Revised ANL-Reported Tensile Data for Unirradiated and Irradiated (FFTF, HFIR) V-Ti and V-Cr-Ti Alloys* -- M. C. Billone (Argonne National Laboratory)

SUMMARY

The tensile data for all unirradiated and irradiated vanadium alloys samples tested at Argonne National Laboratory (ANL) have been critically reviewed and, when necessary, revised. The review and revision are based on reanalyzing the original load-displacement strip chart recordings by a methodology consistent with current ASTM standards. For unirradiated alloys (162 samples), the revised values differ from the previous values as follows: -11±19 MPa (-4±6%) for yield strength (YS), -3±15 MPa (-1±3%) for ultimate tensile strength (UTS), -5±2% strain for uniform elongation (UE), and -4±2% strain for total elongation (TE). For irradiated alloys (91 samples), the differences between revised and previous values are: 30±37 MPa (6±7%) for YS, -1±6 MPa (0±1%) for UTS, -5±2% for UE, and -4±2% for TE. Of these changes, the decrease in UE values for alloys irradiated and tested at 400-435°C is the most significant. This decrease results from the proper subtraction of nongauge-length deformation from measured crosshead deformation. In previous analysis of the tensile curves, the nongauge-length deformation was not correctly determined and subtracted from the crosshead displacement. The previously reported and revised tensile values for unirradiated alloys (20-700°C) are tabulated in Appendix A. The revised tensile values for the FFTF-irradiated (400-600°C) and HFIR-irradiated (400°C) alloys are tabulated in Appendix B, along with the neutron damage and helium levels. Appendix C compares the revised values to the previously reported values for irradiated alloys. Appendix D contains previous and revised values for the tensile properties of unirradiated V-5Cr-5Ti (BL-63) alloy exposed to oxygen.

PROGRESS AND STATUS

Introduction

The V-Ti and V-Cr-Ti tensile data reported by Argonne National Laboratory (ANL) have been reviewed and revised as necessary in this effort. The tensile properties of interest are yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE) and reduction in area (RA) at the failure site. The data have been reported in tabular and/or graphical form in the Fusion Reactor Materials Semiannual Progress Reports from the periods ending March 31, 1987 (DOE/ER-0313/2) to June 30, 1996 (DOE/ER-0313/20), as well as at workshop meetings and in open literature publications. In this report, the original force-displacement strip chart recordings for these tests have been reanalyzed according to a standardized and consistent methodology (see Ref. 1 for ASTM definitions of YS, UTS, UE and TE, along with methods for determining these parameters from strip chart recordings).

Loomis et al. describe the tensile machine and sample parameters in Refs. 2 and 3. The tensile specimens (SS3) used in most ANL tensile tests have a gauge length of 7.62 mm and a cross-sectional area of ≈1 mm^2 (0.9-1.4 mm^2), as shown in Ref. 3. The Instron testing machine is equipped with a 500 kgf (4900 N) load cell. A uniform crosshead speed of 0.5 mm/min was used for all but the oxidation study tests, giving a gauge-length strain rate of 0.11%/s. Based on information recorded on the load-displacement curves, in laboratory notebooks [4, 5] and on data sheets [6], the load cell was varied from a full vertical scale value of 2 to 250 kgf. Useful data for most tests were recorded with a full scale of 50 kgf for unirradiated alloys and 100 kgf for irradiated

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alloys. The strip chart recording speed was generally 50 mm/min, although 100 mm/min was used in several cases. At 50 mm/min, each horizontal grid mark corresponds to 0.02 mm crosshead displacement and 0.262% gauge-length strain.

Reference 2 contains load-strain curves, along with tables of tensile properties, for several of the older V-Ti and V-Cr-Ti alloys tested at room temperature. It is readily apparent from a comparison of the tabular values to those determined directly from the curves that the initial "elastic" portion of the curve is included in the calculation of UE and TE, whereas standard procedures require that the effective "elastic" strain be subtracted from the total strain at any point along the curve to determine the permanent plastic strain. It is also apparent that the slope of the initial linear portion of the load-strain curve is at least one order of magnitude lower than what would be derived from the Young's modulus for vanadium alloys. Based on an analysis of all of the original strip chart recordings, the initial linear portion of the force-displacement curves corresponds to an effective stiffness of about 1.2 kN/mm for unirradiated alloys and 1.8 kN/mm for irradiated alloys. If these are converted to "effective" Young's moduli (E') based on a gauge length of 7.62 mm and the particular gauge cross-sectional area for each sample, then $E' \approx 8.2$ GPa for unirradiated alloys and $E' \approx 12$ GPa for irradiated alloys (vs. 126 GPa for vanadium alloys [7]). Clearly, the nongauge displacement must be subtracted from the crosshead displacement in order to determine the permanent or plastic deformation and strain of the sample at a particular stress (load/initial-cross-sectional-area).

The purpose of the current work is to revise the tensile data to be consistent with a proper interpretation of the original load-displacement data curves. The reduction in area values reported in Refs. 8 and 10 are determined directly from the failed samples, so no corrections to the RA data base are necessary. Specific references for the data to be reanalyzed and reinterpreted include Ref. 9 for tabular listing of the tensile properties of most of the unirradiated alloys, Ref. 10 for graphical representation of the tensile properties of the newer heats of unirradiated V-(4-5)Cr-(4-5)Ti (i.e., BL-71 and BL-72), Refs. 12-14 for graphical representation of the tensile properties of FFTF-irradiated alloys, Ref. 15 for the graphical representation of the tensile properties of HFIR-irradiated alloys at 400°C, and Ref. 18 for the tensile data on the effects of oxygen on unirradiated V-5Cr-5Ti (BL-63).

Methodology

Determination of YS, UTS, UE and TE

The terminology and methodology for analyzing tensile data from strip chart recordings are established in ASTM Designations E 6 and E 8, respectively [1]. It is worthwhile to review these terms and methods. For monotonically increasing load vs. displacement curves up to the maximum load, YS is the load (divided by the initial gauge cross-sectional area) corresponding to an offset strain of 0.2%. The offset value of 0.2% has no intrinsic significance, but is based on practicality and experience in analyzing tensile curves. The option to use an offset strain of 0.5% is also allowed by E 8. Offset strain is determined by "analytically" or "graphically" unloading the specimen at a linear load-displacement slope corresponding to the effective linear portion of the load-displacement curve. The intersection of this line with the horizontal axis determines the offset displacement and strain. Some of the analyzed load-displacement curves exhibit discontinuous yielding, which consists of a rise to a high load (upper yield point, UYP) followed by a drop in load to a minimum value (lower yield point, LYP) followed by a rise in load with displacement up to the maximum load. For these cases, the 0.2% offset stress may not be a good measure for YS. For consistency, the stress corresponding to the minimum yield point is designated as YS in the current work for samples that exhibit discontinuous yielding. In the event that 0.2% offset is reached on the rise in load and corresponds to a lower value than determined by LYP, then the stress corresponding to 0.2% offset is used to define YS. Thus, YS is defined as the minimum of the stress corresponding to 0.2% offset and the stress corresponding to LYP. For several of the older alloys irradiated at 400-435°C, the load curve bends to an offset strain of >0.2%, then straightens and bends again at about double the load. These cases generally corresponded to plastic deformation of the support pins used prior to 1992. For these cases, YS, as well as UE, of the gauge section was deemed to be indeterminate. Tabulated values of TE for these tests are based on direct post-test measurement of the change in sample length. After 1991, stiffer pins with near-zero bending span were used to eliminate this problem.

Determination of UTS is relatively straightforward. For monotonically increasing load with displacement up to the maximum load, the UTS is simply the maximum load divided by the initial gauge cross-sectional area. In the case of discontinuous yielding, the UYP may represent a higher load than for the continuous part of the curve after the discontinuous yielding. In such cases, the UYP is not to be used in determining UTS. The offset displacement (or strain) corresponding to the peak load (or UTS) is called the uniform elongation (UE). While UTS can be uniquely determined, more uncertainty is involved in determining UE, particularly for cases for which the maximum load is nearly constant over a displacement (or strain) range. Although the ASTM standards imply that the midpoint of this flat region should be used to determine UE, the maximum offset strain corresponding to the maximum load is used in the current work. This decision is based on detailed analyses of stainless steel stress-strain curves and the criteria for necking. The maximum strain at peak load is more characteristic of the uniform elongation of the gauge section prior to necking. Total elongation (TE) corresponds to the offset strain just prior to failure. The same slope used to determine YS and UE is used to determine TE.

Some of the load-displacement curves exhibit serrations, particularly in the region of the peak load to the failure load. The treatment of these serrations is described in the following. If the serrations are characterized by an instantaneous drop in load followed by a more gradual rise in load, then the maximum of the serrated portion is used. If the serrations are characterized by a more sinusoidal variation with displacement, then the average of the serrated portion is used. If the serrations are characterized by an instantaneous rise in load followed by a more gradual decrease in load, then the minimum of the serrated portion is used. Thus, the choice of maximum, average or minimum is based on the generation of a continuous and smooth curve through serrated and non-serrated regions of the load-displacement trace.

Determination of Effective Modulus

While various methods (e.g., initial tangent modulus, tangent modulus, secant modulus and chord modulus) are given in the ASTM standards to determine the effective modulus, the methodology used in the current work corresponds most closely to the tangent modulus approach. With most of the load-displacement curves for vanadium alloys tested in the ANL Instron machines exhibiting an elongated "S" shape during the initial rise in load, the modulus is determined by the tangent line coinciding with the greatest number of points in the elongated part of the S-shape.

The strip chart recordings from the tensile tests give measured load vs. calculated crosshead displacement. The crosshead displacement is a combination of the axial deformation of the gauge section, the nongauge section, the local deformation of the sample near the pin supports, the pins themselves, the grips supporting the pins and the load train compliance. It has already been established in the Introduction of this report that the initial rise in load for the SS3 samples is not governed by the gauge section. Figure 1 shows the linearized load vs. displacement slope (k) for all of the samples analyzed in the current work. For unirradiated material, k = 1.20±0.20 kN/mm, where the ± values indicate one standard deviation. For irradiated material, k = 1.76±0.34 kN/mm. There is also a decrease in k with temperature for both cases (see best-fit lines in Fig. 1). Because most of the load train is outside the heated region of the sample and does not change with the unirradiated/irradiated condition of the sample, it appears that the nongauge section of the sample, the support pins and the grips play a major role in determining the effective stiffness used to analyze the force-displacement curves.

The effective modulus (E') is determined from the effective stiffness (k) according to

$$E' = k\,(L_o/A_o), \tag{1}$$

where L_o is the initial gauge length and A_o is the initial gauge cross-sectional area. The results for E' are shown in Fig. 2, where the units have been converted to MPa/% rather than to the traditional units of GPa. For unirradiated material, E' = 82±15 MPa/%; for irradiated material, E' = 120±28 MPa/%. The solid lines show the best linear fit of E' with test temperature for the two cases.

Tensile Properties of Unirradiated V-Ti and V-Cr-Ti Alloys

Comparison of YS, UTS, UE and TE

Appendix A contains tables listing both the revised and previously reported values for the tensile properties for unirradiated V-Ti and V-Cr-Ti alloys (Tables A.1-A.12). The revised values have been determined from the original load-displacement strip chart recordings according to the methodology described. Also tabulated are the effective stiffness (k) values used to analyze the data.

The difference between revised and previously reported values for UTS is insignificant for the majority of the cases analyzed. On the average, the new values are 3 MPa lower than the old values with a standard deviation of ±15 MPa. These values correspond to -1±3%. Differences as high as ±20 MPa can be attributed to the methodology used for the cases in which serrations occur at the maximum load. Larger differences in interpretation can occur if the zero-load line does not correspond to the bottom horizontal axis of the chart (see 100°C value for BL-71 in Table A.7). For the majority of the cases analyzed, the difference between new and previously reported values of UTS is less than a few MPa. Overall, the deviation in UTS due to methodology changes is much less than the ±10% expected from heat-to-heat variation for the same nominal composition alloy.

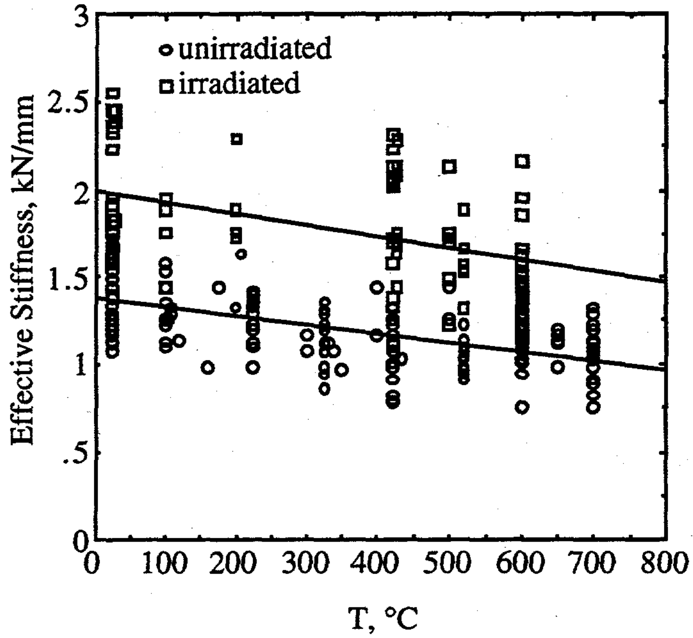

Fig. 1. Effective stiffness vs. temperature determined from the linearized increase of load with crosshead displacement for SS3 vanadium alloy tensile samples. Lower and upper lines are best fits, respectively, to stiffness values for unirradiated and irradiated samples.

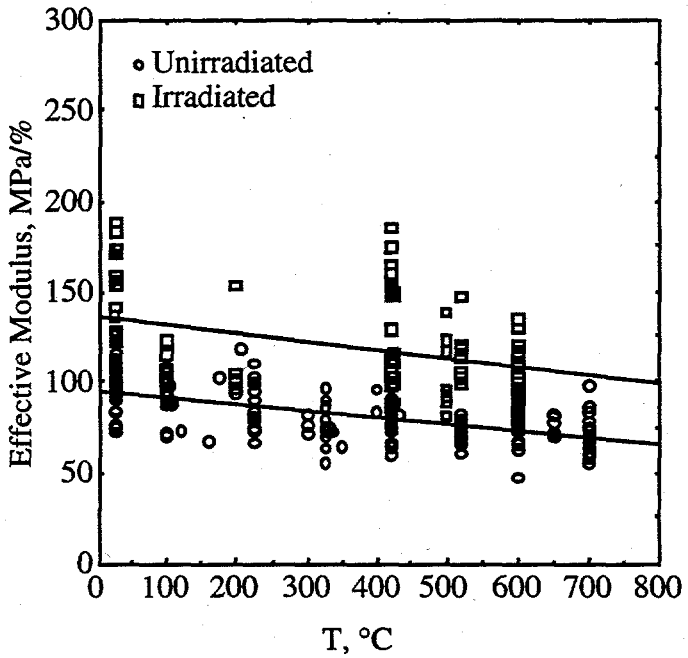

Fig. 2. Effective modulus vs. temperature for SS3 vanadium alloy tensile samples. Lower and upper lines are best fits, respectively, to moduli for unirradiated and irradiated samples.

The new values for YS are generally lower than the previous values because of the change in methodology from the 0.5% offset (previously used) to the 0.2% offset (currently used). For cases in which the material exhibits elastic/perfectly-plastic behavior to plastic strains > 0.5%, the two definitions for YS result in the same value. Larger differences are encountered for samples which reach 0.2% offset before the upper yield point (UYP) and where the ensuing lower yield point (LYP) results in a higher value for YS than does the 0.2% offset stress. These comments apply to all unirradiated cases except for the newer heats presented in Table A.7. For these cases, the previously reported values are either the proportional elastic limit or the 0.2% offset stress. Even with the methodology differences, the new values differ from the old values by only -11±19 MPa (-4±6%), well within the heat-to-heat variation in YS for structural materials.

By properly determining the offset (i.e., plastic) strains from the force-displacement tensile curves, UE decreases by 5±2% from previously reported values. Figure 3 shows the previously reported and revised values. While this correction is significant with regard to showing trends in alloy behavior (e.g., change in uniform ductility with increased ultimate tensile strength), the unirradiated vanadium alloys remain ductile for the full temperature range tested (20-700°C). For higher-strength alloys, the decrease in UE may be as high as 10%.

With regard to the total elongation (TE), this property decreases by 4±2% with proper determination of the plastic strain. The corrected values remain relatively high for most of the alloys tested.

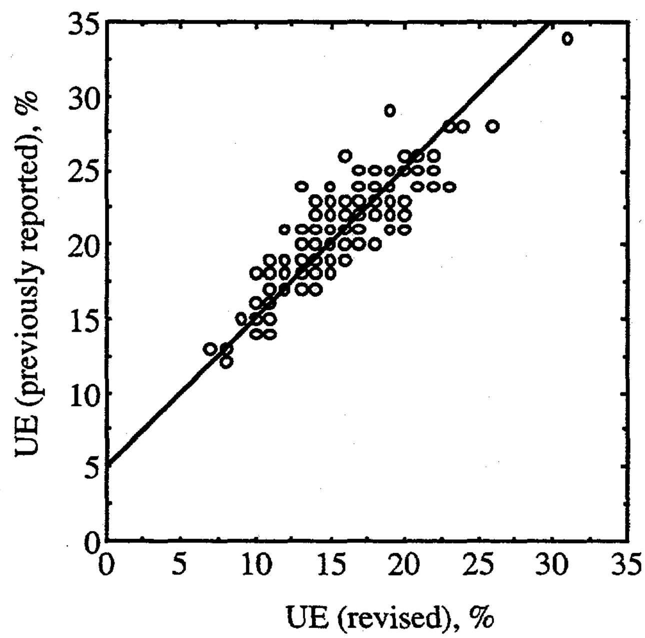

Fig. 3. Previously reported and revised values for uniform elongation (UE) of unirradiated V-Ti and V-Cr-Ti alloys tested at ANL. Total number of data points is 162, many of which overlap.

Stress-Strain Curves

While tables of tensile properties are important, it is instructive to examine a few stress-strain curves in more detail. The engineering stress-strain curves for unirradiated V-3.8Cr-3.9Ti (BL-71) are shown in Figs. 4-6 for test temperatures of 400, 500 and 600°C, which are close to the irradiation/test temperatures for irradiated alloys. In constructing these curves from the original load-displacement curves, an effective linear rise to the curve is used instead of the more S-shaped curve on the strip chart recording. Also, the zero strain point is redefined by the intersection of the effective linear portion with the displacement axis. Finally, the serrations are smoothed by the methods described in a previous section. The change in work-hardening rate in the neighborhood of the yield point has been preserved in the stress-strain plots.

