SUMMARY OF RECOMMENDED CORRELATIONS FOR ITER-GRADE TYPE 316L(N) FOR THE ITER MATERIAL PROPERTIES HANDBOOK -- M. C. Billone (Argonne National Laboratory) and J. E. Pawel (Oak Ridge National Laboratory)

OBJECTIVE

The objective of this work is to summarize and recommend design correlations for the tensile properties for inclusion in the International Thermonuclear Experimental Reactor (ITER) Material Properties Handbook.

SUMMARY

The focus of this effort is the effects of irradiation on the ultimate tensile strength (UTS), the yield strength (YS), the uniform elongation (UE), the total elongation (TE) and the reduction in area (RA) in the ITER-relevant temperature range of 100-400°C. For the purposes of this summary, data for European heats of 316 with $0.02 \leq C \leq 0.03$ wt.% and $0.06 \leq N \leq 0.08$ wt.% are referred to as E316L(N) data and grouped together. Other heats of 316 and Ti-modified 316 are also included in the data base. For irradiation and postirradiation-test temperatures in the range of 200-400°C, the common behavior of these heats of stainless steel is a yield strength approaching the ultimate tensile strength, an ultimate tensile strength approaching 800 MPa, a uniform elongation approaching 0.3%, a total elongation approaching 3-9% and a high (about 60%) reduction in area as the neutron damage approaches 10 dpa.

PROGRESS AND STATUS

Introduction

Previous reports and open literature publications[1-4] have dealt in depth with uncertainties in the data base for solution-annealed Type 316L(N) stainless steels, methods for resolving the uncertainties, recommended design correlations for the tensile properties, and recommended material correlations for inclusion in the ITER Material Properties Handbook. Because of the evolving nature of this work and the length of the detailed reports, it is useful to summarize the results. The focus of this effort is the effects of irradiation on the ultimate tensile strength (UTS), the yield strength (YS), the uniform elongation (UE), the total elongation (TE) and the reduction in area (RA) in the ITER-relevant temperature range of 100-400°C.

There are many different grades of 316L(N). The particular grade recommended for ITER design is referred to as Type 316LN-IG and is very close to the SUPER PHENIX heat (SPH) of 316L(N).[5-7] A rather substantial irradiation data base is available for this heat, as well as for other European heats which are close in composition to the SPH heat. However, it is very difficult to determine from the literature the evolution in terminology and chemical composition of the European heats of 316L(N). Experimental samples are referred to as E316 or EC316, E316L, E316LN, E316L(N) and ERH, but the chemistry presented is often not detailed enough -- particularly with regard to the nitrogen content -- to determine whether or not these samples are from the specific SPH heat. With regard to irradiation effects, the distinction is not significant as all of these steels harden in the same manner. For the purposes of this summary, data for European heats of 316 with $0.02 \leq C \leq 0.03$ wt.% and $0.06 \leq N \leq 0.08$ wt.% are referred to as E316L(N) data and grouped together. Data for other heats of 316 have also been collected and are designated as J316 for a particular Japanese heat and US316 for a particular US heat. A Japanese Ti-modified 316 (JPCA) has also been included. These three other heats are not low in carbon (0.05-0.06 wt.%) and have lower nitrogen contents (0 - 0.04 wt.%) than E316L(N). They have been included in this data assessment and correlation development because their behavior under irradiation is indistinguishable from E316L(N). For irradiation and postirradiation-test temperatures in the range of 200-400°C, the common behavior of these heats of stainless steel is a yield strength approaching the ultimate tensile strength, an ultimate tensile strength approaching 800 MPa, a uniform elongation approaching 0.3%, a total elongation approaching 3-9% and a high (about 60%) reduction in area as the neutron damage approaches 10 dpa.

Data are collected for samples with irradiation and postirradiation-test temperatures of 200, 227, 250, 270, 290, 300, 327, 330, 340, and 400°C. As demonstrated by Pawel et al.[8-10], the stress-stain curves for the 200°C and 400°C cases are distinctly different from those in the range of 250-340°C. While the UTS, YS, TE and RA values are similar enough to be grouped together, the UE values are not. In particular, the 200 and 400°C cases exhibit higher UE values. These topics are discussed in some detail in the sections below.

