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Initial Assessments of Notch Ductility Behavior of A533 Pressure Vessel Steel with Neutron Irradiation

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ABSTRACT

Exploratory assessments have been made of the Charpy-V notch ductility characteristics of heavy section A533-B and A533-C steel plate and submerged arc weldments following neutron irradiation at 550°F. The experimental evaluations were performed largely with commercial production materials and included comparisons of materials in both Class 1 and Class 2 strength ranges. Postirradiation notch ductility properties of one 5-3/4-in. A533-B Class 1 electroslag weldment were also developed. Assessments made of relative irradiation performance were assisted by a compilation of recent information on the response of the ASTM reference A302-B steel plate.

Major research findings include the observation of significant variability in radiation embrittlement sensitivity of A533-B and A533-C steel wherein the sensitivity level of plate and weld metal in some cases exceeded that of the ASTM reference plate. High radiation embrittlement sensitivity was noted for both submerged arc weld deposits examined; however, the data suggest that the performance of the weld-heat-affected zone parallels that of the parent plate. High embrittlement sensitivity was also noted for the electroslag weld deposit, in contrast to markedly low sensitivity of the weldment parent plate.

The notch ductility behavior of A533 plate and weld metal under 550°F irradiation was not found measurably influenced by either the strength class (Class 1 or 2) or by the particular grade of steel (Grade B or C). Similarly, there were no marked variations in irradiation response through the thickness of plate or weld metals, or between RW (longitudinal) versus WR (transverse) orientations in cross-rolled plate.

In accordance with observations on special laboratory heats of A302-B steel, the study demonstrates that the radiation embrittlement resistance of commercially produced A533 steel plate and weld deposits can be predicted in part from their individual chemical compositions. High copper and phosphorus contents generally signify high sensitivity to 550°F radiation-induced changes in notch ductility characteristics.

PROBLEM STATUS

This is a final report on one phase of the problem; work on other phases continues.

AUTHORIZATION

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INITIAL ASSESSMENTS OF NOTCH DUCTILITY BEHAVIOR OF A533 PRESSURE VESSEL STEEL WITH NEUTRON IRRADIATION

INTRODUCTION

Quenched and tempered ASTM A533-B steel is being widely used in the current construction of nuclear reactor pressure vessels, having supplanted ASTM A302-B steel as the prime candidate for this application. While both are basically manganese-molybdenum compositions, A533-B steel contains a fixed amount of nickel (0.4 to 0.7%) and, by specification, is water quenched rather than accelerated (water spray) cooled from the austenitized condition. The development of properties in heavy-section sizes satisfying the design requirements of vessels for advanced pressurized-water and boiling-water reactors is the general objective of the nickel addition and of the quenching treatment. In further contrast to A302-B steel, the more recent A533-B specification provides for two strength classes (50- and 70-kpsi minimum yield strength). A533-C steel (0.7 to 1.0% nickel) also carries two strength classifications but has yet to receive ASME Code approval for vessel construction. While not required by either steel specification, the vacuum degassing of A533 steel heats destined for reactor pressure vessel construction has now become common mill practice. Electroslag welding is another relatively new shop practice which, in conjunction with submerged arc welding, is being used for current vessel fabrication. Such metallurgical, composition, processing, and fabrication differences can be considered as having the potential for influencing (detrimentally or beneficially) the radiation embrittlement sensitivity of A533-B plate and weldments, as compared to counterpart forms of A302-B steel. The unknown contribution or significance of these individual variations formed one basis for the present study.

Variable radiation embrittlement sensitivity among steel compositions, among different heats of a single composition, and even between different thickness layers of heavy-section plate is well documented (1-4). Furthermore, experimental research aimed specifically at determining the source(s) of such variable sensitivity has made marked progress in a relatively short time (5-7). The continuing success of such research should ultimately provide all necessary guidelines for minimizing (or eliminating) variable radiation embrittlement sensitivity in individual steel compositions. However, the immediate needs of industry dictate that a research effort be advanced on A533 steel equivalent to the previous effort which established the basic performance trends and performance variations of A302-B steel. In particular, the relative radiation embrittlement sensitivity of A533 steel compared to the ASTM reference (8)* A302-B steel heat is of general interest to the nuclear power industry.

This report summarizes the results of initial exploratory studies by NRL on the notch ductility performance of irradiated A533-B and A533-C plate and weldments. The experimental results presented include through-thickness determinations of radiation embrittlement sensitivity of heavy section plate and postirradiation assessments of base plate versus weld deposit properties of submerged arc and electroslag weldments. The results of a limited investigation of weld heat-affected zone (HAZ) performance versus base plate behavior are also presented for one submerged arc weldment. More recent information developed on the notch ductility behavior of the ASTM A302-B reference plate (8) are also compiled, including an assessment of directional plate behavior in the postirradiation condition.

*6-inch A302-B steel plate donated to ASTM by the U.S. Steel Corporation; plate specifications outlined in Ref. 8.

MATERIALS

Table 1 identifies the individual plates and weldments included in the exploratory program. With the exception of the A533-C Class 2 submerged arc weldment and the A533-B Class 1 electroslag weldment, all materials were produced commercially and thus are fully representative of normal shop melting and fabrication practices. The chemical composition of the ASTM reference A302-B steel plate has been included in Table 1 for subsequent behavior comparisons. The strength and heat treatment conditions of the respective plates and weldments are given in Table 2.

Preirradiation notch ductility properties of plate and weld deposits are summarized in Table 3. Unless indicated otherwise, Charpy V-notch specimens were taken from the quarter-thickness regions of plate and weld metal with the notch oriented perpendicular to the plate or weldment surface. The longitudinal (RW) orientation was taken as standard for plate specimens; weld metal and weld HAZ specimens were oriented with their long axes perpendicular to the welding direction. The HAZ specimen notches were centered on the weld fusion line, as revealed by conventional metallographic practices. In a limited number of cases the preirradiation nil-ductility transition (NDT) temperature was determined by ASTM Method E208-66T, using Type P-3 drop weight specimens. The specimen surface which received the crack-starter weld bead corresponded to the plane of the thickness layer under test. The data correlations in Table 3 suggest that the Charpy-V 30 ft-lb transition temperature may not always be a conservative index of the NDT of A533-B steel plate. In terms of fracture safety, a requirement of 30 ft-lb at 10°F is not considered sufficient to guarantee that NDT plus 60°F (Fracture Transition Elastic) will not exceed room temperature in every case. For example, the 8-1/8-in. production plate satisfies the 30 ft-lb/10°F criterion but also features an NDT temperature of 50°F. Pending the accumulation of additional Charpy-V/NDT correlations, however, radiation-induced transition temperature increases in this report will be based on the conventional A302-B index of 30 ft-lb. It will be noted that the choice of energy index in the range of 30 to 60 ft-lb in most cases would not markedly alter given transition temperature increase values.

IRRADIATIONS

Material irradiations were performed in the Union Carbide Research Reactor (UCRR), Tuxedo, New York, and in the Low Intensity Test Reactor (LITR) at the Oak Ridge National Laboratory. Equipment and techniques developed by NRL for controlled-temperature specimen irradiations have been described in detail elsewhere (9-11).