The strip chart recording for Fig. 4 exhibits a 0.2% offset YS prior to the leveling off and dip in the curve. Because this value is lower than that corresponding to the lower yield point (LYP), it is used to determine YS. Serrations are initiated at the 0.2% offset stress and continue until failure. The peak-to-peak amplitude of the serrations is ≤1.5 kgf (15 N) corresponding to 14 MPa. The peaks of the serrations are used in constructing Fig. 4. For Fig. 5, the serrations occur closer to the maximum load and have a peak-to-peak value of ≤2.5 kgf (25 N), corresponding to 21 MPa. Again, the peak values are used in constructing Fig. 5. For Fig. 6, the serrations occur after the peak load has been reached. They have a peak-to-peak amplitude ≤ 4 kgf (39 N), which corresponds to 34 MPa. As before, the peaks are used to construct Fig. 6. Because of the location of these serrations, they have no influence on the determination of YS, UTS and UE; however, they have a small influence on the determination of TE.

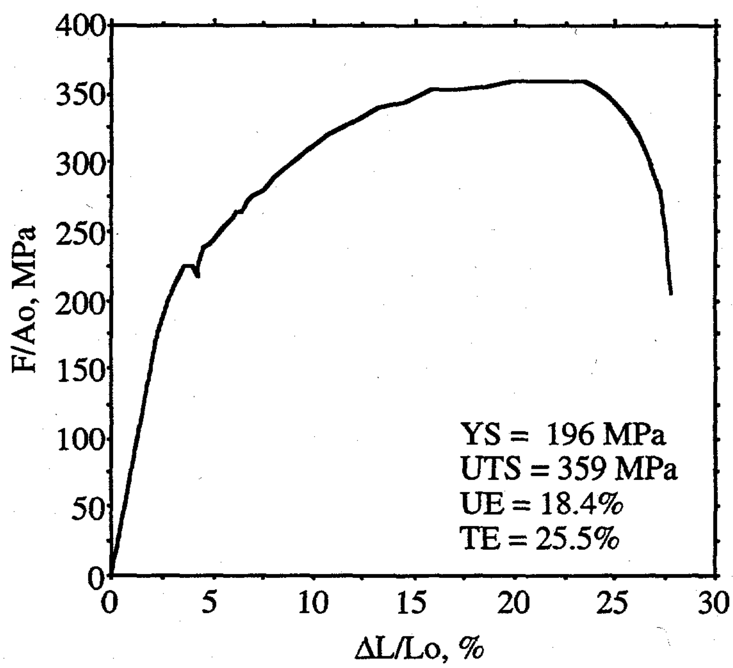

Fig. 4. Engineering stress (F/Ao)-strain (ΔL/Lo) curve for unirradiated V-3.8Cr-3.9Ti (BL-71) tested at 400°C. Gauge strain rate is 0.11%/s. Gauge length (Lo) and cross-sectional area (Ao) are 7.62 mm and 1.078 mm^2, respectively.

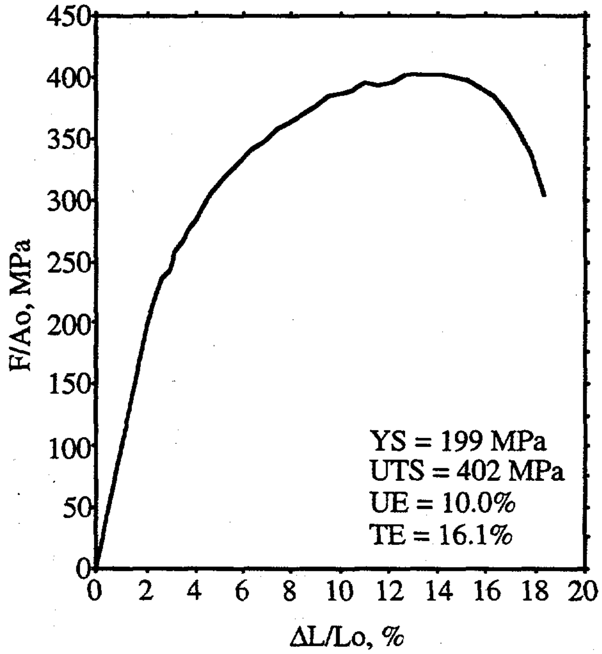

Fig. 5. Engineering stress (F/Ao)-strain (ΔL/Lo) curve for unirradiated V-3.8Cr-3.9Ti (BL-71) tested at 500°C. Gauge strain rate is 0.11%/s. Gauge length (Lo) and cross-sectional area (Ao) are 7.62 mm and 1.147 mm^2, respectively.

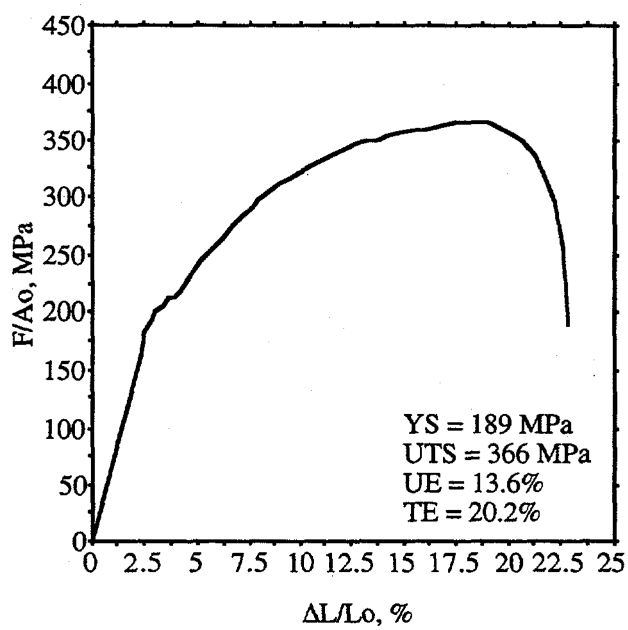

Fig. 6. Engineering stress (F/Ao)-strain (ΔL/Lo) curve for unirradiated V-3.8Cr-3.9Ti (BL-71) tested at 600°C. Gauge strain rate is 0.11%/s. Gauge length (Lo) and cross-sectional area (Ao) are 7.62 mm and 1.1396 mm^2, respectively.

Tensile behavior of V-(4-5)Cr-(4-5)Ti

Because of the interest in the V-(4-5)Cr-(4-5)Ti alloys, it is worthwhile to establish baseline tensile properties for these alloys as a function of temperature. The particular compositions and heats of interest are V-3.8Cr-3.9Ti-0.078Si (BL-71, #832665), V-4.1Cr-4.3Ti-0.087Si (BL-47, #9144), V-4.6Cr-5.1Ti-0.031Si (BL-63, #832394) and V-4.9Cr-5.1Ti-0.055Si (BL-72 or T87). Figures 7-10 show the variations of YS, UTS, UE and TE, respectively, with temperature. The solid lines represent best-fit cubic equations to these parameters.

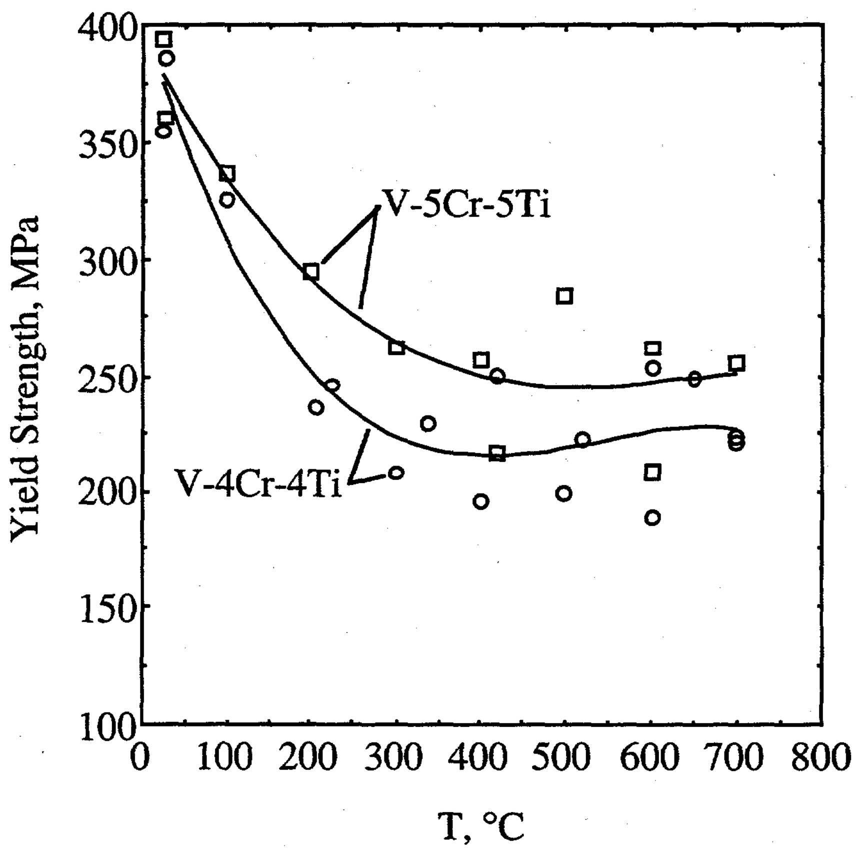

Fig. 7. Yield strength vs. temperature for unirradiated V-4Cr-4Ti (BL-47 and BL-71) and V-5Cr-5Ti (BL-63 and BL-72).

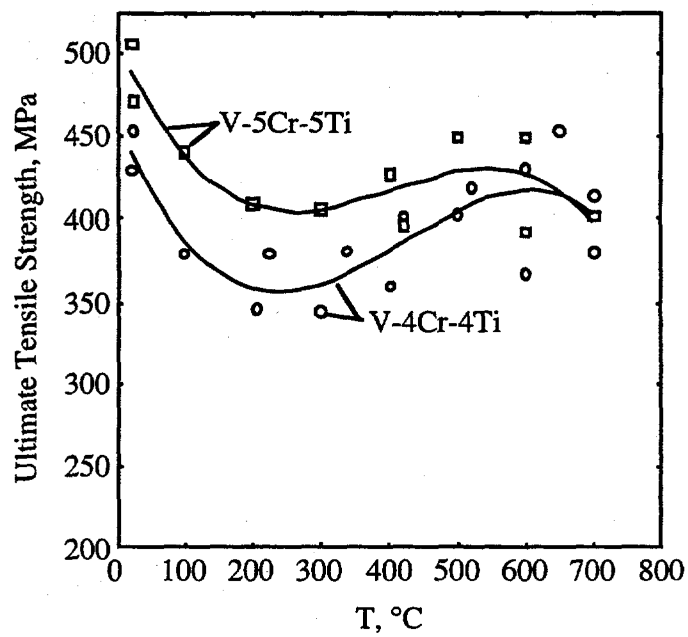

Fig. 8. Ultimate tensile strength vs. temperature for unirradiated V-4Cr-4Ti (BL-47 and BL-71) and V-5Cr-5Ti (BL-63 and BL-72).

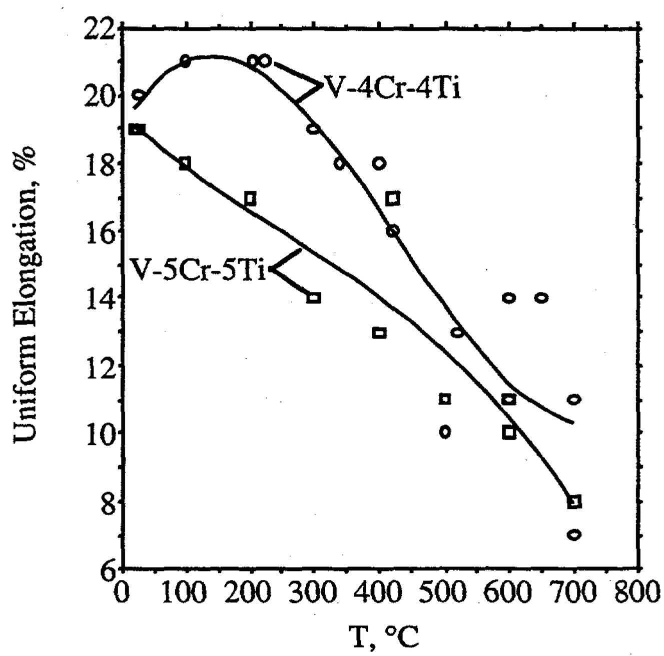

Fig. 9. Uniform elongation vs. temperature for unirradiated V-4Cr-4Ti (BL-47 and BL-71) and V-5Cr-5Ti (BL-63 and BL-72).

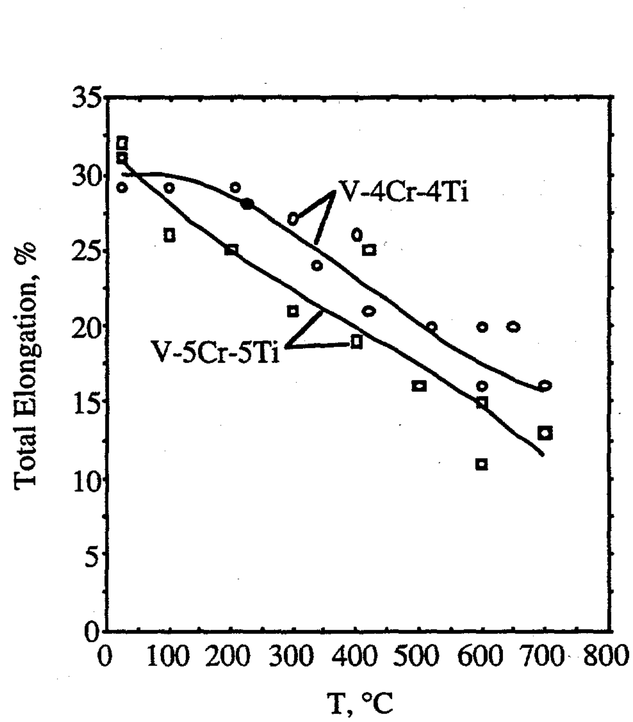

Fig. 10. Total elongation vs. temperature for unirradiated V-4Cr-4Ti (BL-47 and BL-71) and V-5Cr-5Ti (BL-63 and BL-72).

Tensile Properties of Irradiated V-Ti and V-Cr-Ti Alloys

Comparison of YS, UTS, UE and TE

Appendix B contains the irradiation conditions (Tables B.1-B.6) for vanadium alloys irradiated in FFTF MOTA positions. Sample ID numbers are taken from data sheets and lab notebooks [5]. Operating conditions are taken from Ref. 11 for temperature and neutron damage (in dpa) in stainless steel. A factor of 1.31 has been used to convert the Ref. 11 stainless-steel damage values to those for the vanadium alloys [16]. Previously reported values differ somewhat from the revised values in Appendix B because some of the previous values were based on pre-test predictions and expectations rather than on the post-test values listed in Ref. 11. The He values are taken from Refs. 13 and 14 and are based on post-test measurements for a few BL-47 samples.

Tables B.7-B.11 list the revised tensile properties for vanadium alloys irradiated in FFTF. The original load-displacement strip chart recordings have been used to determine these values. Because of the subjective nature of interpreting the strip chart plots, each plot was analyzed twice (on different days) to test the consistency of the methodology and to double-check for clerical and interpretive errors. Table B.12 summarizes the revised values for the tensile properties of vanadium alloys tested at 400°C after irradiation in HFIR at 400°C. No attempt has been made to double-check the reported operating conditions and damage levels for this irradiation.

The revised tensile properties have been compared to the previously published values for FFTF-irradiated alloys [12-14] and HFIR-irradiated alloys [15]. The major changes are in the uniform and total elongation values. Appendix C shows the comparison in tabular form for some of these alloys. The difference between the revised and previously-reported values of UTS for irradiated alloys is -1±6 MPa, which is insignificant. The revised values for YS are higher than previous values by 30±37 MPa (6±7%). While this difference is within the scatter for YS determined from different heats of the same nominal material, it arises primarily because several different methodologies (e.g., proportional elastic limit, 0.2% offset load, 0.5% offset load, etc.) were used to determine the previous values. The decrease in UE is 5±2% (see Fig. 11) and the decrease in TE is 4±2%. The consequences of these elongation decreases are described in the Discussion Section.

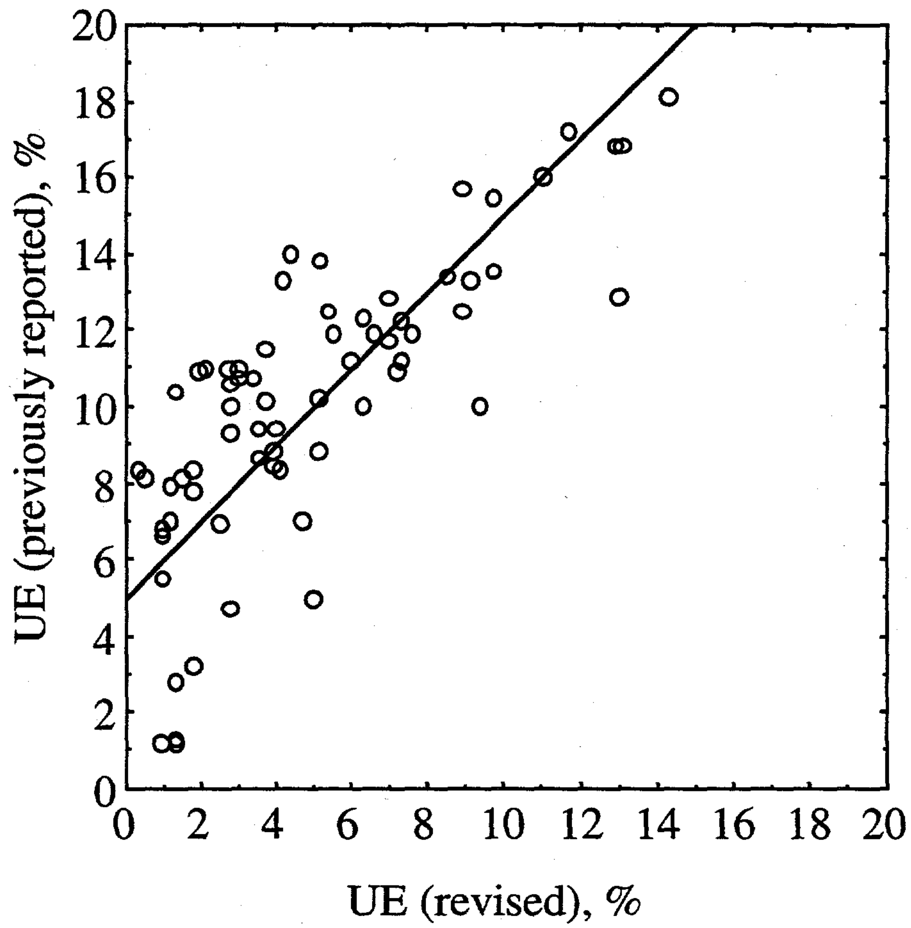

Fig. 11. Previously reported and revised values for uniform elongation (UE) of FFTF- and HFIR-irradiated V-Ti and V-Cr-Ti alloys tested at ANL. Total number of data points is 69, many of which overlap.