Data Base

Tables 1-4 summarize the tensile data which have been collected for E316L(N) (Table 1), JPCA (Table 2), J316 (Table 3) and US316 (Table 4). Reference numbers are also included in the tables. Reported values for the neutron damage (dpa) and the He content (appm) for experiments vary from pre-test reports to post-test reports to open literature publications. Values for UTS, YS, and UE for the same sample vary from publication to publication. Some of these apparent discrepancies are due to the nature of the engineering stress-strain curve (e.g., near elastic/ perfectly-plastic at 250°C and 5.1 dpa), some are due to the double hump nature of the stress-strain curves for 316 (small peak at about 0.2% plastic strain, followed by a broad peak), some are due to analysts converting to true-stress/true-strain curves before deriving values, and some arise from a confusion in terminology. In the present work, direct interpretation of the engineering stress-strain curves available to this study has been used to derive a consistent set of data from the data base. For cases in which the stress-strain curve is ambiguous, analytical methods, graphical methods and engineering judgment have been used to determine the permanent engineering strain at the onset of necking, which is what the uniform elongation is supposed to represent. These are described below.

For unirradiated material, the engineering stress-strain curves tend to be classical in that there is one broad peak in stress at a large plastic strain. For irradiated material which may exhibit near elastic/perfectly-plastic behavior and/or double-peaked behavior (e.g., sharp peak at about 0.2% plastic strain followed by a broad peak) analytical and graphical onset-of-necking criteria were used to resolve ambiguous values of UE. The onset of necking criterion[1] for stainless steels which exhibit very little strain-rate sensitivity is based on true stress (s_t) and true plastic strain (e_{pt}):

$$(1/e_{pt})\, \partial (\ln s_t)/\partial (\ln e_{pt}) = (1/s_t)(\partial s_t/\partial e_{pt}) = 1 \qquad (1)$$

As the stress-strain data for engineering stress (s) and total engineering strain (e) are in analog form with a particular associated error and digitizing these data points introduces additional error, Eq. 1 was not found to be convenient for the determination of the onset of necking. In addition, for the elastic/perfectly-plastic engineering stress-strain curve, Eq. 1 gives a value of 1 over a broad range of permanent strains. As it can be shown that Eq. 1 reduces approximately to $\partial s/\partial e = 0$ for low strain-hardening materials, it was found to be sufficient within the uncertainty of the data to note graphically where the slope of the engineering stress-strain curve made a transition from positive to zero to negative. In this work, the transition between a zero slope and a negative slope was used to determine the uniform strain at the onset of localized necking. For the double-peaked cases, the first sharp peak was ignored unless the curve at higher strain values was characterized by a negative slope throughout. If the slope of the curve beyond the first peak made transitions from negative to zero to negative or negative to zero to positive to zero to negative, then the last transition from zero to negative was used. The precision of this approach is about ±1% for UE values greater than 2%.

Summary of Correlations for UTS and YS

The UTS and YS data for unirradiated 316L(N)-SPH are used as the basis for deriving the correlations for irradiated material. Temperature independent hardening parameters have been determined for UTS (f_{hu}) and YS (f_{hy}) by examining the normalized increase in UTS and YS for E316L(N) steels as a function of neutron damage (D in dpa). This approach is only approximate as the hardening is, in fact, temperature dependent. However, the temperature dependence for unirradiated and irradiated properties is relatively mild in the range of 200-400°C. The recommended correlations are:

$$UTS = 580\, f_{hu}\, (1.03914 - 2.07760 \times 10^{-3}\, T + 6.15684 \times 10^{-6}\, T^2 - 6.15298 \times 10^{-9}\, T^3) \qquad (2)$$

and

$$YS = 297\, f_{hy}\, (1.04396 - 2.26091 \times 10^{-3}\, T + 3.17660 \times 10^{-6}\, T^2 - 1.50601 \times 10^{-9}\, T^3) \qquad (3)$$

Table 1. Summary of the yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE) and reduction in area (RA) for unirradiated and irradiated, solution annealed E316L(N) austenitic stainless steel. Irradiation temperature equals test temperature (T). Values for UE in parentheses have been taken from tables in the literature. UE values not in parentheses have been determined directly from the stress-strain curves to represent onset of necking.