Neutron fluence values ($n/cm^2 > 1$ MeV) in this report are based on an assumed fission spectrum distribution of neutrons indexed by results of analyses of iron neutron detector wires included in each exposure assembly. A fission-averaged cross section of 68 mb was used for the $Fe^{54}(n,p)Mn^{54}$ reaction. Techniques for converting fluence values based on an assumed fission spectrum distribution to values representing calculated spectra have been outlined previously (3,12).

EXPERIMENTAL RESULTS AND OBSERVATIONS

Plate Investigations

Irradiation data developed for prime plate and for base plate from those heavy-section weldments evaluated are summarized in Table 4. In the generation of these data, maximum use was made of simultaneous irradiation procedures wherein two or more materials were exposed within a single in-reactor assembly. Thus, direct comparisons of irradiation performance were possible through identical exposure histories.

Table 1
Chemical Composition of Plate and Weldments

Material Identification				Chemical Composition (wt-%)*										
Type	Thickness (in.)	Source		C	Mn	P	S	Si	Ni	Cr	Mo	Cu	V	Al
Plate														
A533-B Class 1	4†	Lukens Steel Co.		0.21	1.40	0.010	-	0.25	0.50	-	0.45	0.15	-	0.048
				0.20	1.33	0.009	0.022	0.20	0.52	0.16	0.42	0.14	-	0.03
	8†	Lukens Steel Co.		0.19	1.37	0.012	0.011	0.25	0.52	-	0.45	-	-	-
				0.20	1.32	0.010	0.023	0.21	0.52	0.15	0.42	0.14	-	0.05
	8-1/8	Babcock and Wilcox Co.		0.21	1.36	0.007	0.018	0.26	0.49	-	0.47	-	-	-
				0.21	1.21	0.010	0.017	0.26	0.47	0.19	0.50	0.19	-	-
	6-3/8‡	Vender§		0.20	1.39	0.011	0.013	0.20	0.53	0.09	0.48	-	-	0.031
				0.24	1.27	0.008	0.015	0.19	0.53	0.14	0.48	0.09	0.02	-
A533-B Class 2	6-3/8‡	Vender§		0.20	1.39	0.011	0.013	0.20	0.53	0.09	0.48	-	-	0.031
				0.24	1.27	0.008	0.015	0.19	0.53	0.14	0.48	0.09	0.02	-
A302-B (ASTM Reference)	6	U.S. Steel Corp.		0.24	1.34	0.011	0.023	0.23	0.18	0.11	0.51	0.20	-	0.038
				0.23	1.35	0.015	0.021	0.22	0.22	0.12	0.52	0.22	≤0.01	-
Weldment														
A533-B Class 1 (Submerged Arc)	7-1/2	Westinghouse Elec. Corp.	Plate 1	0.20	1.29	0.013	0.022	0.25	0.50	-	0.49	0.14	-	-
				0.27	1.20	0.008	0.015	0.24	0.50	0.08	0.48	0.12	0.02	-
			Plate 2	0.21	1.24	0.011	0.020	0.24	0.53	-	0.48	0.11	-	-
				0.22	1.25	0.008	0.019	0.24	0.51	0.09	0.49	0.11	-	-
			Weld¶	-	-	-	Not Available	-		-	-	-	-	-
				0.17	1.25	0.015	0.011	0.32	0.11	0.16	0.53	0.22	0.03	-
A533-C Class 2 (Submerged Arc)	4	Lukens Steel Co.	Plates 1 and 2	0.19	1.25	0.010	0.013	0.22	0.83	0.07	0.48	0.22	-	0.021
				0.24	1.05	0.006	0.018	0.21	0.78	0.06	0.48	0.20	0.02	-
			Weld¶	0.08	1.84	0.013	0.009	0.37	0.10	0.07	0.51	0.30	-	-
				0.13	1.68	0.016	0.015	0.33	0.14	0.05	0.48	0.27	0.02	-
A533-B Class 1 (Electroslag)	5-3/4	Babcock and Wilcox Co.	Plates 1 and 2	-	-	-	Not Available	-		-	-	-	-	-
				0.22	1.19	0.008	0.018	0.16	0.52	0.14	0.48	0.12	0.03	-
			Weld¶	0.18	1.37	0.014	0.016	0.12	0.36	0.08	0.49	0.21	-	-
				0.22	1.28	0.008	0.014	0.10	0.40	0.14	0.48	0.19	0.03	-

*First number - courtesy of supplier.
Second number - NRL determination.
†Both plates from same steel heat.
‡Both plates from same steel heat.
§Purchased from Lukens Steel Company.
¶As-deposited weld chemistry.

Table 2
Preirradiation Tensile Properties and Heat Treatment Condition of Plate and Weldments

Material Identification			Yield Strength* (0.2% Offset) (ksi)	Tensile† Strength (ksi)	Heat Treatment
Type	Thickness (in.)				
Plate					
A533-B Class 1	4		70.6 -	92.7 -	Austenitized at 1650°F for 4 hr, water dip quenched; tempered at 1250°F for 10 hr, furnace cooled; stress relief annealed at 1150°F for 20 hr, furnace cooled.
	8		75.0 -	89.6 -	Austenitized at 1650°F for 8 hr, water dip quenched; tempered at 1250°F for 10 hr, furnace cooled; reaustenitized at 1550°F for 8 hrs, water spray quenched; tempered at 1260°F for 8 hr, air cooled; stress relief annealed at 1150°F for 20 hr, furnace cooled.
	8-1/8		65.2† 70.9‡	89.5† 93.8‡	Austenitized at 1750-1800°F for 8-1/2 hr, brine quenched; tempered at 1200-1220°F for 8-1/2 hr, water quenched; stress relief annealed at 1115°F for 30 hr, furnace cooled at 50°F/hr (max.).
	6-3/8		- 69.1	- 89.1	Full thickness section of 6-3/8-in. A533-B Class 2 plate (below), retempered at 1225°F for 6-1/2 hr, furnace cooled to below 600°F.
A533-B Class 2	6-3/8		80.3 79.3	99.7 97.7	Austenitized at 1670-1685°F for 6-1/2 hr, water dip quenched; reaustenitized at 1650-1660°F for 6-1/2 hr, water dip quenched; tempered at 1115-1125°F for 6-1/2 hr, air cooled.
A302-B (ASTM Reference)	6		- 65.5†	- 87.9†	Austenitized at 1650°F for 2 hr, water quenched; tempered at 1200°F for 6 hr, furnace cooled to below 600°F.
Weldment					
A533-B Class 1 (Submerged Arc)	7-1/2	Plate	- 63.8‡	- 84.9‡	Plate: Austenitized at 1550-1650°F for 4 hr, dip quenched in agitated water; tempered at 1225 ± 25°F for 4 hr, furnace cooled.
		Weld	- -	- -	Post Weld: Stress relief annealed at 1150° ± 25°F for 8 hr, furnace cooled; reannealed at 1150° ± 25°F for 16 hr, furnace cooled at 50°F/hr (max.).
A533-C Class 2 (Submerged Arc)	4	Plate	83.2 -	98.0 -	Plate: Austenitized at 1650°F, water quenched; tempered at 1225°F, air cooled.
		Weld	79.1 -	90.7 -	Post Weld: Stress relief annealed at 1125°F for 20 hr, furnace cooled.
A533-B Class 1 (Electroslag)	5-3/4	Plate	- -	- -	Post Weld: Austenitized at 1675-1725°F for 6 hr, brine quenched; reaustenitized at 1600-1650°F for 6 hr, brine quenched; tempered at 1200-1225°F for 6 hr, brine quenched; stress relief annealed at 1115-1135°F for 30 hr, furnace cooled at 40°F/hr (max.)
		Weld	73.5 -	91.8 -	

*First number – courtesy of supplier, 0.505-in. diameter specimen.
Second number – NRL determination, 0.252-in. diameter specimen.

