Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*	2a. REPORT SECURITY CLASSIFICATION
Naval Research Laboratory Washington, D.C. 20390	Unclassified
	2b. GROUP

3. REPORT TITLE

TRENDS IN CHARPY-V SHELF ENERGY DEGRADATION AND YIELD STRENGTH INCREASE OF NEUTRON-EMBRITTLED PRESSURE VESSEL STEELS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Interim report; work is continuing.

5. AUTHOR(S) *(First name, middle initial, last name)*

J. Russell Hawthorne

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
December 22, 1969	28	24

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
NRL Problem M01-14	NRL Report 7011
b. PROJECT NO. RR 007-11-46-5409	
c. ERG-11-69	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d. AEC-AT (49-5)-2110	

10. DISTRIBUTION STATEMENT

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Department of the Navy (Office of Naval Research), Dept. of the Army (Corps of Engineers), and U.S. Atomic Energy Com.

13. ABSTRACT

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The data for all three steel types suggest a common pattern of properties behavior. A three-stage change of shelf level versus yield strength is indicated with progressive neutron exposure at <300°F (149°C). Data patterns for strong (longitudinal) versus weak (transverse) test orientations of thick section plate imply strong trend similarities. Properties modified by progressive radiation exposure at 550°F (288°C) are interpreted as following the same damage path described by <300°F (149°C) irradiation. The much slower pace of property changes with elevated temperature exposure is readily identified by trend line presentations.

Observations show that A533 plate and weld metals (Grades B and C, Classes 1 and 2) have greater toughness retention than the ASTM A302-B reference heat (6-in. plate) after 550°F (288°C) radiation. Results for a single reference heat of A543

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DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

Security Classification

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Impact tests						
Embrittlement						
Pressure vessels						
Steels						
Neutron irradiation						
Transition temperature						
Ductility						
Shelf level toughness						
Postirradiation tensile properties						
Nuclear reactor materials						
A533 steel						
A543 steel						
A302-B steel						
Weldments						

Class 1, 8-in. plate demonstrate that a lower initial brittle/ductile transition temperature in itself may not fully eliminate the general problem of providing sufficient notch ductility to allow for radiation embrittlement in service. Studies of A543 steel also reveal that temper embrittlement introduced during fabrication is not a strong influence on subsequent irradiation-induced changes in Charpy-V notch ductility at exposure temperatures up to 750°F (399°C).

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PROBLEM STATUS

This is an interim report on one phase of the problem; work on this and other phases continues.

AUTHORIZATION

NRL Problem M01-14
Projects RR 007-11-46-5409,
AEC AT(49-5)-2110, and ERG-11-69

Manuscript submitted October 21, 1969.

TRENDS IN CHARPY-V SHELF ENERGY DEGRADATION AND YIELD STRENGTH INCREASE OF NEUTRON-EMBRITTLED PRESSURE VESSEL STEELS

INTRODUCTION

The progressive elevation in the Charpy-V brittle/ductile transition temperature of neutron-irradiated carbon and low-alloy structural steels is a well-documented phenomenon* and has been subject to extensive research and analysis. The broad base of information developed by past studies has been essential for one assessment of nuclear components for fracture-safe design and operation (1). In brief, the approach recognizes the rise in ductility over the brittle-to-ductile transition zone and defines a transition temperature below which fracture (cleavage mode) can initiate from small flaws residing in local stress fields of yield point intensity. The approach excludes from analysis those materials having low initial fracture toughness and poorly defined brittle/ductile transition behavior (2,3).

Concomitant to the irradiation effect on the brittle/ductile transition temperature, the reduction in Charpy-V upper shelf energy presents a second material consideration. The shelf level, in combination with the yield strength, broadly indicates the potential for unstable fracture in a tearing mode.† The effect of irradiation on the shelf energy level of various structural steels unfortunately has not been as well documented as the irradiation effect on transition temperature behavior. However, with the projected use of higher strength steels, engineering reliability studies will have an increasing need for definitive trends in this property change. These advanced steels generally have lower preirradiation shelf energies and lower brittle/ductile transition temperatures. Concurrently, the extension of lifetime neutron fluences for moderate-strength steel components now in service reinforces the need for trend definition.

This report examines the postirradiation Charpy-V shelf level behavior of three pressure vessel steel compositions: A302-B, A533, and A543. The preirradiation yield strength range is approximately 65 to 95 ksi. The A302-B and A543 compositions are judged on the performance of single reference heats (4,5) accepted by industry as typical for these compositions in plate form. The assessment of A533 steel is derived from postirradiation evaluations of a large number of A533 plates and weldments encompassing different steel grades and strength classes (6). The progressive change in the resistance to fracture of each type steel with increasing neutron fluence is illustrated by trends showing the simultaneous shelf energy reduction and yield strength increase with irradiation.

MATERIALS AND MATERIAL IRRADIATIONS

The chemical composition, fabrication history, and initial (preirradiation) properties of the various materials are summarized in Tables 1, 2, and 3.‡ With few exceptions the

*Charpy-V 30 ft-lb (5.2 kg/cm^2) temperature is often used as a convenient, arbitrary index of brittle/ ductile transition the pre- and postirradiation assessments of steel performance.

†Low-energy absorption is characteristic of unstable fracture by either fibrous tear or cleavage failure modes.

‡Tables 3 through 9 appear at the end of this report.

plate and weldments were produced commercially, and thus represent normal shop melting and fabrication practices. Specimen irradiations were performed in one of three reactors: the Union Carbide Research Reactor (UCRR), the Oak Ridge Low Intensity Test Reactor (LITR), and the Materials Test Reactor (MTR) at the National Reactor Test Station. Equipment and techniques employed for ambient temperature and controlled temperature specimen irradiations have been described in detail elsewhere (7-9).

Neutron fluence values measured in neutrons per square centimeter for energies greater than 1 MeV (i.e., n/cm^2 >1 MeV) were based on an assumed fission spectrum neutron energy distribution and a fission-averaged cross section of 68 mb for the ^{54}Fe (n,p) ^{54}Mn reaction. Techniques for translating the reported fission spectrum fluence values into calculated spectrum fluence values have been outlined previously (10,11).

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 A302-B (ASTM Reference)	6	U.S. Steel Corp.		0.24 0.23	1.34 1.35	0.011 0.015	0.023 0.021	0.23 0.22	0.18 0.22	0.11 0.12	0.51 0.52	0.20 0.22	- 0.01	0.038 -
A533-B Class 1	4†	Lukens Steel Co.		0.21 0.20	1.40 1.33	0.010 0.009	0.022	0.25 0.20	0.50 0.52	- 0.16	0,45 0.42	0.15 0.14	- -	0.048 0.03
	8†	Lukens Steel Co.		0.19 0.20	1.37 1.32	0.012 0.010	0.011 0.023	0.25 0.21	0.52 0.52	- 0.15	0.45 0.42	- 0.14	- -	- 0.05
	8-1/8	Babcock and Wilcox Co.		0.21 0.21	1.36 1.21	0.007 0.010	0.018 0.017	0.26 0.26	0.49 0.47	- 0.19	0.47 0.50	- 0.19	- -	- -
	6-3/8‡	Vender§		0.20 0.24	1.39 1.27	0,011 0.008	0.013 0.015	0.20 0.19	0.53 0.53	0.09 0.14	0.48 0.48	- 0.09	- 0.02	0.031 -
A533-B Class 2	6-3/8‡	Vender§		0.20 0.24	1.39 1.27	0.011 0.008	0.013 0.015	0.20 0.19	0.53 0.53	0.09 0.14	0.48 0.48	- 0.09	- 0.02	0.031 -
A543 Class 1 (Reference)	8	U.S. Steel Corp.		0.17	0.38	0.013	0.023	0.29	3.65	1.88	0.51		-	0.02
			Section 1	0.17	0.34	0.010	0.015	0.25	3.45	1.93	0.51	0.06	0.02	0.02
			Section 2	0.17	0.31	0.012	0.016	0.25	3.28	1.90	0.50	0.04	0.02	0.02
Weldment A533-B Class 1 (Submerged Arc)	7-1/2	Westinghouse Elec. Corp.	Plate 1	0.20 0.27	1.29 1.20	0.013 0.008	0.022 0.015	0.25 0.24	0.50 0.50	- 0.08	0.49 0.48	0.14 0.12	- 0.02	- -
			Plate 2	0.21 0.22	1.24 1.25	0.011 0.008	0.020 0.019	0.24 0.24	0.53 0.51	- 0.09	0.48 0.49	0.11 0.11	- -	- -
			Weld¶	- 0.17	- 1.25	- 0.015	Not Available 0.011	0.32	- 0.11	- 0.16	- 0.53	- 0.22	- 0.03	- -
A533-B Class 1	8	Vender	Plates 1 and 2	0.24 0.27	1.40 1.24	0.016 0.008	0.016 0.014	0.23 0.18	0.61 0.63	- 0.09	0.45 0.45	0.11 0.09	- 0.02	- 0.02
(Submerged Arc)			Weld¶ (Main)	0.18 0.19	1.09 1.24	0.013 0.010	0.011 0.014	0.28 0.19	0.82 0.93	0.05 0.08	0.51 0.45	0.32 0.14	0.01 0.02	- .007
(Manual Metal Arc)			Weld¶ (Root)	- 0.11	- 1.13	- 0.005	Not Available 0.014	0.21	- 0.99	- 0.24	- 0.36	- 0.06	- -	- 0.02
A533-C Class 2 (Submerged Arc)	4	Lukens Steel Co.	Plates 1 and 2	0.19 0.24	1.25 1.05	0.010 0.006	0.013 0.018	0.22 0.21	0.83 0.78	0.07 0.06	0.48 0.48	0.22 0.20	- 0.02	0.021 -
			Weld¶	0.08 0.13	1.84 1.68	0.013 0.016	0.009 0.015	0.37 0.33	0.10 0.14	0.07 0.05	0.51 0.48	0.30 0.27	- 0.02	- -
A533-B Class 1 (Electroslag)	5-3/4	Babcock and Wilcox Co.	Plates 1 and 2	- 0.22	- 1.19	- 0.008	Not Available 0.018	0.16	- 0.52	- 0.14	- 0.48	- 0.12	- 0.03	- -
			Weld¶	0.18 0.22	1.37 1.28	0.014 0.008	0.016 0.014	0.12 0.10	0.36 0.40	0.08 0.14	0.49 0.48	0.21 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.

