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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Tensile strength and Charpy-V (C_V) notch ductility changes with 550 F (288 C) irradiation were explored for several low alloy structural steels. The study was addressed to metal fracture resistance at upper shelf temperatures and encompassed A302-B, A533-B, A543-1, 9Ni-4Co-.20C, 12-6PH, and 12Ni-5Cr-3Mo steel compositions. Material forms included plate, forging, and weld deposit. Specimen irradiations were conducted in the Advanced Test Reactor (ATR); neutron fluences ranged from 1 to 7 $\times$ 10^{20} n/cm^2 >1 MeV.

20. Abstract (Continued)

Consistent trends in pre- and postirradiation yield strength vs temperature were observed for all materials. Some capability for uniform strain hardening was shown by each material, irrespective of fluence condition. A significant detrimental effect of high copper content (> or = 0.15 % copper) on yield strength behavior with neutron exposure was noted for A302-B/A533-B and A543 steels.

The implications to postirradiation fracture resistance of C_v upper-shelf values were assessed using NRL-developed Ratio Analysis Diagram (RAD) procedures. RAD assessments of a low copper content A533-B plate and weld deposit indicated that thick sections of either material would exhibit plastic fracture behavior after 2.5×10^{20} n/cm^2 >1MeV at 550° (288°C). An experimental 12-6PH alloy of higher strength is also shown to have promise for high-fluence applications.

A predicted trend for C_v upper-shelf energy vs yield strength change with increasing fluence was confirmed by the present findings.

CONTENTS

STRENGTH AND NOTCH DUCTILITY OF SELECTED STRUCTURAL ALLOYS AFTER HIGH-FLUENCE, 550 F (288 C) IRRADIATION

INTRODUCTION

Structural applications of low-alloy steels in advanced nuclear reactor systems are tending toward higher lifetime neutron fluences than previously considered in design. The reactor pressure vessel is only one application contributing to this trend. Higher service fluences have prompted the tailoring of alloys for improved radiation embrittlement resistance [1-4]; still, radiation performance trends for both conventional and improved alloys have been explored in detail only to fluences of about 5×10^{19} n/cm^2 >1 MeV. Trend investigations, moreover, have been directed mainly to the increase in the ductile-to-brittle transition temperature.

Recently, extensive interest has developed in the elevation in strength with irradiation and the degradation in upper-shelf energy determined by Charpy-V (C_v) or dynamic tear (DT) tests. Jointly, these two properties are an indicator of metal fracture resistance at the temperatures at which reactor structures normally operate. Current engineering interest in upper-shelf notch toughness is reflected in part by Title 10, Code of Federal Regulations, Part 50, Appendix G, which sets forth fracture toughness requirements for the upper-shelf condition. To extend available information on upper-shelf performance, this study investigates several advanced commercial and promising experimental structural alloys exposed to neutron fluences of 1 to 7×10^{20} n/cm^2 >1 MeV. The investigation centers on pre- and postirradiation C_V and tensile-strength determinations. NRL-developed Ratio Analysis Diagram (RAD) procedures [5] are applied to qualify metal toughness in terms of plastic, elastic-plastic, and elastic fracture performance capabilities.

MATERIALS

Plate, forging, and weld deposit materials selected for the investigation are described in Tables 1, 2, and 3, according to chemical composition, heat treatment condition, and yield and tensile strength, respectively. Among the materials listed, the most extensive radiation effects information exists for the ASTM A302-B reference plate [6]. The 6-in.-thick A533-B plate and the 6-in.-thick A533-B submerged arc weld deposit, identified as commercial scale demonstration materials, represent tests of improved radiation embrittlement resistance by the minimization of copper and phosphorus impurities. Both tests proved highly successful with moderate fluence exposures (i.e., 3 to 4×10^{19} n/cm^2 >1 MeV) at 550°F (288°C), typical of present reactor vessel service [2-3]. The 2 1/4-in.-thick A543-1 submerged arc weld deposits were from a larger laboratory weld series [4] fabricated for a detailed study of the detrimental effect of copper content on radiation resistance. Note that weld Code N40 represents a low copper content and that weld