†Before stress relief anneal.

‡After stress relief anneal.

Table 3
Preirradiation Notch Ductility Properties of Plate and Weldments

Material Identification		Thickness Layer	C_V 30 ft-lb Transition (°F)	C_V Full Shear Energy Absorption (ft-lb)	NDT (°F)	Approximate C_V Energy Level at NDT (ft-lb)
Type	Thickness (in.)					
Plate						
A533-B Class 1	4	S	-120	100	-115*	35
		Q	-25	≥100	±0*	45
		H	-10	100	±0*	35
	8	S	-35	≥100	-40*	28
		Q	-10	116	-10*	32
		H	-10	116	-10*	32
	8-1/8	S	±0	103	+40	51
		Q	+10	101	+50	46
		Q(T)	+35	89	-	-
	6-3/8	Q	-50	137	-20	55
A533-B Class 2	6-3/8	S	-120	113	-40	62
		Q	-75	120	+20	85
		H	-60	102	±0	62
A302-B (ASTM Reference)	6	Q (Sections 1,2)	+30	78	+10	24
		Q (Section 3)	+15	81	+10	28
Weldment						
A533-B Class 1 (Submerged Arc)	7-1/2	Plate 1 Q	-40	136	-	-
		Plate 2	-10	126	-	-
		Weld	-60	109	-	-
		HAZ	-115	≈136	-	-
A533-C Class 2 (Submerged Arc)	4	Plate S (Face)	-130	100	-	-
		S (Root)	-60	96	-	-
		Q	-50	108	-	-
		H	-50	108	-	-
		Weld Face	≈-20*	>45*	-	-
		Q, H	-40	86	-	-
		Root*	-50	≥80*	-	-
A533-B Class 1 (Electroslag)	5-3/4	Plate S,Q,H	-60	148	-	-
		Weld S	+15	82	+20	32
		Q	+15	82	-	-
		H	+15	82	+40	45

*Courtesy of Lukens Steel Corporation.

Table 4
Postirradiation Notch Ductility Properties of Plate and Weldments

Material Identification		Neutron Fluence (n/cm^2 · 1 MeV)	Thickness Layer	C_v 30-ft-lb Transition Temperature (°F)			Approximate Postirradiation C_v Full Shear Energy Absorption (ft-lb)
Type	Thickness (in.)			Initial	Irradiated	ΔT	
Plate							
A533-B Class 1	4	2.3×10^{19}	S	-120	5	125	75
			Q	-25	95	120	77
			H	-10	110	120	75
	8	2.3×10^{19}	S	-35	45	80	90
			Q	-10	85	95	98
			H	-10	85	95	98
	8-1/8	0.5×10^{19}	Q	+10	150	140	96
		1.7×10^{19}	Q	+10	200	190	86
		1.7×10^{19}	Q(T)	+35	-	-	74
	6-3/8	0.2×10^{19}	Q	-50	-50	0	137
		2.0×10^{19}	Q	-50	30	80	130
		2.0×10^{19}	Q(T)	-50	40	90	75
A533-B Class 2	6-3/8	0.5×10^{19}	Q	-75	-40	35	
		2.0×10^{19}	Q	-75	0	75	70
		2.0×10^{19}	S	-120	-55	65	84
		2.0×10^{19}	H	-60	0	60	85
A302-B (ASTM Reference)	6	0.2×10^{19}	Q	+20	70	50	81
		1.1×10^{19}		+30	170	140	69
		1.5×10^{19}		+30	185	155	57
		1.7×10^{19}		+30	170	140	55
		2.1×10^{19}		+15	165	140	60
		2.3×10^{19}		+30	190	160	69
		3.0×10^{19}		+15	170	155	65
		3.1×10^{19}		+30	190	160	60
		3.1×10^{19}		+30	200	170	60
		3.1×10^{19}		+30	185	155	63
		3.4×10^{19}		+30	210	180	64
		4.8×10^{19}		+15	210	195	64
		4.1×10^{19}	(650°F exposure)	+15	105	90	65
		5.1×10^{19}	(740°F exposure)	+15	80	65	75
Weldment							
A533-B Class 1 (Submerged Arc)	7-1/2	1.7×10^{19}	Plate 1 Q	-40	30	70	100
			Plate 2 Q	-10	75	85	121
			Weld- Q	-60	140	200	63
			(40 ft-lb index)	+5	165	160	
			HAZ Q	-115	-45 (min.)	70	
					+30 (max.)	145	80
A533-C Class 2 (Submerged Arc)	4	1.4×10^{19}	Plate Q	-50	130	180	96
			Weld Q,H	-40	165	205	59
A533-B Class 1 (Electroslag)	5-3/4		Plate Q	-60	-10	50	115
		1.8×10^{19}	Weld Q,H	+15	180	165	79

Figures 1, 2, and 3 illustrate some of the more significant observations concerning the general performance of A533-B steel. In Figs. 1 and 2, the data suggest that neither plate thickness (4 in. versus 8 in.) nor plate strength level (Class 1 versus Class 2) have an appreciable effect on irradiation response in terms of the Charpy-V 30 ft-lb transition temperature increase. Irradiation embrittlement sensitivity of A533-B plate also appears to be relatively independent of test location through the plate thickness, regardless of initial (preirradiation) differences in transition temperature between plate surface, quarter and half-thickness positions. The data in Fig. 2 suggest that properties in the longitudinal (RW-strong) and the transverse (WR-weak) plate test orientations are equally

sensitive to radiation-induced changes. A similar pattern of behavior by the ASTM reference plate is seen in Fig. 4. Figures 2 and 3 also suggest that where heavy cross-rolling is indicated by preirradiation data, irradiation reductions in full shear energy absorption level of A533-B steel in RW and WR orientations will be approximately the same. In the case of the A302-B reference plate, however, the relatively large initial difference (33 ft-lb) in full shear energy level between strong and weak plate orientations was not maintained with 550°F irradiation; rather, a marked reduction in energy absorption level was observed for the strong, but not for the weak orientation in this exposure condition. Data for a low- temperature irradiation of this steel, on the other hand, suggest that, with high fluence at <280°F, the WR orientation energy absorption level is reduced similarly. In view of the significance which can be attached to full shear energy absorption values versus brittle fracture resistance (13,14), investigations are continuing to develop more information on this property change as functions of plate orientation and exposure history (i.e., fluence and service temperature).