** Both plates from same steel heat.

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

Material Identification: Type	Material Identification: Thickness (in.)	Yield Strength* (0.2% Offset) (ksi)	Tensile† Strength (ksi)	Heat Treatment
Plate				
A302-B (ASTM Reference)	6	- 67.5†	- 89.7†	Austenitized at 1650°F for 2 hr, water quenched; tempered at 1200°F for 6 hr, furnace cooled to below 600°F.
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	- 69.4	- 89.4	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.
A543 Class 1 (Reference)	8	96.2 Section 1 95.2 Section 2 94.6	119.1 118.3 119.6	Austenitized at 1650°F with 8 hr heating and 2 hr hold, water quenched for 17 min.; reaustenitized at 1500°F with 8 hr heating and 2 hr hold, water quenched for 17 min.; tempered at 1185°F with 8 hr heating and 2 hr hold, water quenched cold.
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	- 64.3‡	- 83.7‡	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-B Class 1 (Submerged Arc)	8 Plate	65.3† 66.8‡	88.1† 89.4‡	Plate: Austenitized at 1600° ± 50°F for 4 hr, water quenched; tempered at 1225° ± 25°F for 4 hr, furnace cooled.
	Weld	- 69.3‡	87.2‡ 87.7‡	Post Weld: Stress relief annealed at 1150° ± 25°F for 40 hr, furnace cooled to below 600°F.
A533-C Class 2 (Submerged Arc)	4 Plate	83.2† 66.8‡	98.0† 88.2‡	Plate: Austenitized at 1650°F, water quenched; tempered at 1225°F, air cooled.
	Weld	79.1‡ 76.4‡	90.7‡ 90.1‡	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† 70.7‡ 87.6‡[a]	91.8† 91.0‡ 102.8‡[a]	

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

†Before stress relief anneal.

‡After stress relief anneal.

[a]Surface Layer Specimen.

TRANSITION TEMPERATURE RESPONSE TO ELEVATED TEMPERATURE IRRADIATION

To provide background on the individual steels in Table 1, observed brittle/ductile transition temperature responses with irradiation will be reviewed briefly. It is to be noted that reactor pressure vessel operations should be reviewed periodically on the basis of lowered resistance to fibrous fracture and elevated nil ductility transition (NDT) temperature resulting from accumulated neutron embrittlement.

A302-B Steel

The progressive increase in the Charpy-V 30 ft-lb (5.2 kg/cm^2) transition temperature of the ASTM A302-B reference heat with 550°F (288°C) irradiation is shown in Fig. 1. This figure was developed from a recent tabulation of NRL data (6) for the strong (longitudinal-RW) plate orientation. A relatively rapid elevation in transition temperature with the first increments of exposure is indicated. With successively higher fluences at 550°F (288°C), a decrease in the rate of damage accumulation above 1×10^{19} n/cm^2>1 MeV and a general tendency toward radiation embrittlement saturation is seen.* Figure 2 shows the performance of this heat after high-fluence exposure ($4\text{-}5 \times 10^{19}$ n/cm^2) at 550, 650, and 740°F (288, 343, and 383°C) and illustrates the normal trend of decreasing radiation embrittlement with increasing exposure temperature. The reduction in apparent sensitivity level with increasing temperature is attributed to beneficial thermal processes which partially nullify the detrimental radiation processes. However, this interaction may not be apparent with all steels at all temperatures, as indicated below.

Limited data for the weak (transverse-WR) orientation of this steel and other steels suggest that specimen orientation is not a significant factor in the observed brittle/ductile transition temperature increase (6). On the other hand, shelf energy values for the weak and strong directions may or may not be reduced equally by irradiation, depending upon the initial difference between the two values, as well as their absolute magnitudes.

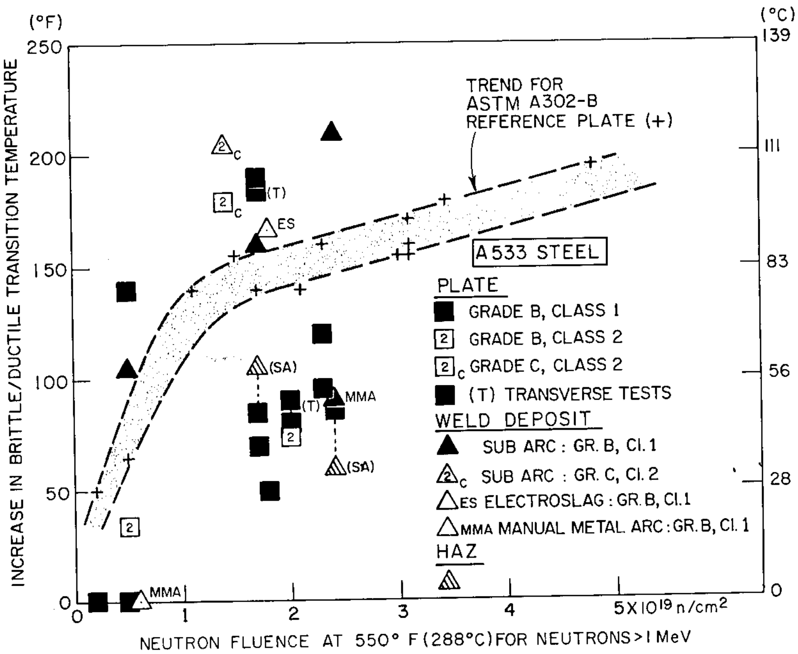

Fig. 1 - Increase in Charpy-V 30 ft-lb (5.2 kg/cm^2) transition temperature with increasing neutron fluence at 550°F (288°C) observed for the ASTM A302-B reference plate and for a number of A533 plates, weld metals, and weld heat affected zones illustrating a wide range of radiation embrittlement sensitivities. After a fluence accumulation of about 1×10^{19} n/cm^2, a marked change in the rate of transition temperature increase is noted.

*A neutron fluence value of $2\text{-}4 \times 10^{19}$ n/cm^2 is often taken as a lifetime service maximum encompassing most water-cooled reactor pressure vessels.

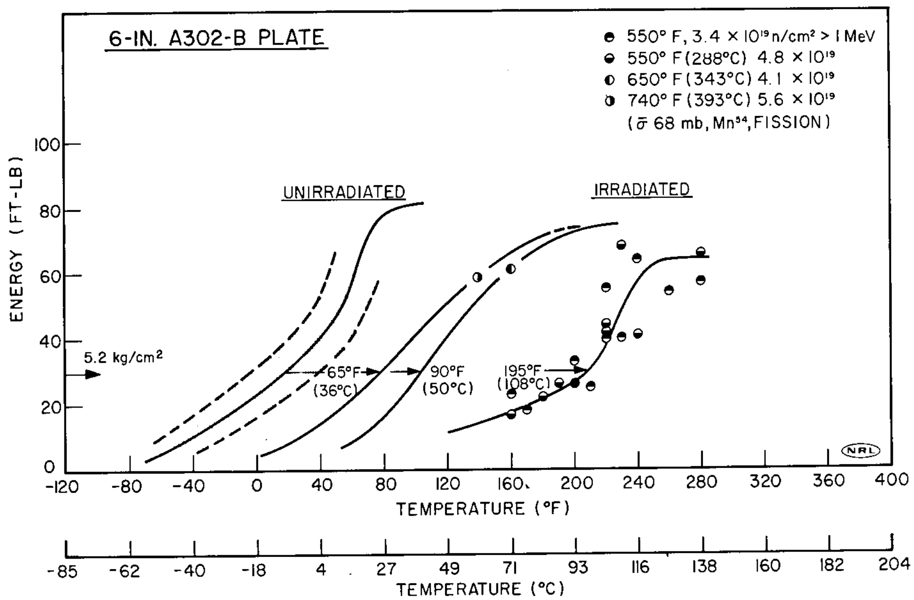

Fig. 2 - High-temperature/high-fluence irradiation response of the ASTM A302-B reference plate

A533 Steel

Data for A533 steel plate, weld metals, and weld heat affected zones (HAZ) (6) are shown superimposed on the trend for the A302-B reference heat in Fig. 1. An immediate observation is the broad range of behavior among the several materials and the lack of consistent behavior relative to the reference heat. Examining the data closely, nonconsistent transition temperature increases with neutron fluence are observed among plates, among welds, and between plates and welds. A discussion of research on the causes of variable radiation sensitivity in structural steels (12-15) is beyond the scope of this paper. From Fig. 1, however, it appears that transition temperature response is independent of steel grade and strength class. Similar transition temperature increases for HAZ and parent plate are also suggested. Observations for the ASTM reference heat using the RPI hot ductility tester (Gleeble) to simulate a HAZ thermal cycle are in agreement with this general trend (6).