Stress-Strain Curves

Figure 12 shows the load-displacement curve for a V-4.1Cr-4.3Ti alloy (BL-47) sample irradiated at 430°C in FFTF to 27 dpa with 23 appm He and tensile-tested at 425°C. The curve shows the initial change in slope, along with the slight discontinuities with load-cell recording scale change, and the serrations in the region of the UTS. Figure 13 shows the simplifications made in deriving the engineering stress-strain curve from the load-displacement data in Fig. 12. The effective elastic modulus has been used to draw the initial linear portion of the curve, and the serrations have been smoothed by taking the minimum values to generate a smooth, continuous curve. The results of graphical analysis for YS, UTS, UE and TE are also shown in Fig. 13. The same simplifications have been used in constructing the engineering stress-strain curves for alloy BL-47 shown in Figs. 14-21.

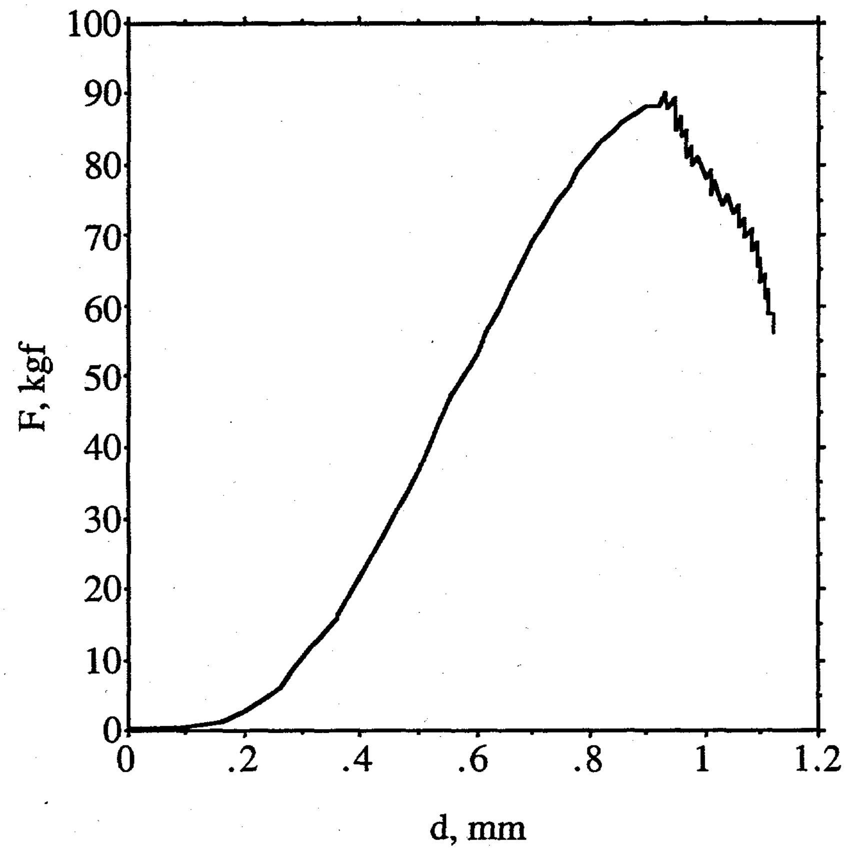

Fig. 12. Load (F)/displacement (d) curve for V-4.1Cr-4.3Ti alloy BL-47 (FFTF Cycle 12, MOTA 2B position 4D2) at 425°C after irradiation at 430°C to 27 dpa with 23 appm He. Tensile specimen gauge length (Lo) and cross-sectional area (Ao) are 7.62 mm and 1.26 mm^2, respectively. Scale changes occurred at d = 0.36 mm (20 to 50 kgf) and at d = 0.56 mm (50 to 100 kgf). Spring constant for the nongauge part of the specimen, grips and tensile machine is ≈1.5 kN/mm, where 1 kgf = 9.806 N. Crosshead speed is 0.5 mm/min and strip chart recording speed is 50 mm/min.

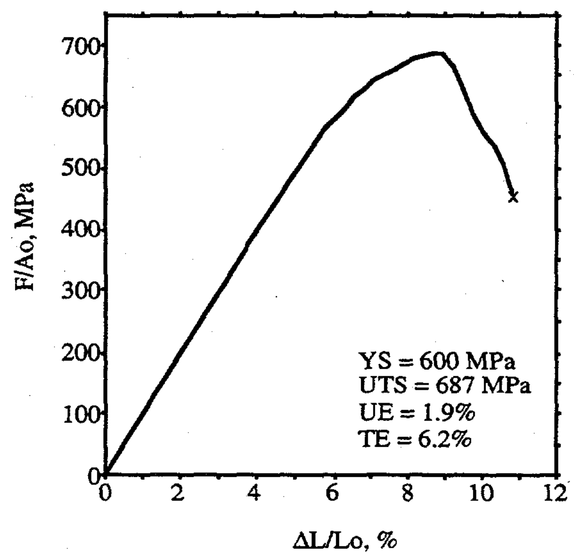

Fig. 13. Engineering stress-strain curve for V-4.1Cr-4.3Ti alloy BL-47 (FFTF Cycle 12, MOTA 2B position 4D2) at 425°C after irradiation at 430°C to 27 dpa with 23 appm He. Lo = 7.62 mm, Ao = 1.26 mm^2 and gauge strain rate = 0.11%/s.

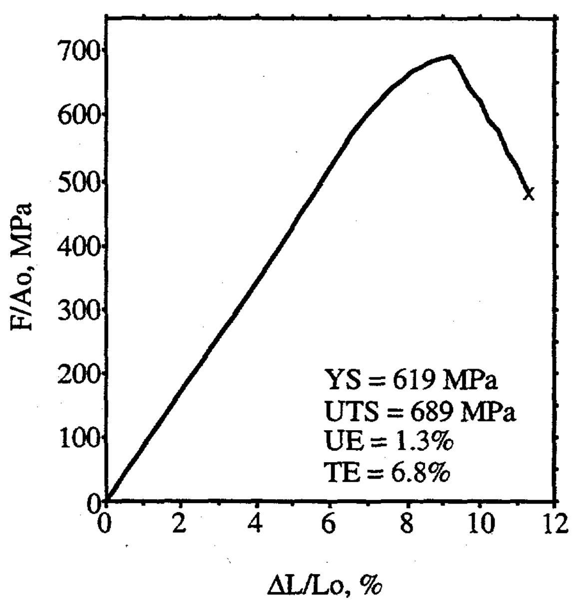

Fig. 14. Engineering stress-strain curve for V-4.1Cr-4.3Ti alloy BL-47 (FFTF Cycle 12, MOTA 2B position 4D1) at 425°C after irradiation at 430°C to 25 dpa with 12 appm He. Lo = 7.62 mm, Ao = 1.42 mm^2 and gauge strain rate = 0.11%/s.

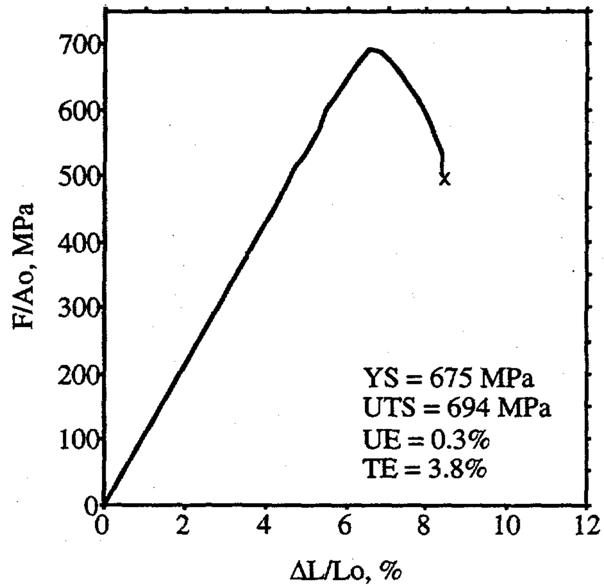

Fig. 15. Engineering stress-strain curve for V-4.1Cr-4.3Ti alloy BL-47 (FFTF Cycle 12, MOTA 2B position 3D6, sample ID #47-484-2) at 420°C after irradiation at 427°C to 33 dpa and ≈0 appm He. Lo = 7.62 mm, Ao = 1.16 mm^2 and gauge strain rate = 0.11%/s.

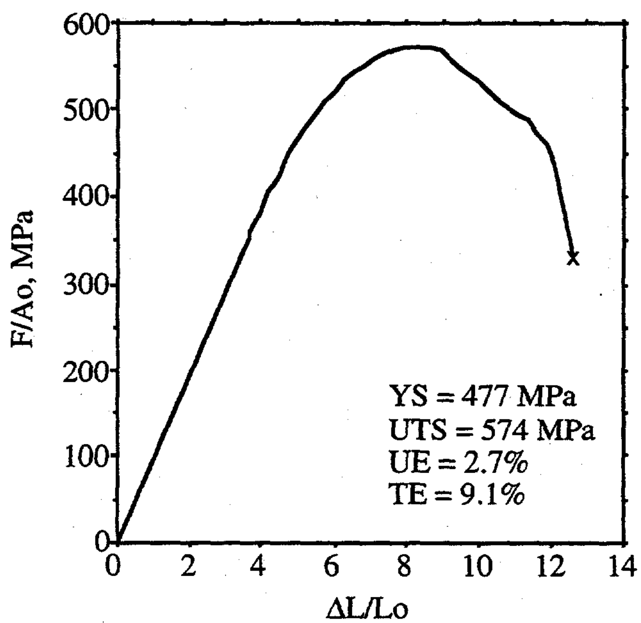

Fig. 16. Engineering stress-strain curve for V-4.1Cr-4.3Ti alloy BL-47 (FFTF Cycle 12, MOTA 2B position 5D2) at 500°C after irradiation at 500°C to 18 dpa with 7 appm He. Lo = 7.62 mm, Ao = 1.38 mm^2 and gauge strain rate = 0.11%/s.

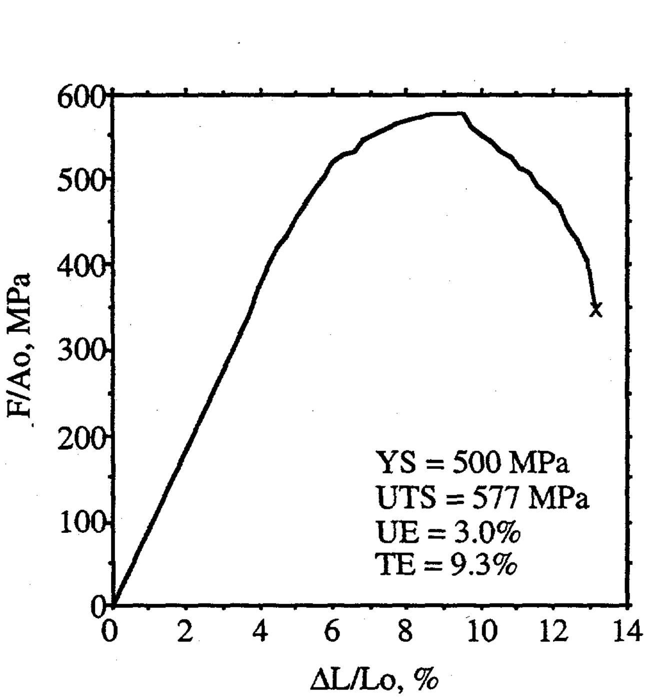

Fig. 17. Engineering stress-strain curve for V-4.1Cr-4.3Ti alloy BL-47 (FFTF Cycle 12, MOTA 2B position 5D1) at 500°C after irradiation at 500°C to 14 dpa with 12 appm He. Lo = 7.62 mm, Ao = 1.40 mm^2 and gauge strain rate = 0.11%/s.

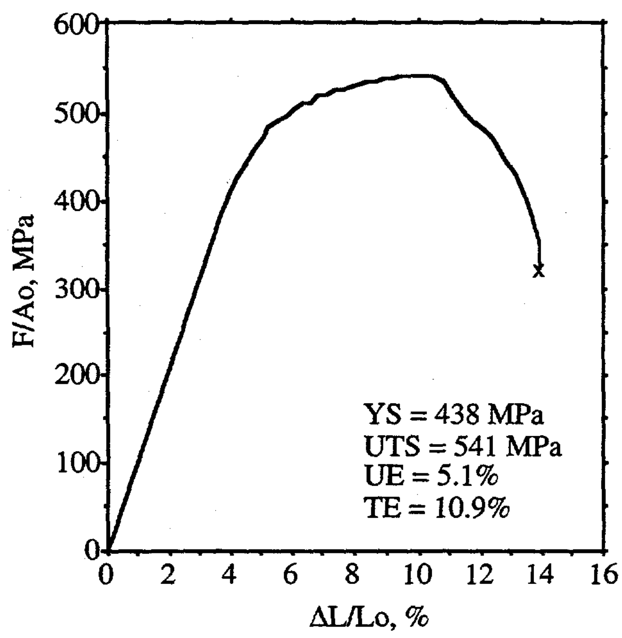

Fig. 18. Engineering stress-strain curve for V-4.1Cr-4.3Ti alloy BL-47 (FFTF Cycle 12, MOTA 2B position 1D3, sample ID #47-562-1) at 520°C after irradiation at 519°C to 14 dpa and ≈0 appm He. Lo = 7.62 mm, Ao = 1.16 mm^2 and strain rate is 0.11%/s.

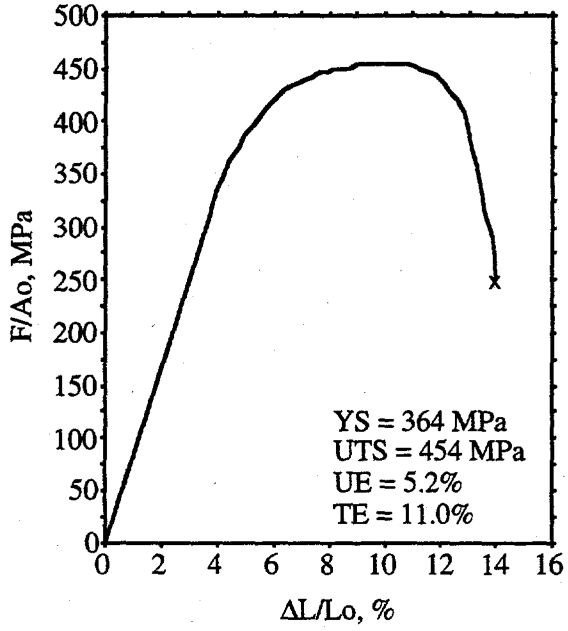

Fig. 19. Engineering stress-strain curve for V-4.1Cr-4.3Ti alloy BL-47 (FFTF Cycle 12, MOTA 2B position 5C1) at 600°C after irradiation at 599°C to 14 dpa with 10 appm He. Lo = 7.62 mm, Ao = 1.05 mm^2 and gauge strain rate = 0.11%/s.

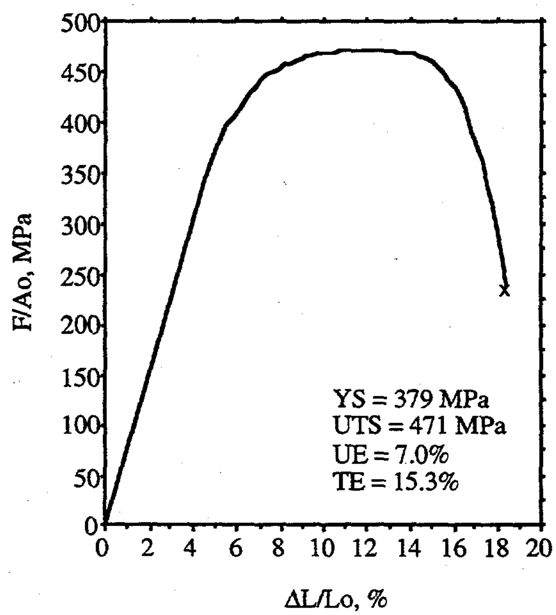

Fig. 20. Engineering stress-strain curve for V-4.1Cr-4.3Ti alloy BL-47 (FFTF Cycle 12, MOTA 2B position 5C2) at 600°C after irradiation at 599°C to 18 dpa with 75 appm He. Lo = 7.62 mm, Ao = 1.40 mm^2 and gauge strain rate = 0.11%/s.

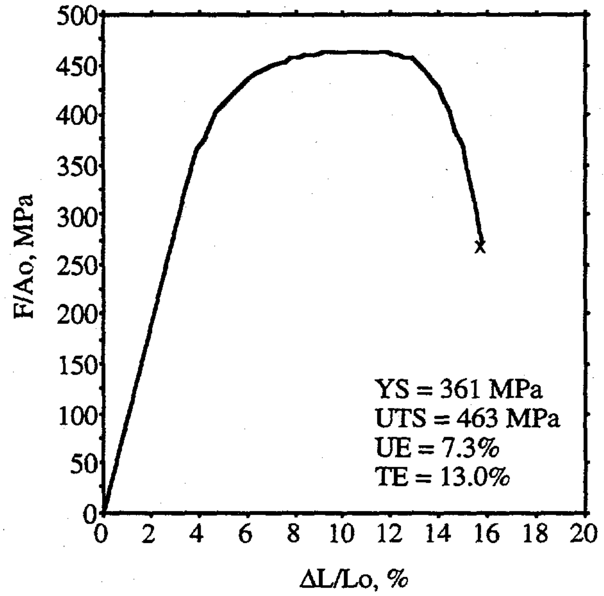

Fig. 21. Engineering stress-strain curve for V-4.1Cr-4.3Ti alloy BL-47 (FFTF Cycle 12, MOTA 2B position 1E2, sample ID # 47-672-1) at 600°C after irradiation at 599°C to 17 dpa and ≈0 appm He. Lo = 7.62 mm, Ao = 1.17 mm^2 and gauge strain rate = 0.11%/s.

The serrations for the curves in Figs. 14-18 (420-430°C and 500-520°C irradiation/test temperatures) all begin at or near the peak load and continue until failure. The peak values are used for Figs. 14-18. For samples irradiated/tested at 600°C, the serrations begin well after the peak load has been achieved. The serrations disappear when sibling samples are tested at lower temperatures (25-200°C).