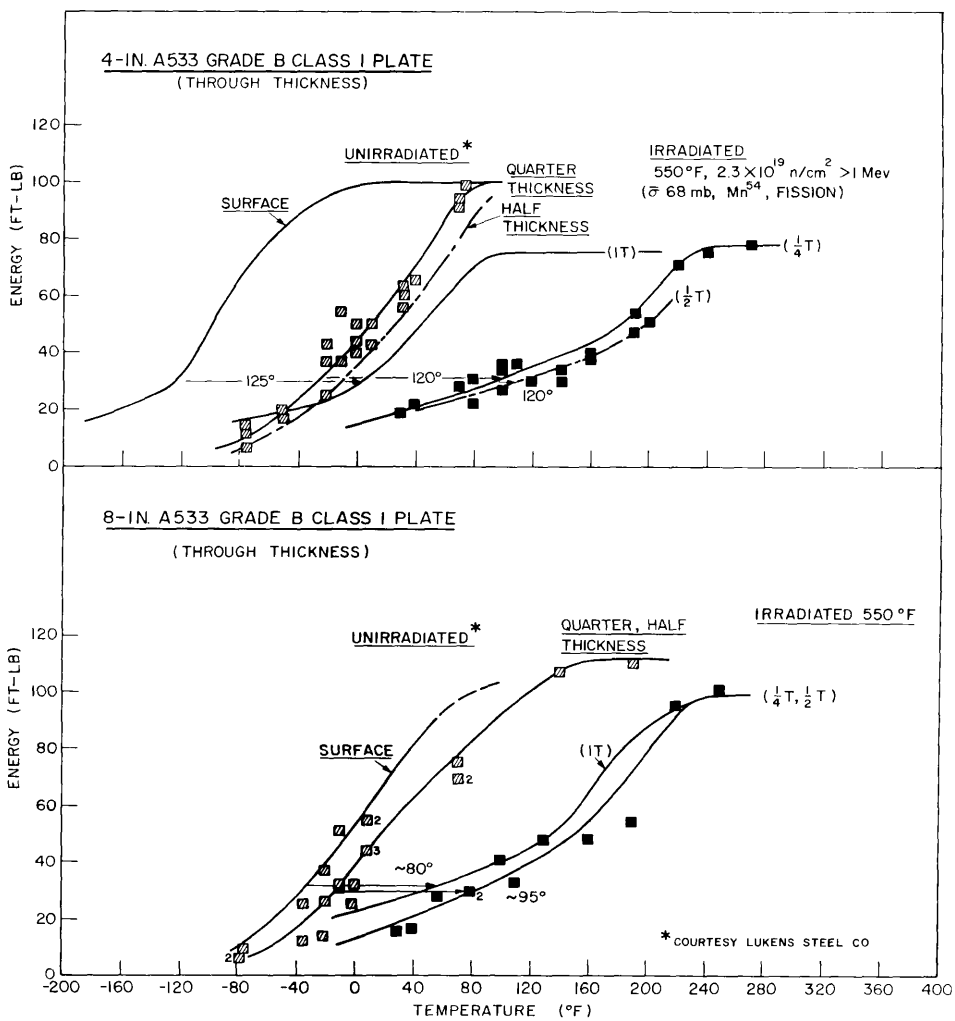

Fig. 1 - Charpy-V notch ductility characteristics of 4-in. and 8-in. A533-B Class 1 steel plates from the same parent heat showing through-thickness response to neutron irradiation at 550°F

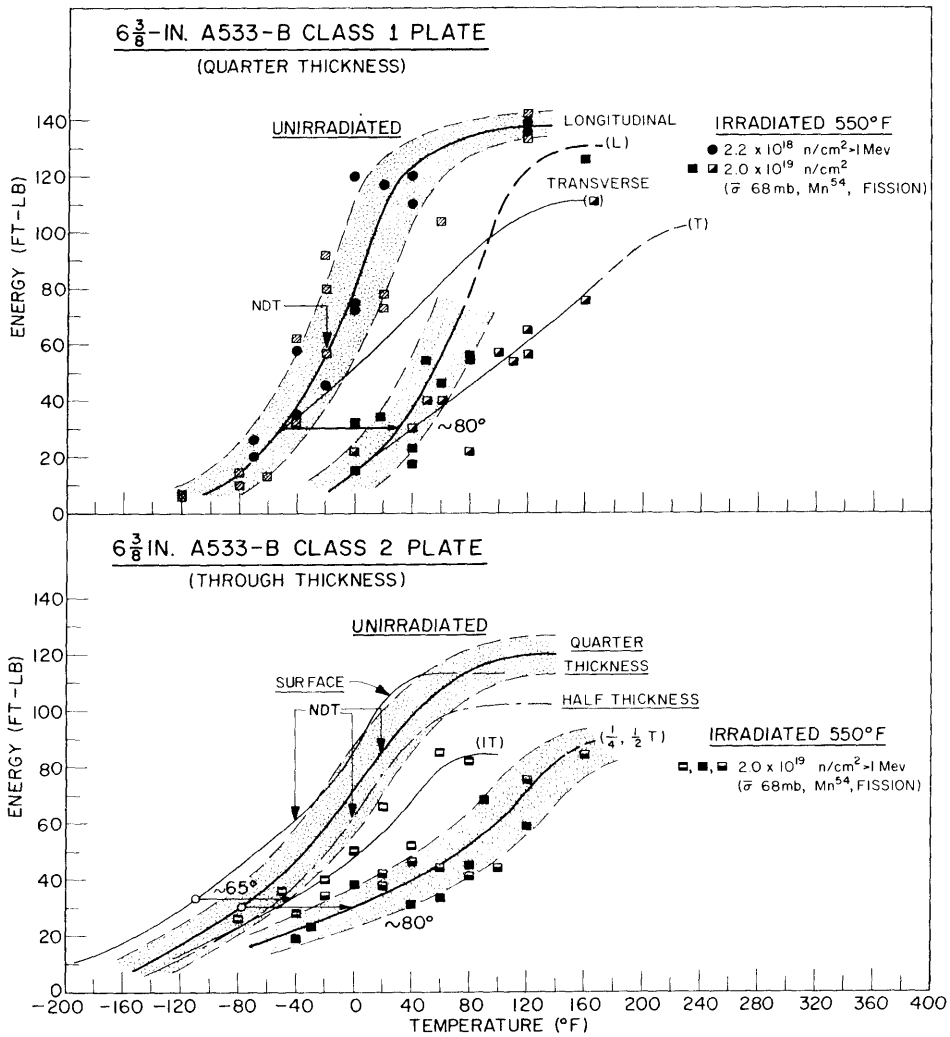

Fig. 2 - Charpy-V notch ductility characteristics of a 6-3/8-in. A533-B steel plate in Class 1 and Class 2 heat treatment conditions before and after irradiation at 550°F. The upper figure presents a comparison of irradiation response in the RW (longitudinal) and WR (transverse) plate orientations. The lower figure illustrates the relative performance of the plate surface, quarter, and half thickness layers with 550°F irradiation.

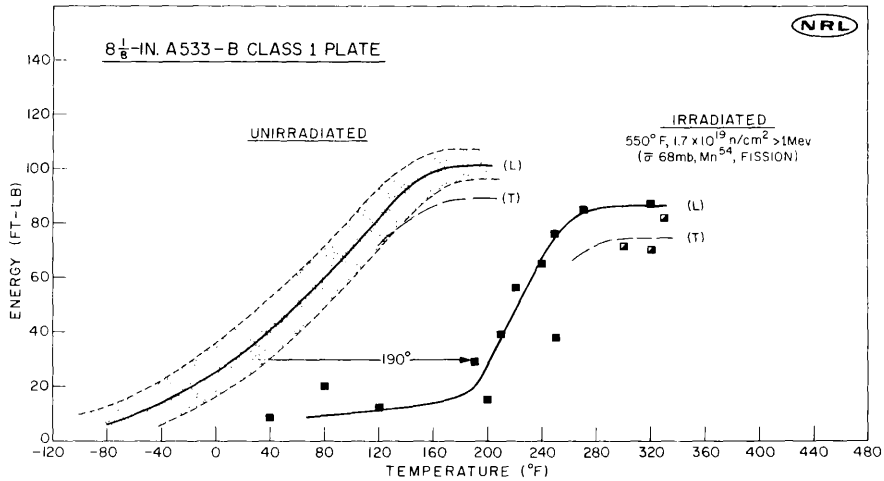

Fig. 3 - Notch ductility behavior of a 8-1/8-in. A533-B Class 1 steel plate with 550° F neutron irradiation depicting the relatively high radiation embrittlement sensitivity of this plate. Results from an exploratory assessment of full shear energy absorption in WR (transverse) versus RW (longitudinal) plate orientations are also shown.