Material Composition wt.%	Damage dpa	He appm	T °C	YS MPa	UTS MPa	UE %	TE %	RA %	Reactor	Ref.
17.5–Cr	0	0	200	211±17	479±5	(34±3)	47±3	-		11-15
1.8–Mn			227	186±20	478±9	(23±6)	46±2	-		11-15
12.3–Ni			250	200±21	469±9	(31±4)	42±6	79±11		11-15
2.4–Mo			250	289	481	(28.7)	36.5	-		16
0.18–Co			270	272	512	(25.3)	31.9	-		16
0.21–Cu			290	292	523	(27.7)	35.7	-		16
0.43–Si			300	179±3	463±16	(34±2)	46±2	-		11-15
0–Nb			327	164±19	471±17	(23±6)	42±2	68±4		11-15
<0.15–Ta			340	264	523	(25.5)	32.8	-		16
0–Ti			350	155	466±21	(34±2)	44±2	-		11-15
≤0.0023–B			400	173±15	467±21	(33±4)	42±5	74±4		11-15
0.021–C			400	237	488	(24.4)	30.4	-		16
<0.009–S	3.0	69	250	760	764	11.7	18.8	-	HFIR	9,10
<0.029–P				724	735	12.7	20.8	-		9,10
0.06–N	3.1	17.4	250	647	684	9.8	14.5	73	R2	11
				660	693	12.9	18.7	73		11
				664	693	9.8	15.6	72		11
	5.1	140	250	724	724	13	20.4	-	HFIR	16
	6.8	220	270	807	807	6.8	14.6	-		16
	8.2	290	290	827	827	0.23	9.4	-		16
	9.7	380	400	765	772	0.95	7.0	-		16
	9.9	390	340	821	821	0.33	9.3	-		16
	10	140	227	836	844	3.8	12.1	-	HFR	13
			327	804	806	0.5	9.3	-		13
	10.2	103	250	774	774	(0.20)	7.4	72	R2	11
				774	774	(0.10)	6.7	69		11
	10.9	85	250	853	863	0.37	7.1	55	HFR	16
				802	803	0.29	8.7	65		16
				786	793	0.45	7.1	62		16
				779	779	0.20	8.7	67		16
				747	752	0.49	8.7	65		16
				840	843	0.41	7.6	64		16
				837	837	0.20	7.1	56		16
				831	834	0.14	8.0	57		16
				829	829	0.17	8.1	65		16
				819	821	0.14	8.7	60		16

Table 2. Summary of the yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE) and reduction in area (RA) for unirradiated and irradiated, solution annealed Japanese PCA austenitic stainless steel (JPCA). Irradiation temperature equals test temperature (T). Values for UE in parentheses have been taken from tables in the literature. UE values not in parentheses have been determined directly from the stress-strain curves to represent onset of necking.

