-10^{-3}Pa. The equilibrium hydrogen concentrations in vanadium at these partial pressures are <1 wppm. These concentrations are well below the concentrations required to degrade the mechanical properties. The most important constraint is probably the tritium inventory. In a lithium blanket the tritium will preferentially distribute from the vanadium to the lithium (the equilibrium distribution is ~1000 wppm hydrogen in lithium to 1 wppm hydrogen in vanadium). Since hydrogen is highly mobile in vanadium and since the tritium concentration in lithium will be controlled at low levels (~1 wppm) by design, the tritium inventory in a vanadium alloy structure for this concept will be low by design. More rigorous analyses are required for other blanket concepts.

Vanadium alloys are compatible with liquid alkali metals to high-temperature. Control of nonmetallic impurity elements (O, N, C, & H) are required just as water chemistry must be controlled in water-cooled systems. At temperatures below ~450°C the kinetics of reactions with O, N, and C are relatively low and are probably not a serious problem for projected ITER conditions. Figure 13 shows the effects of nitrogen concentrations in lithium on the interactions with vanadium alloys containing varying titanium concentrations [18]. This issue is dominated by the electrical insulator coating requirement for liquid-metal systems, which is beyond the scope of this paper. The presence of an insulator coating will modify any direct nonmetallic interaction between breeder and structure.

Although vanadium alloys have not generally been proposed for aqueous systems, alloys with chromium additions appear to be resistant to both aqueous corrosion and stress corrosion at temperatures of ~300°C [19]. These results indicate that these alloys could probably be used with water-cooled systems in order to accommodate high-surface heat fluxes.

7. Effects of Irradiation on Properties

Candidate vanadium base alloys are resistant to irradiation damage and offer a potential for a long operating lifetime. The vanadium alloys exhibit favorable neutronic characteristics, in particular, lower He and H production rates compared to the steels and SiC. Table 2 presents a summary of key neutronic data for candidate structural materials. Effects of helium transmutations produced by the high-energy neutrons is one of the major concerns regarding the integrity of materials in a fusion environment. The helium generation rate in the vanadium alloy is a factor of 2-3 lower than those for the steels and a factor of 25 lower than that for SiC. The hydrogen transmutation rate and nuclear heating rate are also much lower than those for the other materials. These effects alone provide significant advantages for the vanadium alloys.

Vanadium alloys have been shown to be among the most resistant to neutron irradiation-induced swelling.[20-27] Both binary V-Ti alloys and ternary V-Cr-5Ti alloys with a few percent titanium are resistant to irradiation-induced swelling. Figure 14 shows the measured density change of several V-Cr-5Ti alloys (0-14% Cr) at 400 to 600°C for fluences up to 84 dpa [27]. The V-4Cr-4Ti alloy shows good swelling resistance. The dynamic helium-changing experiment [28] has been conducted to investigate the effects of fusion-relevant helium-generation rates on the properties of neutron-irradiated vanadium alloys. This experiment utilizes the *in situ* decay of tritium to helium during irradiation to simulate the high transmutation rate of helium characteristic of a fusion environment. Preliminary results obtained in the first experiment of this kind show differences in the microstructure of the irradiated alloys indicating that the approach appears to work [29]. Preliminary results show little differences in overall swelling rates. This experiment can also provide results of increased hydrogen/tritium concentrations on the properties.

The V-4Cr-4Ti alloy shows good resistance to irradiation-induced embrittlement both at low strain rates (normal tensile tests) and at high strain rates (Charpy tests). The uniform elongations of several vanadium alloys after irradiation at 420, 520, and 600°C to fluences of 28-46 dpa are shown in Fig. 15 [30]. The uniform elongation for the V-4Cr-4Ti alloy remains above 8% at all three temperatures. Similar uniform elongations are observed when tested at room temperature after irradiation at 420°C. The effect of He (cyclotron preinjected) on the tensile properties of several vanadium alloys has been investigated after neutron irradiation to 6 dpa at temperatures of 500-800°C. The V-4Fe-3Ti-1Si-0.3 Y and V-3.6 Mn-3Ti-1Si-0.3 Y exhibited good ductility at

600°C even with approximately 100 appm He [31]. Preliminary results from the DHCE-1 experiment [29] indicate no substantial effect on the uniform elongation with estimated helium concentrations of 10-30 appm.

Results from Charpy impact tests indicate that vanadium alloys are also resistant to irradiation-induced embrittlement at high strain rates. Figure 16 is a plot of Charpy impact energy of the V-4Cr-4Ti alloy after irradiation at 425, 520, and 600°C to about 30 dpa [32]. The Charpy impact energy remains high down to -200°C. Figure 17 is a plot of the DBTT for several vanadium alloys after irradiation at 425, 520, and 600°C. Alloys with less than ~10% Cr+Ti exhibit high resistance to embrittlement. Preliminary data from the DHCE experiment indicate that the fracture properties are not substantially degraded for the conditions tested [29]. Additional data at lower irradiation temperatures, 250-350°C, are needed to demonstrate resistance to embrittlement at projected ITER operating temperatures.

8. Key R&D Needs

The critical R&D required for the vanadium alloys have been defined. These include:

- Scale up of production and fabrication capability.
- Optimization of weld parameters and demonstration of acceptable weld properties for thick sections.
- Further investigations of nonmetallic elements (O, N, C, & H) for the range of conditions projected for specific design concepts.
- Investigation of fatigue properties in lithium for the ITER application.

- Further investigations of the effects of neutron irradiation, particularly at temperatures in the range 200-400°C, including helium and hydrogen effects on the mechanical properties at fluences to 30 dpa for the ITER application.
- Additional high-temperature, high-fluence neutron-irradiation data with appropriate He/dpa ratios for DEMO applications.
- Further investigations of the responses of a vanadium alloy structure to possible accident scenarios.

9. Conclusions

The vanadium-chromium-titanium alloys provide an attractive structural material option for a fusion first-wall/blanket system. A V-4Cr-4Ti alloy appears to be a near optimum composition, although further development and optimization is required.

Results obtained to date indicate that these alloys offer the following features that can enhance the attractiveness of fusion as an energy source:

- Vanadium alloys are readily fabricable and can be welded.
- Vanadium alloys can operate at high temperatures and accommodate high-surface heat fluxes.
- Vanadium alloys provide safety and environmental advantages associated with low-activation characteristics, high-temperature properties, and low-decay heat-generation rate.
- Vanadium alloys are resistant to irradiation-induced swelling and embrittlement, and offer a potential for long operating time.

The critical R&D needs for near-term ITER applications and for DEMO applications have been defined. Critical data required to evaluate the potential of vanadium alloys for the limited ITER conditions can be obtained in a few years with an aggressive program. Several years will be required to determine the performance limits for the high fluence, high operating temperatures projected for the DEMO.

Table 1. Selected Physical Properties of Three Candidate Structural 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	33.6
500°C	21.0	27.3	34.5
600°C	22.5	27.7	35.3
Electrical resistivity (μΩm)			
400°C	1.01	0.91*	0.67
500°C	1.06	0.99*	0.74
600°C	1.12	1.05*	0.81
Specific heat (J/kg K)			
400°C	560	600	535
500°C	575	680	560
600°C	580	800	575

*Data for 410 SS.

FIGURE CAPTIONS

1. Calculated first wall heat flux limits based on thermal stress (5 mm thick wall) for candidate structural alloys.

2. Temperature dependence of UTS for V-(0 15)Cr-5Ti alloys.

3. Thermal creep properties of vanadium alloys compared to those of austenitic and ferritic/martensitic steels.

4. Induced radioactivity after shutdown for selected elements exposed to first wall fluence of 12.5 MW/m^2.

5. Specific radioactivity for candidate first wall structural materials after exposure for 5 years to a typical neutron wall load of 5 MW/m^2.

6. Decay heat generation rate for candidate first wall materials after exposure for 5 years at a neutron wall load of 5 MW/m^2.

7. Contact dose for candidate first wall materials after exposure for 5 years at a neutron wall loading of 5 MW/m^2.

8. Biological hazard potential for candidate first wall materials after exposure for 5 years to a neutron wall loading of 5 MW/m^2.

9. Effect of TIG weld on tensile properties of V-Cr-5Ti alloys as a function of Cr content. Yield strength and total elongation of weldments are either comparable to or higher than those of recrystallized material.