The engineering stress-strain curves are compared in Fig. 22 for V-4.1Cr-4.3Ti alloy BL-47 irradiated and tested at 400-430°C. In comparing these curves to the curve for unirradiated V-4Cr-4Ti (BL-71), it is clear that there is significant increase in strength and decrease in ductility. This is particularly true for the non-DHCE sample irradiation to 33 dpa where the uniform elongation drops to ≈0.3% – too low a value to be determined accurately. For the DHCE samples with He, the uniform elongation remains at 2-3% at about 26 dpa. It is not clear whether the He actually modifies the microstructure of V-4Cr-4Ti to produce a more ductile alloy under irradiation or that the higher dpa value of the non-DHCE sample causes more hardening. It is likely that the presence of the He in these samples actually improves the irradiation performance of V-4Cr-4Ti, although more data would be needed, along with microstructural studies, to support this view.

Figure 23 shows the stress-strain curves for V-4Cr-4Ti irradiated/tested at 500-520°C. The two DHCE samples and the one non-DHCE sample all have adequate ductility. Again, without more data, it is not clear whether the irradiation damage partially anneals out at ≈ 500°C or the lower neutron damage level (about 15 dpa) results in less damage. Figure 24 compares the results at an irradiation/test temperature of ≈600°C. At this temperature, the irradiated alloy still has adequate ductility.

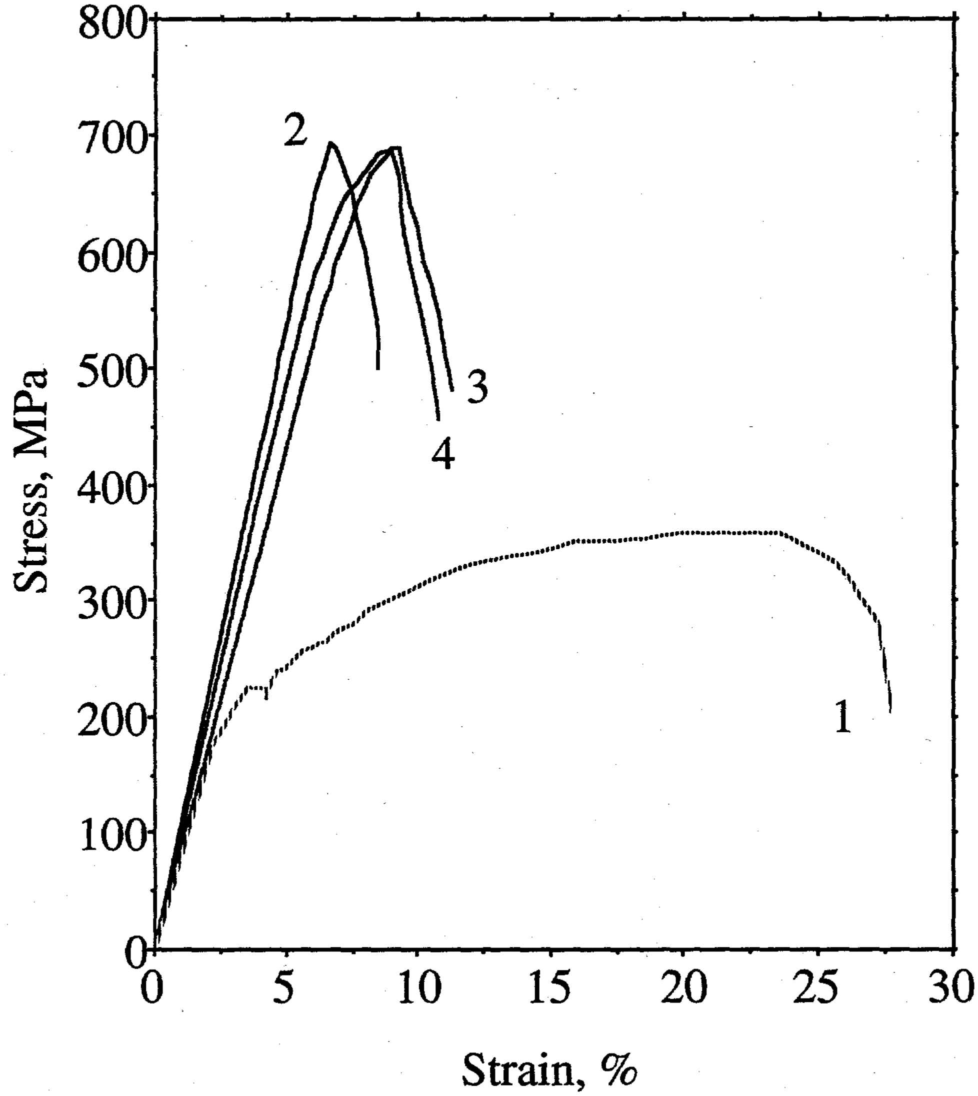

Fig. 22. Unirradiated (Fig. 4), non-DHCE (Fig. 15) and DHCE (Figs. 13 and 14) engineering stress-strain curves for V-4Cr-4Ti irradiated in FFTF (cycle 12) MOTA 2B. Gauge strain rate = 0.11%/s, gauge length = 7.62 mm and cross-sectional area is 1.08 to 1.42 mm^2. ANL heat, irradiation/test temperatures, neutron damage level and He concentration in appm for each curve are: 1) BL-71, ---/400°C, 0 dpa, 0 appm; 2) BL-47, 427/420°C, 33 dpa, ≈0 appm; 3) BL-47, 430/425°C, 25 dpa, 12 appm; and 4) BL-47, 430/425°C, 27 dpa, 23 appm.

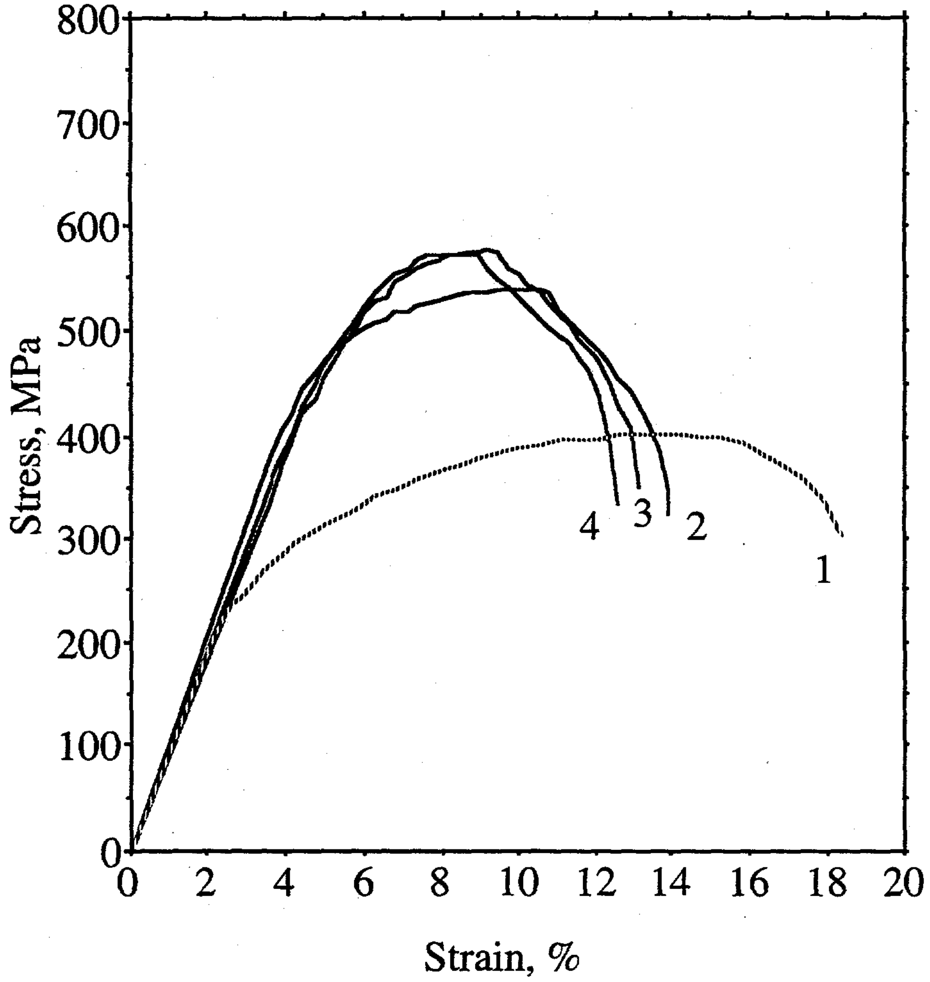

Fig. 23. Unirradiated (Fig. 5), non-DHCE (Fig. 18) and DHCE (Figs. 16 and 17) engineering stress-strain curves for V-4Cr-4Ti irradiated in FFTF (cycle 12) MOTA 2B. Gauge strain rate = 0.11%/s, gauge length = 7.62 mm and cross-sectional area is 1.15 to 1.40 mm². ANL heat, irradiation/test temperatures, neutron damage level and He concentration in appm for each curve are: 1) BL-71, ---/500°C, 0 dpa, 0 appm; 2) BL-47, 519/520°C, 14 dpa, ≈0 appm; 3) BL-47, 500/500°C, 14 dpa, 12 appm; and 4) BL-47, 500/500°C, 18 dpa, 7 appm.

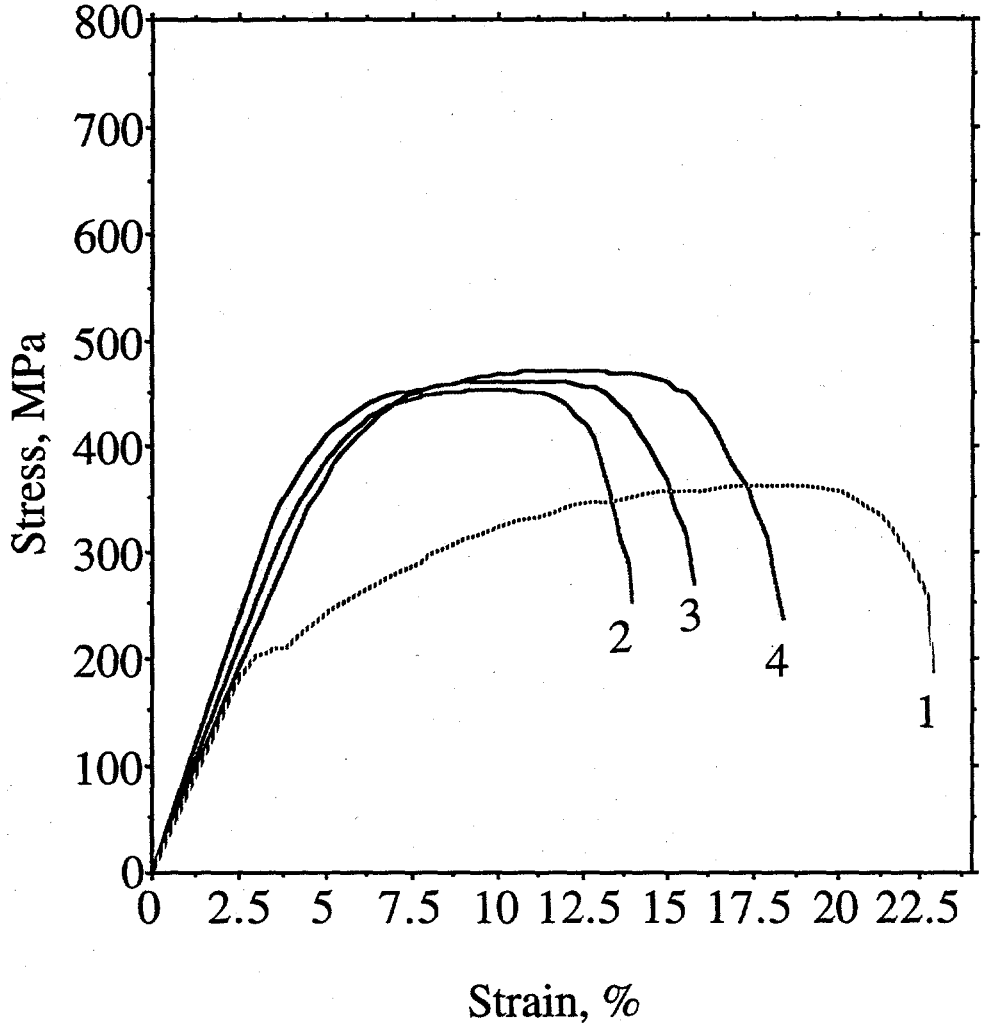

Fig. 24. Unirradiated (Fig. 6), non-DHCE (Fig. 21) and DHCE (Figs. 19 and 20) engineering stress-strain curves for V-4Cr-4Ti irradiated in FFTF (cycle 12) MOTA 2B. Gauge strain rate = 0.11%/s, gauge length = 7.62 mm and cross-sectional area is 1.14 to 1.40 mm^2. ANL heat, irradiation/test temperatures, neutron damage level and He concentration in appm for each curve are: 1) BL-71, ---/600°C, 0 dpa, 0 appm; 2) BL-47, 599/600°C, 14 dpa, 10 appm; 3) BL-47, 599/600°C, 17 dpa, ≈0 appm; and 4) BL-47, 599/600°C, 18 dpa, 75 appm.

Tensile behavior of irradiated V-4Cr-4Ti alloy BL-47

Based on the data presented in this report, V-4Cr-4Ti exhibits both an increase in strength and a decrease in ductility with irradiation. The degree of hardening and embrittlement decreases with increasing irradiation/test temperature. Based on results for samples irradiated and tested at about the same temperature, the increase in UTS is: 79% for 400-430°C, 35% for 500-520°C, and 8% for 600°C. The same pattern holds true for YS but the increases are larger: 162% for 400-430°C, 112% for 500-520°C, and 45% for 600°C. UE decreases with irradiation to strain values of 1.6±1.0% for 400-430°C, 3.6±1.3% for 500-520°C and 6.5±1.1% for 600°C. Similarly, TE decreases to strain values of 5.5±1.3% for 400-430°C, 10±1% for 500-520°C, and 13±2% for 600°C.

Discussion

The tensile data for unirradiated and irradiated vanadium alloys tested at ANL have been reviewed and reanalyzed in accordance with ASTM procedures. The resulting values for ultimate tensile strength are in good agreement with values reported previously. On the average, the changes in yield strength are small and well within the heat-to-heat scatter for this parameter. The differences between the new and old values for YS are due primarily to different methodologies used in determining YS. In the current work, YS is determined to be the minimum of the 0.2% offset stress and the stress corresponding to the lower yield point. The previous YS values for unirradiated materials were determined mainly from the 0.5% offset stress criterion. For irradiated materials, several different methodologies (proportional elastic limit, upper yield point, 0.2% offset stress, etc.) were used previously. The main contribution of the current set of values is that they have been determined by a consistent methodology.

Consistency in methodology does not necessarily ensure that the best results are obtained, particularly for the yield strength of the unirradiated alloys. It has been established that the initial rise in load with crosshead displacement is dominated by the nongauge sections of the sample, the support pin, the grips, and the compliance of the load train. A transition occurs as the gauge section deforms plastically. If the nonlinear load vs. displacement response is due solely to plastic deformation of the gauge, then the 0.2% offset method of determining YS should lead to reasonably good values for YS. If the initial nonlinearity is a combination of gauge displacement, plastic deformation in the transition region of the dog-boned specimen, plastic deformation around the support hole, plastic deformation of the support pin, and geometrical factors such as the untwisting of an improperly aligned specimen, then 0.2% offset may not be large enough to be in the region of the load-displacement curve dominated by the gauge length. Referring to Figs. 4-6, the analyst could use a case-by-case method to decide that the flattening off and/or inflection point of the nonlinear portion of the curve is more representative of YS than the stress determined from the 0.2% offset strain. However, this would lead to too much freedom and inconsistency in data interpretation from experimenter to experimenter and laboratory to laboratory within the fusion materials program.

The current values for uniform and total elongation are smaller than those reported previously. This arises from properly subtracting nongauge-length deformation from the total crosshead deformation. For unirradiated and irradiated alloys, the decreases in UE and TE are 5±2% and 4±2%, respectively, where the ± value refers to one standard deviation. There is a significant impact on the ductility of the alloys irradiated and tested at 400-430°C. For unirradiated alloys and alloys irradiated/tested at ≥500°C, the revised values for UE are still within the ductile range.

FUTURE WORK

The tensile data set presented in the current work should be combined with tensile data for vanadium alloys irradiated in other reactors (e.g., EBR-II, HFIR, ATR, BOR-60, HFBR, etc.) at a range of temperatures and neutron damage levels to form a more complete picture of the temperatures, neutron damage levels and helium levels for which the uniform elongation decreases to a low value (e.g. <1%). Currently, the number of data points for any one alloy is insufficient to determine uniform elongation transition temperatures. The case of V-4.1Cr-4.3Ti (BL-47) is a good example. Based on irradiation/test temperatures of 420-435°C and neutron damage levels of 10-33 dpa, three samples give UE values in the range of 1.3-2.8% and one sample indicates a UE value of 0.3%.

To support the point that more data are needed to characterize the transition of UE to <1%, the case of 316L(N) is reviewed [19]. Twenty-three UE data points are available in the irradiation/test temperature range of 227-400°C and the neutron damage range of 3-11 dpa. An additional 31 data points are available for 316-type stainless steels (e.g., Japanese PCA and 316) which exhibit the same behavior as 316L(N). As each data point was added to the plot, the pattern evolved to show that UE decreased from ≈10% at 5 dpa to ≈0.3% at 7 dpa for 227-340°C.

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Appendix A:

Baseline Tensile Properties for Unirradiated V-Ti and V-Cr-Ti Alloys

The baseline tensile properties for V-Ti and V-Cr-Ti alloys are listed in Tables A.1-A.12. Cr and Ti values refer to weight %. The properties of interest are yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE) and reduction in area (RA). The tests were performed in an Instron tensile machine with a 500 kgf load cell. A uniform crosshead speed of 0.5 mm/min and a specimen gauge length of 7.62 mm were used for all tests. The gauge cross-sectional area varied from sample to sample, but was ≈1 mm². Gauge-length strain rate was 0.11%/s based on crosshead displacement rate and gauge length. The strip chart recordings give load vs. time. The speed of the recorder (50-100 mm/min) and the crosshead speed allow the horizontal time axis to be converted to displacement and engineering strain. The final extensometer reading provides a cross-check for this methodology. Direct measurement of the change in total specimen length after failure provides an additional check on the results. The initial cross-sectional area of the gauge allows conversion of the load to engineering stress.