Material Composition wt.%	Damage dpa	He appm	T °C	YS MPa	UTS MPa	UE %	TE %	RA %	Reactor	Ref.
14.2–Cr	0	0	250	269	483	(32.8)	40.1	-		10
1.8–Mn				207	474	(30.7)	38.5	-		16
15.6–Ni			270	215	479	(30.8)	38.0	-		16
2.3–Mo			340	175	453	(31.5)	38.4	-		16
<0.002–Co			400	169	441	(30.7)	37.4	-		16
0–Cu	3.0	69	250	779	827	3.0	11.8	-	HFIR	9,10
0.50–Si	3.1	17.4	250	648	689	9.6	14.9	74	R2	11
<0.08–Nb				655	696	10.1	15.6	73		11
0–Ta	5.3	210	250	703	724	8.6	15.6	-	HFIR	11
0.24–Ti	6.9	86	200	714	717	8.8	11.3	-	ORR	17,18
≤0.0024–B				696	703	8.5	11.1	-		17,18
0.06–C	7.4	118	330	821	821	(0.23)	2.5	-		17,18
0.005–S				800	807	(0.38)	3.2	-		17,18
0.027–P				876	883	0.3	2.7	-		17,18
0.004–N			400	505	652	(10.5)	12.9	-		17,18
				549	667	(8.5)	10.5	-		17,18
	10.0	530	400	800	807	(1.4)	7.2	-	HFIR	16
	10.2	550	340	807	807	(0.38)	8.3	-		16
	10.2	103	250	827	827	(0.2)	6.4	73	R2	11
				788	788	(0.2)	7.0	73		11
	10.9	85	250	815	831	2.0	8.1	63	HFR	16
				828	834	3.4	9.8	57		16
				857	857	0.20	7.1	67		16
				825	827	0.25	8.7	62		16
				789	804	0.30	8.1	61		16
				822	822	0.20	8.7	63		16
				809	811	2.0	8.7	61		16
				887	890	0.20	6.5	61		16
				849	850	0.26	8.0	62		16
				814	814	3.5	9.8	64		16
	14	1064	300	884	889	(0.5)	8.0	-	HFIR	17-19
	21	1585	400	878	888	(0.38)	6.4	-		17-19
				896	910	(0.44)	6.0	-		17-19
	25	1973	300	770	789	(2.43)	9.9	-		17-19
	27	2008	500	650	732	(4.7)	8.2	-		17-19
				631	724	(7.2)	11.7	-		17-19
	36	2817	400	858	872	(0.55)	5.7	-		17-19
	44	3488	430	742	781	(1.8)	5.0	-		17-19

Table 3. Summary of the yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE), and reduction in area (RA) for irradiated, solution annealed Japanese 316 austenitic stainless steel (J-316). Irradiation temperature equals test temperature (T). Values for UE in parentheses have been taken from tables in the literature. UE values not in parentheses have been determined directly from the stress-strain curves to represent onset of necking. All data are from References 8-10.

Material Composition wt.%	Damage dpa	He appm	T °C	YS MPa	UTS MPa	UE %	TE %	Reactor
16.7–Cr	0	0	200	254	492	(32)	36	-
1.8–Mn				263	503	(31)	35	-
13.5–Ni			330	230	484	(29)	31	-
2.46–Mo				262	508	(28)	35	-
0.61–Si			400	252	476	(26)	28	-
0.005–Ti				222	476	(33)	35	-
0.058–C	6.9	75	200	758	765	13.6	16	ORR
0.003–S				733	737	12	15	
0.028–P	7.4	102	330	848	855	0.3	3.1	ORR
				869	869	0.3	2.9	
			400	595	677	5.1	7.0	
				650	717	4.9	6.8	
	19	225	330	903	913	0.4	3.1	ORR/
				909	921	0.4	3.1	HFIR

where UTS and YS are in MPa and T is in °C.

Recommended correlations for f_{hu} and f_{hy} are

$$f_{hu} = (1 + 0.3830\, D^{0.2725}) \qquad (4)$$

and

$$f_{hy} = (1 + 2.119\, D^{0.1703}) \qquad (5)$$

Figures 1 (a) and (b) are trend curves which show the correlation-predicted values vs. dpa at 250°C and all the data collected in the irradiation/test temperature range of 200-400°C. The irradiation hardening factors give good agreement with the UTS and YS data for E316L(N) steel irradiated to 3.0-10.9 dpa at 227-400°C. The predicted results are also in agreement with data for the other steels considered for fluences up to 21 dpa and temperatures as low as 200°C.