The initial (preirradiation) brittle/ductile transition temperatures of most A533 steels included in Fig. 1 are in the range of -60 to +20°F (-51 to -7°C) and generally overlap the Charpy-V 30 ft-lb transition temperature of the A302-B reference plate, +15 to +30°F (-9 to -1°C), depending on test location. Thus, the engineering significance of a given elevation in transition temperature by irradiation would be about the same for both type steels.

A543 Steel

Typical performance by the A543 Class 1 reference heat with elevated temperature irradiation is shown in Fig. 3 (12). In this case, the normal trend of decreasing irradiation embrittlement with increasing exposure temperature is followed up to a temperature of 650°F (343°C) but not to 740°F (393°C). However, long-term 740°F thermal aging (2400 hours) comparable to the irradiation period revealed an 85°F (47°C) elevation in the brittle/ductile transition temperature. If this aging effect can be subtracted from the apparent embrittlement, the actual change due to irradiation is of the expected order of magnitude consistent with A302-B performance (~55 degrees elevation). By comparison, thermal aging at 600°F (316°C) for an equivalent time period essentially had no effect on the notch ductility properties of this heat.

A separate study on the possible influence of prior temper embrittlement on subsequent irradiation response of Ni-Cr-Mo steel has not revealed an interaction between the two embrittling mechanisms (Fig. 4). Therefore, temper embrittlement, if introduced during component fabrication, should not change the basic trend picture for radiation serviceability. On the other hand, temper embrittlement can contribute in a separate manner to overall embrittlement (Fig. 3) when the steel is irradiated in its temperature-sensitive range for extended time periods (several months or years).

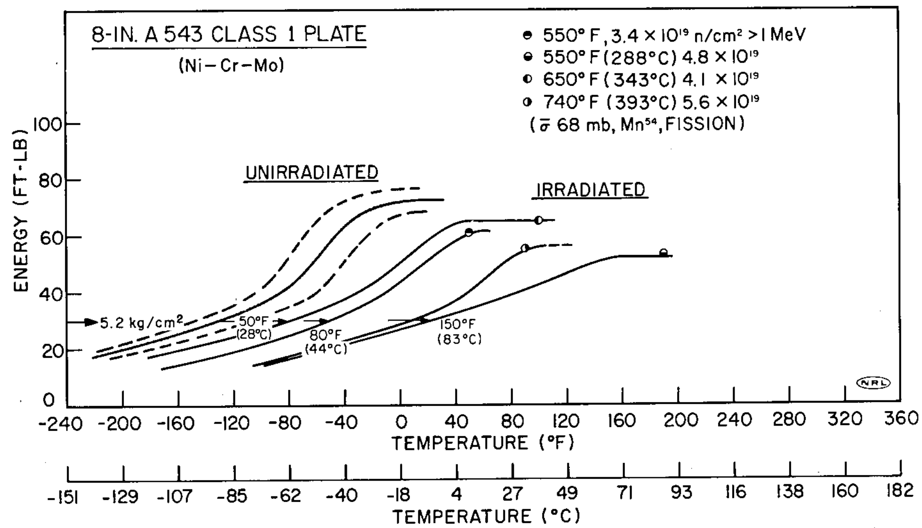

Fig. 3 - High-temperature/high-fluence irradiation response of the A543 Class 1 reference plate (12)

The low initial brittle/ductile transition temperature of the A543 reference heat (-130°F (-91°C)) is obviously a desirable characteristic for nuclear service applications provided that normal radiation embrittlement sensitivity is also exhibited. As illustrated in Fig. 3, the brittle/ductile transition temperature of this steel was not elevated above room temperature by the respective exposures even though high fluences were involved. At a low temperature (< 250°F (121°C)), however, the irradiation effect was much more pronounced (Fig. 5) and a marked increase in transition temperature (strong and weak plate orientations) occurred with a relatively low fluence accumulation. Figure 5 broadly illustrates one possible crossover in point of concern from the radiation-induced transition temperature increase to the shelf level reduction. Specifically, the shelf drop with the higher fluence precludes development of a characteristic or meaningful brittle/ductile transition.

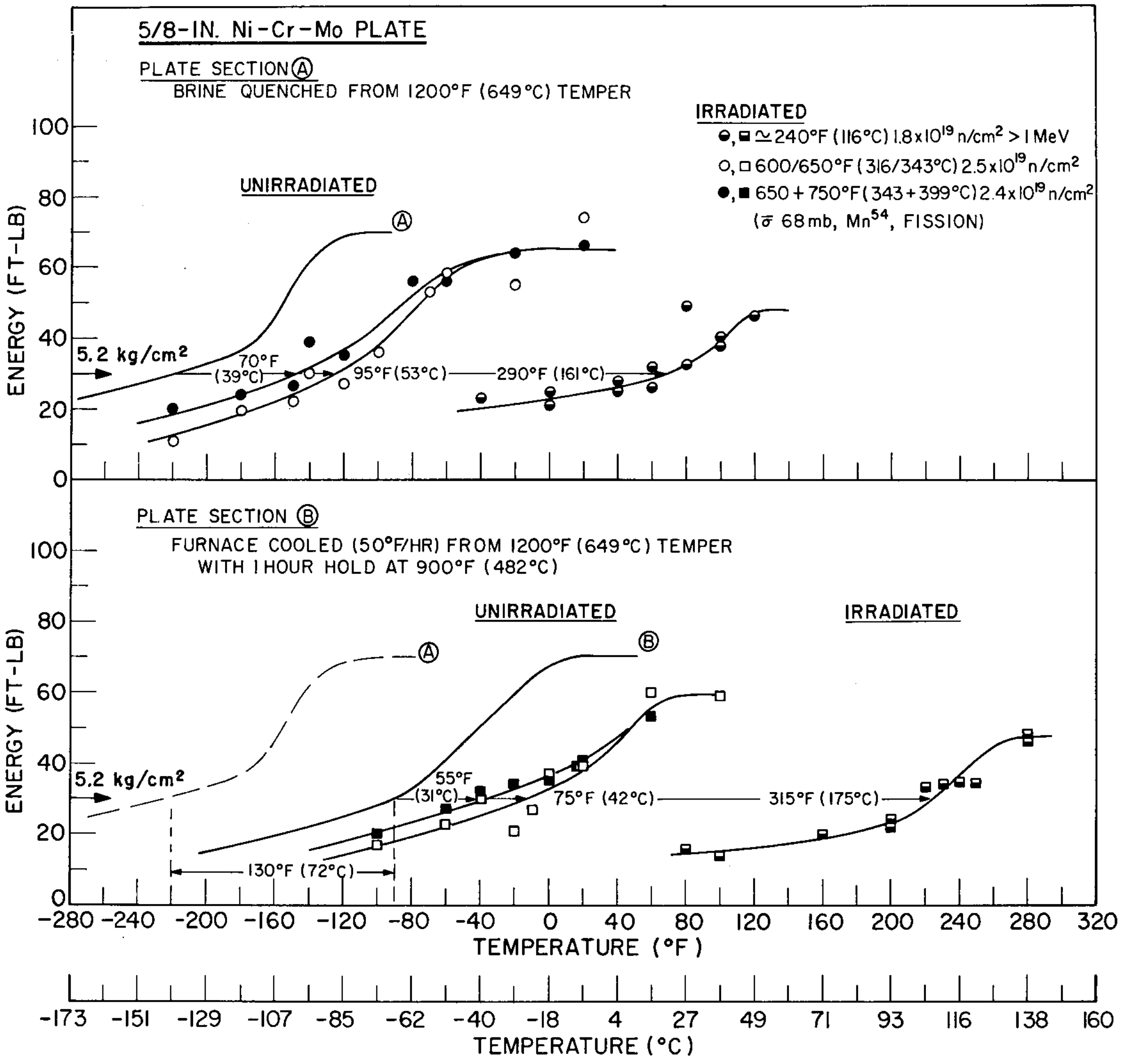

Fig. 4 - Influence of prior temper embrittlement on the irradiation response of A543 steel at low and elevated temperatures. The preirradiation brittle/ductile transition curve for the nonembrittled condition (plate section A) is repeated in the lower figure for the temper embrittled condition (plate section B) to illustrate the 130-degree difference in preirradiation 30 ft-lb (5.2 kg/cm^2) transition temperatures.