10. Charpy impact energy and percent ductile fracture morphology for unirradiated V-4Cr-4Ti alloy.

11. Effects of hydrogen and irradiation on the DBTT (Charpy-impact loading) of vanadium-base alloys.

12. Temperature dependence of the parabolic oxidation rates for bare and aluminized V-5Cr-5Ti alloy specimens in air.

13. Micro hardness profiles of vanadium alloys after tests in lithium indicating nitrogen pickup in the alloys..

14. Irradiation-induced swelling of selected vanadium alloys.

15. Uniform elongation of several vanadium alloys after irradiation to 28-46 dpa.

16. Charpy impact energy for V-4Cr-4Ti alloy after irradiation in fast fission spectrum to ~30 dpa.

17. Charpy ductile-brittle transition temperatures for several vanadium alloys after irradiation to 24-43 dpa.

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First Wall Heat Flux Limit Based on Thermal Stress - 5mm Thickness

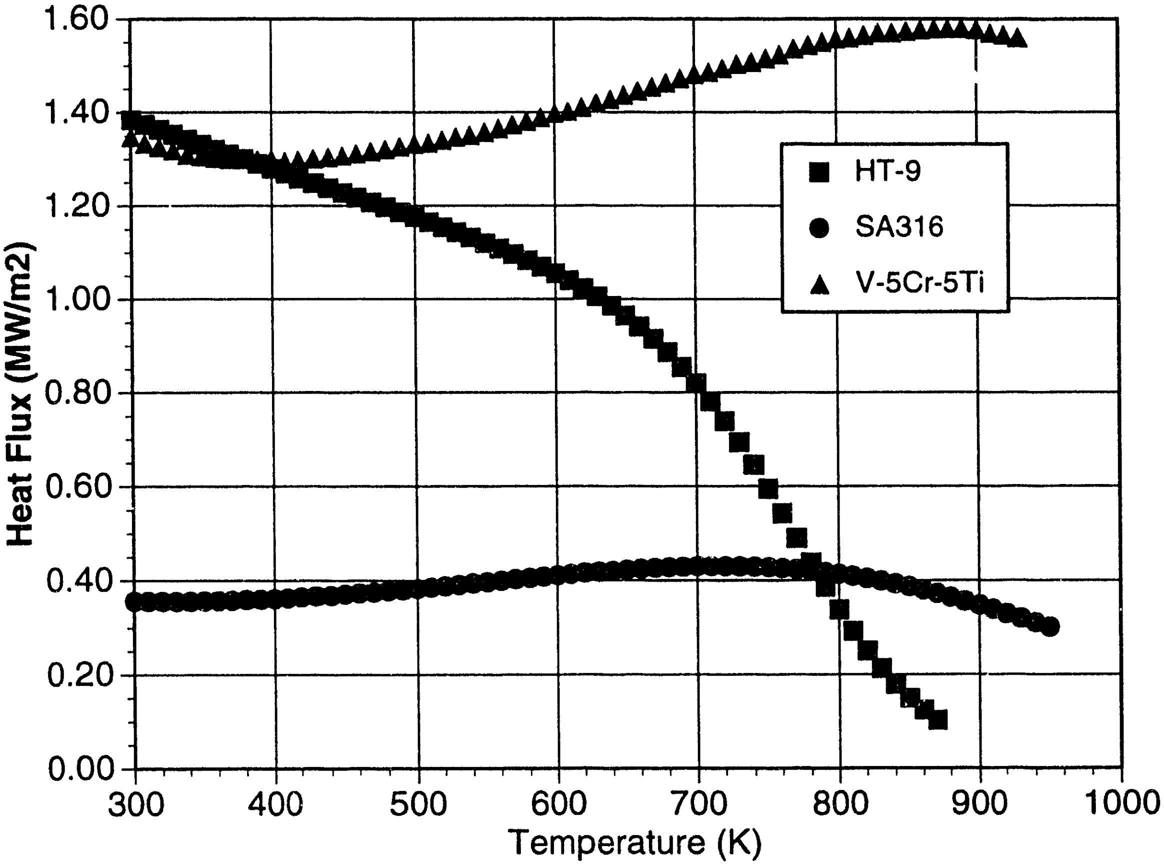

Figure 1

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Development of Vanadium Base Alloys...