Summary of Correlation for UE

From the data in Tables 1-3 it is clear that the 200°C and 400°C data for these three steels exhibit higher uniform elongation than the 227-340°C data. For the low-ductility temperature range, there is a transition between high UE (~10%) and low UE (~0.3%) at a damage level of about 7 dpa. This transition is subtle as it may occur as a result of a slight shift from positive to near zero to negative slope of the stress-strain curves beyond the first sharp peak. The recommended correlation for the uniform elongation (UE in %) of E316L(N), J316 and JPCA steels in the temperature range of 227-340°C is

$$UE = 45.24\, f_{hue}\, (1.08089 - 3.48419 \times 10^{-3}\, T + 1.01876 \times 10^{-5}\, T^2 - 9.75233 \times 10^{-9}\, T^3) \qquad (6)$$

where

$$f_{hue} = 0.311\, [1 + 2.22 \exp(-0.9\, D)] \qquad \text{for } 0 \le D < 7 \text{ dpa}$$
$$f_{hue} = 0.0096 \qquad \text{for } D \ge 7 \text{ dpa} \qquad (7)$$

Table 4. Summary of the yield strength (YS), ultimate tensile strength (UTS), uniform elongation (UE), total elongation (TE) and reduction in area (RA) for irradiated, solution annealed US 316 austenitic stainless steel (US-316). Double temperatures are test/irradiation. Values for UE in parentheses have been taken from tables in the literature. All data are from Reference 17.

Material Components wt.%	Damage dpa	He appm	T °C	YS MPa	UTS MPa	UE %	TE %	Reactor
17.8% Cr	8.4	<1	700/710	145	235	(6.5)	7.7	EBR–II
1.72% Mn	9.7	<1	430	605	661	(4.8)	8.0	
13.6% Ni			480/430	605	656	(4.9)	8.0	
2.35% Mo	12	<1	430/400	605	681	(6.9)	9.1	
0.2% Cu			700/710	130	235	(6.0)	6.8	
0.38% Si	13	<1	430/410	679	707	(1.7)	5.0	
0.052% C			430	641	696	(3.1)	6.3	
0.02% S			480/430	607	640	(2.2)	5.1	
0.012%			540/480	308	493	(12.8)	14.0	
0.041% N	17	<5	430/400	758	773	(1.1)	4.2	
	18	<5	430/390	748	756	(0.9)	3.9	
	19	<5	650/670	269	331	(2.8)	3.1	
	23	<5	650/670	288	341	(1.9)	2.1	

Equation 6 is based on the UE data for unirradiated 316L(N)-SPH steel. The irradiation hardening factor (Eq. 7) is based on the behavior of irradiated E316L(N), J316 and JPCA in the temperature range of 227-340°C. It is more of an intuitive fit than a best fit. The nature of the data base is a drop of a factor of about 3 in UE from 0 to 3 dpa with no intermediate data, a near constant UE value of about 11% from 3.0-5.3 dpa and a sharp decrease in UE between 6.9 and 8.2 dpa. This transition is assumed to occur at 7 dpa in Eq. 7. Also, the value of 0.3% UE for $D \geq 7$ dpa represents the average of the E316L(N) data and most of the data for J316 and JPCA.

Equation 6 has been evaluated at 250°C and the combined Eqs. 6 and 7 have been evaluated and compared in Fig. 1 (c) to the data in Tables 1-3. The same type of fit could be used for the 400°C data with the transition between high and low UE occurring more gradually with dpa and at a slightly higher damage level. The data base is not complete enough in the range of 7.4-21 dpa to allow this transition to be determined with reasonable confidence. From a design point of view, Eq. 7 should represent a reasonable description of ITER-grade 316L(N) in the temperature range of 227-340°C and a lower bound for higher and lower temperatures.

Summary of Correlation for Total Elongation

The total elongation (TE in %) of irradiated 316 steel is much less temperature sensitive than the uniform elongation. Based on the unirradiated data for 316L(N)-SPH steel, the temperature dependence is taken as:

$$TE = 66.238\, f_{hte}\, (1.05383 - 2.80202\times10^{-3}\, T + 5.59853\times10^{-6}\, T^2 - 3.09260\times10^{-9}\, T^3) \qquad (8)$$

The hardening parameter is determined based on all of the TE data in Tables 1-3 to be

$$f_{hte} = 1 - 0.29593\, D + 3.9148\times10^{-2}\, D^2 - 2.2082\times10^{-3}\, D^3 + 4.3795\times10^{-5}\, D^4 \qquad (9)$$

Figure 1 (d) shows a comparison between the recommended correlation evaluated at 250°C and the TE data for E316L(N), J316 and JPCA vs. neutron damage in the temperature range of 200-400°C. The correlation represents a best fit to the combined data sets.