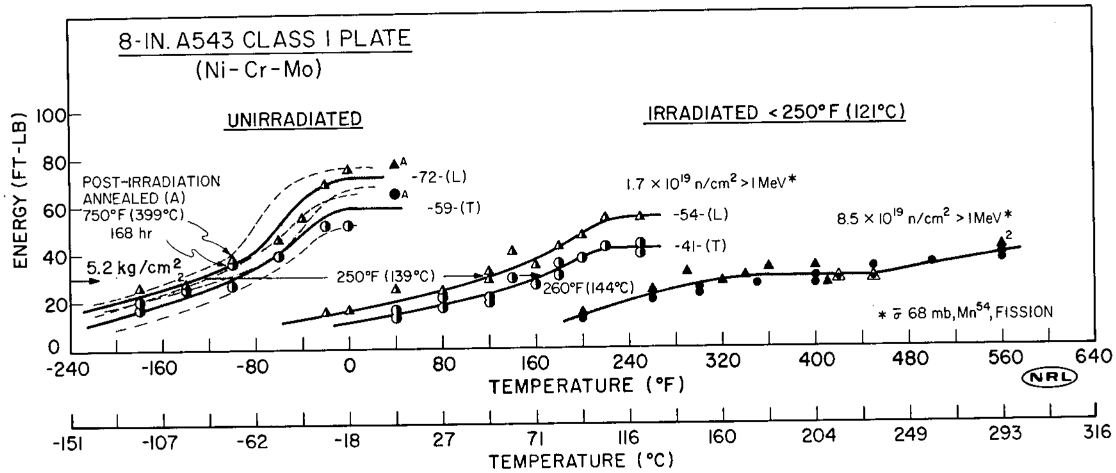

Fig. 5 - Low-temperature irradiation responses of the strong (longitudinal-L) versus weak (transverse-T) test orientations of the A543 Class 1 reference plate. The high-fluence exposure has depressed the shelf energy level of both orientations to a nominal 30 ft-lb (5.2 kg/cm^2) with which an energy transition becomes meaningless. The increase in energy absorption above 450°F (232°C) is believed due to partial annealing of radiation effects while the specimens were conditioned for test.

YIELD STRENGTH INCREASE

Postirradiation tensile properties data are compiled by composition type in Tables 4-6. The limited information in most cases is sufficient for development of the shelf energy versus yield strength trends to follow. Tensile properties were obtained with 0.252-in.-diam., 1.750-in. gage length specimens using equipment described previously (16). Graphic presentations of the yield strength increase as a function of the fluence and of the exposure temperature are given in Figs. 6-8. In view of the paucity of data for the A533 composition, an average increase in yield strength of 20 ksi will be assumed for a neutron exposure of $\sim 2\times10^{19}$ n/cm^2 >1 MeV at 550°F (288°C).

DEGRADATION OF CHARPY-V SHELF ENERGY LEVEL

A302-B Steel

Table 7 is a compilation of postirradiation Charpy-V shelf energy values for the ASTM A302-B reference heat observed with many reactor experiments. Average pre-irradiation shelf values for the strong plate orientation (longitudinal-RW) ranged from 71 to 81 ft-lb depending on test location; the weak orientation (transverse-WR) developed about 45 ft-lb at all points. In Fig. 6 the data have been plotted as a function of neutron fluence using a linear coordinate system. Solid circles represent low-temperature (<300°F (149°C)) exposures; open circles signify 550°F (288°C) controlled-temperature irradiations. Data trends for both temperature conditions have several interesting features. Paralleling the trend of transition temperature increase previously described (Fig. 1), values for the strong orientation decrease markedly during the first 1×10^{19} n/cm^2 fluence interval, after which a strong tendency towards a saturation of irradiation effect is evident. Data for the 550°F (288°C) exposure condition clearly indicate a plateau in the fluence interval $1\text{-}5\times10^{19}$ n/cm^2. Analysis of limited data for the weak plate orientation would suggest a trend similar to the response trend described by the strong orientation data.

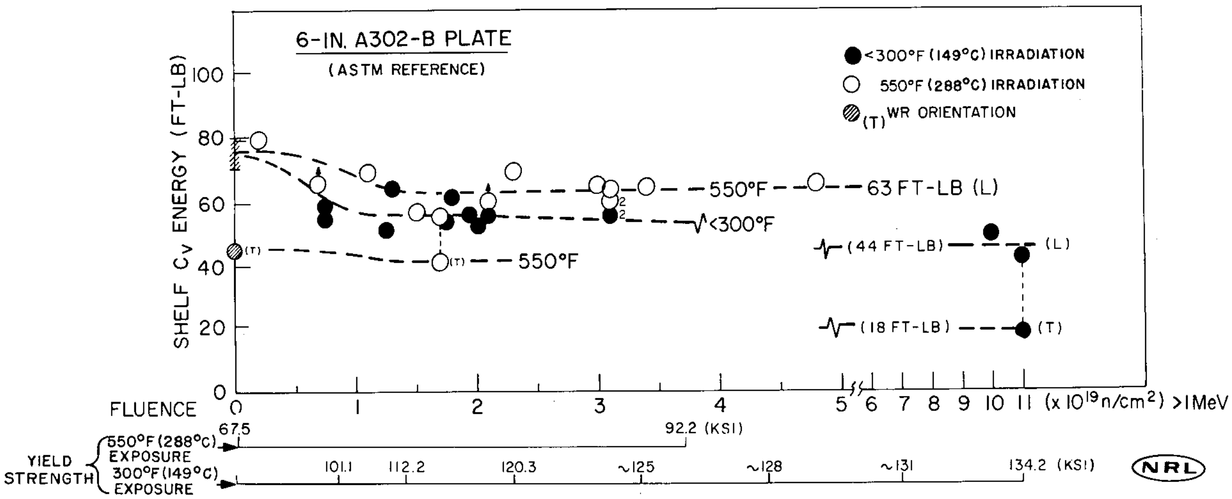

Fig. 6 - Decrease in the Charpy-V shelf energy level of the ASTM A302-B reference plate with increasing fluence at <300°F (149°C) and at 550°F (288°C). Concomitant yield strength increase (0.2% offset) for various fluence conditions are also shown.

At the bottom of Fig. 6 a scale of postirradiation yield strength is indexed to the fluence coordinate with data taken from Table 4. Interpolated values are identified by the symbol ~. Notably, the trend of yield strength increase with increasing fluence at <300°F (149°C) coincides with the data trend describing shelf level behavior; a general transition from a high to a low rate of change is again marked by the fluence ~ 1×10^{19} n/cm^2. Above this initial exposure level, a tenfold increase in fluence is required to produce an additional increase in yield strength equivalent to that developed during the first fluence interval. The relative effectiveness of elevated temperature versus low-temperature irradiation in producing a yield strength change is also quite apparent in Fig. 6. This temperature effect will be identified as a primary consideration in the analysis of overall trend behavior below.

A533 Steel

A compilation of shelf energy data developed for the 550°F (288°C) irradiation condition of A533 steel plate, weld metals, and weld HAZ is given in Table 8 (6). In Fig. 7 the A533 data have been entered on the summary data plot for the ASTM A302-B reference heat (Fig. 6) as a direct comparison of the results. Companion data relating the low-temperature exposure condition have not been developed.

Figure 7 illustrates the wide variance noted among individual material values; however, the presentation suggests that the performance of A533 plate (irrespective of test orientation) and weld metals is consistently as good as the best performance of the A302-B reference plate (i.e., strong orientation) over the range of interest. In fact, the general performance of A533 steel is shown to be superior to that of the reference plate. Recalling Fig. 1, the relative brittle/ductile transition temperature response as opposed to Charpy-V shelf levels did not suggest a consistent superiority of A533 steel over the reference heat. Consequently, the data indicate a requirement for separate analyses of shelf behavior and transition temperature response for qualifying individual steels for nuclear service.