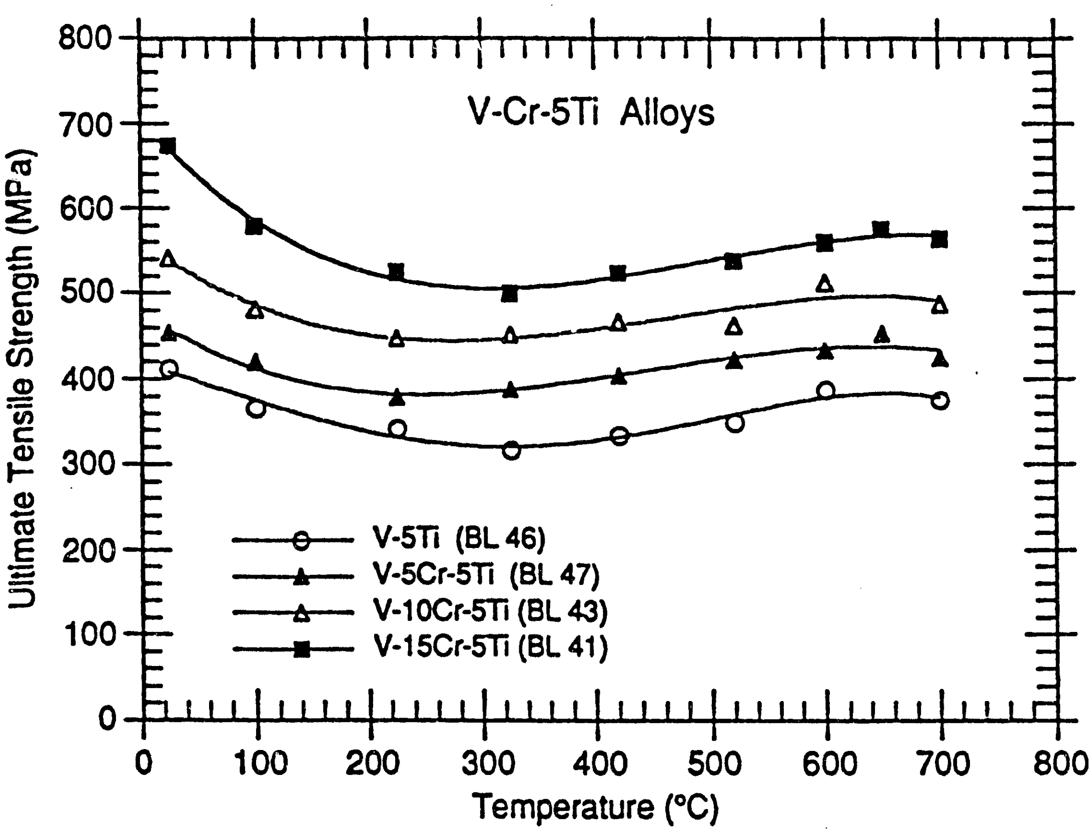

Figure 2

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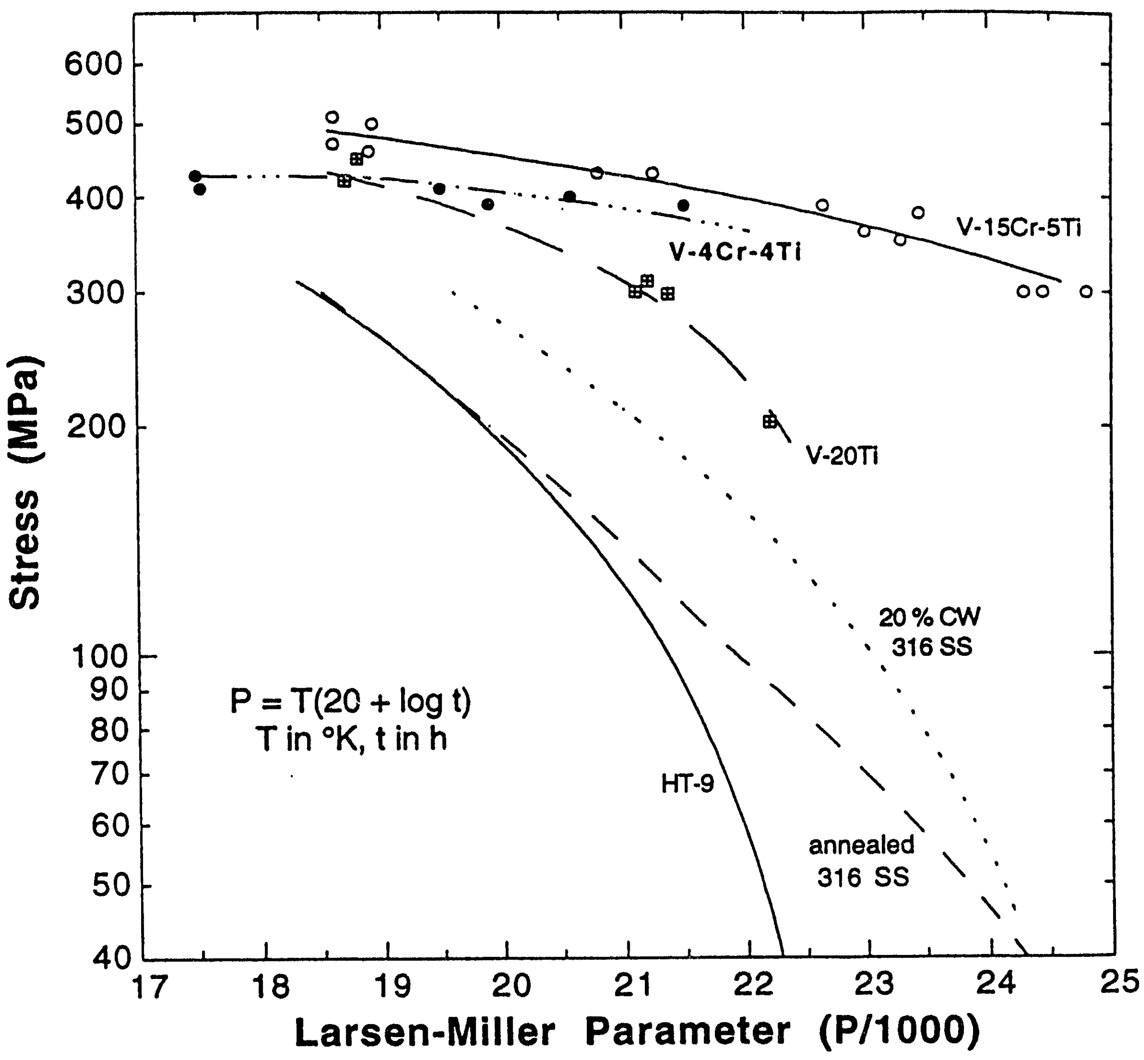

Figure 3

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Development of Vanadium Base Alloys...

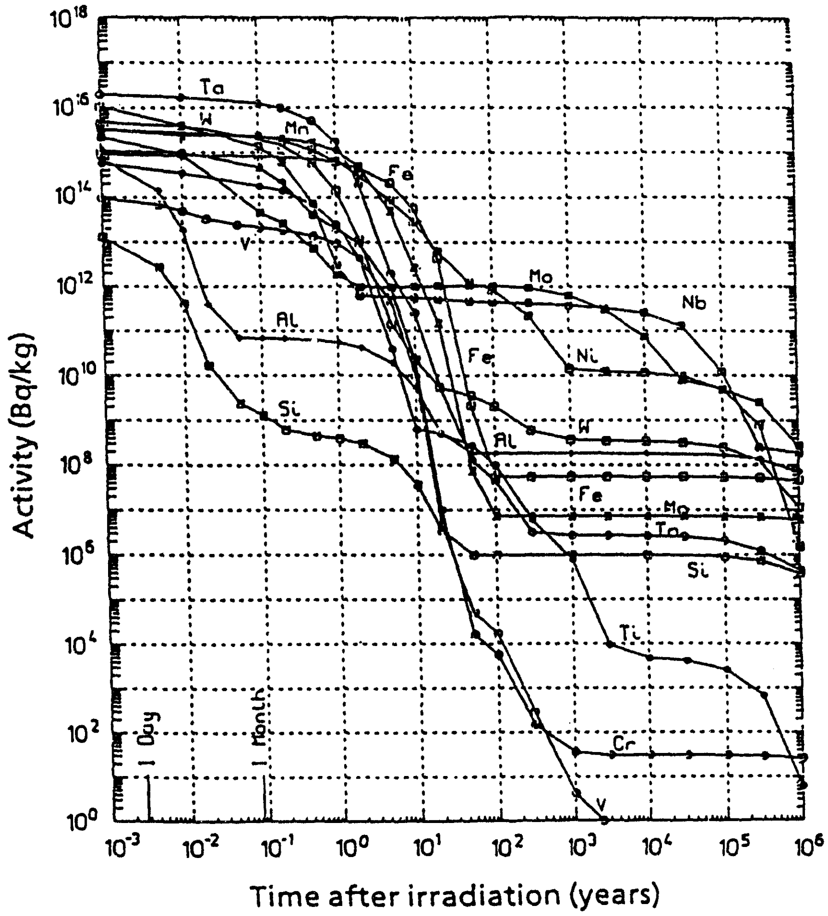

Figure 4

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Development of Vanadium Base Alloys...