The references in the tables refer to the previously reported tensile properties listed in parentheses. Fabrication, polishing and annealing of the tensile specimens are described in Refs. 9 and 10. In general, samples were polished and then annealed for 1 h in vacuum at temperatures ranging from 1000 to 1125°C. The tensile values just above those in parentheses are the revised values based on reanalyses of the original strip chart recordings of load vs. displacement [4]. Revisions are based primarily on the proper accounting for the tensile machine and sample springback if unloading were to occur at the load of interest. The new values for yield strength are based on the engineering stress corresponding to an offset (i.e., plastic) strain of 0.2% except for cases that exhibit upper and lower yield points and/or discontinuous yielding (see Ref. 1 for definitions of terms). For these cases, the stress corresponding to the minimum of the 0.2% offset strain and the lower yield point is defined as YS. Most of the previously reported values for YS correspond to an offset strain of 0.5% and are higher than the new values. Reduction in area (RA) at the failure site is used to determine the true strain at rupture. The RA values listed in the tables are those that were published [8,10]. These values are determined directly from post-test analysis of the failed samples and require no correction .

For several samples, the original force-displacement curves could not be located. Because significant changes in YS and UTS are not anticipated, the previously reported values are recommended for these cases. Algorithms for correcting previously reported values of uniform (UE') and total (TE') elongations are based on an analysis of the spring constants (k) and effective Young's moduli (E') for the known force-displacement curves. This analysis indicates that E' = 82±15 MPa/% for the SS3 unirradiated vanadium alloys tested at ANL. Thus, the recommended algorithms for correcting UE and TE are:

$$UE = UE' - UTS/(82\ MPa/\%) \qquad (A.1)$$

and

$$TE = TE' - YS/(82\ MPa/\%). \qquad (A.2)$$

Equation A.1 has a fundamental basis, while Eq. A.2 has been determined empirically.

Table A.1. Revised tensile properties for unirradiated V and V-1.0Ti alloys: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE) and reduction in area (RA). k = force-displacement slope used to reanalyze the data [4]. UE/TE values with superscript "c" are calculated from Eqs. A.1/A.2. Previous values are in parentheses and are from the Refs. listed.

Alloy (ANL ID)	ID #	T °C	k kN/mm	YS MPa	UTS MPa	UE %	TE %	RA %	Ref.
V	1	25	1.13	259	309	23	48	—	9
				(259)	(309)	(28)	(49)		
(BL-51)	10	100	—	—	—	20[c]	29[c]	—	
				(220)	(290)	(24)	(32)		
287 wppm Si	5	225	a	a	a	18[c]	26[c]	—	
297 wppm O				(175)	(279)	(21)	(28)		
35 wppm N	9	300	1.07	181	348	20	27	—	
30 wppm C				(181)	(348)	(26)	(32)		
	4	325	0.94	144	329	22	30	—	
				(153)	(335)	(24)	(32)		
	8	350	0.96	133	310	19	29	—	
				(138)	(310)	(24)	(32)		
	2	420	1.23	167	282	22	35	—	
				(167)	(283)	(25)	(36)		
	7	520	0.91	133	187	31	64	—	
				(134)	(187)	(34)	(65)		
	3	600	0.94	124	134	26	64	—	
				(124)	(134)	(28)	(64)		
	6	700	0.98	124	124	1.4	18	—	
				(124)	(124)	(4)[b]	(18)[b]		
V-1.0Ti	1	25	1.20	268	343	19	33	—	9
				(268)	(343)	(23)	(34)		
(BL-50)	8	120	1.14	236	317	20	34	—	
				(236)	(317)	(23)	(34)		
1050 wppm Si	4	225	1.11	188	275	16	26	—	
230 wppm O				(188)	(275)	(20)	(28)		
130 wppm N	7	325	0.86	174	386	16	24	—	
235 wppm C				(174)	(396)	(23)	(29)		
	3	420	0.98	198	401	16	25	—	
				(198)	(402)	(22)	(28)		
	6	520	1.09	175	398	24	32	—	
				(181)	(398)	(28)	(37)		
	5	600	0.75	150	350	18	31	—	
				(174)	(351)	(24)	(32)		
	9	700	0.89	147	317	16	27	—	
				(157)	(317)	(21)	(29)		

[a]Recording too faint to read. [b]UE and TE values from strip chart. Ref. 9 values may be misprints.

Table A.2. Revised tensile properties for unirradiated V-3.1Ti alloys : yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE) and reduction in area (RA). k = force-displacement slope used to reanalyze the data [4]. UE/TE values with superscript "c" are calculated from Eqs. A.1/A.2. Previous values are in parentheses and are from the Refs. listed.

Alloy (ANL ID)	ID #	T °C	k kN/mm	YS MPa	UTS MPa	UE %	TE %	RA %	Ref.
V-3.1Ti	1	25	1.49	245	356	23	36	—	9
				(295)	(409)	(24)	(33)		
(BL-62)	—	100	—	—	—	18^c	24^c	—	
				(210)	(340)	(22)	(27)		
660 wppm Si	—	225	—	—	—	18^c	26^c	—	
320 wppm O				(180)	(298)	(22)	(28)		
86 wppm N	—	325	—	—	—	17^c	22^c	—	
109 wppm C				(177)	(350)	(20)	(24)		
	2	420	a	a	a	15^c	24^c	—	
				(183)	(404)	(20)	(26)		
	—	520	—	—	—	14^c	21^c	—	
				(170)	(406)	(19)	(23)		
	3	600	1.09	173	359	15	23	—	
				(177)	(410)	(21)	(25)		
	—	700	—	—	—	14^c	21^c	—	
				(183)	(405)	(19)	(23)		
V-3.1Ti	1	25	1.49	344	456	21	31	—	9
				(367)	(465)	(24)	(33)		
(BL-27)	14	100	1.14	343	465	19	23	80	8,9
				(352)[b]	(464)[b]	(22)	(27)		
2500 wppm Si	6	225	0.98	235	344	18	25	90	
210 wppm O				(235)	(344)	(22)	(28)		
310 wppm N	5	325	1.07	228	373	15	20	90	
300 wppm C				(227)	(386)	(20)	(24)		
	2	420	1.07	245	431	15	22	84	
				(242)	(431)	(20)	(26)		
	3	520	1.02	207	424	15	20	87	
				(228)	(428)	(19)	(23)		
	4	600	1.02	213	435	15	20	77	
				(230)	(435)	(21)	(25)		
	10	700	0.75	203	413	12	18	68	
				(224)	(413)	(19)	(23)		

[a]Recording too faint to read. [b]YS and UTS values from strip chart. Ref. 9 values may be misprints.

Table A.3. Revised tensile properties for unirradiated V-3Ti alloys: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE) and reduction in area (RA). k = force-displacement slope used to reanalyze the data [4]. Previous values are in parentheses and are from the Refs. listed.

Alloy (ANL ID)	ID #	T °C	k kN/mm	YS MPa	UTS MPa	UE %	TE %	RA %	Ref.
V-2.5Ti	10	25	1.20	412 (421)	480 (480)	19 (25)	26 (34)	—	9
(BL-45)	5	105	1.26	352 (355)	431 (430)	21 (26)	28 (33)	—	
9900 wppm Si, 345 wppm O	9	225	1.33	286 (286)	392 (392)	22 (26)	29 (32)	—	
125 wppm N, 90 wppm C	2	325	0.98	257 (259)	405 (405)	15 (21)	22 (26)	—	
	2'	420	0.82	208 (274)	382 (447)	17 (24)	21 (29)	—	
	6	520	0.96	264 (274)	446 (447)	18 (24)	24 (29)	—	
	1	600	1.09	234 (265)	445 (446)	16 (21)	20 (26)	—	
	3	700	0.98	233 (260)	436 (437)	11 (17)	17 (21)	—	
V-3.1Ti	L1[a]	25	1.53	447 (459)	552 (552)	14 (18)	21 (24)	—	4
(BL-42)	1	25	1.17	436 (473)	545 (545)	14 (20)	22 (26)	88	8,9
5400 wppm Si, 580 wppm O	6	100	1.09	433 (405)	503 (519)	13 (19)	19 (22)	76	
190 wppm N, 140 wppm C	2	225	1.23	299 (317)	410 (410)	13 (18)	20 (23)	75	
	3	325	1.07	259 (300)	431 (436)	15 (21)	22 (27)	79	
	4	420	1.26	302 (328)	464 (463)	10 (16)	16 (20)	63	
	5	520	1.07	296 (312)	482 (466)	11 (18)	17 (23)	—	9
	8	600	b	b (308)	b (470)	b (18)	b (21)	—	
	9	700	1.02	319 (291)	452 (452)	11 (17)	14 (20)	—	

[a]Exposed to Li at 482°C for 1001 h prior to tensile testing.
[b]Recording is too garbled to interpret with confidence.

Table A.4. Revised tensile properties for unirradiated V-4.6Ti and V-9.8Ti alloys: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE) and reduction in area (RA). k = force-displacement slope used to reanalyze the data [4]. Previous values are in parentheses and are from the Refs. listed.

Alloy (ANL ID)	ID #	T °C	k kN/mm	YS MPa	UTS MPa	UE %	TE %	RA %	Ref.
V-4.6Ti	9	25	1.07	336 (336)	412 (412)	17 (22)	32 (35)	—	9
(BL-46)	6	108	1.29	307 (294)	336 (366)	11 (16)	21 (24)	—	
160 wppm Si 305 wppm O	10	160	0.98	239 (259)	342 (342)	15 (20)	23 (25)	—	
53 wppm N 85 wppm C	3	225	1.09	194 (217)	317 (317)	18 (23)	26 (28)	—	
	5	330	1.11	209 (214)	338 (342)	18 (22)	25 (28)	—	
	2	420	0.78	183 (215)	316 (334)	11 (15)	16 (19)	—	
	8	520	0.91	176 (195)	344 (350)	15 (20)	20 (24)	—	
	7	600	1.20	191 (195)	386 (388)	16 (19)	21 (25)	—	
	4	700	0.91	204 (203)	377 (376)	11 (17)	15 (19)	—	
V-9.8Ti	1	25	1.23	434 (435)	532 (532)	19 (25)	29 (33)	—	9
(BL-12)	8	100	1.26	336 (374)	477 (477)	20 (25)	30 (32)	—	
245 wppm Si 1670 wppm O	6	225	1.33	310 (326)	463 (463)	18 (23)	25 (28)	—	
390 wppm N 450 wppm C	5	325	1.06	310 (310)	477 (479)	17 (21)	23 (27)	—	
	2	420	1.11	300 (308)	486 (496)	16 (21)	23 (27)	—	
	7	520	0.98	299 (303)	525 (529)	14 (21)	20 (25)	—	
	3	600	1.23	299 (298)	538 (538)	17 (23)	20 (25)	—	
	4	700	1.14	247 (262)	466 (466)	14 (19)	20 (24)	—	

Table A.5. Revised tensile properties for unirradiated V-17.7Ti alloy : yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE) and reduction in area (RA). k = force-displacement slope used to reanalyze the data [4]. UE/TE values with superscript "c" are calculated from Eqs. A.1/A.2. Previous values are in parentheses and are from the Refs. listed.

Alloy (ANL ID)	ID #	T °C	k kN/mm	YS MPa	UTS MPa	UE %	TE %	RA %	Ref.
V-17.7Ti	L1[a]	25	1.44	693 (693)	731 (731)	13 (18)	20 (25)	—	4
(BL-15)	L3[a]	25	1.34	674 (681)	728 (728)	13 (19)	21 (25)	—	4
480 wppm Si 830 wppm O	1	25	1.61	628 (628)	692 (692)	17 (22)	27 (32)	68	8,9
160 wppm N 380 wppm C	18	100	—	— (525)	— (640)	14[c] (22)	24[c] (30)	76	
	6	225	1.42	437 (437)	588 (588)	13 (20)	19 (25)	66	
	5	325	1.29	436 (436)	636 (636)	17 (24)	23 (29)	69	
	3	420	0.91	394 (443)	612 (658)	13 (24)	19 (30)	60	
	2	520	1.14	404 (445)	680 (678)	19 (29)	24 (33)	59	
	4	600	1.29	417 (417)	667 (667)	13 (20)	22 (28)	55	
	8	650	1.20	350 (400)	554 (554)	15 (20)	25 (29)	72	
	7	700	1.29	405 (393)	496 (496)	9 (15)	18 (23)	67	

[a]Exposed to Li at 482°C for 1001 h (L1) and 3377 h (L3) prior to tensile testing.

Table A.6. Revised tensile properties for unirradiated V-(4-5)Cr-(3-5)Ti alloys: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE) and reduction in area (RA). k = force-displacement slope used to reanalyze the data [4]. UE/TE values with superscript "c" are calculated from Eqs. A.1/A.2. Previous values are in parentheses and are from the Refs. listed.

Alloy (ANL ID)	ID #	T °C	k kN/mm	YS MPa	UTS MPa	UE %	TE %	RA %	Ref.
V-5.1Cr-3.0Ti	1	25	1.53	327	430	14	24	—	9
				(337)	(430)	(18)	(25)		
(BL-54, #9928)	2	420	0.79	205	349	12	21	—	
				(208)	(349)	(17)	(23)		
655 wppm Si	3	600	1.09	182	346	10	16	—	
480 wppm O				(204)	(346)	(14)	(21)		
82 wppm N									
133 wppm C									
V-4.1Cr-4.3Ti	9	25	1.53	404	461	20	31	—	9
				(386)	(454)	(25)	(34)		
(BL-47, #9144)	10	100	—	—	—	20^c	29^c	—	
				(325)	(420)	(25)	(33)		
870 wppm Si	5	225	1.20	246	379	21	28	—	
350 wppm O				(272)	(379)	(26)	(31)		
220 wppm N	3	337	1.07	229	381	18	24	—	
200 wppm C				(254)	(388)	(20)	(28)		
	11	420	1.25	250	401	16	21	—	
				(250)	(405)	(21)	(25)		
	8	520	1.02	222	419	13	20	—	
				(244)	(423)	(19)	(24)		
	4	600	1.17	253	430	11	16	—	
				(256)	(434)	(16)	(21)		
	7	650	1.17	249	453	14	20	—	
				(264)	(453)	(19)	(23)		
	6	700	1.04	223	414	11	16	—	
				(266)	(414)	(17)	(20)		
V-4.6Cr-5.1Ti	4	25	1.49	360	470	19	32	—	9
				(386)	(465)	(22)	(34)		
(BL-63, #832394)	5	420	1.00	216	396	17	25	—	
				(238)	(396)	(21)	(28)		
310 wppm Si	5'	600	1.07	209	382	10	11	—	
440 wppm O				(225)	(382)	(15)	(20)		
28 wppm N									
73 wppm C									

Table A.7. Revised tensile properties for unirradiated V-(4-5)Cr-(4-5)Ti alloys : yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE) and reduction in area (RA). k = force-displacement slope used to reanalyze the data [4]. Previous values are in parentheses and are from the Refs. listed.

Alloy (ANL ID)	ID #	T °C	k kN/mm	YS MPa	UTS MPa	UE %	TE %	RA %	Ref.
V-3.8Cr-3.9Ti		23	1.63	355	429	19	29	94	6,10
				(457)	(528)	(24)	(32)		
(BL-71, #832665)		100	1.36	325[a]	379[a]	21	29	—	
				(337)	(435)	(24)	(30)		
783 wppm Si		206	1.63	236	345	21	29	92	
310 wppm O				(230)	(346)	(24)	(30)		
85 wppm N		300	1.07	208	343	19	27	93	
80 appm C				(216)	(343)	(23)	(30)		
		400	1.17	196	359	18	26	—	
				(205)	(359)	(23)	(28)		
		500	1.44	199	402	10	16	84	
				(232)	(402)	(18)	(22)		
		600	1.11	189	366	14	20	—	
				(245)	(409)	(19)	(24)		
		700	1.23	221	380	7	13	48	
				(212)	(380)	(13)	(17)		
V-4.9Cr-5.1Ti		23	1.58	394	503	19	31	88	6,10
				(397)	(503)	(23)	(33)		
(BL-72, T87)		100	1.44	337	439	18	26	83	
				(317)	(439)	(22)	(29)		
545 wppm Si		200	1.33	294	408	17	25	88	
380 wppm O				(280)	(408)	(22)	(28)		
89 wppm N		300	1.17	262	405	14	21	91	
109 wppm C				(249)	(405)	(21)	(25)		
		400	1.44	256	427	13	19	82	
				(256)	(427)	(18)	(23)		
		500	1.26	285	449	11	16	81	
				(265)	(453)	(14)	(19)		
		600	1.44	262	449	11	15	73	
				(254)	(449)	(17)	(20)		
		700	1.33	255	401	8	13	36	
				(241)	(401)	(13)	(16)		

[a]Uncertainty of ±47 MPa due to uncertainty in load baseline.

Table A.8. Revised tensile properties for unirradiated V-(8-9)Cr-(5-6)Ti alloys : yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE) and reduction in area (RA). k = force-displacement slope used to reanalyze the data [4]. Previous values are in parentheses and are from the Refs. listed.

Alloy (ANL ID)	ID #	T °C	k kN/mm	YS MPa	UTS MPa	UE %	TE %	RA %	Ref.
V-7.9Cr-5.7Ti	3	25	1.11	404	512	20	33	—	9
				(440)	(541)	(23)	(33)		
(BL-49)	9	108	1.33	394	489	18	28	—	
				(393)	(489)	(23)	(30)		
36 wppm Si	10	175	1.44	313	404	8	9	—	
400 wppm O				(318)	(404)	(12)	(13)		
150 wppm N	8[a]	225	1.36	228	347	13	21	—	
127 wppm C				(236)	(347)	(17)	(23)		
	6	325	1.07	250	424	15	23	—	
				(261)	(429)	(18)	(26)		
	4	420	1.26	289	461	15	22	—	
				(287)	(470)	(20)	(25)		
	5	600	1.33	261	486	14	20	—	
				(285)	(486)	(19)	(22)		
	7	700	1.11	270	487	16	21	—	
				(271)	(487)	(21)	(26)		
V-9.2Cr-4.9Ti	L1[b]	25	1.26	498	599	15	26	—	4
				(504)	(599)	(21)	(30)		
(BL-43)	L3[b]	25	1.63	511	617	16	24	—	4
				(511)	(617)	(21)	(29)		
340 wppm Si	9	25	1.29	430	541	19	30	91	8,9
230 wppm O				(440)	(541)	(23)	(33)		
31 wppm N	8	100	1.12	423	533	17	29	91	
100 wppm C				(387)	(482)	(20)	(32)		
	3	225	1.29	318	448	17	25	82	
				(334)	(448)	(22)	(29)		
	6	325	1.23	300	452	19	27	86	
				(312)	(452)	(21)	(30)		
	1	420	1.17	291	460	14	21	83	
				(300)	(467)	(20)	(25)		
	4	520	1.07	275	459	12	19	84	
				(297)	(463)	(18)	(23)		
	5	600	1.02	273	502	14	19	78	
				(297)	(512)	(21)	(25)		
	7	700	1.07	259	488	15	23	62	
				(277)	(488)	(21)	(27)		

[a]Sample may have been prematurely loaded. [b]Exposed to Li at 482°C for 1001 h (L1) and 3377 h (L3) prior to tensile testing.