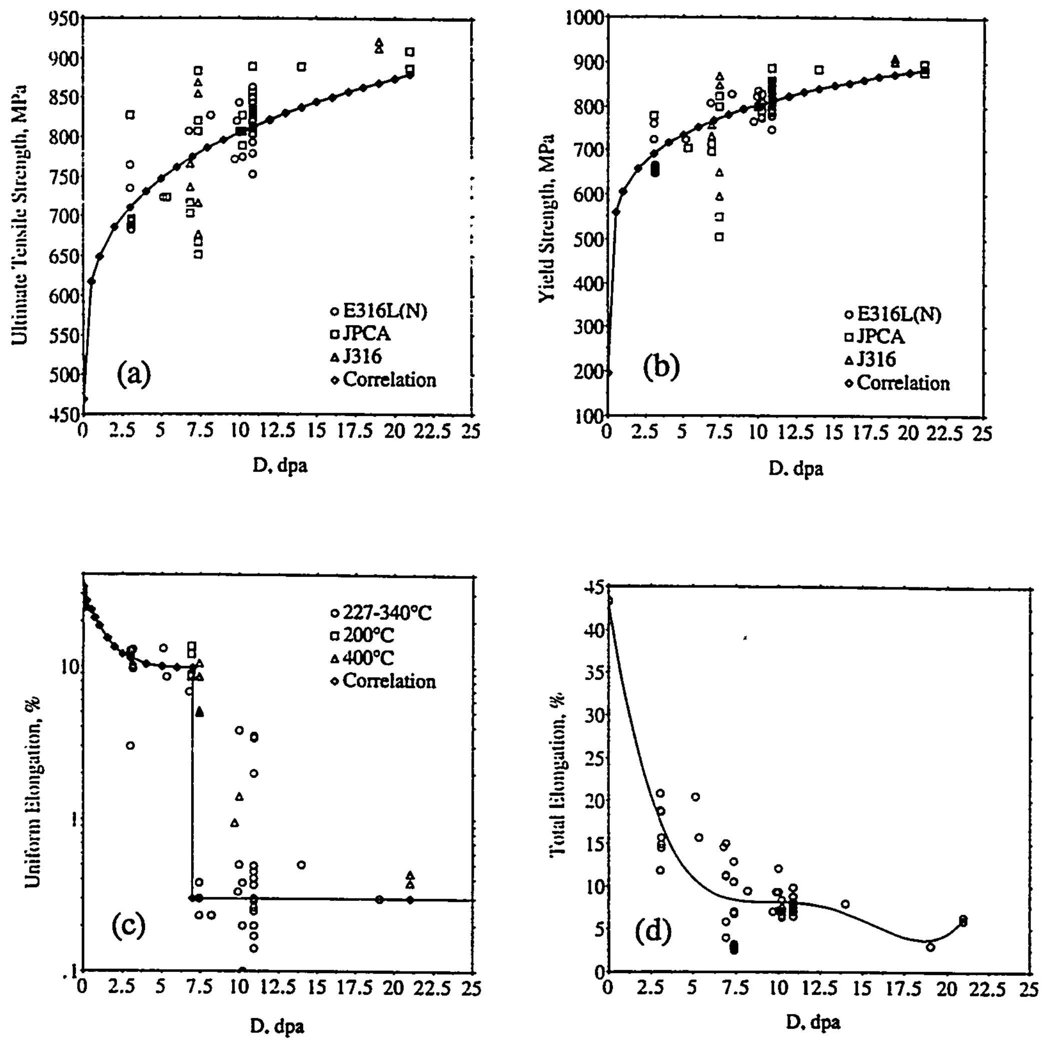

Figure 1. Comparison of correlation values at 250°C of E316L(N) vs. neutron damage (D) in dpa with the data for E316L(N), JPCA, and J316 irradiated at 200-400°C. Test temperature equals irradiation temperature. (a) ultimate tensile strength; (b) yield strength; (c) uniform elongation; (d) total elongation.