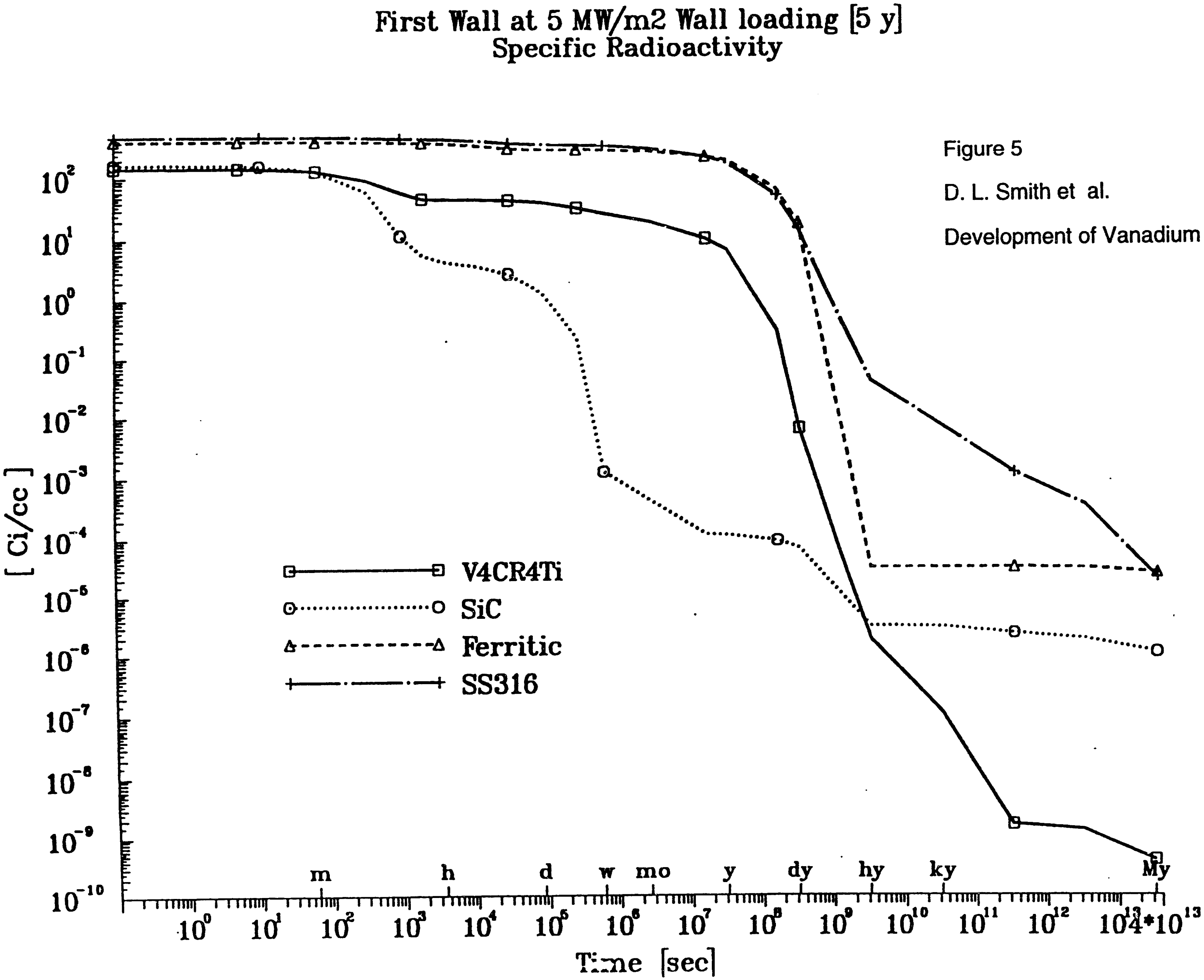

Figure 5

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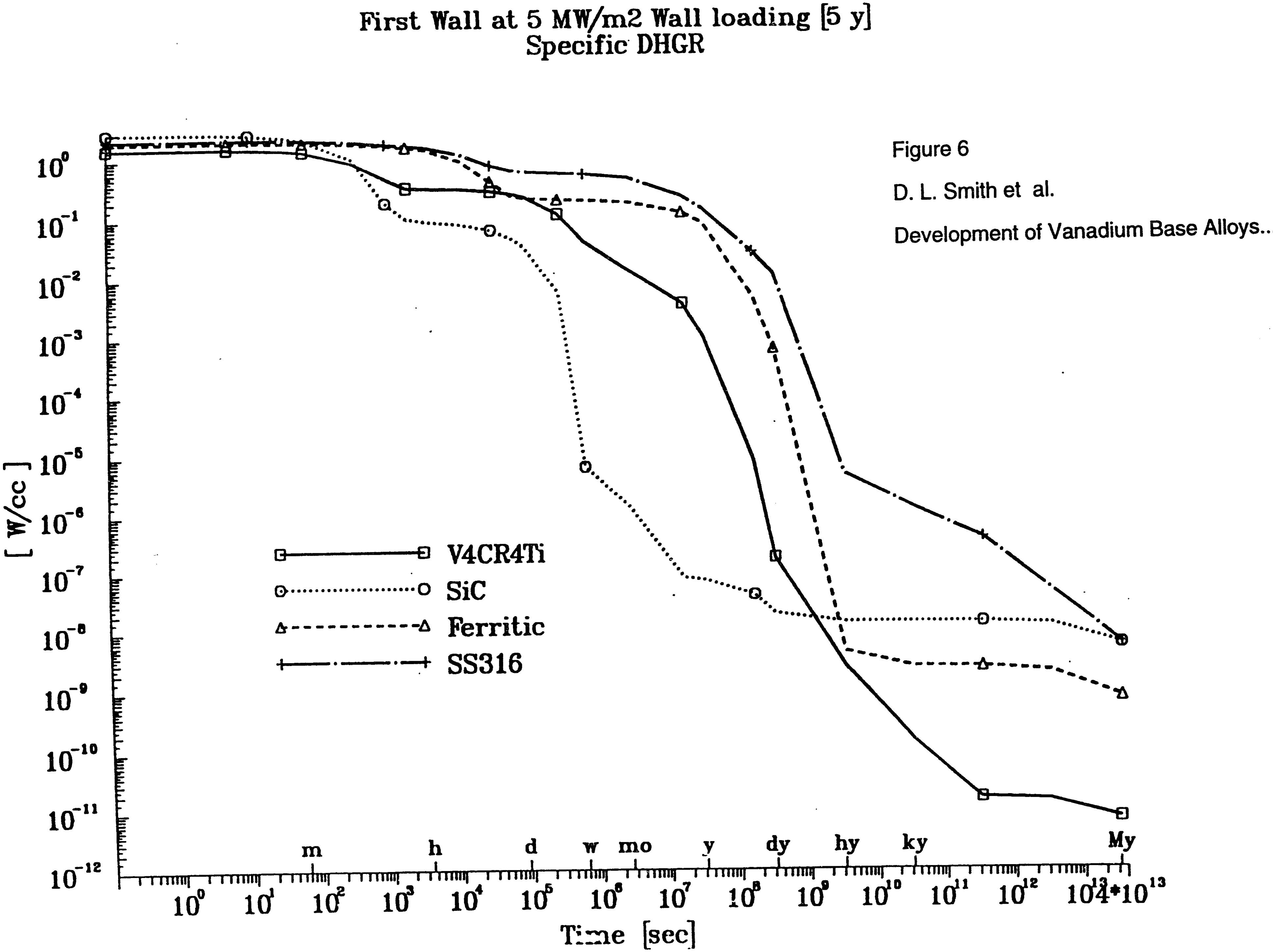
Development of Vanadium Base Alloys...


First Wall at 5 MW/m2 Wall loading [5 y]
Specific DHGR
Figure 6
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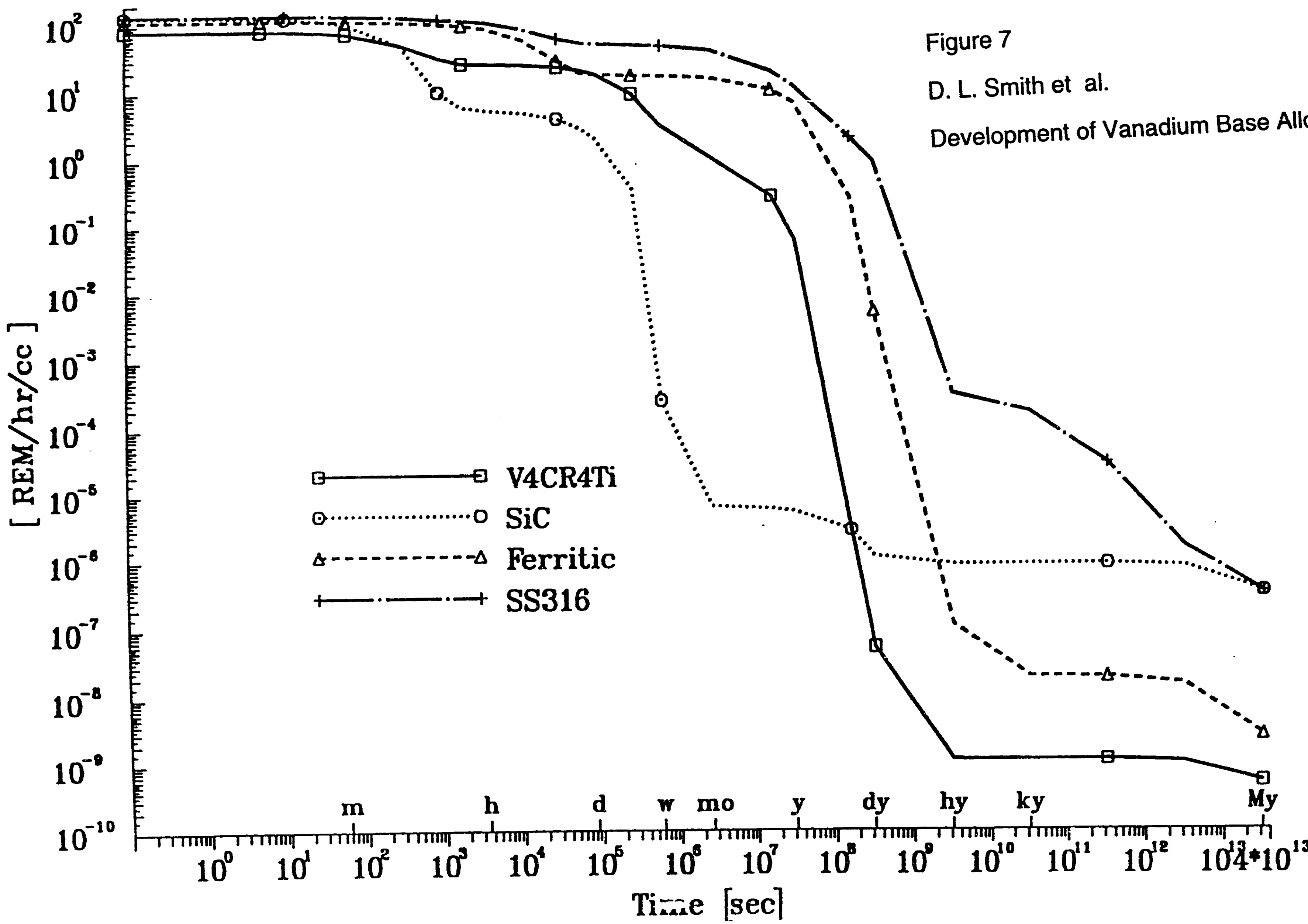
Development of Vanadium Base Alloys...
[W/cc]
V4CR4Ti
SiC
Ferritic
SS316
m
h
d
w
mo
y
dy
hy
ky
My
Time [sec]

First Wall at 5 MW/m2 Wall loading [5 y]
Contact Dose [1m air] (ICRU-46)