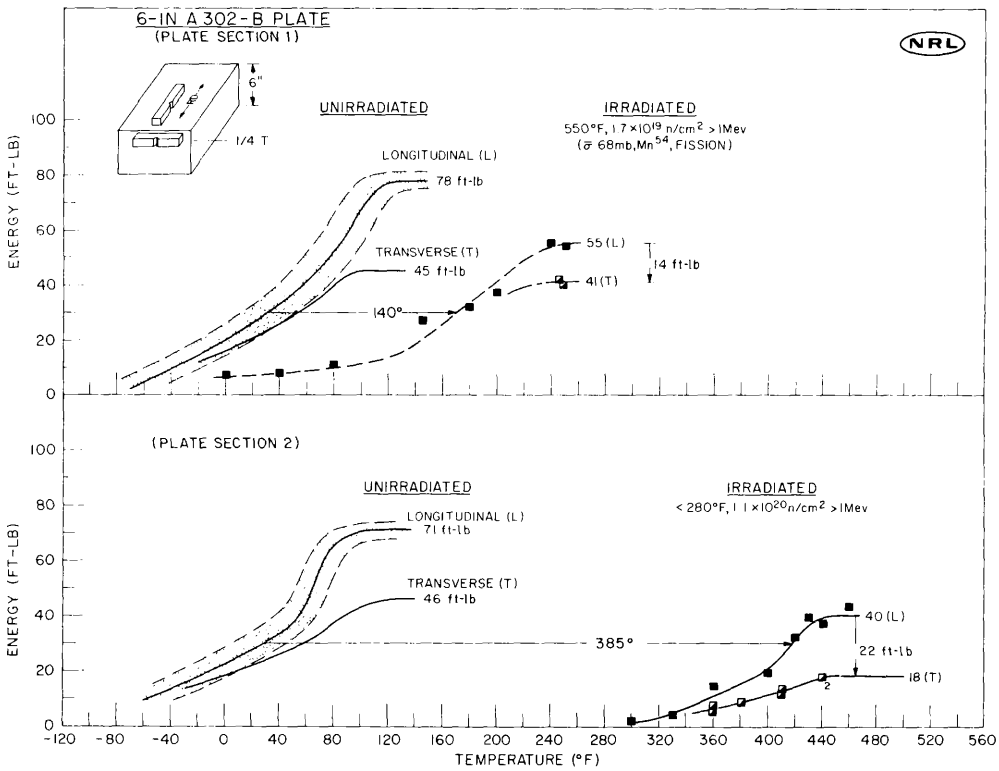

Fig. 4 - Notch ductility performance of the ASTM reference A302-B steel plate in the RW and WR orientations with irradiation exposure at 550 °F and at low (< 280 °F) temperatures

The data presented in Table 4 illustrate the degree of possible variability in radiation embrittlement sensitivity among different heats of A533-B steel. A comparison of Figs. 1 and 2 versus Fig. 3 emphasizes this difference by suggesting as much as a two-fold difference in irradiation response. Comparisons of Figs. 3 and 4 suggest that the 8-1/8-in. A533-B plate may be even more radiation-embrittlement sensitive than the 6-in. ASTM reference A302-B plate. A partial explanation for each of the observed differences will be offered in a later section. The possible saturation of radiation-induced changes in A533 and A302-B steel will also be discussed.

Weldment Investigations

The primary objective of experimental studies of heavy-section weldments was to develop direct comparisons of property changes with irradiation of weld deposit versus base plate, including the weld heat-affected zone (HAZ) for determining the weakest link in welded nuclear structures. Secondary objectives included examination and analysis of expected radiation embrittlement sensitivity differences for their probable cause(s) as potentially related to welding practice (submerged arc versus electroslag), strength level (Class 1 versus Class 2), and base plate grade (Grade B versus Grade C). A summary of information developed by the exploratory irradiation experiments is given in Table 5. Pictorial comparisons of submerged arc deposited weld metal versus plate versus HAZ performance are given by Figs. 5 and 6. Figures 7 and 8 illustrate the relationship of base-plate versus weld metal properties of an A533-C Class 2 submerged arc weldment and of an A533-B Class 1 electroslag weldment, respectively.

Referring to the 7-1/2-in. submerged arc production weldment (Fig. 5), its multipass weld deposit was found to be quite sensitive to 550°F radiation embrittlement. The data depict a 200 degree transition temperature increase (30 ft-lb index) or 160 degree increase (40 ft-lb index) for the weld metal, compared to 70 and 85 degree increases shown for the respective base plates. The loss in full shear energy absorption by the weld metal was also much more severe than that of either parent plate. As illustrated in Fig. 6, HAZ properties were generally superior to those of base plate (and of weld metal). After irradiation, this performance relationship appeared to be unchanged. At the minimum, properties of the HAZ were equal to base plate properties and were superior to weld metal properties for the indicated neutron exposure. An investigation of simulated HAZ properties, as developed by the RPI hot ductility tester (Gleeble), suggested that the same relationship holds for the ASTM reference A302-B plate. Charpy-V specimens in this study were heat treated to simulate the maximum grain coarsened region in 4-in.-thick plate submerged arc welded using 100, 000 joules per inch heat input. After irradiation at 550°F to 3.1×10^{19} n/cm^2 > 1 MeV, HAZ specimens and reference "base plate" specimens depicted transition temperatures of 195°F and 185°F, respectively, corresponding to transition temperature increases of 130 and 155 degrees.

Figure 7 presents the results for the 4-in. experimental submerged arc test weld of A533-C, Class 2 steel. Unlike the plate versus weld-deposit performance of the Grade B, Class 1 weldment, quarter-thickness properties of both the plate and the weld metal appeared to be quite sensitive to 550°F irradiation. The Charpy-V transition temperature increases were 180 and 205 degrees, respectively. In spite of the large increases for the fluence condition (as compared to the ASTM reference steel, Fig. 4), the losses in full shear energy absorption were relatively minor.