Summary of Correlation for Reduction in Area

The recommended reduction in area (RA in %) correlation is based on the correlation for unirradiated 316L(N)-SPH and the data for irradiated E316L(N) and JPCA (see Fig. 2). The irradiation data base includes irradiation/test temperatures of only 250°C and neutron damage levels of 0-10.9 dpa:

$$RA = 94.82\, f_{hra}\, (1.02111 - 1.07266\times10^{-3}\, T + 8.61609\times10^{-7}\, T^2) \tag{10}$$

$$f_{hra} = 1 - 1.597\times10^{-2}\, D \tag{11}$$

The variation in reduction in area with neutron damage level is small at 250°C relative to the other tensile properties. Although no data have been found for samples irradiated/tested at higher or lower temperatures, it is recommended that Eq. 11 be used for the full ITER temperature range of 100-400°C.

Discussion

The correlations for UTS, YS, UE, TE and RA presented in this summary are expressed in a format which is convenient for design criteria analysis. The numerical constant in front of the parenthesis represents the room temperature (20°C) value and the temperature-dependent term in parentheses is normalized to one at 20°C. The standard practice in determining design values for these parameters is to decrease the room temperature value from the average given in the recommended materials correlations to the minimum measured value. The normalized temperature dependence, based on the average of the data, is also used. Thus, for design criteria applications, only the factor in front of Eqs. 2, 3, 6, 8 and 10 needs to be lowered to represent the lower bound of the room temperature values.

While it is difficult to put absolute uncertainty values on the operating conditions and the tensile test parameters for the solution-annealed Type 316 stainless steel data base, several estimates can be made. The neutron damage levels and helium generation listed for each data point in Tables 1-4 are calculated quantities. The accuracy of the calculated results depends on the uncertainties associated with neutron cross-sections, method of analysis, and the details of the neutron flux spectrum for the sample position in the reactor. Based on variations in reported values for the same test specimen, the estimated uncertainty in reported values is about 10%. This order of uncertainty is not large enough to merit a detailed review of the data base to fine tune the reported values of dpa and appm He. The question of the number of data points is an interesting one. In many publications, data are summarized according to temperature, dpa, appm He, UTS, YS, UE and TE. A cross-check for cases in which the sample number is given indicates that the reader cannot determine the number of data points from such summary tables because there is no unique correlation between reported values of dpa, appm He, UTS, YS, UE and TE for an individual sample. With regard to the accuracy of reported tensile properties, two factors are taken into account. The first is the accuracy of the tensile test measurements. The second is a kind of "precision" related to the results of more than one experimenter analyzing the same stress-strain curve. The best consistency and accuracy is in the reported values for TE and RA. The next best consistency and accuracy is in the reported values for UTS. Even for near elastic/perfectly-plastic stress strain curves, the reported values for UTS for the same sample and the spread in the data for a number of samples tested under identical conditions vary by less than 5%. More uncertainty is associated with reported values for YS. Because of the uncertainty in determining the 0.2% off-set stress from the stress strain curves and because of the nature of 316SS which may exhibit an upper and lower yield strength, reported values can vary by as much as ±25%, even though the spread in the data reported by an individual experimenter may be less than 5%. Some of this variation may be due to heat-to-heat variations in chemistry. For example, the JRC heat of E316L(N) reported in Ref. 16 has unirradiated yield strength values which are about 50% higher than the average values reported for the SPH heat. By far, the highest uncertainty is associated with the determination of UE, particularly as the steels harden and lose their work hardening capability. The variation in reported values can span one to two orders of magnitude. This problem in interpretation has been resolved for most of the E316L(N), J316 and JPCA by re-analyzing the engineering stress-strain curves in a consistent manner.