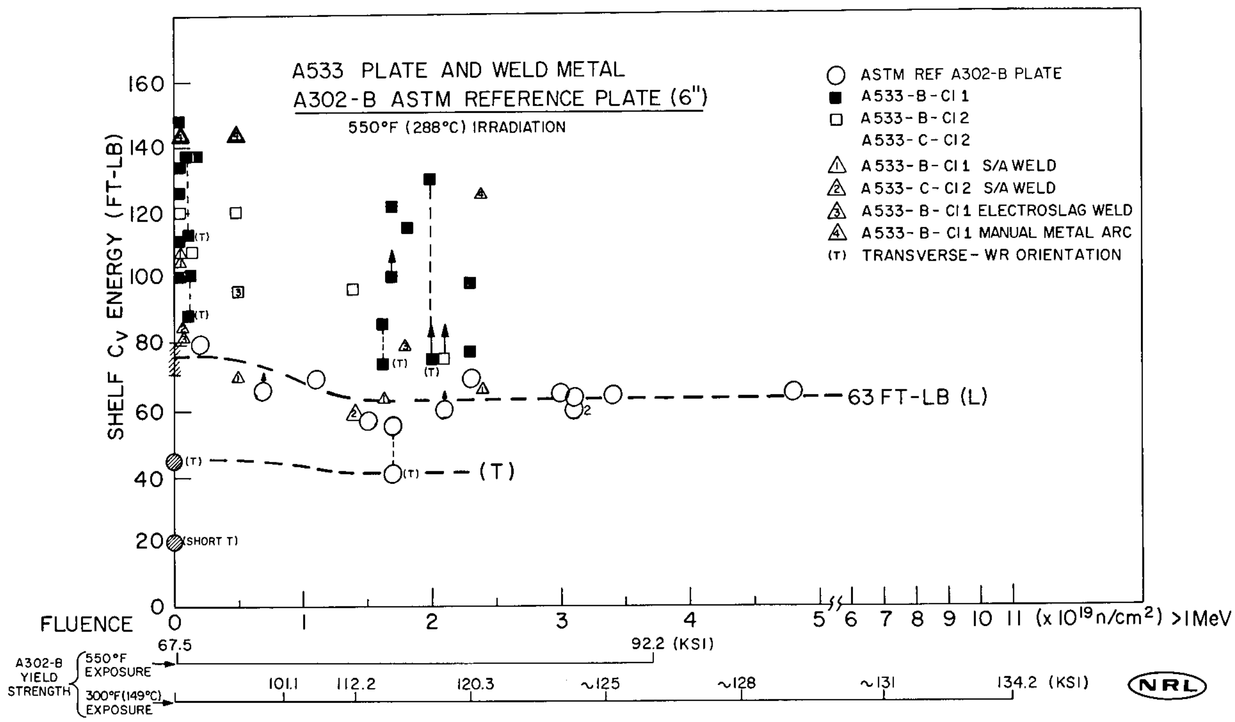

Fig. 7 - Decrease in the Charpy-V shelf energy levels of several A533 plates, weld metals, and weld heat affected zones with increasing fluence at 550°F (288°C) relative to the 550°F trend performance of the ASTM A302-B reference plate

A543 Steel

Postirradiation shelf values obtained with the 8-in. A543 Class 1 reference plate are plotted as a function of fluence in Fig. 8. A summary tabulation of these and other results is given in Table 9, together with initial results for a recent production plate.

From the trend indications in Figs. 8 and 6, a close parallel between the shelf response patterns of the A543 and A302-B reference plates is observed. It should be noted that the postirradiation values for the strong orientations of each plate are roughly comparable throughout the fluence range investigated. With high exposures, the weak orientation values for the A543 plate are somewhat higher than those of the A302-B plate, due perhaps to a better preirradiation level (58 ft-lb versus 45 ft-lb). Emphasis on optimum cross-rolling practice resulted in the smaller initial difference in shelf level between strong and weak orientations in this case.

The two reference plates are also shown to describe comparable irradiation responses in terms of yield strength increases. A fluence of 3.7×10^{19} n/cm^2 at <300°F (149°C) and at 550°F (288°C), for example, produced, respectively, elevations of 56 to 61 ksi and 22 to 24 ksi in yield strength for both steels. In the fluence interval 3.7-10×10^{19} n/cm^2, an additional increase of 10 to 15 ksi (maximum) would be projected for the A543 reference plate on the basis of the depicted trend behavior.

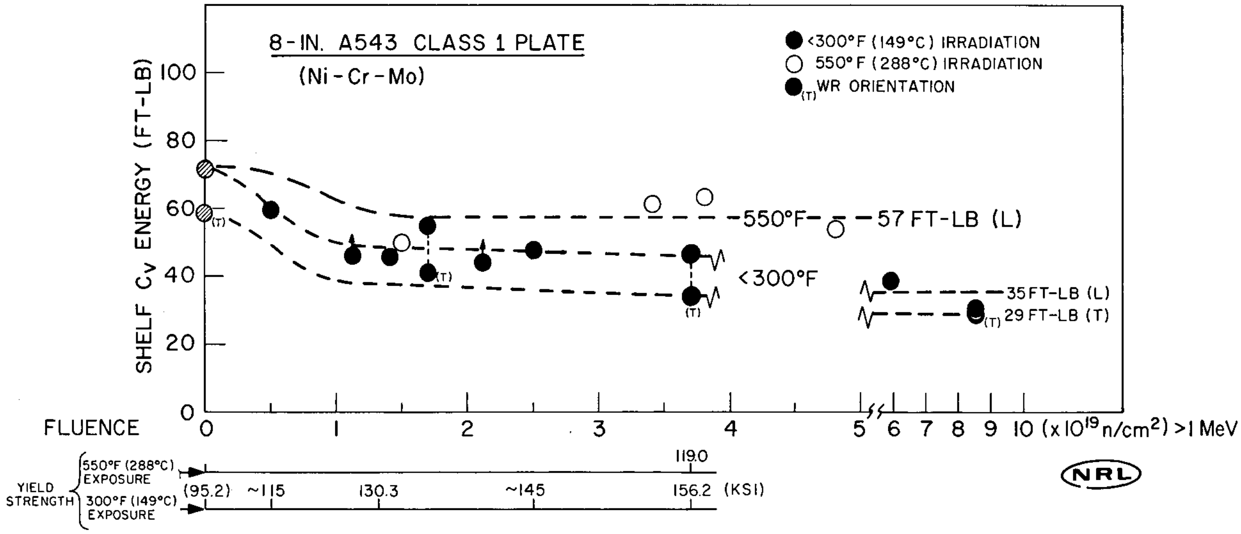

Fig. 8 - Decrease in the Charpy-V shelf energy level of the A543 Class 1 reference plate with increasing fluence at <300°F (149°C) and at 550°F (288°C). Concomitant yield strength increases (0.2% offset) for various fluence conditions are also indicated.

TRENDS IN SHELF ENERGY REDUCTION VERSUS YIELD STRENGTH INCREASE

A302-B and A533 Steels

Figure 9 is a summary plot developed from Figs. 6 and 7 depicting the relative rate of shelf energy degradation or reduction versus increase in yield strength for A302-B and A533 steel. Solid points represent <300°F (149°C) irradiations of the A302-B reference plate; the two open points represent one 550°F (288°C) controlled-temperature irradiation of strong (S) and weak (W) orientation specimens to a moderately high neutron fluence. All data for the A533 steels (Grades B and C, Classes 1 and 2, plate and weld) are represented in Fig. 9 by the cross-hatched enclosure (unirradiated condition) and shaded enclosure (550°F (288°C) irradiation data). Based on A302-B tensile behavior, an average radiation-induced increase in yield strength of 20 ksi was assumed for the various A533 materials for a fluence of $\sim 2 \times 10^{19}$ n/cm^2.

The data trend for the reference plate (< 300°F (149°C) irradiation) has many interesting aspects. A rather rapid initial decrease in shelf level and increase in yield strength is illustrated for the fluence interval $0\text{-}1 \times 10^{19}$ n/cm^2 and is consistent with the trend in transition temperature increase described earlier (Fig. 1). The fluence interval $\sim 1\text{-}3 \times 10^{19}$ n/cm^2 has little additional effect on shelf level but does produce a further increase in yield strength. Above this intermediate plateau region, the data depict a quite rapid reduction of shelf energy values with small additional increases in yield strength. Thus, three stages of behavior are suggested. It is noted that data for the weak plate direction, though limited, present similar trend indications. It is even more significant that shelf level/yield strength changes with 550°F (288°C) irradiation would appear to follow the same damage path described for < 300°F (149°C) irradiation conditions. Of course, the extent of embrittlement is much less at the higher temperature due to beneficial thermal processes partially counteracting detrimental irradiation processes (see Fig. 2).

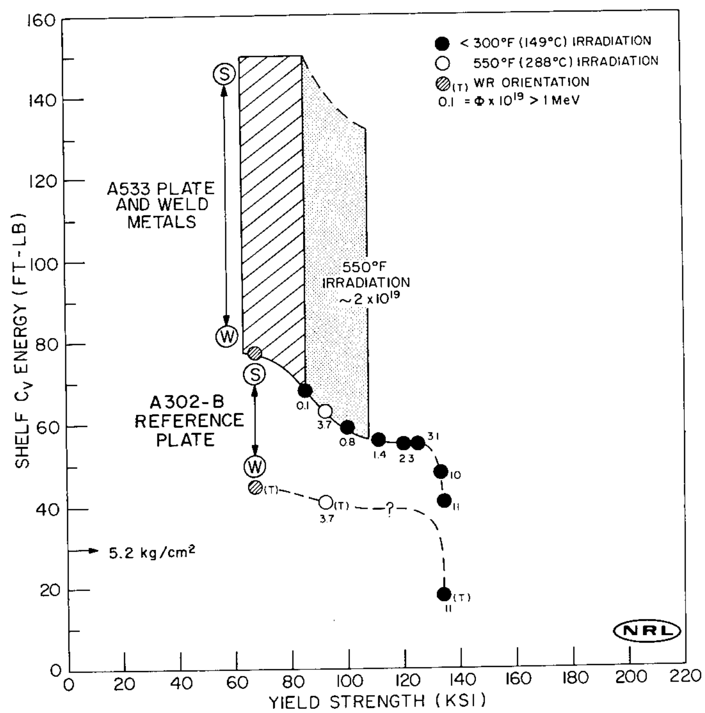

Fig. 9 - Trend in Charpy-V shelf energy reduction versus yield strength increase for the neutron-irradiated ASTM A302-B reference plate and various A533 plate and weld metals. Shaded enclosures for the A533 steels represent data for multiple grades and strength classes of thick section material before and after irradiation at 550° F (288°C). Numbers such as 3.7 adjacent to individual data points indicate measured neutron fluences (in 10^{19} n/cm^2).