Experimental results developed with the 5-3/4-in. electroslag test weldment are presented in Fig. 8. Figure 9 is a photograph of the weld joint cross section showing the size of the fusion zone. Unlike the submerged arc weldments examined, a significant difference in preirradiation ductile-brittle transition temperatures was found between the weld deposit and parent plate of this weldment. With irradiation, a very marked (threefold) difference in the respective transition temperature responses of weld deposit

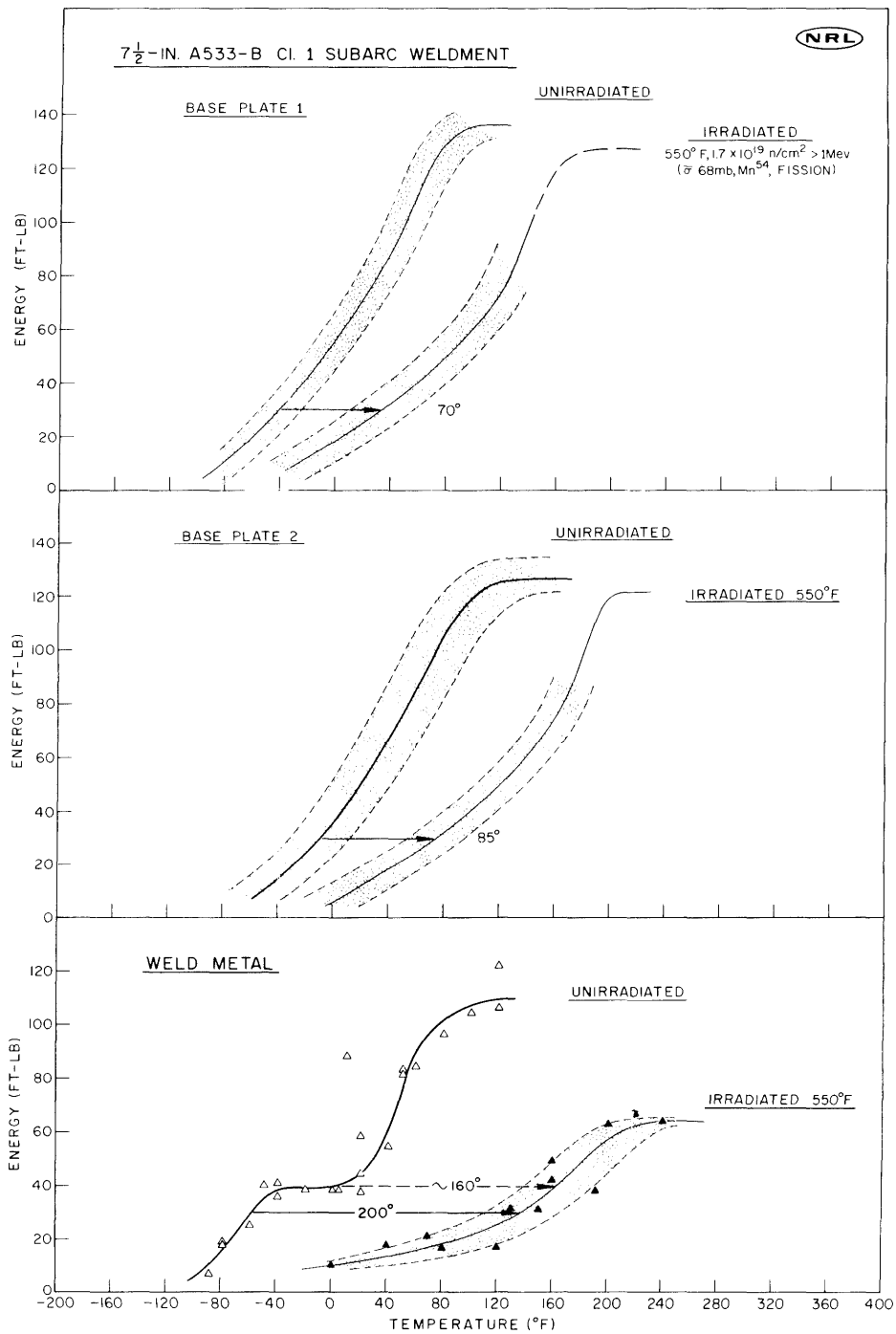

Fig. 5 - Notch ductility characteristics of a 7-1/2-in. A533-B Class 1 production weldment before and after 550°F neutron irradiation showing the relative performance of the base plate versus the submerged arc weld deposit

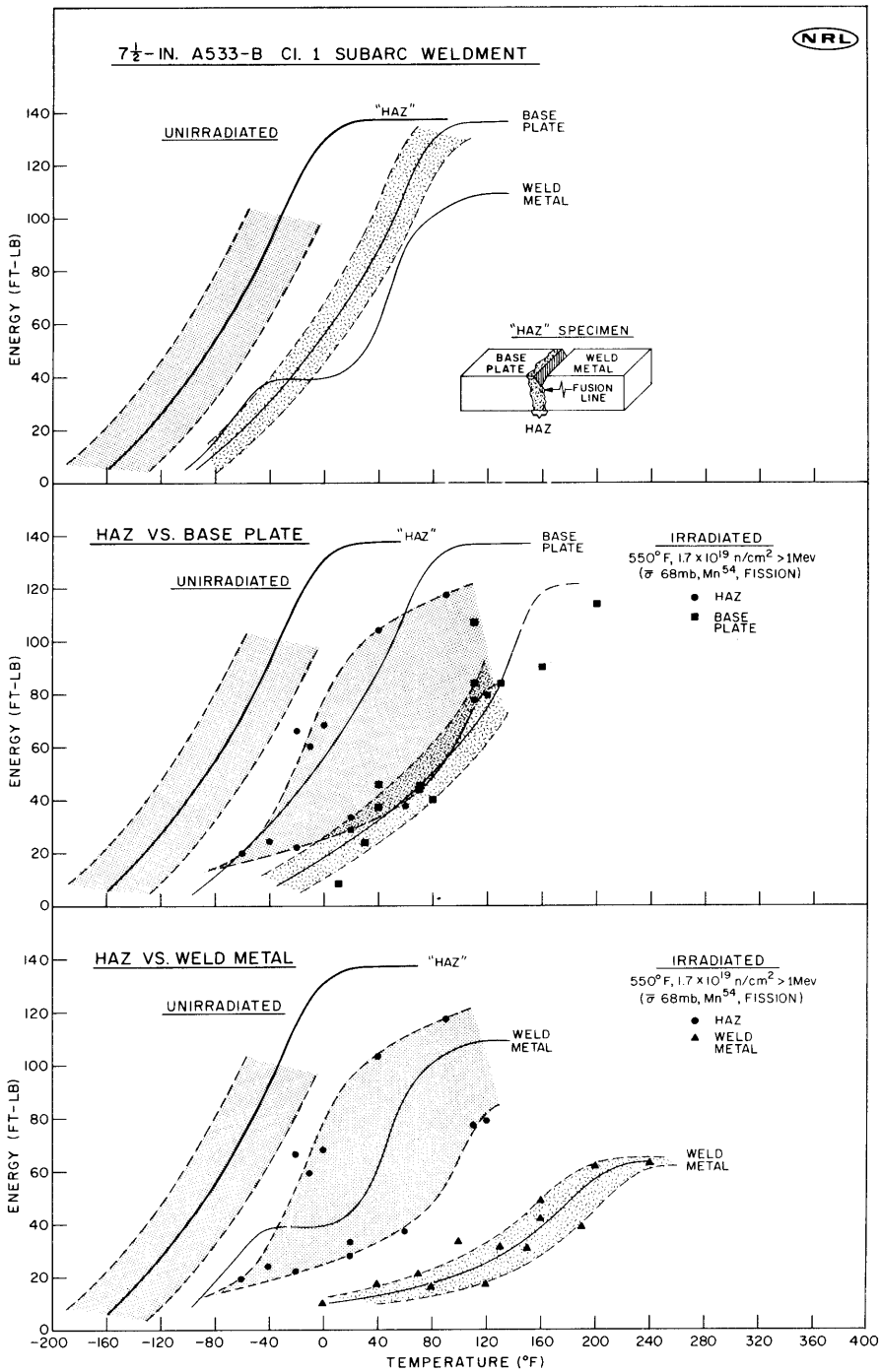

Fig. 6 - Comparison of weld heat-affected zone (HAZ) notch ductility properties with those of the base plate and weld metal forming a 7-1/2-in. A533-B Class 1 weldment. After irradiation at 550°F, the HAZ properties are observed to be as good as the plate properties and superior to the weld properties. The data points well demonstrate the difficulties in obtaining consistent HAZ results with specimens taken from actual weldments in the manner shown.