The importance of the accuracy of the data and correlations for the tensile properties varies from property to property. Both the ultimate tensile strength and the yield strength are used to derive design correlations (see Ref. 3), which are then used to determine allowable stress or stress intensity (S_m) values. Confidence in the S_m values increases with the number of data points more than with the

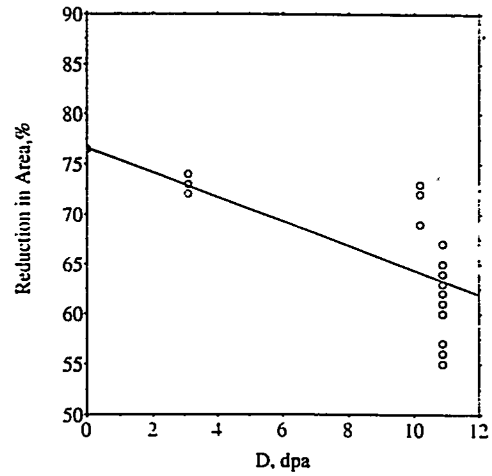

Figure 2. Comparison between the recommended reduction in area (RA) correlation for E316L(N) and the data for E316L(N) and JPCA irradiated and tested at 250°C.

accuracy/precision of individual data points. The uniform elongation is used to classify structural materials (ductile vs. semi-brittle vs. brittle) and to scale certain design limit parameters in the event that a full data set is not available. For stainless steel classification purposes, ductile corresponds to UE ≥ 5%, semi-brittle corresponds to 1 < UE < 5% and brittle corresponds to UE ≤ 1%. In this sense, a high degree of accuracy/precision is not required. Scaling of irradiated/unirradiated UE values is often used when the irradiation data base for certain design limit parameters (e.g., fracture toughness[4]) is incomplete. In the context of the current ITER Interim Structural Design Criteria Guidelines, UE values greater than 1% will result in no additional limit beyond those imposed by parameters for unirradiated material, while UE less than 1% will. In this sense, it matters more whether UE is less than 1% than whether UE = 10 or 13% . Thus, more important to the designer than a very accurate correlation for UE is a map of irradiation temperature and neutron damage level for which UE = 1% (see Fig. 4 of Ref. 9 for a sample plot). The total elongation at room temperature is part of manufacturers' specifications and design code description of materials. As it is dependent on the geometry of the gauge section, it is not really a material property. However, it is sometimes used in design criteria in place of the reduction in area, which is more of a material property. The reason for this is that TE is routinely and easily measured whereas RA is not. The reduction in area can be converted to a true or engineering local failure strain. The ratio of irradiated-to-unirradiated local failure strain (to a power between 1 and 2) is used to scale low-cycle fatigue damage. This is often done if the fatigue data base for irradiated materials is insufficient. While it is certainly important in design guidelines, the data for E316L(N) and JPCA at 250°C and up to 11 dpa indicate very little reduction in RA with neutron damage. Based on average RA values, the fatigue life of 10 dpa steel is predicted to be only 30% less than the fatigue life of unirradiated steel. This is consistent with 227, 327 and 427°C data at 10 dpa which imply an average reduction of only 17%. These small reductions are lost in the very conservative design code practices with regard to fatigue rules.

The focus of this summary is the tensile-test data base for ITER-relevant stainless steels. For mechanistic interpretations of the performance of these steels, the reader is referred to Refs. 4 and 9. With the exception of uniform elongation, the determination of the other tensile properties (UTS, YS, TE and RA) is relatively straightforward. In the case of UE, there is still some question as to how to interpret the zero-slope region of the engineering stress-strain curves, as this region can span about 10% plastic strain. Such behavior may be indicative of diffuse necking followed by localized necking to failure. This issue could be resolved by measuring the reduction in area of the tensile specimens as a function of axial position. Until such measurements are performed, there remains some uncertainty in the interpretation of such regions and the resulting values for UE.

With regard to extrapolating the recommended correlations, which are based on fission-reactor data, to ITER fusion spectra, no indication was found in this study that transmutation helium influences the results in the temperature range of 200-400°C. However, other transmutations which may occur in thermal and mixed neutron spectra, but not in fusion spectra, may influence the hardening. This subject is beyond the scope of the current work.

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