Table A.9. Revised tensile properties for unirradiated V-(11-13)Cr-(5-6)Ti alloys: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE) and reduction in area (RA). k = force-displacement slope used to reanalyze the data [4]. Previous values are in parentheses and are from the Refs. listed.

Alloy (ANL ID)	ID #	T °C	k kN/mm	YS MPa	UTS MPa	UE %	TE %	RA %	Ref.
V-10.9Cr-5.0Ti	12	25	1.11	471	575	19	28	85	8,9
				(491)	(573)	(23)	(31)		
(BL-40)	T3	100	1.23	434	539	20	26	91	
				(402)	(500)	(21)	(27)		
270 wppm Si	6	225	1.23	332	464	17	23	80	
470 wppm O				(347)	(464)	(21)	(26)		
80 wppm N	5	325	1.11	287	446	14	20	82	
90 wppm C				(304)	(448)	(17)	(24)		
	2	433	1.02	308	496	14	20	78	
				(321)	(501)	(18)	(24)		
	3	520	0.94	277	485	12	17	72	
				(303)	(488)	(17)	(22)		
	4	600	1.11	293	520	16	22	72	
				(299)	(519)	(22)	(26)		
	T2	650	0.98	286	529	14	20	66	
				(310)	(529)	(20)	(25)		
	T1	700	0.82	297	513	14	20	64	
				(299)	(513)	(21)	(26)		
V-12.9Cr-5.9Ti	15	25	1.29	526	627	21	33	85	8,9
				(533)	(627)	(25)	(37)		
BL-23	14	100	1.36	474	589	22	32	59	
				(483)	(589)	(25)	(37)		
1230 wppm Si	6	225	1.40	386	548	17	26	82	
400 wppm O				(407)	(548)	(23)	(29)		
490 wppm N	5	325	1.20	341	518	17	25	85	
280 wppm C				(368)	(522)	(23)	(30)		
	12	420	1.33	370	554	15	22	78	
				(379)	(571)	(21)	(27)		
	3	520	1.23	337	562	15	22	72	
				(360)	(567)	(21)	(27)		
	4	600	1.23	346	611	18	25	71	
				(384)	(610)	(25)	(31)		
	10	650	1.11	332	573	17	26	70	
				(373)	(573)	(22)	(30)		
	13	700	1.09	346	541	15	30	73	
				(355)	(519)	(21)	(32)		

Table A.10. Revised tensile properties for unirradiated V-13.5Cr-5.2Ti alloy: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE) and reduction in area (RA). k = force-displacement slope used to reanalyze the data [4]. Previous values are in parentheses and are from the Refs. listed.

Alloy (ANL ID)	ID #	T °C	k kN/mm	YS MPa	UTS MPa	UE %	TE %	RA %	Ref.
V-13.5Cr-5.2Ti	L1[a]	25	1.44	551	652	16	20	—	4
				(571)	(652)	(—)	(28)		
(BL-24)	L3[a]	25	1.72	589	685	18	25	—	4
				(592)	(685)	(28)	(34)		
390 wppm Si	18	25	1.29	532	633	18	28	80	8,9
1190 wppm O				(545)	(634)	(23)	(32)		
360 wppm N	27	100	1.58	482	593	20	27	86	
500 wppm C				(439)	(545)	(22)	(31)		
	12	225	1.40	347	478	14	22	86	
				(370)	(478)	(17)	(25)		
	2	325	1.36	303	448	14	20	81	
				(317)	(449)	(17)	(23)		
	11	420	1.26	327	512	16	23	83	
				(341)	(518)	(21)	(27)		
	15	520	1.04	317	500	11	18	75	
				(326)	(502)	(17)	(23)		
	13	600	0.94	305	555	14	19	72	
				(342)	(555)	(21)	(26)		
	26	650	1.17	305	559	17	24	61	
				(342)	(559)	(25)	(30)		
	25	700	1.20	340	544	13	20	60	
				(337)	(544)	(21)	(26)		

[a]Exposed to Li at 482°C for 1001 h (L1) and 3377 h (L3) prior to tensile testing.

Table A.11. Revised tensile properties for unirradiated V-14.5Cr-5.0Ti and V-9.9Cr-9.2Ti alloys: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE) and reduction in area (RA). k = force-displacement slope used to reanalyze the data [4]. Previous values are in parentheses and are from the Refs. listed.

Alloy (ANL ID)	ID #	T °C	k kN/mm	YS MPa	UTS MPa	UE %	TE %	RA %	Ref.
V-14.5Cr-5.0Ti	1	25	1.63	570 (570)	674 (674)	20 (26)	26 (33)	83	8,9
(BL-41)	13	100	1.36	492 (494)	599 (579)	17 (23)	23 (29)	82	
400 wppm Si, 330 wppm O	T1	225	1.23	387 (399)	525 (525)	16 (22)	24 (27)	82	
96 wppm N, 120 wppm C	5	325	1.11	346 (348)	500 (500)	14 (19)	22 (26)	81	
	2	420	1.23	326 (346)	514 (524)	14 (20)	21 (26)	80	
	3	520	0.94	344 (350)	542 (538)	11 (19)	19 (25)	70	
	4	600	1.00	327 (335)	560 (560)	12 (21)	18 (25)	66	
	T3	650	1.14	307 (356)	575 (575)	14 (22)	21 (27)	63	
	T2	700	1.09	337 (339)	563 (564)	15 (22)	22 (28)	62	
V-9.9Cr-9.2Ti	7	25	1.58	506 (534)	628 (628)	19 (24)	30 (34)	—	9
(BL-44)	12	100	1.58	457 (469)	571 (571)	19 (24)	34 (36)	—	
270 wppm Si, 300 wppm O	8	225	1.40	382 (387)	516 (516)	16 (21)	26 (29)	—	
87 wppm N, 150 wppm C	5	325	1.31	352 (367)	528 (532)	16 (23)	25 (30)	—	
	9	420	1.17	364 (364)	567 (570)	15 (23)	24 (30)	—	
	10	520	1.23	347 (349)	558 (560)	14 (23)	23 (29)	—	
	11	600	1.29	351 (352)	565 (565)	17 (23)	24 (30)	—	
	3	700	0.98	312 (328)	492 (492)	16 (20)	21 (28)	—	

Table A.12. Revised tensile properties for unirradiated V-7.2Cr-14.5Ti alloy: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE) and reduction in area (RA). k = force-displacement slope used to reanalyze the data [4]. Previous values are in parentheses and are from the Refs. listed.

Alloy (ANL ID)	ID #	T °C	k kN/mm	YS MPa	UTS MPa	UE %	TE %	RA %	Ref.
V-7.2Cr-14.5Ti	L1[a]	25	1.38	738	835	16	25	—	4
				(738)	(835)	(23)	(31)		
(BL-10)	L3[a]	25	1.69	790	884	14	21	—	4
				(788)	(884)	(22)	(28)		
400 wppm Si	12	25	1.58	634	717	15	24	75	8,9
1100 wppm O				(636)	(717)	(20)	(28)		
250 wppm N	13	100	1.53	537	647	14	23	77	
400 wppm C				(556)	(647)	(21)	(28)		
	6	225	1.33	479	618	13	20	74	
				(490)	(618)	(20)	(25)		
	5	325	1.29	485	673	13	19	69	
				(487)	(682)	(21)	(25)		
	T1	420	1.26	469	695	17	23	67	
				(471)	(695)	(22)	(29)		
	2	520	1.02	465	727	15	20	62	
				(468)	(730)	(24)	(28)		
	3	600	1.11	465	738	16	18	51	
				(469)	(738)	(26)	(27)		
	10	650	b	b	b	b	b	53	
				(441)	(661)	(23)	(28)		
	T2	700	1.23	359	584	12	24	53	
				(404)	(584)	(18)	(30)		

[a]Exposed to Li at 482°C for 1001 h (L1) and 3377 h (L3) prior to tensile testing.
[b]Poor chart performance (i.e., stops and starts) renders data difficult to interpret.

Appendix B:

Revised Tensile Properties for FFTF- and HFIR-Irradiated V-Ti and V-Cr-Ti Alloys

The revised tensile properties for V-Ti and V-Cr-Ti alloys are listed in Tables B.7-B.11 for alloys irradiated in FFTF and in Table B.12 for alloys irradiated in HFIR. Alloy composition, specimen identification number, MOTA positions and operating conditions for FFTF-irradiated ANL alloys are taken from Ref. 11 and are listed in Tables B.1-B.6. The subcapsule and specimen identification numbers in these tables are consistent with those specified on the loading charts. The properties listed are yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), and total elongation (TE). These have been determined from the original load-displacement strip chart recordings [4]. The tests were performed in an Instron tensile machine with a 500 kgf load cell. A uniform crosshead speed of 0.5 mm/min and a specimen gauge length of 7.62 mm were used for all tests. The gauge cross-sectional area varied from sample to sample, but was ≈1 mm^2. The gauge-length strain rate was 0.11%/s, based on crosshead displacement rate and gauge length. The strip chart recordings give load vs. time. The speed of the recorder (50-100 mm/min) and the crosshead speed allow the horizontal time axis to be converted to engineering strain. The final extensometer reading provides a cross-check for this methodology. Direct measurement of the change in total specimen length after failure provides an additional check on the results. The specimen gauge initial cross-sectional area allows conversion of the load to engineering stress. In some cases (e.g., plastic deformation of support pins for irradiated, high strength alloys tested before 1992), the direct measurement of sample elongation is much smaller than the extensometer reading and the reanalyzed values. For these cases, this direct measurement is used to determine TE. It is also assumed that the UTS values determined from the recording are reasonably accurate, but that YS and UE cannot be determined accurately.

The values in Tables B.7-B.12 have been determined by a standard and consistent methodology that properly accounts for tensile-machine and sample springback in order to determine permanent plastic values for UE and TE. In general, YS values have been determined to correspond to the load giving an offset (i.e., plastic) strain of 0.2%. In cases that exhibit upper and lower yield points and/or discontinuous yielding (see Ref. 1 for definitions), the minimum of the 0.2% offset load and the lower yield point load has been used to determine YS.

The irradiation test temperatures and dpa levels in Tables B.7 to B.12 are consistent with those listed in Tables B.1 to B.6. The Specimen ID numbers are consistent with those listed on the strip chart recordings. In general, the loading chart ID numbers and the strip chart ID numbers are consistent. For some cases involving samples of the same composition and the same subcapsule (e.g., 45-485), they are distinguished on the strip charts by adding an extra number (e.g., 45-485-1 and 45-485-2). In these examples, the 45 refers to the ANL heat identification (BL-45 , V-2.5Ti-1.0Si) and the 485 refers to the subcapsule ID (V485). The helium contents listed in Tables B.7-B.11 are based on direct measurements of the BL-47 samples. It is assumed that vanadium alloys in the same subcapsule have the same helium content as the BL-47 alloy. Unusual behavior exhibited in these strip chart recordings and uncertainties in their interpretation are mentioned in footnotes to the tables. Also noted in the tables are the force-displacement slope (k in kN/mm) values used to reanalyze the strip chart recordings.

Table B.1. Vanadium-alloy tensile specimens and FFTF operating conditions for MOTA 1D in Cycle 8 (185.8 EFPD at 400 MWth). Damage values are listed for Cycle 8. Total accumulated damage values are included in parentheses; they were obtained from the stainless steel values listed in Ref. 11 by multiplying by 1.31. Under "Tensile Curve," Y means the strip chart recording has been located and analyzed, B means the specimen was damaged during irradiation/handling, and N means no tensile curve was found, which may indicate that the sample was not tensile-tested.

Alloy (ANL ID)	Specimen ID	Subcapsule ID	MOTA Position	T °C	Damage dpa	Tensile Curve
V-3.1Ti-0.25Si (BL-27)	MK01	V424	2E-3	404	38	Y
	MK02*	V519	1B-3	520	21	N
	MK03*	V624	5D-3	601	15	Y
V-17.7Ti (BL-15)	ML01	V425	2E-3	404	38	B
	ML02*	V519	1B-1	520	27	N
	ML03	V624	5D-3	601	15	N
V-7.2Cr-14.5Ti (BL-10)	MH01	V424	2E-3	404	38	N
	MH02*	V519	1B-1	520	27	N
	MH03*	V623	5D-3	601	15	B
V-13.5Cr-5.2Ti (BL-24)	MF01	V423	2E-3	404	38	B
	MF02*	V521	1B-3	520	21	B
	MF03	V627	5D-2	601	12	B

*These samples experienced temperature excursions during irradiation in FFTF.

Table B.2. Vanadium-alloy tensile specimens and FFTF operating conditions for MOTA 1E in Cycle 9 (341.8 EFPD at 291 MWth). Damage values are listed for Cycle 9. Total accumulated damage values are included in parentheses; they were obtained from the stainless steel values listed in Ref. 11 by multiplying by 1.31. Under "Tensile Curve," Y means the strip chart recording has been located and analyzed, B means the specimen was damaged during irradiation/handling, C means the irradiated sample was reloaded into the next MOTA, and N means no tensile curve was found, which may indicate that the sample was not tensile-tested.

Alloy (ANL ID)	Specimen ID	Subcapsule ID	MOTA Position	T °C	Damage dpa	Tensile Curve
V-3.1Ti-0.25Si (BL-27)	MK04	V441	2E-3	396	53	Y
	MK06	V441	2E-3	396	53	B
	MK08	V441	2E-3	396	53	Y
	MK05	V531	1B-3	520	24	B
	MK07	V530	1B-3	520	24	Y
	MK09	V530	1B-3	520	24	Y
	MK10	V637	2B-3	599	50	C
V-17.7Ti (BL-15)	ML04	V440	2E-3	396	53	Y
	ML06	V440	2E-3	396	53	Y
	ML08	V440	2E-3	396	53	N
	ML10	V637	2B-3	599	50	C
V-7.2Cr-14.5Ti (BL-10)	MH04	V439	2E-3	396	53	Y
	MH06	V439	2E-3	396	53	Y
	MH10	V439	2E-3	396	53	Y
	MH14	V439	2E-3	396	53	Y
	MH07	V440	2E-3	396	53	B
	MH11	V440	2E-3	396	53	N
	MH12	V441	2E-3	396	53	N
	MH05	V530	1B-3	520	24	B
	MH08	V530	1B-3	520	24	B
	MH13	V530	1B-3	520	24	B
	MH16	V530	1B-3	520	24	N
	MH09	V637	2B-3	599	50	C
	MH17	V637	2B-3	599	50	C
V-13.5Cr-5.2Ti (BL-24)	MF04	V439	2E-3	396	53	Y
	MF07	V439	2E-3	396	53	Y
	MF11	V439	2E-3	396	53	Y
	MF14	V439	2E-3	396	53	Y
	MF05	V441	2E-3	396	53	Y
	MF08	V441	2E-3	396	53	Y
	MF12	V441	2E-3	396	53	B
	MF15	V441	2E-3	396	53	B
	MF06	V530	1B-3	520	24	B
	MF09	V530	1B-3	520	24	B
	MF13	V530	1B-3	520	24	B
	MF16	V530	1B-3	520	24	N
	MF10	V637	2B-3	599	50	C
	MF17	V637	2B-3	599	50	C

Table B.5. Vanadium-alloy non-DHCE tensile specimens and FFTF operating conditions for MOTA 2B in Cycle 12 (203.3 EFPD at 291 MWth). The damage values listed are those accumulated during Cycle 12; they were obtained from the stainless steel values listed in Ref. 11 by multiplying by 1.31. Under "Tensile Curve," Y means the strip chart recording has been located and analyzed, C means the irradiated sample was reloaded into the next MOTA, and N *means no tensile curve was found, which may indicate that the sample was not tensile-tested.*

Alloy (ANL ID)	Specimen ID (number)	Subcapsule ID	MOTA Position	T °C	Damage dpa	Tensile Curve
V-2.5Ti-1Si (BL-45)	45-485-1, 2 45-563-1, 2 45(2)	V485 V563 V676	3D-6 1D-3 1E-3	427 519 599	33 14 14	Y, Y Y, N C
V-4.6Ti (BL-46)	46(2) 46-561-1, 2 46-678-1, 2	V483 V561 V678	3D-6 1D-2 1E-2	427 519 599	33 17 17	N, N Y, Y Y, N
V-9.8Ti (BL-12)	12(1) 12(1) 12(1)	V486 V564 V674	3D-6 1D-3 1E-3	427 519 599	33 14 14	C C C
V-17.7Ti (BL-15)	15(1)	V675	1E-3	599	14	C
V-4.1Cr-4.3Ti (BL-47)	47-484-1, 2 47-562-1, 2 47-672-1, 2	V484 V562 V672	3D-6 1D-3 1E-2	427 519 599	33 14 17	Y, Y Y, N Y, N
V-7.9Cr-5.7Ti (BL-49)	49-486 49-564 49-673	V486 V564 V673	3D-6 1D-3 1E-2	427 519 599	33 14 17	Y C Y
V-9.2Cr-4.9Ti (BL-43)	43-673	V673	1E-2	599	17	Y
V-13.5Cr-5.2Cr (BL-24)	24-674	V674	1E-3	599	14	Y

Table B.3. Vanadium-alloy tensile specimens and FFTF operating conditions for MOTA 1F in Cycle 10 (335.4 EFPD at 291 MWth). Damage values are listed for Cycle 10. Total accumulated damage values are included in parentheses; they were obtained from the stainless steel values listed in Ref. 11 by multiplying by 1.31. Under "Tensile Curve," Y means the strip chart recording has been located and analyzed, B means the specimen was damaged during irradiation/handling, C means the irradiated sample was reloaded into the next MOTA, and N means no tensile curve was found, which may indicate that the sample was not tensile-tested.