Turning next to the A533 data, the shaded enclosures indicate that all plate and weldment values lie at, or above, the trend line (strong direction) for the A302-B reference heat. Since weak as well as strong plate orientations are well represented, an overall superior performance of the A533 relative to the A302-B steel is signified. This is considered a reflection of improved melt processing resulting in cleaner heats and the generally lower sulfur and phosphorus contents of the more recent A533 heats compared to the older ASTM A302-B reference heat, which was cast in 1959.

A543 Steel

The summary plot for the A543 Class 1 reference plate is given in Fig. 10. The general trend in shelf level versus yield strength behavior first noted with the A302-B reference heat is seen repeated here, including the intermediate plateau region with <300°F (149°C) irradiation. Data for this steel indicate that the plateau may extend up to a 4-5$\times 10^{19}$ n/cm^2 fluence condition before the onset of a third-stage behavior. As expected from Fig. 8, the trend for the weak plate orientation (transverse) parallels the trend for the strong orientation (longitudinal). Overall, the A543 reference plate gives further evidence that shelf level/yield strength changes for 550°F (288°C) irradiation follow the same damage path described for <300°F (149°C) irradiation conditions, but at a slower pace.

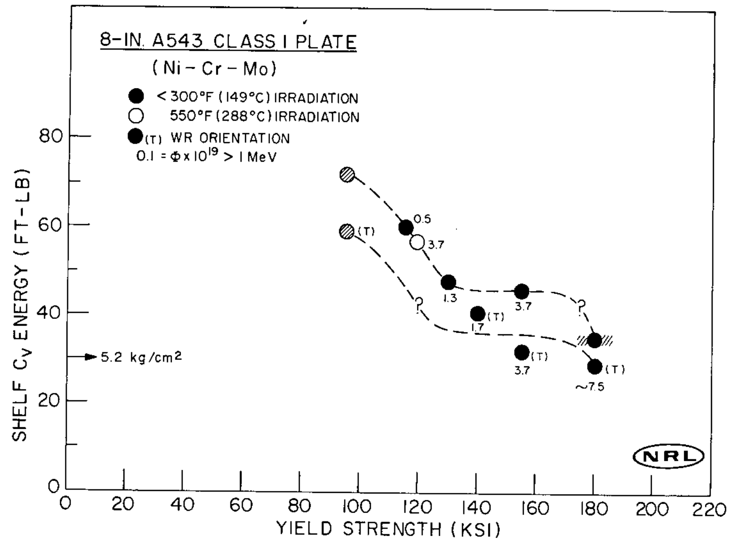

Fig. 10 - Trend in Charpy-V shelf energy reduction versus yield strength increase of the A543 Class 1 reference plate with neutron irradiation

It is interesting to note that the trend line for the A543 reference plate spans a yield strength and fluence interval roughly comparable to the trend line span for the A302-B reference plate (Fig. 9). Since the trend line patterns for the two steels have matching characteristics, it becomes evident that the lower initial transition temperature of the A543 plate (-130°F (-90°C)), versus the 15-30°F (-9 to +1°C) transition for the A302-B reference heat, in itself may not fully eliminate the general problem of providing sufficient notch ductility to allow for radiation embrittlement in service. In effect, only a tradeoff between a maximum transition temperature requirement and a minimum shelf level requirement may be accomplished with some higher strength steels in certain fluence/exposure temperature applications.

DISCUSSION

The foregoing presentation illustrates the need for qualifying the "weak" as well as the "strong" direction properties of structural alloys intended for certain nuclear service applications. Of course, individual structural components represent separate engineering analysis problems. Thus, it is not implied that the weak direction should invariably be considered as the deciding direction of interest. Only if the particular analysis indicates that the conditions for possible fracture exist, or will develop, in the weak direction with neutron exposure will cognizance of properties in that direction be essential.

Experimental comparisons of weak versus strong (best) orientations have indicated a general correspondence in transition temperature increases; however, the relative reduction in the shelf energy values of one orientation versus the other appear dependent upon the initial difference between the two values produced by the specific cross-rolling practice. Some indications of a direct relationship between shelf reduction and initial shelf level for a given exposure condition can also be discerned in the data. Documentation of preirradiation shelf energy levels undoubtedly can be of great value to later interpretations of irradiated materials performance. The present lack of complete tensile properties data covering a wide range of neutron fluence and exposure temperature conditions is also evident.

Experimental effort is being directed to the interpretation of the Charpy-V shelf drop with neutron irradiation. For the case of nonirradiated steels, the significance of shelf values has been investigated in terms of correspondence to plane strain fracture toughness (K_{Ic}) and K_{Ic}/σ_{ys} ratio parameters by NRL (17-20) and by the U. S. Steel Corporation Research Laboratory (21,22). A ratio analysis procedure defined as RAD has evolved from the NRL studies. This analysis is in general agreement with the U. S. Steel data, which are expressed as formula relationships. With these advances, the NRL RAD indexes Charpy-V and dynamic tear (DT) test shelf energy scales to a system of K_{Ic}/σ_{ys} ratio lines for a wide range of yield strength conditions. Since individual ratios define specific levels of plane strain fracture toughness, recourse can then be made to fracture mechanics flaw-size/stress calculations. The principal advantage of the RAD system is that the presentation is in graphical form and, therefore, is simple to use.

The data of Figs. 9 and 10 can be analyzed by the RAD as representing a progressive change from ductile fracture (plane stress) characteristics to relatively brittle (plane strain) characteristics. This decrease in notch toughness is temperature independent because of the noncleavage micromode fracture process typically involved with shelf level determinations; however, the point of transition from plane stress to plane strain behavior is a function of steel thickness and yield strength as well as shelf energy level. These relationships are inherent to fracture mechanics theory. (For further description of those relationships see Refs. 17, 23, and 24.)

The RAD analysis system is actively being considered for application to the irradiated case. The principal research requirement involves establishing if the Charpy-V/DT scale correspondence to K_{Ic} values is the same as developed for the nonirradiated case. If the relationships are the same, direct use of the existing RAD definition can be made. If the relationships are different, the only change required will be an adjustment of the scales. Investigations of this type are underway.

SUMMARY AND CONCLUSIONS

Charpy-V shelf energy degradation and yield strength increase have been examined for three neutron-irradiated pressure vessel steel compositions: A302-B, A533, and A543. The effects of radiation exposure at low temperatures (<300°F (149°C)) and at elevated temperatures (550°F (288°C) to 740°F (393°C)) on overall notch ductility are documented and compared. Summary plots relating radiation-induced changes in the shelf energy level (in ft-lb) and the yield strength (in ksi) are presented to broadly illustrate the progressive change from ductile fracture performance to relatively brittle characteristics.

Some specific observations made on trend behavior are:

1. Data trends for A302-B, A533, and A543 steel show a common pattern of irradiation effects behavior.

2. Three stages of shelf level versus yield strength change are indicated with progressive neutron exposure at <300°F (149°C). The neutron fluence interval from 0 to $\sim 1\times10^{19}$ n/cm^2 for energies >1 MeV typically produces a rather rapid change in shelf energy and yield strength. The intermediate fluence interval from $\sim 1\times10^{19}$ to $\sim 3\text{-}5\times10^{19}$ n/cm^2 has little additional effect on shelf level but does produce a further increase in yield strength. Above $\sim 5\times10^{19}$ n/cm^2 a marked reduction of shelf energy occurs with only a small additional increase in yield strength.

3. Individual data patterns exhibited by strong (longitudinal-RW) and weak (transverse-WR) test orientations in thick section plate imply strong trend similarities. A 1:1 cross-rolling practice minimizes the relative difference between the strong and weak orientations.

4. The shelf energy versus yield strength behavior with progressive 550°F (288°C) radiation exposure is interpreted as following the same damage path described for <300°F (149°C) irradiation. The much slower rate of properties change with elevated temperature exposures is readily assessed from trend line plots.

5. The trend line for the strong orientation of the ASTM A302-B reference heat approximates the lower bound limit for both strong and weak orientation properties of the several A533 materials analyzed. Generally superior shelf energy values of A533 plate and weld metals (Grades B and C, Classes 1 and 2) indicate greater toughness retention with 550°F (288°C) irradiation than the ASTM A302-B reference heat.

6. The A543 reference heat demonstrates that a lower initial brittle/ductile transition temperature in itself may not fully eliminate the general problem of providing sufficient notch ductility to allow for radiation embrittlement in selected service applications.

7. Studies of A543 steel revealed that temper embrittlement introduced during fabrication (prior to radiation service) does not have a strong influence on subsequent nuclear performance at low or elevated temperatures up to 750°F (399°C).

ACKNOWLEDGMENTS

Metallurgy Division research investigations of the effects of radiation on advanced structural alloys are sponsored by the Office of Naval Research and the U. S. Atomic Energy Commission. This continuing support is acknowledged with gratitude.

The author expresses appreciation to Mr. W. S. Pellini for the many helpful discussions in the preparation of this report.