Structural Materials @ Na – ITER [1 MW/m2 – 3 MWa/m2

Specific BHP of Air

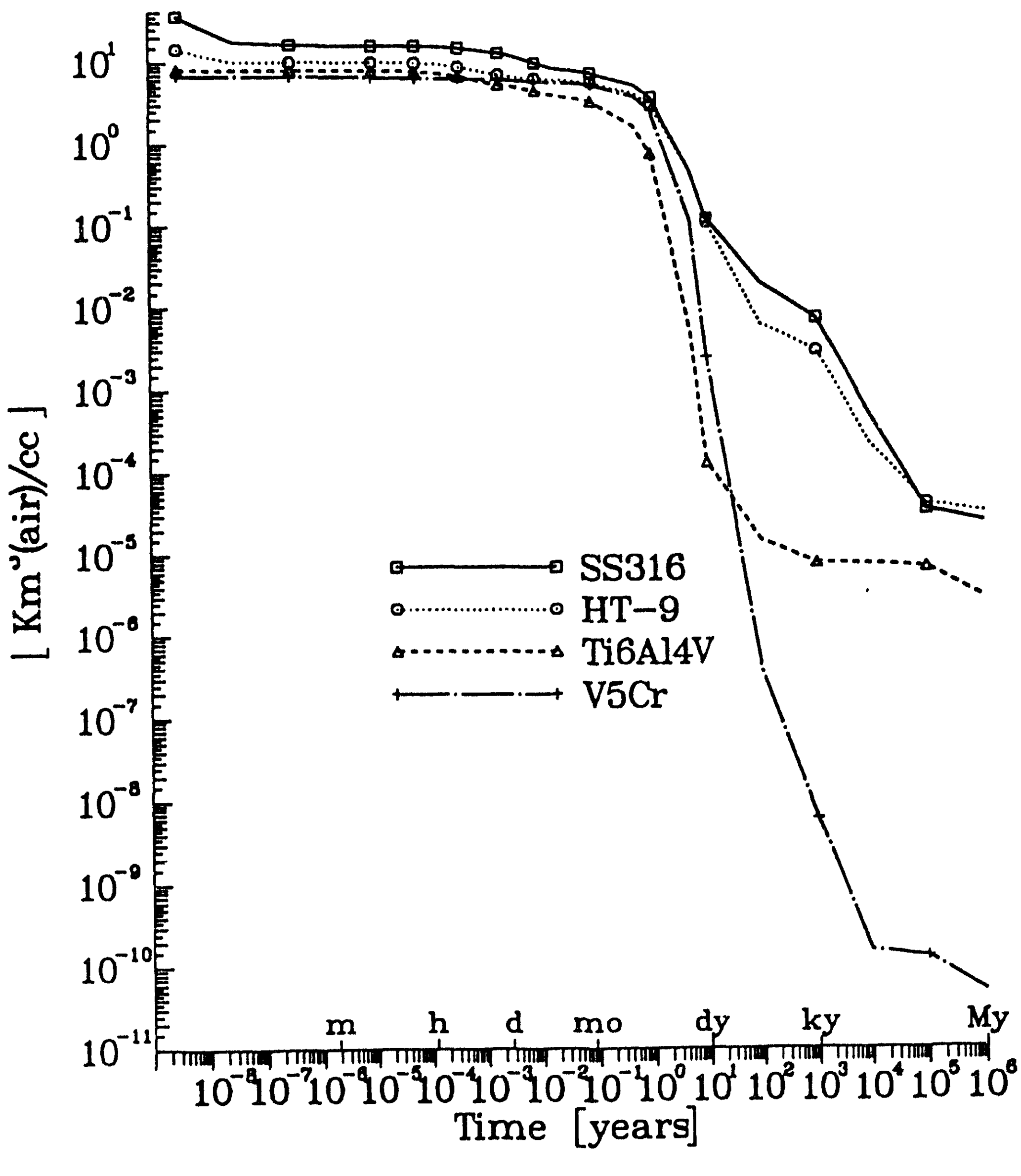


Figure 8

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Development of Vanadium Base Alloys...

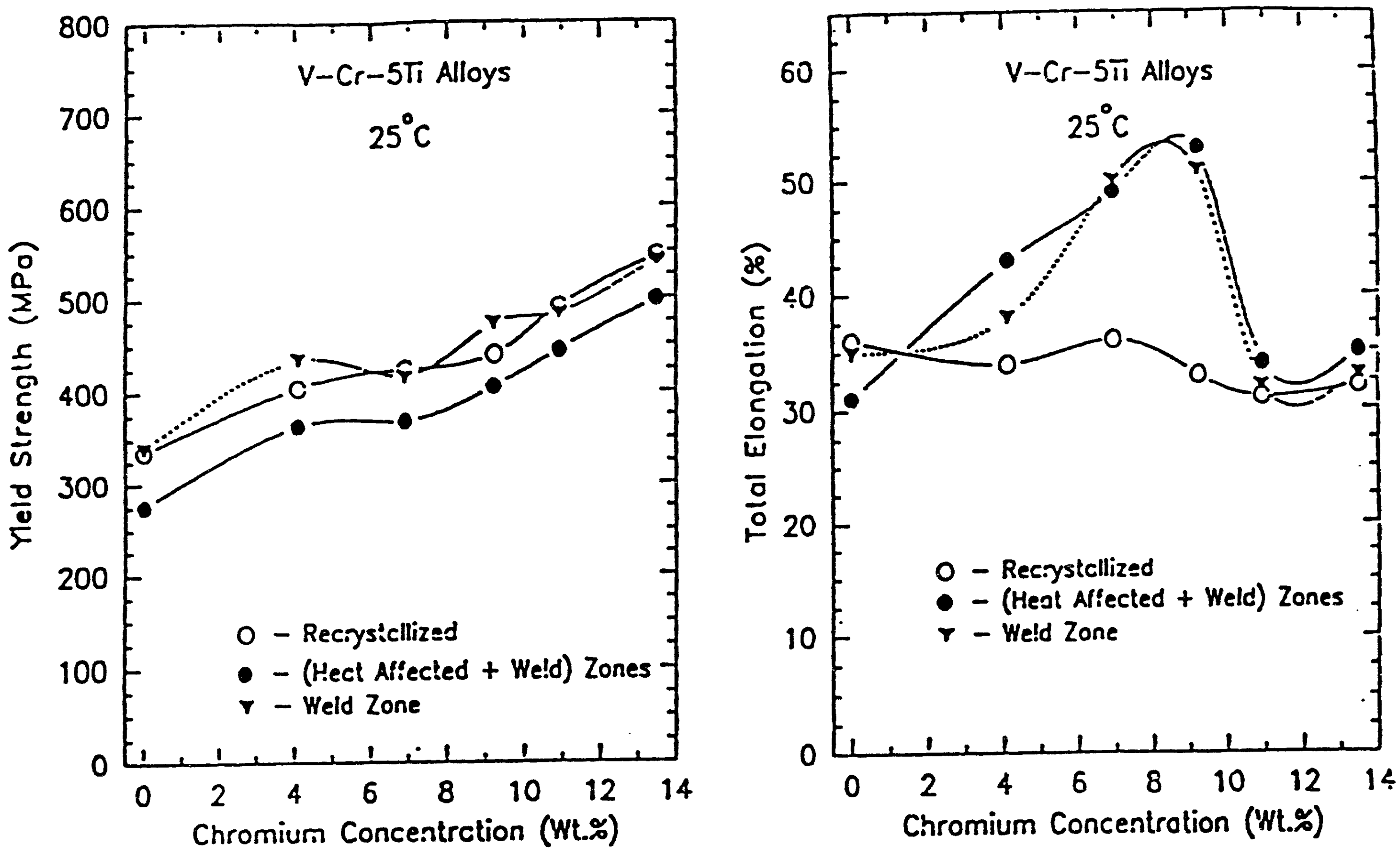

Figure 9

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Development of Vanadium Base Alloys...