Alloy (ANL ID)	Specimen ID	Subcapsule ID	MOTA Position	T °C	Damage dpa	Tensile Curve
V-3.1Ti-0.25Si (BL-27)	MK10	V637	2B-3	600	46 (96)	Y
V-17.7Ti (BL-15)	ML11	V448	2D-5	404	46	Y
	ML12	V537	1E-3	520	26	Y
	ML10	V637	2B-3	600	46 (96)	Y
	ML13	V642	2B-2	600	49	Y
	ML14	V643	2B-3	600	46	C
V-7.2Cr-14.5Ti (BL-10)	MH18	V447	2D-5	404	46	Y
	MH19	V536	1E-3	520	26	Y
	MH21	V538	1E-3	520	26	C
	MH22	V539	2A-4	520	46	C
	MH09	V637	2B-3	600	46 (96)	N
	MH20	V641	2B-2	600	49	Y
	MH17	V637	2B-3	600	46 (96)	Y
V-9.2Cr-4.9Ti (BL-43)	MV01	V448	2D-5	404	46	Y
	MV02	V537	1E-3	520	26	Y
	MV03	V642	2B-2	600	49	Y
	MV04	V643	2B-3	600	46	C
V-13.5Cr-5.2Cr (BL-24)	MF18	V447	2D-5	404	46	Y
	MF19	V536	1E-3	520	26	Y
	MF21	V538	1E-3	520	26	C
	MF22	V539	2A-4	520	46	C
	MF10	V637	2B-3	600	46 (96)	N
	MF20	V641	2B-2	600	49	Y
	MF17	V637	2B-3	600	46 (96)	Y

Table B.4. Vanadium-alloy tensile specimens and FFTF operating conditions for MOTAs 1G and 2A in Cycle 11 (299.7 EFPD at 291 MWth). Damage values are listed for Cycle 11. Total accumulated damage values are included in parentheses; they were obtained from the stainless steel values listed in Ref. 11 by multiplying by 1.31. Under "Tensile Curve," N means no tensile curve was found, which may indicate that the sample was not tensile-tested. Only ANL samples are listed.

Alloy (ANL ID)	Specimen ID (number)	Subcapsule ID	MOTA/ Position	T °C	Damage dpa	Tensile Curve
V-3.1Ti-0.5Si	42	V548	1G/2F-3	520	41	N
(BL-42)	42	V549	1G/2F-3	520	41	N
	42/42L	V552	1G/2A-4	520	46	N
	42/42L (2)	V653	2A/4C-2	600	47	N
	42 (2)	V656	2A/4C-3	600	51	N
	42 (2)	V657	2A/4C-3	600	51	N
V-17.7Ti	15	V548	1G/2F-3	520	41	N
(BL-15)	15	V550	1G/2A-4	520	46	N
	15	V551	1G/2A-4	520	46	N
	ML14	V643	1G/4A-4	600	46 (92)	N
V-7.2Cr-14.5Ti	MH21	V538	1G/2F-3	520	41	N
(BL-10)	MH22	V539	1G/2A-4	520	46	N
	10/10L	V548	1G/2F-3	520	41	N
	10/10L (2)	V658	2A/4C-3	600	51	N
V-9.2Cr-4.9Ti	43 (2)	V548	1G/2F-3	520	41	N
(BL-43)	43	V552	1G/2A-4	520	46	N
	MV04	V643	1G/4A-4	600	46 (92)	N
	43	V655	2A/4C-2	600	47	N
	43 (2)	V658	2A/4C-3	600	51	N
V-9.9Cr-9.2Ti	44	V548	1G/2F-3	520	41	N
(BL-44)	44	V549	1G/2F-3	520	41	N
	44	V550	1G/2A-4	520	46	N
	44	V551	1G/2A-4	520	46	N
	44 (2)	V654	2A/4C-2	600	47	N
	44	V655	2A/4C-2	600	47	N
	44 (2)	V658	2A/4C-3	600	51	N
V-13.5Cr-5.2Cr	MF21	V538	1G/2F-3	520	41 (67)	N
(BL-24)	MF22	V539	1G/2A-4	520	46 (92)	N
	24 (2)	V548	1G/2F-3	520	41	N
	24 (2)	V658	2A/4C-3	600	51	N

Table B.6. Vanadium-alloy DHCE tensile specimens and FFTF operating conditions for MOTA 2B in Cycle 12 (203.3 EFPD at 291 MWth). The damage values refer to damage accumulated during Cycle 12; they have been obtained from the stainless steel values listed in Ref. 11 by multiplying by 1.31. Under "Tensile Curve," Y means the strip chart recording has been located and reanalyzed and N means that no tensile curve was found, which may indicate that the sample was not tensile-tested.

Alloy (ANL ID)	Specimen ID #	Subcapsule ID	MOTA Position	T °C	Damage dpa	Tensile Curve
V-2.5Ti-1Si (BL-45)	453	4D-1	4D-1	430	25	Y
	456	4D-2	4D-2	430	27	Y
	45	5E-2	5E-2	435	13	Y
	458	5D-1	5D-1	500	14	Y
	455	5D-2	5D-2	500	18	N
	45(5E1)	5E-1*	5D-2*	500	18	Y
	457	5C-1	5C-1	599	14	Y
	454	5C-2	5C-2	599	18	Y
V-4.6Ti (BL-46)	46, 46	4D-1	4D-1	430	25	Y, Y
	46, 46	4D-2	4D-2	430	27	Y, Y
	46, 46	5E-2	5E-2	435	13	Y, Y
	46, 46	5D-1	5D-1	500	14	Y, Y
	46, 46	5D-2	5D-2	500	18	Y, Y
	46(5E1),	5E-1*	5D-2*	500	18	Y, Y
	46(5E1)	5C-1	5C-1	599	14	Y, Y
	46, 46	5C-2	5C-2	599	18	Y, Y
	46, 46					
V-9.8Ti (BL-12)	12	4D-1	4D-1	430	25	N
	12	4D-2	4D-2	430	27	N
	12	5E-2	5E-2	435	13	N
	12	5D-1	5D-1	500	14	N
	12	5D-2	5D-2	500	18	N
	12(5E1)	5E-1*	5D-2*	500	18	N
	12	5C-1	5C-1	599	14	N
	12	5C-2	5C-2	599	18	N

*Subcapsule and/or specimen ID has been referred to as 5E-1 in the literature because that was the planned MOTA-2B location. However, it was actually put in the 5D-2 position (see Ref. 16).

Table B.6. Vanadium-alloy DHCE tensile specimens and FFTF operating conditions for MOTA 2B in FFTF cycle 12 (203.3 EFPD at 291 MWth). The damage values refer to damage accumulated during cycle 12; they have been obtained from the stainless steel values listed in Ref. 9 by multiplying by 1.31. Under "Tensile Curve," Y means the strip chart recording has been located and analyzed and N means no tensile curve was found, which may indicate that the sample was not tensile-tested. (continued)

Alloy (ANL ID)	Specimen ID #	Subcapsule ID	MOTA Position	T °C	Damage dpa	Tensile Curve
V-4.1Cr-4.3Ti (BL-47)	474, 47	4D-1	4D-1	430	25	Y, Y
	475, 47	4D-2	4D-2	430	27	Y, Y
	47, 47	5E-2	5E-2	435	13	Y, N
	476, 47	5D-1	5D-1	500	14	Y, Y
	473, 47	5D-2	5D-2	500	18	Y, Y
	47(5E1),	5E-1*	5D-2*	500	18	Y, Y
	47(5E1)	5C-1	5C-1	599	14	Y, Y
	477, 47	5C-2	5C-2	599	18	Y, Y
	478, 47					
V-7.9Cr-5.7Ti (BL-49)	49	4D-1	4D-1	430	25	Y
	49	4D-2	4D-2	430	27	Y
	49	5E-2	5E-2	435	13	Y
	49	5D-1	5D-1	500	14	Y
	49	5D-2	5D-2	500	18	N
	49(5E1)	5E-1*	5D-2*	500	18	Y
	49	5C-1	5C-1	599	14	Y
	49	5C-2	5C-2	599	18	Y
V-9.2Cr-4.9Ti (BL-43)	43	4D-1	4D-1	430	25	Y
	43	4D-2	4D-2	430	27	Y
	43	5E-2	5E-2	435	13	Y
	43	5D-1	5D-1	500	14	Y
	43	5D-2	5D-2	500	18	N
	43(5E1)	5E-1*	5D-2*	500	18	Y
	43	5C-1	5C-1	599	14	Y
	43	5C-2	5C-2	599	18	Y

*Subcapsule and/or specimen ID has been referred to as 5E-1 in the literature because that was the planned MOTA-2B location. However, it was actually put in the 5D-2 position (see Ref. 15).

Table B.7. Revised tensile properties for V-3Ti-xSi alloys irradiated in FFTF: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), and total elongation (TE). k = force-displacement slope used to reanalyze the data [4].

Alloy (ANL ID)	Specimen ID (Position)	T, °C Irr./Test	Dam./He dpa/appm	k kN/mm	YS MPa	UTS MPa	UE %	TE %
V-2.5Ti-1Si	453 (4D1)	430/425	25/12	2.09	547	649	6.3	10
(BL-45)	456 (4D2)	430/25	27/23	1.96	671	750	9.4	16
	45(5E2)	435/425	13/4	1.44	512	645	5.1	10
	45-485-2	427/420	33/≈0	1.58	564	691	3.7	8.0
	45-485-1	427/25	33/≈0	1.58	783	823	4.1	6.8
	458 (5D1)	500/500	14/15	1.69	407	554	7.6	13
	45(5E1)	500/26	18/7	1.92	529	626	9.4	15
	45-563-1	519/520	14/≈0	1.32	341	491	8.5	14
	457 (5C1)	599/600	14/10	1.66	381	439	11	19
	454 (5C2)	599/25	18/75	1.75	403	545	15	21
V-3.1Ti-	V424/MK01	404/420	38/≈0	2.23	817	930	1.8	3.4
0.25Si	V441/MK08	[b]	53/≈0	2.04	912	1003	1.5	2.3
(BL-27)	V441/MK04	396/420	53/≈0	2.33	896	1020	4.0	8.9
		[b]						
	V531/MK09	396/25[b]	24/≈0	1.57	571	678	1.0	1.7
	V531/MK07		24/≈0	1.63	634	712	3.9	6.6
		520/520						
	V624/MK03	520/25	15/≈0	1.26	422	520	6.6	14
	V627/MK10		96/≈0	1.21	441	574	5.4	12
		601/600						
		600/600						

[a]Sample annealed at 7°C/min to 510°C for H_2 removal prior to tensile testing; test temperature may be as low as 340°C for this case due to a broken thermocouple.

[b]Sample annealed at 7°C/min to 510°C for H_2 removal prior to tensile testing.

Table B.8. Revised tensile properties for V-4.6Ti and V-17.7Ti alloys irradiated in FFTF: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), and total elongation (TE). k = force-displacement slope used to reanalyze the data [4].

Alloy (ANL ID)	Specimen ID (Position)	T, °C Irr./Test	Dam./He dpa/appm	k kN/mm	YS MPa	UTS MPa	UE %	TE %
V-4.6Ti (BL-46)	46(5E2)	435/425	13/4	1.75	499	587	1.8	7.5
	46(5E2)	435/200	13/4	1.72	547	614	3.0	9.1
	46(4D2)	430/425	27/23	1.69	561	645	1.4	6.3
	46(4D2)	430/100	27/23	1.75	624	705	2.4	5.9
	46(4D1)	430/425	25/12	1.69	582	648	1.4	4.5
	46(4D1)	430/27	25/12	1.82	680	797	4.5	8.4
	46(5E1)	500/500	18/7	1.49	337	437	4.5	12
	46(5E1)	500/200	18/7	1.75	330	439	6.2	13
	46(5D1)	500/500	14/15	1.23	342	450	5.5	11
	46(5D1)	500/25	14/15	1.82	422	520	9.0	20
	46-561-2	519/520	17/≈0	1.57	343	430	5.1	9.4
	46-561-1	519/420	17/≈0	1.38	324	406	4.3	10
	46(5C2)	599/600	18/75	1.56	190	377	6.7	15
	46(5C2)	599/100	18/75	1.44	281	402	12	20
	46(5C1)	599/600	14/10	1.29	215	349	7.3	13
	46(5C1)	599/26	14/10	1.40	305	439	15	26
	46-678-1	599/600	17/≈0	1.58	326	384	9.1	14
V-17.7Ti (BL-15)	V448/ML11	404/420[a]	46/≈0	1.33	694	982	3.7	8.9
	V440/ML06	396/420	53/≈0	2.23	1001	1212	4.1	7.3
	V440/ML04	396/25[a]	53/≈0	2.36	973	1049	2.8	8.5
	V537/ML12	520/520	26/≈0	1.53	533	743	12	17
	V642/ML13	600/600	49/≈0	1.56	415	587	13	20
	V637/ML10	600/600	96/≈0	1.07	396	535	13	20

[a]Sample annealed at 7°C/min to 510°C for H_2 removal prior to tensile testing.

Table B.9. Revised tensile properties for V-4.1Cr-4.3Ti alloy irradiated in FFTF: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), and total elongation (TE). k = force-displacement slope used to reanalyze the data [4].

Alloy (ANL ID)	Specimen ID (Position)	T, °C Irr./Test	Dam./He dpa/appm	k kN/mm	YS MPa	UTS MPa	UE %	TE %
V-4.1Cr-4.3Ti (BL-47)	475 (4D2)	430/425	27/23	1.63	600	687	1.9	6.2
	47 (4D2)	430/100	27/23	1.89	650	748[a]	2.1[a]	9.8
	474 (4D1)	430/425	25/12	1.63	619	689	1.3	6.8
	47 (4D1)	430/24	25/12	1.66	698	783	4.4	11
	47 (5E2)	435/200	13/4	1.89	606	681	3.0	11
	47-484-2	427/420	33/≈0	1.69	675	694	0.3	3.8
	47-484-1	427/25	33/≈0	1.85	824	841	0.5	5.8
	47 (5E1)	500/500	18/7	1.72	477	574	2.7	9.1
	47 (5E1)	500/200	18/7	1.75	519	599	2.8	12
	476 (5D1)	500/500	14/12	1.69	500	577	3.0	9.3
	47 (5D1)	500/24	14/12	1.58	525	604	b	b
	47-562-1	519/520	14/≈0	1.54	438	541	5.1	11
	477 (5C1)	599/600	14/10	1.17	364	454	5.2	11
	47 (5C1)	599/24	14/10	1.75	424	575	13	20
	478 (5C2)	599/600	18/75	1.44	379	471	7.0	15
	47 (5C2)	599/100	18/75	1.44	403	518	9.7	16
	47-672-1	599/600	17/≈0	1.46	361	463	7.3	13

[a]Values obtained by extrapolation as load recording was off scale near peak.

[b]Stoppages of chart recorder render these parameters very difficult to determine with any degree of certainty.

Table B.10. Revised tensile properties for V-7.9Cr-5.7Ti and V-9.2Cr-4.9Ti alloys irradiated in FFTF: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), and total elongation (TE). k = force-displacement slope used to reanalyze the data [4].

Alloy (ANL ID)	Specimen ID (Position)	T, °C Irr./Test	Dam./He dpa/appm	k kN/mm	YS MPa	UTS MPa	UE %	TE %
V-7.9Cr-5.7Ti (BL-49)	49 (5E2)	435/425	13/4	2.13	690	774	1.8	7.5
	49 (4D1)	430/425	25/12	2.13	609	656	1.0	5.9
	49 (4D2)	430/26	27/23	2.23	748	857	4.2	10
	49-486-1 (3D6)	427/420	33/≈0	2.13	772	821	1.2	6.7
	49 (5D1)	500/500	14/15	1.75	435	530	2.5	7.9
	49 (5E1)	500/25	18/7	2.45	615	750	9.7	16
	49 (5C1)	599/600	14/10	1.66	325	446	7.2	14
	49 (5C2)	599/24	18/75	1.96	450	576	14	21
	49-673 (1E2)	599/600	17/≈0	1.63	387	517	7.6	14
V-9.2Cr-4.9Ti (BL-43)	43 (4D1)	430/425	25/12	2.28	811	860	1.0	6.4
	43 (4D2)	430/27	27/23	2.45	887	967	6.3	13
	43 (5E2)	435/200	13/10	2.29	817	895	3.5	10
	V448/MV01	404/420[a]	46/≈0	1.72	788	930	1.2	6.7
	43 (5D1)	500/500	14/15	2.13	587	716	3.5	9.2
	43 (5E1)	500/27	18/7	2.38	679	829	7.0	15
	V537/MV02	520/520	26/≈0	1.53	606	738	3.9	9.7
	43 (5C2)	599/600	18/75	1.85	416	559	7.0	14
	43 (5C1)	599/100	14/10	1.96	467	605	13	23
	V642/MV03	600/600	49/≈0	1.42	430	566	7.3	14
	43-673 (1E2)	599/600	17/≈0	1.96	457	581	6.0	12

[a]Sample annealed at 7°C/min to 510°C for H_2 removal prior to tensile testing.

Table B.11. Revised tensile properties for V-7.2Cr-14.5Ti and V-13.5Cr-5.2Ti alloys irradiated in FFTF: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), and total elongation (TE). k = force-displacement slope used to reanalyze the data [4].

Alloy (ANL ID)	Specimen ID	T, °C Irr./Test	Dam./He dpa/appm	k kN/mm	YS MPa	UTS MPa	UE %	TE %
V-7.2Cr-14.5Ti (BL-10)	V447/MH18	404/420[a]	46/≈0	1.44	b	1120	b	10[b]
	V439/MH10	396/420	53/≈0	2.31	1009	1136	3.0	6.2
	V439/MH04	396/420	53/≈0	2.02	1075	1190	2.6	6.2
	V439/MH14	396/420	53/≈0	2.23	953	1153	4.9	7.9
	V439/MH06	396/25	53/≈0	2.33	1086	1210	2.8	8.1
	V536/MH19	520/520	26/≈0	1.66	562	855	8.9	14
	V641/MH20	600/600	49/≈0	1.53	468	685	8.9	8.9
	V637/MH17	600/600	96/≈0	1.10	432	547	3.4	3.4
V-13.5Cr-5.2Ti (BL-24)	V447/MF18	404/420[a]	46/≈0	1.10	b	1064	b	7.6[b]
	V439/MF07	396/420[a]	53/≈0	1.38	b	1130	b	8.8[b]
	V439/MF14	396/420	53/≈0	2.06	1152	1195	0.9	3.9
	V439/MF04	396/420	53/≈0	1.38	b	1124	1.8[b]	1.8[b]
	V441/MF08	396/420	53/≈0	—	c	c	c	c
	V441/MF05	396/420	53/≈0	—	d	d	d	d
	V440/MF11	396/25	53/≈0	2.55	1259	1358	1.3	1.3
	V536/MF19	520/520	26/≈0	1.89	747	930	4.7	10
	V641/MF20	600/600	49/≈0	1.36	542	713	5.1	9.3
	V637/MF17	600/600	96/≈0	1.40	566	730	5.5	10
	V674/24	599/600	14/≈0	2.16	549	725	6.4	13

[a]Sample annealed at 7°C/min to 510°C for H_2 removal prior to testing.

[b]Support pins are obviously plastically deformed; TE is measured directly; YS and UE obtained from force-displacement curve are considered unreliable.