Table 3
Preirradiation Notch Ductility Properties of Plate and Weldments

Material Identification		Thickness Layer	C_v 30 ft-lb Transition (°F)	C_v Shelf Energy (ft-lb)	NDT (°F)	Approximate C_v Energy Level at NDT (ft-lb)
Type	Thickness (in.)					
Plate						
A302-B (ASTM Reference)	6	Q (Sections 1,2)	+30	71,78	+10	24
		Q (Sections 3,4)	+15	81,86	+10	28
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)[a]	+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
A543 Class 1 (Reference)	8	Section 1 S	-200	82	-200	30
		Q	-130	72	-110	34
		Q(T)	-100	59	-	-
		H	-120	74	-110	33
		Section 2 Q	-130	71	-110	35
		H	-130	71	-110	35
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-B Class 1 (Submerged Arc)	8	Plate 1 S	-135	122	-	-
		Q	+25	136	-	-
		Q(T)	+30	115	-	-
		H	+25	136	-	-
		Weld Face	-50	>100	-	-
		Q, H	-35	106	-	-
		Root	-80	144	-	-
		HAZ	<-40	>100	-	-
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.
[a]Quarter thickness transverse (WR-weak) orientation.

Table 4
Postirradiation Tensile Properties of 6-in. ASTM A302-B Reference Plate

Plate Section	Specimen Orientation*	Experiment No.	Irrad. Temp. (°F)	Fluence ϕ† (>1 MeV) ($\times 10^{19}$ n/cm²)	Test Temp. (°F)	Yield Strength‡ (0.2% Offset) (ksi)	Tensile Strength (ksi)	Reduction of Area (%)	Elongation (%)
1	L (1/4, 3/4T)	–	–	0.0	75	71.8(max.)	94.3	66.9	31.4
						66.0(min.)	88.6	60.2	22.3
						70.7(avg. 10 tests)	92.3	64.8	27.2
	L (3/4T)	IRL-4	<250	0.07	75	83.2	97.5	a	b
				0.11	75	85.5	98.0	a	b
				0.19	75	88.4	97.6	a	b
				0.31	75	94.2	102.2	a	b
				0.50	75	100.0	104.5	a	b
	L (1/4, 3/4T)	BNL-10	<300	0.55	75	103.6(avg. 2)	114.1	52.0	19.4
	L (1/4T)	C(53)-48C	<250	0.85	75	101.1(avg. 2)	102.4	62.7	21.5
					300	90.8	92.8	58.7	18.7
					550	84.8	90.5	53.4	20.1
	L (1/4T)	C(28)-66C	<250	1.3	75	112.2(avg. 2)	112.2	50.7	15.4
	L (1/4, 3/4T)	C(55)-77H	550	3.7	75	92.2	107.4	59.7	b
					350	86.5	102.0	50.1	b
					450	84.0	105.2	42.0	b
					550	82.5	106.2	41.3	b
2	L (3/4T)	–	–	0.0	75	65.6(avg. 2)	87.9	64.1	26.3
	L (1/4T)	(Stress relief annealed-SRA) ¶		0.0	75	62.4(avg. 2)	83.9	67.3	27.2
	L (3/4T)	S-36	<250	5.9	75	131.7(avg. 2)	132.1	54.3	12.4
	L (SRA) (1/4T)	S-36	<250	5.9	75	128.7	128.7	54.0	13.0
	L (3/4T)	S-37	<250	6.2	75	128.5(avg. 2)	128.5	43.2**	10.8**
3	L (1/4, 1/2, 3/4T)	–	–	0.0	75	69.3(max.)	92.0	68.2	32.6
						63.8(min.)	84.5	66.0	26.5
						66.1(avg. 10)	87.9	67.3	28.4
	L (1/4, 3/4T)	–	–	0.0	250	62.0	82.5	66.9	24.2
					350	61.2(avg. 2)	82.8	65.3	23.1
					450	63.0	85.0	63.1	21.8
	T (1/4, 3/4T)	–	–	0.0	75	67.3(max.)	90.3	54.0	23.8
						64.5(min.)	87.0	56.6	26.7
						65.9(avg. 2)	88.7	55.4	25.3
	Th (1/4, 1/2, 3/4T)	–	–	0.0	75	65.8(max.)	84.3	22.4	14.3
						63.3(min.)	82.1	14.5	8.6
						64.2(avg. 5)	83.3	19.1	12.1
4	L (1/4, 3/4T)	–	–	0.0	75	68.3(max.)	91.7	67.3	30.5
						65.5(min.)	90.0	62.2	26.9
						67.6(avg. 6)	90.8	65.1	28.7
	L (3/4T)	C(18)-32C	<250	2.4	75	120.4(avg. 2)	120.4	53.9	b
					300	101.0	101.0	58.7	b
					450	91.0	94.0	52.3	b
					550	84.8	93.0	52.3	b
	L (1/4T)	S-29	<250	9.6	75	134.2	134.4	49.5	b
					300	116.8	116.8	55.0	b
					450	103.0	107.0	46.7	b
					550	99.3	99.5	a	b
					650	88.5	96.0	a	b

*L — Longitudinal (parallel to primary plate rolling direction)
T — Transverse (perpendicular to primary plate rolling direction)
Th — Thickness (parallel to plate thickness direction).

†Fission $\bar{\sigma} = 68$ mb, ^{54}Fe.
‡0.252-in.-diam specimen.
¶Stress relief annealed by six cycles at 1125°F for 30 hours total.
**One determination only.
[a]Not available.
[b]Specimen broke out of 1-in. gage length.

Table 5
Postirradiation Tensile Properties of Heavy Section A533 Plate and Weldments

Material Ident.	Specimen Orientation*	Experiment No.	Irrad. Temp. (°F)	Fluenceϕ† (>1 MeV) ($\times 10^{19}$ n/cm^2)	Test Temp. (°F)	Yield Strength‡ (0.2% Offset) (ksi)	Tensile Strength (ksi)	Reduction of Area (%)	Elongation (%)
PLATE Gr.B Cl.1 (8-1/8 in.)	L (1/4, 3/4T)	-	-	0.0	75	70.7 (avg. 3 tests)	93.4	67.9	24.2
	T (1/2, 1T)	-	-	0.0	75	67.8 (avg. 4)	93.2	65.2	25.4
	L (1/4T)	S-46	<300	3.0	75	125.9 (avg. 2)	125.9	49.0	11.5
	L (1/4, 3/4T)	T(D3)-40T	540	0.58	75 550	83.2 (avg. 2) 72.9 (avg. 3)	103.8 97.0	63.6 51.7	23.5 19.4
Gr.B Cl.1 (6-3/8 in.)	L (1/4, 3/4T)	-	-	0.0	75 585	69.4 (avg. 4) 61.6 (avg. 2)	89.4 87.1	70.7 63.6	28.1 26.4
	L (3/4T)	T(D3)-40T	530	0.58	75	71.1 (avg. 2)	89.6	67.2	27.1
Gr. B Cl.2 (6-3/8 in.)	L (1/4, 3/4T)	-	-	0.0	75 600	79.3 (avg. 2) 71.3 (avg. 2)	97.7 95.5	69.4 61.4	25.9 24.9
	L (1/2T)	-	-	0.0	75	75.6	94.5	67.9	27.1
	L (1/2T)	S-50	-	3.3	75	126.0 (avg. 2)	127.9	4.3	a
	T (1/2T)	-	-	0.0	75	74.2	94.2	61.7	23.4
	L (1/4, 3/4T)	T(D3)-40T	530	0.58	75 550	82.2 (avg. 2) 74.1 (avg. 3)	100.5 97.8	67.1 61.0	24.6 23.6
	L (1/2T)	T(B3)-32DT	≈550	1.9	75	85.4	102.5	64.1	23.9
	T (1/2T)	T(B3)-32DT	550	1.9	75	84.8	101.9	57.1	22.7
WELDMENT Submerged Arc Gr. B Cl.1 (7-1/2 in.)	Plate 1 L (1/4, 3/4T)	-	-	0.0	75	63.8 (avg. 2)	84.9	71.7	29.1
	T (1/4T)	-	-	0.0	75	62.7	84.0	64.1	27.8
	L (1/4T)	T(D3)-40T	535	0.8	75	68.0 (avg. 2)	89.3	68.8	28.5
	Plate 2 L (1/4, 3/4T)	-	-	0.0	75	64.4 (avg. 2)	86.8	68.8	29.0
	Weld (T) (1/2T)	-	-	0.0	75 550	64.3 (avg. 2) 58.3	83.7 78.2	70.4 58.2	26.6 20.1
	Weld (T) (1/2T)	T(D3)-40T	535	0.8	75 550	77.0 (avg. 2) 69.6	93.7 88.8	62.6 57.6	23.1 19.8
Submerged Arc Gr.C Cl.2 (4-in.)	Plates 1 & 2 L (1/4, 3/4T)	-	-	0.0	75 550	66.8 (avg. 2) 59.0 (avg. 2)	88.2 86.5	70.2 58.9	28.2 23.9
	Plates 1 & 2 L (1/4, 3/4T)	T(D3)-40T	550	0.58	75 550	78.7 (avg. 2) 72.0 (avg. 2)	97.1 94.0	65.5 53.9	24.2 21.4
	Weld (T) (1/4, Root)	-	-	0.0	75 550	76.4 (avg. 2) 67.6 (avg. 2)	90.1 84.2	70.6 59.2	26.5 19.3
	Weld (T) (1/4, Root)	T(D3)-40T	570	0.58	75 550	89.5 (avg. 2) 80.6 (avg. 2)	100.1 94.4	68.9 52.3	26.3 19.0