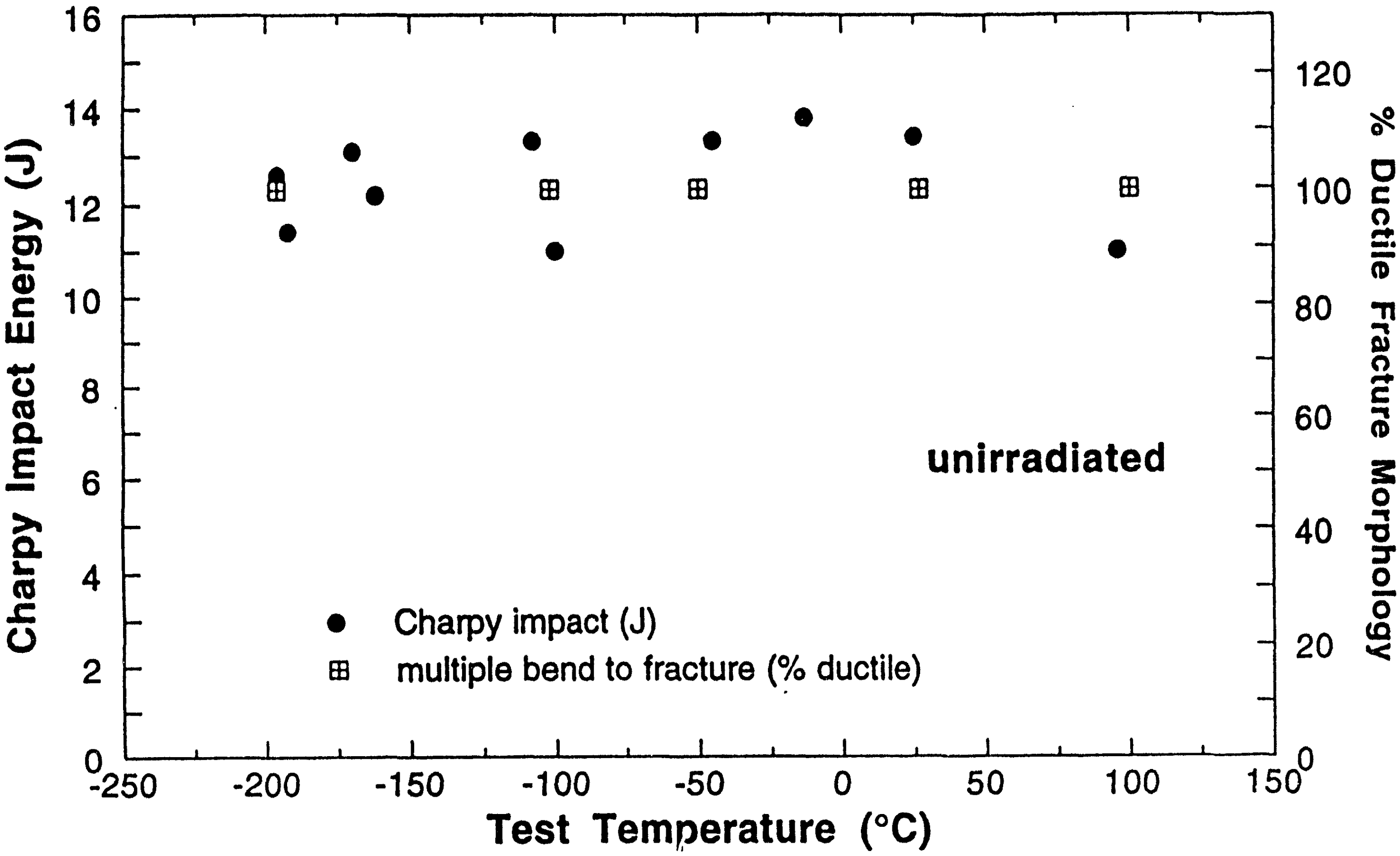

Figure 10

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Development of Vanadium Base Alloys...

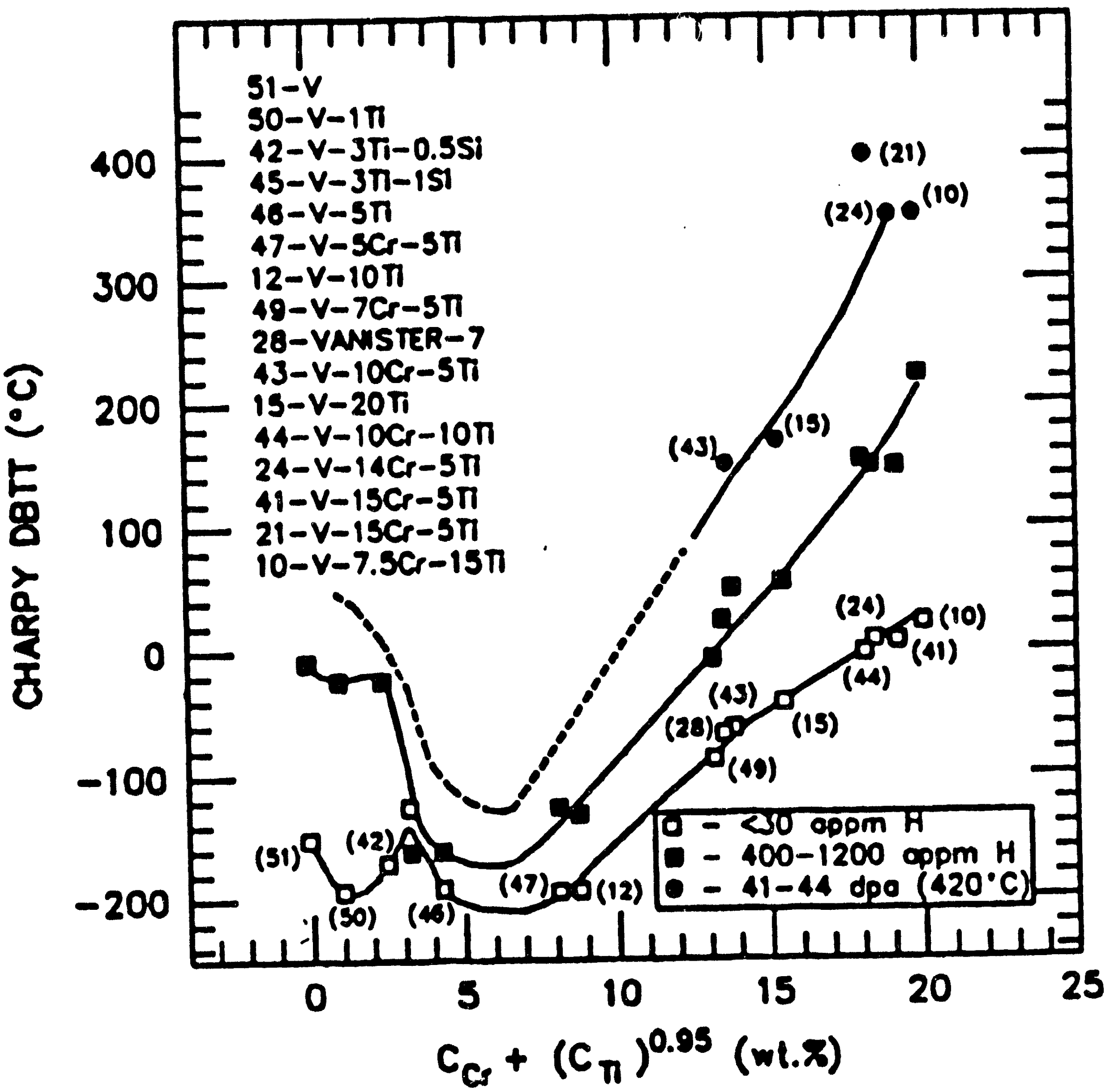

Figure 11

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Development of Vanadium Base Alloys...

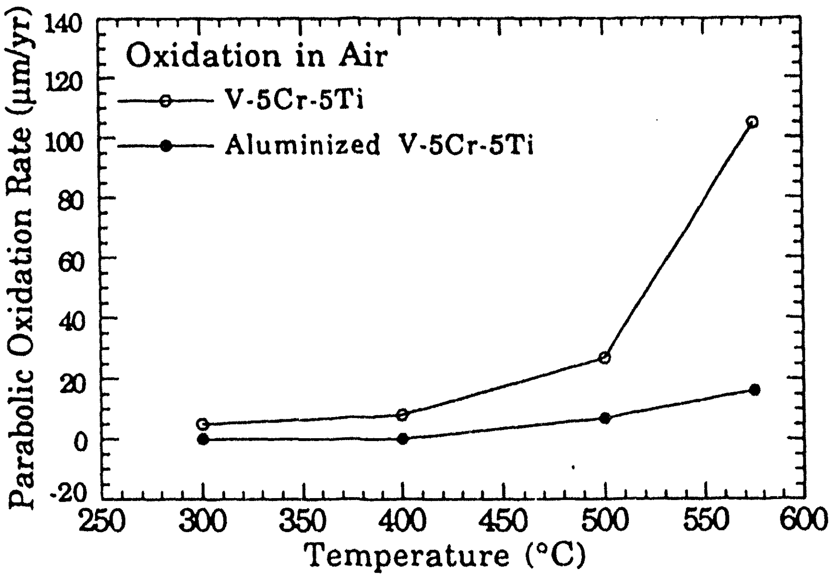

Figure 12

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Development of Vanadium Base Alloys...