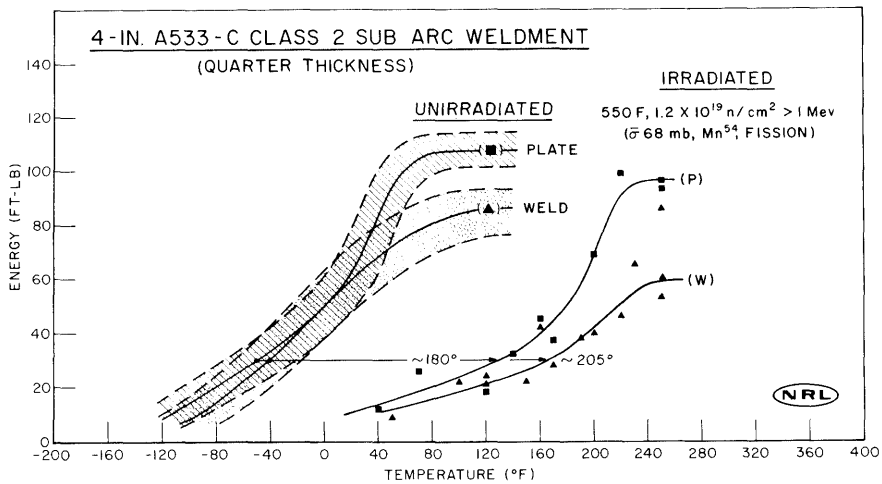

Fig. 7 - Notch ductility characteristics of a 4-in. A533-C Class 2 experimental weldment before and after 550°F irradiation, showing the similarity in performance of the base plate versus the submerged arc weld deposit

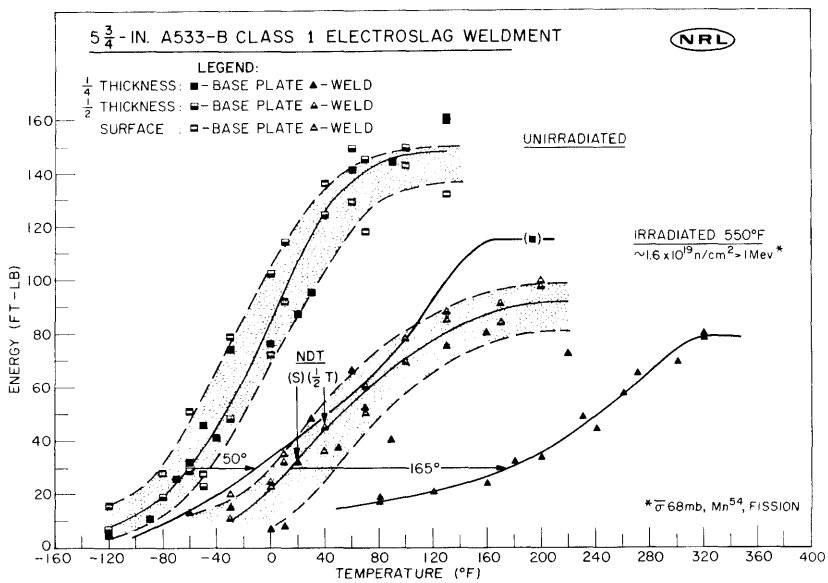

Fig. 8 - Experimental results developed for the 5-3/4-in. A533-B Class 1 electroslag weldment. The notch ductility properties of the parent plate are markedly superior to those of the weld metal, both before and after 550°F irradiation.

and parent plate was also denoted by the data. In effect, the difference in preirradiation transition temperatures of the plate and weld was further compounded by neutron exposure. From the relative performances of electroslag and submerged arc weld deposits, however (Fig. 8 versus Figs. 5 and 7), the consistently high radiation embrittlement sensitivity would suggest that the choice of welding process is not critical to the observed level of irradiation response. However, the limited data also point out that submerged

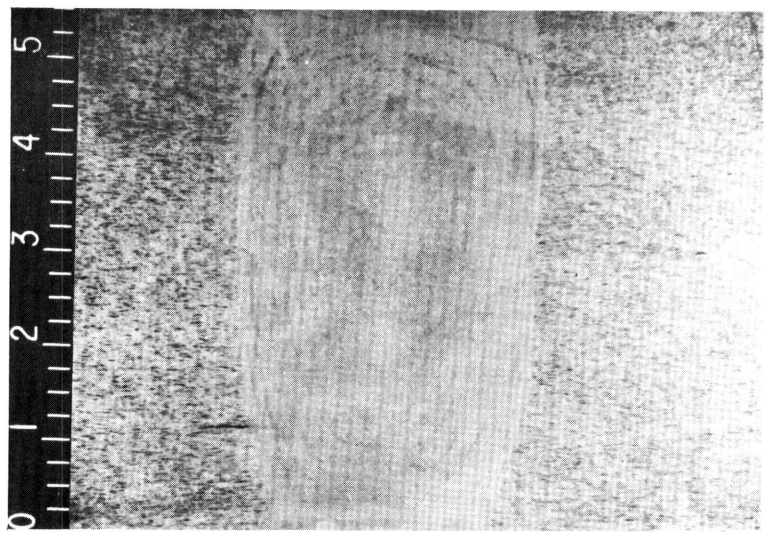

Fig. 9 - Electroslag weldment showing the etched weld metal joint (hot 50% HCl). The initial gap between the straight-sided base plates was 1-3/8-in.

Table 5
Comparison of 550°F Radiation Embrittlement Sensitivity of Plate and Weldments versus ASTM Reference A302-B Plate

Material Identification		Chemical Composition (wt-%)				Neutron Fluence (n/cm^2 > 1 MeV)	Charpy-V 30 ft-lb Transition Temperature Increase*	
Type	Thickness (in.)		Cu	P	P+S		ΔT (Observed)	ΔT ASTM Ref. (Projected)
Plate								
A302-B (ASTM Reference)	6		0.22	0.015	0.036	-	-	-
A533-B Class 1	4		0.14	0.009	0.031	2.3×10^{19}	120	150-160
	8		0.14	0.010	0.033	2.3×10^{19}	95	150-160
	8-1/8		0.19	0.010	0.027	1.7×10^{19}	190	140-150
	6-3/8		0.09	0.008	0.023	2.0×10^{19}	80	145-155
A533-B Class 2	6-3/8		0.09	0.008	0.023	2.0×10^{19}	75	145-155
Weldment								
A533-B Class 1 (Submerged Arc)	7-1/2	Plate 1	0.12	0.008	0.023	1.7×10^{19}	70	140-150
		Plate 2	0.11	0.011	0.031		85	140-150
		Weld	0.22	0.015	0.026		200/160†	140-150
A533-C Class 2 (Submerged Arc)	4	Plates 1 and 2	0.20	0.006	0.024	1.4×10^{19}	180	135-145
		Weld	0.27	0.016	0.031		205	135-145
A533-B Class 1 (Electroslag)	5-3/4	Plates 1 and 2	0.12	0.008	0.026	1.8×10^{19}	50	140-150
		Weld	0.19	0.008	0.022		165	140-150

*Quarter thickness layer.
†40 ft-lb index.

arc welding generally produced welds with lower initial transition temperatures than electroslag welding (i.e., -40/-60°F versus 15°F). Therefore, a given transition temperature increase by neutron irradiation would be more critical to plant operation in the case of the electroslag weld deposit by virtue of a higher initial transition temperature.