[c]Specimen broke at pin before plastic flow of gauge length initiated.

[d]Plastic flow part of curve is off scale.

Table B.12. Revised tensile data for V-Cr-Ti alloys irradiated in HFIR: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), and total elongation (TE). k = force-displacement slope used to reanalyze the data [4].

Alloy (ANL ID)	Specimen ID	T, °C Irrad./Test	Dam./He dpa/appm	k kN/mm	YS MPa	UTS MPa	UE %	TE %
V-4.1Cr-4.3Ti (BL-47)	—	~400/400	~10/≈0	2.45	722	803	2.8	5.0
V-7.9Cr-5.7Ti (BL-49)	—	~400/400	~10/≈0	2.23	775	829	1.3	5.0
V-9.2Cr-4.9Ti (BL-43)	—	~400/400	~10/≈0	2.33	834	871	1.3	2.1
V-14.5Cr-5.0Ti (BL-41)	—	~400/400	~10/≈0	2.33	980	1022	0.9	3.5

Appendix C:

Comparison of Revised and Previously Reported Tensile Properties of FFTF- and HFIR-Irradiated V-Ti and V-Cr-Ti Alloys

The revised tensile properties for V-Ti and V-Cr-Ti alloys irradiated in FFTF and HFIR [Appendix B] are compared to previously reported values [12-15] in Tables C.1 to C.7. The revised values have been determined from the original strip chart recordings [4] by a standard and consistent methodology that properly accounts for tensile-machine and sample springback in order to determine permanent plastic strain values for UE and TE. Unusual behavior exhibited in these strip chart recordings and uncertainties in their interpretation are given in footnotes to the tables in Appendix B. In the case of ANL alloy BL-47, previously reported tensile values have been thoroughly traced from those printed on strip chart recordings, from those described in laboratory notebooks and from those that appear graphically in the more recent semiannual publications. For some of the older alloys, only the strip-chart-recorded and laboratory-notebook-recorded values have been examined. These values have been modified over a period of time based on interim reanalyses of the strip chart data and post-test observations (e.g., bent pins, extensometer readings, direct measurements of sample length change, etc.) The previously reported values are listed in parentheses under the revised values.

Table C.1. Revised and previously reported (in parentheses) tensile data for V-17.7Ti alloy irradiated in FFTF: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), and total elongation (TE).

Alloy (ANL ID)	Specimen ID (Pos.)	T, °C Irr./Test	Dam./He dpa/appm	YS MPa	UTS MPa	UE %	TE %
V-17.7Ti	V448/ML11	404/420	46/≈0	694	982	3.7	8.9
(BL-15)				(710)	(982)	(12)	(14)
	V440/ML06	396/420	53/≈0	1001	1212	4.1	7.3
				(—)	(—)	(—)	(—)
	V440/ML04	396/25	53/≈0	973	1049	2.8	8.5
				(947)	(1049)	(10)	(11)
	V537/ML12	520/520	26/≈0	533	743	12	17
				(543)	(755)	(15)	(18)
	V642/ML13	600/600	49/≈0	415	587	13	20
				(427)	(592)	(17)	(23)
	V637/ML10	600/600	96/≈0	396	535	13	20
				(419)	(537)	(18)	(26)

Table C.2. Revised and previously reported (in parentheses) tensile data for V-3Ti-xSi alloys irradiated in FFTF: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), and total elongation (TE).

Alloy (ANL ID)	Specimen ID (Pos.)	T, °C Irr./Test	Dam./He dpa/appm	YS MPa	UTS MPa	UE %	TE %
V-2.5Ti-1Si (BL-45)	453 (4D1)	430/425	25/12	547 (—)	649 (659)	6.3 (10)	10 (15)
	456 (4D2)	430/25	27/23	671 (—)	750 (750)	9.4 (10)	16 (20)
	45-485-2	427/420	33/≈0	564 (540)	691 (671)	3.7 (10)	8.0 (13)
	45-485-1	427/25	33/≈0	783 (779)	823 (823)	4.1 (8.3)	6.8 (9.6)
	458 (5D1)	500/500	14/15	407 (—)	554 (554)	7.6 (—)	13 (17)
	45(5E1)	500/26	18/7	529 (—)	626 (627)	9.4 (—)	15 (18)
	45-563-1	519/520	14/≈0	341 (360)	491 (491)	8.5 (13)	14 (17)
	457 (5C1)	599/600	14/10	381 (300)	439 (480)	11 (16)	19 (21)
	454 (5C2)	599/25	18/75	403 (—)	545 (545)	15 (—)	21 (25)
V-3.1Ti-0.25Si (BL-27)	V424/MK01	404/420	38/≈0	817 (746)	930 (930)	1.8 (8.3)	3.4 (12)
	V441/MK08	396/420	53/≈0	912 (867)	1003 (1003)	1.5 (8.1)	2.3 (8.6)
	V441/MK04	396/25	53/≈0	896 (911)	1020 (1020)	4.0 (9.4)	8.9 (13)
	V531/MK09	520/520	24/≈0	571 (522)	678 (678)	1.0 (6.6)	1.7 (7.0)
	V531/MK07	520/25	24/≈0	634 (595)	712 (712)	3.9 (8.8)	6.6 (11)
	V624/MK03	601/600	15/≈0	422 (390)	520 (520)	6.6 (12)	14 (19)
	V627/MK10	600/600	96/≈0	441 (381)	574 (574)	5.4 (13)	12 (19)

Table C.3. Revised and previously reported (in parentheses) tensile data for V-4.6Ti alloy irradiated in FFTF: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), .and total elongation (TE).

Alloy (ANL ID)	Specimen ID (Pos.)	T, °C Irr./Test	Dam./He dpa/appm	YS MPa	UTS MPa	UE %	TE %
V-4.6Ti (BL-46)	46(5E2)	435/425	13/4	499 (—)	587 (587)	1.8 (—)	7.5 (13)
	46(5E2)	435/200	13/4	547 (—)	614 (614)	3.0 (—)	9.1 (13)
	46(4D2)	430/425	27/23	561 (—)	645 (645)	1.4 (—)	6.3 (16)
	46(4D2)	430/100	27/23	624 (—)	705 (705)	2.4 (—)	5.9 (12)
	46(4D1)	430/425	25/12	582 (—)	648 (648)	1.4 (—)	4.5 (15)
	46(4D1)	430/27	25/12	680 (—)	797 (796)	4.5 (—)	8.4 (14)
	46(5E1)	500/500	18/7	337 (—)	437 (437)	4.5 (—)	12 (15)
	46(5E1)	500/200	18/7	330 (—)	439 (439)	6.2 (—)	13 (16)
	46(5D1)	500/500	14/15	342 (—)	450 (450)	5.5 (—)	11 (15)
	46(5D1)	500/25	14/15	422 (—)	520 (527)	9.0 (—)	20 (24)
	46-561-2	519/520	17/≈0	343 (322)	430 (430)	5.1 (9.8)	9.4 (14)
	46-561-1	519/420	17/≈0	324 (308)	406 (406)	4.3 (—)	9.9 (14)
	46(5C2)	599/600	18/75	190 (—)	377 (379)	6.7 (—)	15 (19)
	46(5C2)	599/100	18/75	281 (—)	402 (402)	12 (—)	20 (22)
	46(5C1)	599/600	14/10	215 (—)	349 (349)	7.3 (—)	13 (18)
	46(5C1)	599/26	14/10	305 (—)	439 (439)	15 (—)	26 (30)
	46-678-1	599/600	17/≈0	326 (290)	384 (384)	9.1 (13)	14 (19)

Table C.4. Revised and previously reported (in parentheses) tensile data for V-4.1Cr-4.3Ti alloy BL-47 irradiated in FFTF: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE).

Alloy (ANL ID)	Specimen ID (Pos.)	T, °C Irr./Test	Dam./He dpa/appm	YS MPa	UTS MPa	UE %	TE %
V-4.1Cr-4.3Ti	475(4D2)	430/425	27/23	600	687	1.9	6.2
(BL-47)				(567)	(700)	(11)	(13)
	47(4D2)	430/100	27/23	650	748	2.1	9.8
				(612)	(748)	(11)	(15)
	474(4D1)	430/425	25/12	619	689	1.3	6.8
				(567)	(689)	(10)	(13)
	47(4D1)	430/24	25/12	698	783	4.4	11
				(625)	(783)	(14)	(17)
	47(5E2)	435/200	13/4	606	681	3.0	11
				(564)	(681)	(11)	(15)
	47-484-2	427/420	33/≈0	675	694	0.3	3.8
				(594)	(694)	(8.3)	(10)
	47-484-1	427/25	33/≈0	824	841	0.5	5.8
				(795)	(832)	(8.1)	(10)
	47(5E1)	500/500	18/7	477	574	2.7	9.1
				(421)	(574)	(11)	(14)
	47(5E1)	500/200	18/7	519	599	2.8	12
				(477)	(599)	(11)	(15)
	476(5D1)	500/500	14/12	500	577	3.0	9.3
				(421)	(577)	(11)	(15)
	47(5D1)	500/24	14/12	525	604	—	—
				(500)	(609)	(14)	(—)
	47-562-1	519/520	14/≈0	438	541	5.1	11
				(450)	(541)	(10)	(14)
	477(5C1)	599/600	14/10	364	454	5.2	11
				(318)	(454)	(14)	(18)
	47(5C1)	599/24	14/10	424	575	13.0	20.0
				(391)	(575)	(13)	(20)
	478(5C2)	599/600	18/75	379	471	7.0	15
				(400)	(471)	(13)	(23)
	47(5C2)	599/100	18/75	403	518	9.7	16
				(455)	(518)	(15)	(20)
	47-672-1	599/600	17/≈0	361	463	7.3	13
				(360)	(462)	(12)	(16)

Table C.5. Revised and previously reported (in parentheses) tensile data for V-7.9Cr-5.7Ti and V-9.2Cr-4.9Ti alloys irradiated in FFTF: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), and total elongation (TE).

Alloy (ANL ID)	Specimen ID (Pos.)	T, °C Irr./Test	Dam./He dpa/appm	YS MPa	UTS MPa	UE %	TE %
V-7.9Cr-5.7Ti (BL-49)	49 (5E2)	435/425	13/4	690 (624)	774 (775)	1.8 (7.8)	7.5 (10)
	49 (4D1)	430/425	25/12	609 (493)	656 (656)	1.0 (5.5)	5.9 (8.9)
	49 (4D2)	430/26	27/23	748 (660)	857 (858)	4.2 (13)	10 (9.8)
	49-486-1 (3D6)	427/420	33/≈0	772 (727)	821 (821)	1.2 (7.9)	6.7 (11)
	49 (5D1)	500/500	14/15	435 (409)	530 (531)	2.5 (6.9)	7.9 (11)
	49 (5E1)	500/25	18/7	615 (570)	750 (751)	9.7 (14)	16 (19)
	49 (5C1)	599/600	14/10	325 (280)	446 (447)	7.2 (11)	14 (16)
	49 (5C2)	599/24	18/75	450 (405)	576 (578)	14 (18)	21 (26)
	49-673 (1E2)	599/600	17/≈0	387 (332)	517 (517)	7.6 (12)	14 (17)
V-9.2Cr-4.9Ti (BL-43)	43 (4D1)	430/425	25/12	811 (728)	860 (860)	1.0 (6.8)	6.4 (10)
	43 (4D2)	430/27	27/23	887 (838)	967 (967)	6.3 (12)	13 (16)
	43 (5E2)	435/200	13/10	817 (740)	895 (894)	3.5 (9.4)	10 (14)
	V448/MV01	404/420	46/≈0	788 (712)	930 (930)	1.2 (7.0)	6.7 (8.9)
	43 (5D1)	500/500	14/15	587 (524)	716 (716)	3.5 (8.6)	9.2 (13)
	43 (5E1)	500/27	18/7	679 (674)	829 (819)	7.0 (12)	15 (17)
	V537/MV02	520/520	26/≈0	606 (568)	738 (738)	3.9 (8.4)	9.0 (9.0)
	43 (5C2)	599/600	18/75	416 (408)	559 (559)	7.0 (12)	14 (17)
	43 (5C1)	599/100	14/10	467 (451)	605 (604)	12.9 (17)	23 (25)
	V642/MV03	600/600	49/≈0	430 (447)	566 (566)	7.3 (11)	14 (15)
	43-673 (1E2)	599/600	17/≈0	457 (427)	581 (581)	6.0 (11)	12 (16)

Table C.6. Revised and previously reported (in parentheses) tensile data for V-7.2Cr-14.5Ti and V-13.5Cr-5.2Ti alloys irradiated in FFTF: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE).

Alloy (ANL ID)	Specimen ID (pos.)	T, °C Irr./Test	Dam./He dpa/appm	YS MPa	UTS MPa	UE %	TE %
V-7.2Cr-14.5Ti (BL-10)	V447/MH18	404/420	46/≈0	— (764)	1120 (1120)	— (12)	10 (13)
	V439/MH10	396/420	53/≈0	1009 (—)	1136 (—)	3.0 (—)	6.2 (—)
	V439/MH04	396/420	53/≈0	1075 (—)	1190 (—)	2.6 (—)	6.2 (—)
	V439/MH14	396/420	53/≈0	953 (—)	1153 (—)	4.9 (—)	7.9 (—)
	V439/MH06	396/25	53/≈0	1086 (1086)	1210 (1210)	2.8 (9.3)	8.1 (13)
	V536/MH19	520/520	26/≈0	562 (608)	855 (855)	8.9 (13)	14 (15)
	V641/MH20	600/600	49/≈0	468 (492)	685 (683)	8.9 (16)	8.9 (16)
	V637/MH17	600/600	96/≈0	432 (452)	547 (547)	3.4 (11)	3.4 (11)
V-13.5Cr-5.2Ti (BL-24)	V447/MF18	404/420	46/≈0	— (866)	1064 (1064)	5.0 (5.0)	7.6 (7.6)
	V439/MF07	396/420	53/≈0	— (636)	1130 (1130)	— (6.3)	8.8 (8.8)
	V439/MF14	396/420	53/≈0	1152 (—)	1195 (—)	0.9 (—)	3.9 (—)
	V439/MF04	396/420	53/≈0	— (687)	1124 (1124)	1.8 (3.2)	1.8 (3.2)
	V441/MF08	396/420	53/≈0	— (—)	— (—)	— (—)	— (—)
	V441/MF05	396/420	53/≈0	— (—)	— (—)	— (—)	— (—)
	V440/MF11	396/25	53/≈0	1259 (1174)	1358 (1358)	1.3 (2.8)	1.3 (2.8)
	V536/MF19	520/520	26/≈0	747 (710)	930 (950)	4.7 (7.0)	10 (15)
	V641/MF20	600/600	49/≈0	542 (563)	713 (713)	5.1 (8.8)	9.3 (11)
	V637/MF17	600/600	96/≈0	566 (521)	730 (730)	5.5 (12)	10 (16)
	V674/24	599/600	14/≈0	549 (—)	725 (—)	6.4 (—)	13 (—)

Table C.7. Revised and previously reported (in parentheses) tensile data for V-Cr-Ti alloys irradiated in HFIR: yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE).

Alloy (ANL ID)	Specimen ID	T, °C Irr./Test	Damage/ He dpa/appm	YS MPa	UTS MPa	UE %	TE %
V-4.1Cr-4.3Ti (BL-47)		~400/400	~10/≈0	722 (704)	803 (803)	2.8 (4.7)	5.0 (12)
V-7.9Cr-5.7Ti (BL-49)		~400/400	~10/≈0	775 (713)	829 (829)	1.3 (1.3)	5.0 (8.8)
V-9.2Cr-4.9Ti (BL-43)		~400/400	~10/≈0	834 (784)	871 (871)	1.3 (1.2)	2.1 (8.8)
V-14.5Cr-5.0Ti (BL-41)		~400/400	~10/≈0	980 (922)	1022 (1022)	0.9 (1.2)	3.5 (10)

Appendix D:

Comparison of Revised and Previously Reported Tensile Properties of Unirradiated V-5Cr-5Ti Preoxidized in Air

Natesan and Soppet [18] have reported the effects of oxidation on the tensile properties of V-4.6Cr-5.1Ti (BL-63). Tensile specimens were prepared according to ASTM specifications. The approximate gauge dimensions were 19-mm length, 4.5-mm width and 1.0-mm thickness. The control specimens (unoxidized) were tensile-tested at crosshead speeds ranging from 0.005 to 20 mm/min, which correspond to gauge length strain rates of 0.00044 to 0.18%/s. The preoxidized samples were tested at a gauge-length strain rate of 0.018%/s. Table D.1 shows the revised values of tensile properties (determined from the original strip chart recordings) and the previously reported values. The primary difference is in determination of total elongation (TE). In the revised values, the contribution of the machine and nongauge compliance to the crosshead displacement is subtracted from the total displacement in order to determine TE.

Table D.1 Comparison between revised and previously reported (in parentheses) values for tensile properties of V-4.6Cr-5.1Ti (BL-63) preexposed to air: yield stress (YS), ultimate tensile stress (UTS), uniform elongation (UE), and total elongation (TE). Also indicated are initial cross-sectional areas (Ao) for samples and oxidation conditions. Specimens were preoxidized in air at 500°C for times indicated. Tensile tests were conducted in air.

Tensile Test Temperature °C	Preexposure Time in Air at 500°C, h	Specimen ID# Test #	Room Temp. Ao, mm²	YS MPa	UTS, MPa	UE %	TE %
24	0	T5-28	4.78	326	406	19	31
		VNAT-26		(—)	(—)	(—)	(32)
	24	T5-21	4.90	414	510	16	24
		VNAT-23		(—)	(—)	(—)	(27)
	260	T5-22	5.03	439	511	3.5	3.5
		VNAT-24		(—)	(—)	(—)	(6.5)
	600	T5-23	4.94	455	468	0.3	0.3
		VNAT-21		(—)	(—)	(—)	(3.2)
	1050	T5-24	4.97	467	483	0.4	0.4
		VNAT-29		(—)	(—)	(—)	(3.2)
500	0	V-2	4.88	241	405	15	23
		VNAT-2		(—)	(—)	(—)	(23)
	24	V-7	4.91	243	412	14	18
		VNAT-7		(—)	(—)	(—)	(22)
	250	V-3	4.91	272	457	11	14
		VNAT-34		(—)	(—)	(—)	(17)
	600	V-6	5.02	266	454	9.5	11
		VNAT-6		(—)	(—)	(—)	(15)
	1000	V-8	4.97	313	448	7.2	10
		VNAT-8		(—)	(—)	(—)	(14)
	2060	V-9	5.05	336	392	5.6	6.2
		VNAT-9		(—)	(—)	(—)	(9.0)