Microhardness profile of V-base alloys after test in lithium

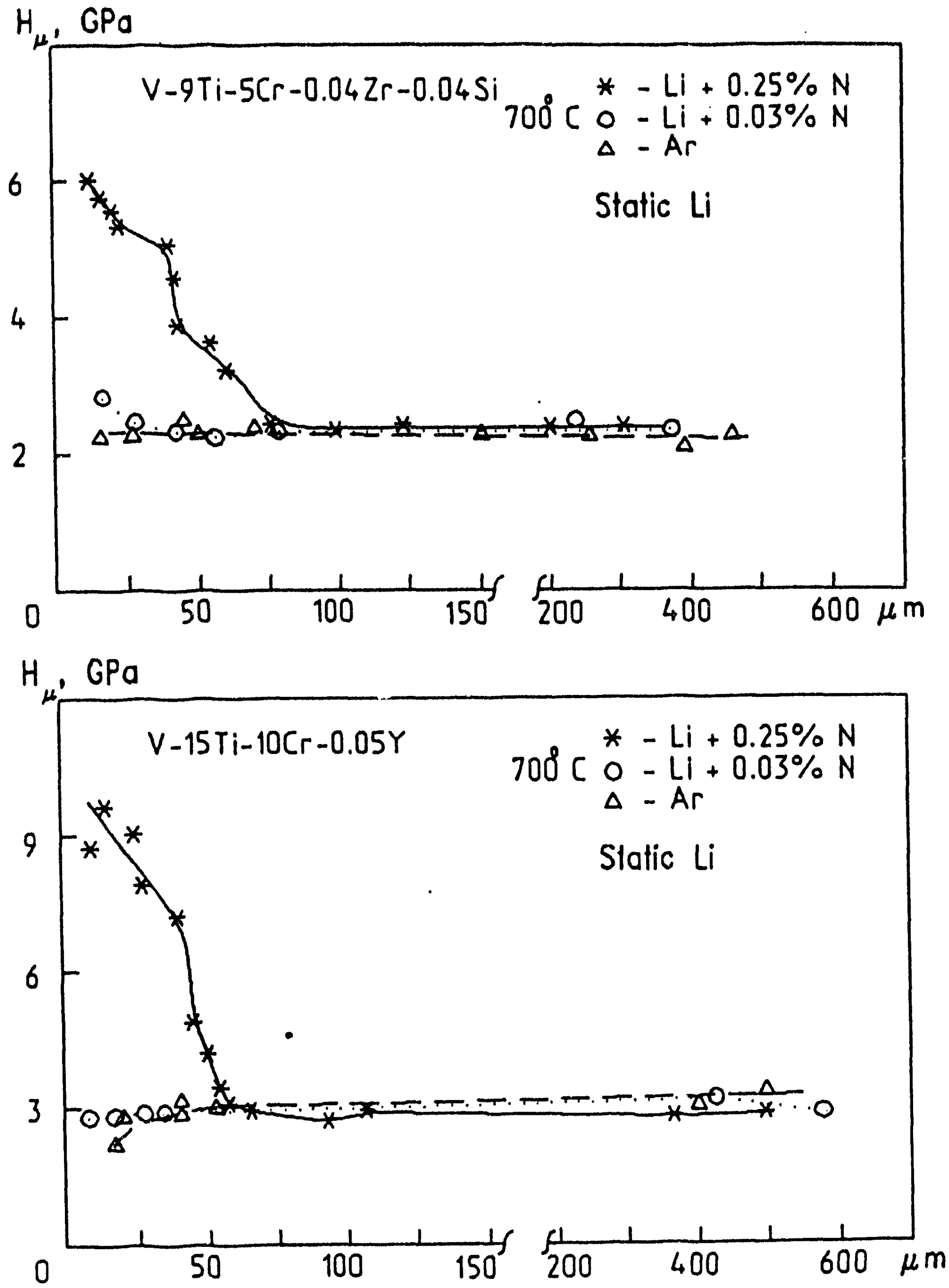

Figure 13

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Development of Vanadium Base Alloys...

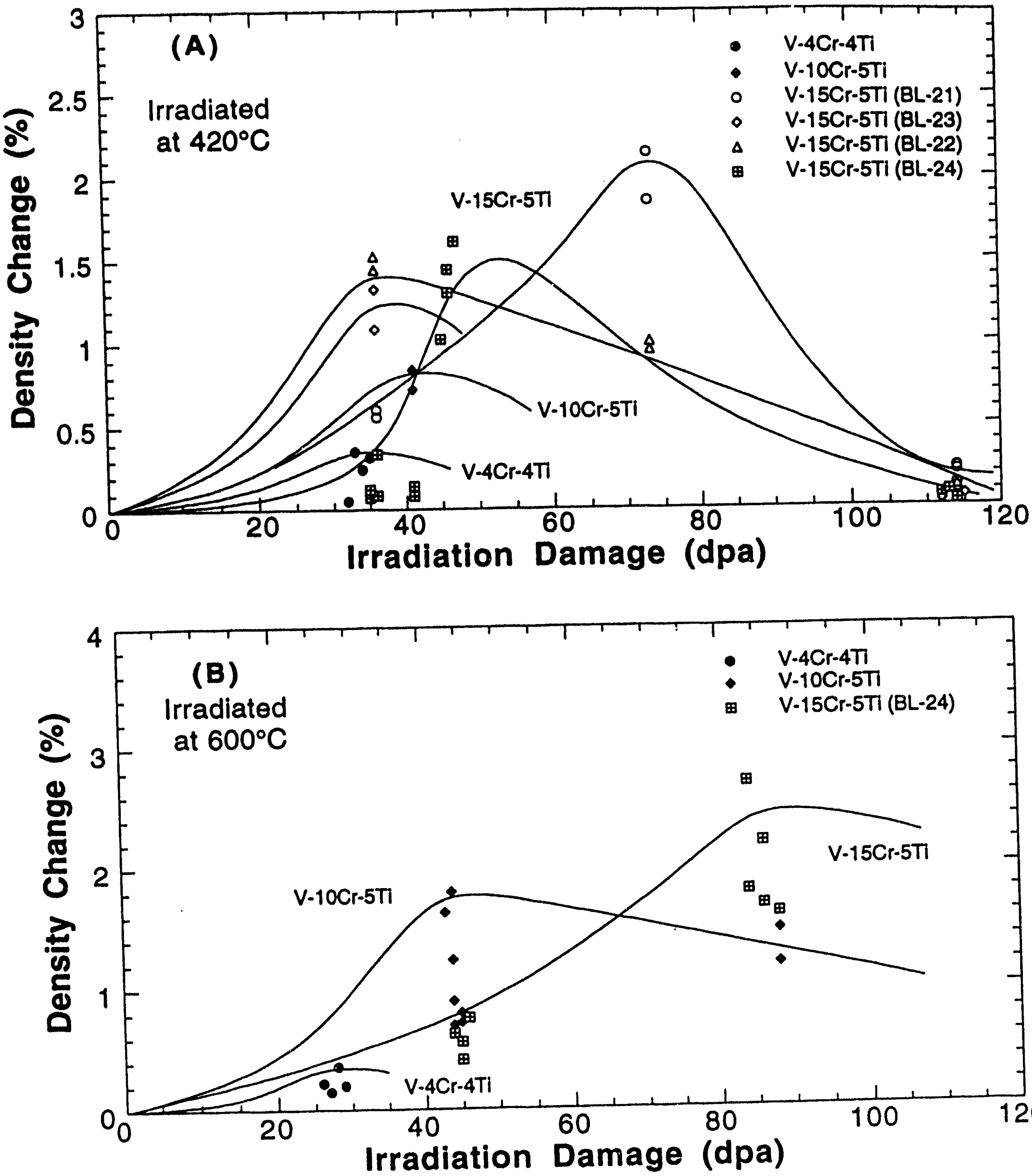

Figure 14

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Development of Vanadium Base Alloys...