DISCUSSION

The data presented in the foregoing sections demonstrate that significant variability in 550°F irradiation response as given by Charpy-V 30 ft-lb transition temperature increases, can exist in A533-B plate. For two of the eight plates examined, the observed radiation embrittlement sensitivities were somewhat higher than that of the ASTM A302-B reference plate. Other comparisons of plate performance revealed sensitivity levels much lower than that of the reference plate. However, the embrittlement sensitivities of all weld deposits examined were classified as being equal to or greater than that of the reference plate. The reasons for such sensitivity differences are believed to be largely due to the individual chemical compositions of the plate and welds.

Recent studies of variable radiation embrittlement sensitivity in A302-B steel by the authors (6) demonstrate that copper content and phosphorus (or phosphorus plus sulfur content) contribute significantly to the observed sensitivity level. Moreover, laboratory heats of A302-B steel, in which all residual elements including Cu and P were held to a minimum low level, appeared seemingly insensitive to 550°F radiation embrittlement. Sulfur content alone was not found instrumental in radiation sensitivity development, nor was total nitrogen content in the range of 0.007 to 0.014% if the deoxidation practice employed conventional amounts of aluminum. On the basis of such information, the dissimilarities in observed irradiation responses of plate materials, and the consistently high radiation embrittlement sensitivity of those weld metals examined can be partially explained.

In Table 5, the general irradiation response levels of the individual experimental materials compared to the ASTM reference steel are referenced to their respective copper and phosphorus contents. It becomes immediately apparent that, where copper content is in the range of 0.19 to 0.27 or more, the plate exhibits relatively high sensitivity. Where the copper content is low (0.09 to 0.12), the plate sensitivity is low. Similarly, the welds which contain copper as a strengthening agent generally show relatively high radiation embrittlement sensitivity. The particular combinations of low copper base plate and copper-alloyed weld metal (7-1/2-in. weld) and of high-copper-bearing plate and weld metal (4-in. weld) are well suited for this analysis. Due to composition similarities, it also becomes somewhat obvious why the postirradiation performance of the HAZ of production weldment and of Gleeble-simulated submerged arc weldments were not poorer than that of the base plate.

The comparisons of production-size lots have provided an exacting test of those considerations of radiation embrittlement sensitivity gleaned from investigations of laboratory-size heats. Knowledge of the influence on radiation embrittlement sensitivity of selected elements, including Cu, P, As, Sb, Sn, and others, is being expanded and refined for universal application to the several carbon and low-alloy steels of interest to the nuclear industry. In the interim, a 30-ton heat of A533-B steel has been ordered to specifications intended to provide minimum sensitivity to 550°F radiation embrittlement as a further test of principles learned from laboratory-scale heats.

One additional observation which merits discussion is the apparent trend toward a saturation of radiation effects noted in Table 4. This trend is most clearly depicted by data for the ASTM reference A302-B plate; however, data for the 8-1/8-in. A533-B plate and for the 6-3/8-in. A533-B Class 2 plate are also suggestive of a plateau for transition

temperature increase above a certain fluence. In all cases, a strong tendency toward saturation might be considered evident when the fluence at 550°F approximates 1 to 1.5×10^{19} n/cm^2 > 1 MeV.

CONCLUSIONS

Major findings and conclusions of the exploratory research program on A533 steel plate and weldments may be summarized as follows.

1. Significant variability in radiation embrittlement sensitivity was found among A533-B and A533-C steel plates from different heats. The sensitivity levels of two plates equaled if not exceeded that of the ASTM A302-B reference plate; other plates exhibited appreciably lower irradiation responses.

2. Consistently high radiation embrittlement sensitivity at 550°F was observed for A533-B electroslag and A533-B and A533-C submerged arc weld deposits; transition temperature increases produced in parent plate under equivalent exposure conditions did not exceed that of the weld metal in any one case. The most marked difference in transition temperature increase between parent plate and weld deposit was exhibited by the electroslag weldment.

3. The notch ductility performance of the weld heat-affected zone after irradiation at 550°F was shown to equal the performance of the parent plate of one submerged arc production weldment.

4. In accordance with observations on special laboratory heats of A302-B steel, it was found that the radiation embrittlement sensitivity of A533 steel plate and companion weld metal can be predicted, in part, from their individual chemical compositions. High copper and phosphorus contents generally signify high 550°F irradiation response.

5. The response of A533 plate and weld metal to 550°F irradiation does not appear measurably influenced by either the strength class (Class 1 versus Class 2) or the particular grade of steel (Grade B versus Grade C).

6. None of the materials investigated exhibited significant through-thickness variations in 550°F irradiation response. Similarly, there were no marked variations in radiation sensitivity between longitudinal (RW) versus transverse (WR) test orientations in selected plates.

7. The nil-ductility transition (NDT) temperatures of three A533-B steel plates suggest that the average Charpy-V energy index for this type steel is somewhat higher than the 30 ft-lb index commonly used for A302-B steel. (Preceding observations are independent of the selection of energy index at least up to 50 or 60 ft-lb.)

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13. ABSTRACT

Exploratory assessments have been made of the Charpy-V notch ductility characteristics of heavy section A533-B and A533-C steel plate and submerged arc weldments following neutron irradiation at 550°F. The experimental evaluations were performed largely with commercial production materials and included comparisons of materials in both Class 1 and Class 2 strength ranges. Postirradiation notch ductility properties of one 5-3/4-in. A533-B Class 1 electroslag weldment were also developed. Assessments made of relative irradiation performance were assisted by a compilation of recent information on the response of the ASTM reference A302-B steel plate.

Major research findings include the observation of significant variability in radiation embrittlement sensitivity of A533-B and A533-C steel wherein the sensitivity level of plate and weld metal in some cases exceeded that of the ASTM reference plate. High radiation embrittlement sensitivity was noted for both submerged arc weld deposits examined; however, the data suggest that the performance of the weld-heat-affected zone parallels that of the parent plate. High embrittlement sensitivity was also noted for the electroslag weld deposit, in contrast to markedly low sensitivity of the weldment parent plate.

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The notch ductility behavior of A533 plate and weld metal under 550 °F irradiation was not found to be measurably influenced by either the strength class (Class 1 or 2) or by the particular grade of steel (Grade B or C). Similarly, there were no marked variations in irradiation response through the thickness of plate or weld metals, or between RW (longitudinal) versus WR (Transverse) orientations in cross-rolled plate.

In accordance with observations on special laboratory heats of A302-B steel, the study demonstrates that the radiation embrittlement resistance of commercially produced A533 steel plate and weld deposits can be predicted in part from their individual chemical compositions. High copper and phosphorus contents generally signify high sensitivity to 550°F radiation-induced changes in notch ductility characteristics.