* L - Longitudinal (parallel to primary plate rolling direction).
T - Transverse (perpendicular to primary plate rolling direction).
(T) - Perpendicular to welding direction.
†Fission $\bar{\sigma}$ = 68 mb, ^{54}Fe.
‡0.252-in.-diam specimen.
a - Specimen broke out of 1-inch gage length

Table 6
Postirradiation Tensile Properties of 8-in. A543 Class 1 Reference Plate

Plate Section	Specimen Orientation*	Experiment No.	Irrad. Temp. (°F)	Fluence ϕ† (>1 MeV) ($\times 10^{19}$ n/cm^2)	Test Temp. (°F)	Yield Strength‡ (0.2% Offset) (ksi)	Tensile Strength (ksi)	Reduction of Area (%)	Elongation (%)
1	L (1/4, 1/2, 3/4, 1T)	–	–	0.0	75	96.0 (max.) 84.5 (min.) 95.2 (avg. 6 tests)	124.0 113.8 118.4	73.4 63.6 68.8	27.8 23.8 26.0
	L (1/4T)	–	–	0.0	600	95.2	121.5	60.7	19.9
2	L (1/4, 1/2T)	–	–	0.0	75	96.6 (avg. 3)	120.5	68.4	22.6
	L (1/4, 3/4T)	–	–	0.0	585	93.3 (avg. 2)	115.7	60.7	21.0
1	L (1/4T)	T(C3)-4C	<250	0.52	75	124.3 (avg. 2)	135.8	63.3	16.7
	L (1/4T)	C(28)-66C	<250	1.3	75	136.6 (avg. 2)	142.1	a	12.9
	L (1/4T)	C(28)-67C	<250	1.3	75	133.0 (avg. 2)	138.4	62.9	16.3
	L (3/4T)	T(A5)-7C	<300	1.4	75	141.5 (avg. 2)	150.0	60.7	17.3
2	L (1/2T)	S-48	<250	3.7	75	156.2 (avg. 2)	160.7	61.4	14.8
1	L (1/2, 3/4)	T(D3)-40T	540	0.8	75	107.6 (avg. 2)	129.6	63.9	23.4
	L (3/4T)	T(D3)-40T	540	0.8	550	102.9 (avg. 2)	126.3	54.7	19.6
1	L (1/4, 3/4T)	C(55)-77H	550	3.7	75 350 450 550 650	120.5 116.0 106.0 a a	137.5 131.0 131.0 130.5 128.8 (avg. 2)	59.7 52.3 57.6 62.2 59.7	b b b 19.1 b
3 (Heat No. 2)	L (1/4T)	–	–	0.0	75 550	100.8 (avg. 2) 89.2 (avg. 2)	115.6 106.6	68.3 64.5	23.6 21.2
	T (1/4T)	–	–	0.0	75 550	102.9 (avg. 2) 92.1 (avg. 3)	117.2 107.8	67.4 63.8	23.1 19.5
	L (1/4T)	T(D3)-40T	540	0.8	75 550	107.8 (avg. 2) 94.6 (avg. 2)	122.1 110.6	66.0 63.9	23.4 19.3

*L - Longitudinal (parallel to primary plate rolling direction)
T - Transverse (perpendicular to primary plate rolling direction).
†Fission $\bar{\sigma}$ = 68 mb, ^{54}Fe.
‡0.252-in.-diam specimen.
a-Not available.
b-Specimen broke out of 1-in. gage length.

Table 7
Postirradiation Charpy-V Shelf Energy Values
for 6-in. ASTM A302-B Reference Plate

Irradiation Temperature (°F)	Fluence ϕ* (>1 MeV) ($\times 10^{19}$ n/cm^2)	Experiment No.	Approximate Charpy-V Shelf Energy (ft-lb)
Preirradiation	0.0	Sections 1, 2, 3, 4 Sections 1, 3	71, 78, 81, 86 46, 45 (T)†
<300	0.75	T(C3)-1C	59
	0.75	C(49)-47C	56
	1.25	C(28)-49C	51
	1.3	S-19	64
	1.8	C(18)-62C	61
	1.8	S-17	54
	2.0	C(53)-25C	52
	2.0	C(53)-25B	57
	2.2	S-20	57
	3.1	C(43)-72C	55
	3.1	C(43)-72CSRA	56
	10.0	S-33	48
	11.0	S-30	40
	11.0	S-30	18 (T)
	1.2	C(53)-50C	49
550	0.2	T(D3)-14H	81
	0.7	C(18)-8	>66
	1.1	C(57)-88H	69
	1.5	C(53)-68H	57
	1.7	C(55)-111H	55
	1.7	C(55)-111H	41 (T)
	2.1	C(18)-105H	>60
	2.3	C(55)-99H	69
	3.0	C(43)-108H	65
	3.1	C(55)-54H	63
	3.1	C(43)-86H	59
	3.1	C(43)-86HSRA	61
	3.1	C(55)-61H	60
	3.4	C(43)-89H	64
	4.8	C(55)-85H	64
600	2.6	C(55)-80H	≈66
650	4.1	C(43)-95H	>65
740	5.6	C(43)-98H	75

*Fission $\bar{\sigma}$ = 68 mb, ^{54}Fe.
†Quarter-thickness transverse (WR-weak) orientation.

Table 8
Postirradiation Charpy-V Shelf Energy Values for Heavy Section A533 Plate and Weldments

Material Identification	Irradiation Temperature (°F)	Fluence ϕ* (>1 MeV) ($\times 10^{19}$ n/cm²)	Experiment No.	Thickness Layer†	Approximate Charpy-V Shelf Energy (ft-lb)
Plate					
Gr. B Cl. 1 (4-in.)	550	2.3	C(55)-99H	S	75
				Q	77
				H	75
Gr. B Cl. 1 (8-in.)	550	2.3	C(55)-99H	S	>90
				Q	98
				H	98
Gr. B Cl. 1 (8-1/8-in.)	<300	3.0	S-46	Q	77
		3.0	S-46	Q	69 (T)‡
	550	0.5	T(D3)-20H	Q	96
		1.7	C(55)-111H	Q	86
		1.7	C(55)-111H	Q	74 (T)
Gr. B Cl. 1 (6-3/8-in.)	<300	2.8	S-49	Q	100
	550	0.2	T(D3)-14H	Q	137
		2.0	C(43)-112H	Q	≈130
		2.0	C(43)-112H	Q	>75 (T)
Gr. B Cl. 2 (6-3/8-in.)	<300	3.3	S-50	Q	≈54
	550	0.5	T(D3)-20H	Q	120
		2.0	C(43)-112H	Q	>70
		2.0	C(43)-112H	S	84
		2.0	C(43)-112H	H	>85
Weldment					
Submerged Arc Gr. B Cl. 1 (7-1/2-in.)	550	1.7	C(55)-111H	Plate 1 Q	>100
				Plate 2 Q	121
				Weld Q	63
				HAZ Q	>80
Submerged Arc Gr. B Cl. 1 (8.0-in.)	550	0.5	T(B3)-18H	Plate 1 Q,H	136
				Q	110 (T)
				S	122
				Weld Q,H	69
				Root	144
				HAZ Q	>115
		2.4	T(D3)-22H	Plate 1 Q,H	>120
				Q	102
				S	122
				Weld Q,H	67
				Root	≈125
				HAZ Q	>90
Submerged Arc Gr. C Cl. 2 (4-in.)	550	1.4	T(D3)-19H	Plates 1,2 Q	96
				Weld Q	59
Electroslag Gr. B Cl. 1 (5-3/4-in.)	550	1.8	T(B3)-21H	Plates 1,2 Q	115
				Weld Q,H	79

*Fission $\bar{\sigma}$ = 68 mb, ^{54}Fe.
†S - Surface layer
Q - Quarter thickness
H - Half thickness.
‡Quarter-thickness transverse (WR-weak) orientation.

Table 9
Postirradiation Charpy-V Shelf Energy Values
for 8-in. A543 Class 1 Reference Plate

Irradiation Temperature (°F)	Fluence ϕ* (>1 MeV) ($\times 10^{19}$ n/cm^2)	Experiment No.	Approximate Charpy-V Shelf Energy (ft-lb)
Preirradiation	0.0	Sections 1,2	72,71
		Section 1	59 (T)†
<300	0.50	T(C3)-4C	60
	1.1	C(53)-36C	>46
	1.4	T(A5)-7C	46
	1.7	T(F5)-10C	54
	1.7	T(F5)-10C	41 (T)
	2.1	C(55)-84H	>44
	2.5	C(53)-55C	47
	3.7	S-48 (Section 2)	45
	3.7	S-48	32 (T)
	5.9	S-40	38
	8.5	S-39	30
	8.5	S-39	29 (T)
550	1.5	C(55)-65H	49
	3.4	C(43)-89H	61
	3.8	C(55)-44D	63
	4.8	C(55)-85H	53
650	4.1	C(43)-95H	65
740	5.6	C(43)98H	>55

*Fission $\bar{\sigma}$ = 68 mb, ^{54}Fe.
†Quarter-thickness transverse (WR-weak) orientation.

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