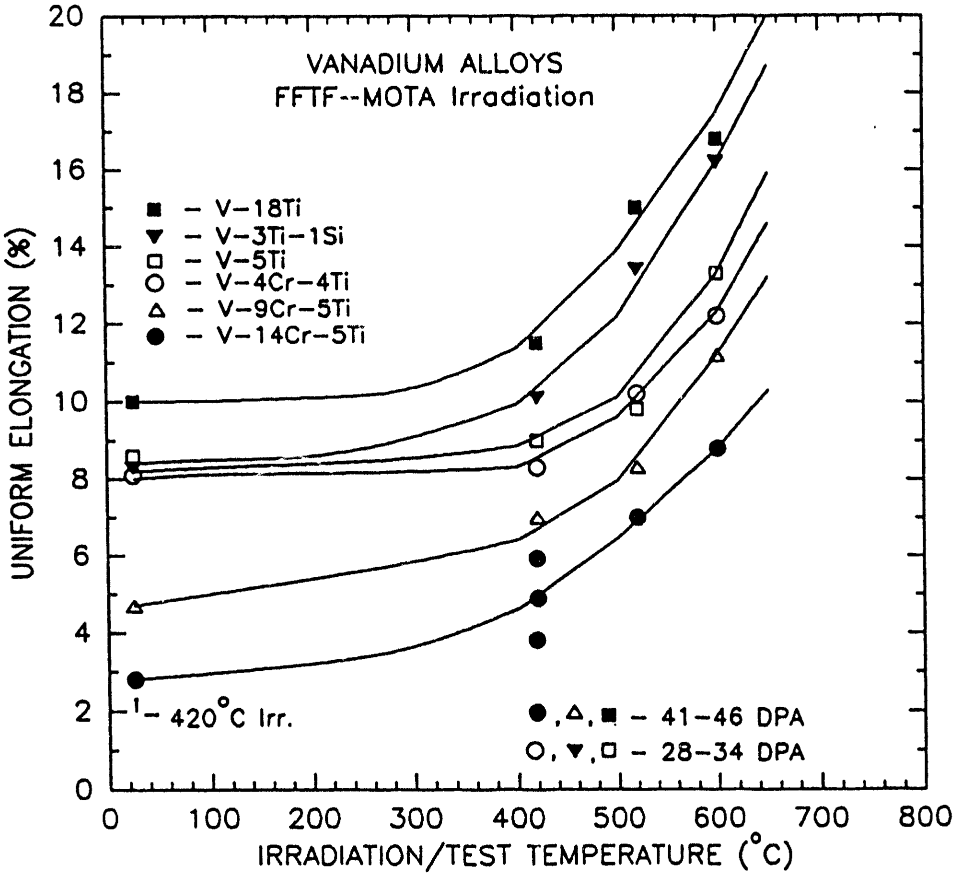

Figure 15

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Development of Vanadium Base Alloys...

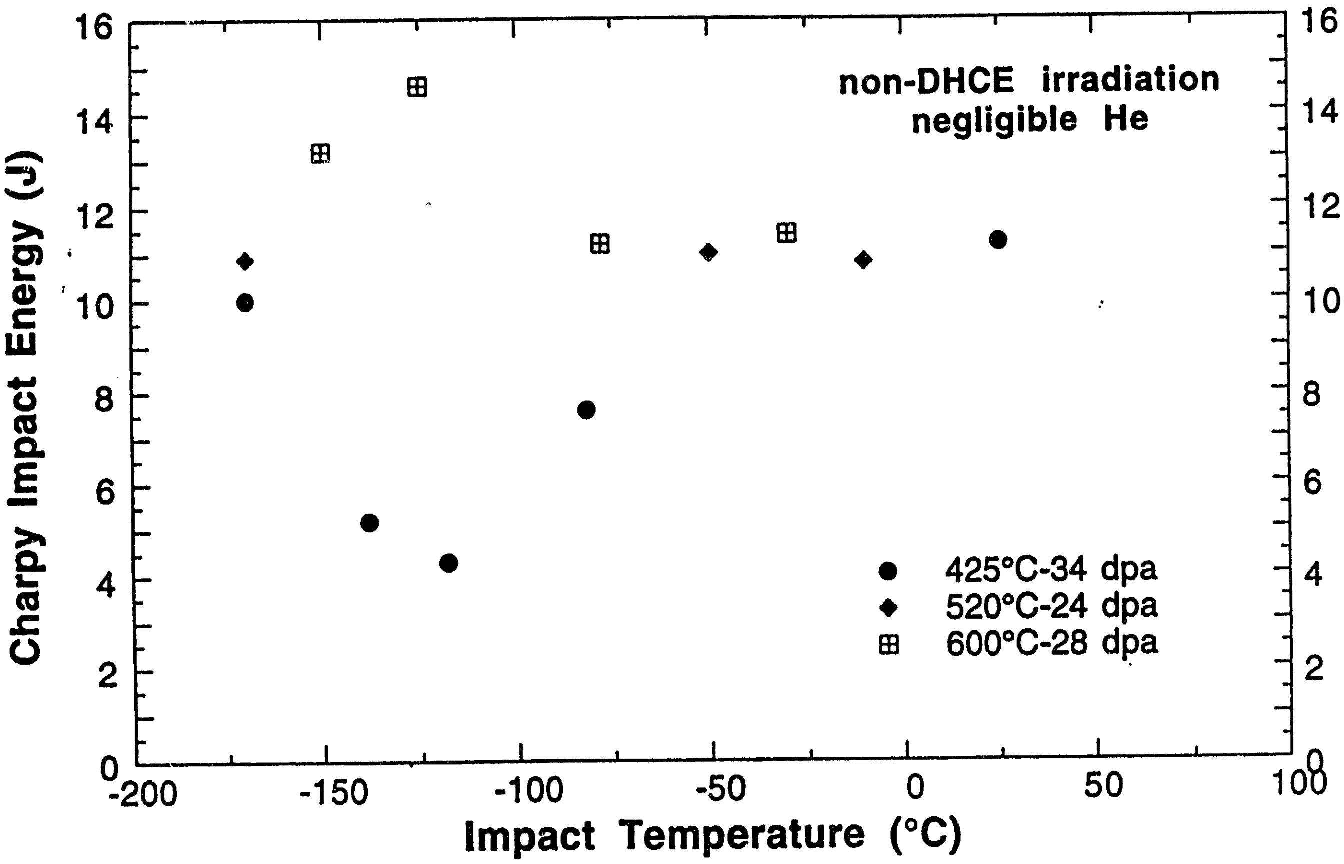

Figure 16

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Development of Vanadium Base Alloys...

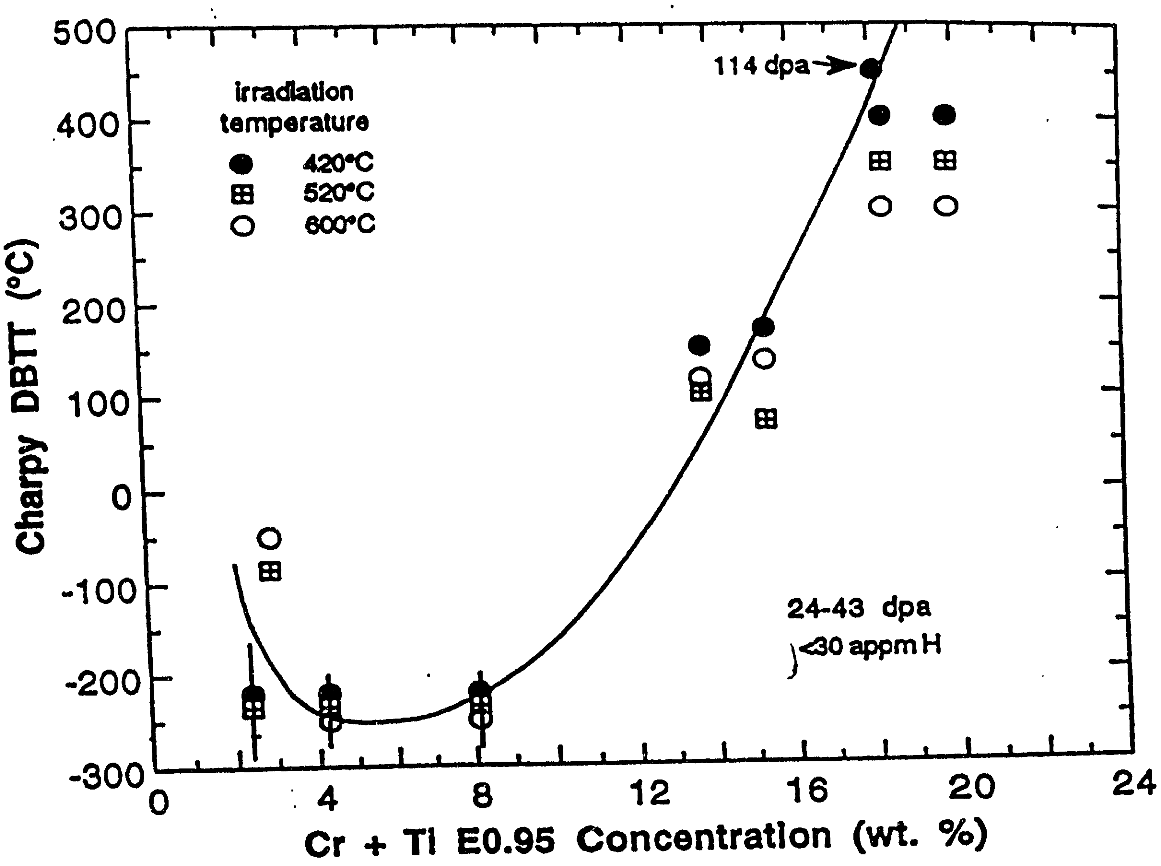

Figure 17

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Development of Vanadium Base Alloys...

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