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Table 1
Chemical Composition of Plates, Forgings, and Weld Deposits

Material Identification		Composition (%, by weight)									
Material Type	Thickness (in.)	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Other
PLATE											
A302-B (ASTM Reference)	6	0.23	1.35	0.015	0.021	0.22	0.22	0.12	0.52	0.22	0.01 V, 0.038 Al
A533-B (Demonstration Melt)	6	0.17	1.22	0.008	0.008	0.19	0.58	0.06	0.50	0.03	0.02 V, 0.015 Al, 0.02 Sn
A543-1	8	0.17	0.32	0.011	0.016	0.25	3.37	1.92	0.50	0.05	0.02 V, 0.02 Al
A543-1	6	0.18	0.30	0.006	0.019	0.25	3.25	1.71	0.52	0.20	0.02 V
9Ni-4Co-.20C	2	0.18	0.20	0.006	0.009	0.02	9.00	0.77	0.95	0.10	0.08 V, 4.50 Co
FORGING											
12-6 PH* (H1025)	4	0.038	0.01	0.010	0.007	0.06	5.96	11.82	. . .	3.01	0.13 Nb, 0.007 N
12-6 PH* (H1100)	4	0.038	0.01	0.010	0.007	0.06	5.96	11.82	. . .	3.01	0.13 Nb, 0.007 N
WELD DEPOSIT											
A533-B-2 (S/A) (Demonstration Weld)	6	0.15	1.28	0.010	0.012	0.20	0.66	0.06	0.48	0.05	0.02 V, <0.01 Sn
A543-1 (S/A)	6	0.10	0.84	0.006	0.008	0.35	0.83	2.40	1.10	0.01	0.02 V
A543-1 (S/A) (NRL Code N40)	2.25	0.07	1.23	0.007	0.006	0.51	0.71	2.07	0.96	0.04	0.05 V
A543-1 (S/A) (NRL Code N43)	2.25	0.07	1.21	0.007	0.006	0.49	0.80	2.07	0.93	0.26	0.04 V
9Ni-4Co-.20C (GTA)	2	0.15	0.39	0.005	0.003	0.17	10.00	1.0	0.60	0.11	0.08 V, 3.8 Co
12Ni-5Cr-3Mo (TIG)	4	0.01	0.02	0.010	0.002	0.14	11.00	5.07	2.78	. . .	0.48 Ti, 0.18 Al

*Composition courtesy Armco Steel Corporation

Table 2
Heat Treatment of Plates, Forgings, and Weld Deposits

Material Identification		Heat Treatment*
Material Type	Thickness (in.)	
PLATE		
A302-B (ASTM Reference)	6	Austenitized 1650°F (899°C) - 2 h, WQ; tempered 1200°F (649°C) - 6 h, FC to below 600°F (316°C)
A533-B (Demonstration Melt)	6	Austenitized 1675°F (913°C) - 6 h, WQ; reaustenitized 1575°F (857°C) - 6 h, WQ; tempered 1250°F (677°C) - 6 h, FC; stress relief annealed (SRA) 1125°F (607°C) - 2 h, FC; Re-SRA 1150°F (621°C) - 8 hr, FC to 600°F (316°C) at 90°F/hr (50°C/hr max.)
A543-1	8	Austenitized 1650°F (899°C) - 8 h heating + 2 h hold, WQ 17 min; reaustenitized 1500°F (816°C) - 8 h heating + 2 h hold, WQ 17 min; tempered 1185°F (640°C) - 8 h heating + 2 h hold, WQ cold
A543-1	6	Austenitized 1675°F (913°C) - 7.5 h, WQ; reaustenitized 1575°F (857°C) - 7.5 h, WQ; tempered 1160°F (627°C) - 6 h, WQ; SRA 1050°F (566°C) - 2 h, AC; Re-SRA 1135°F (613°C) - 6 h, AC
9Ni-4Co-.20C	2	Normalized 1650°F (899°C) - 2 h, WQ; austenitized 1550°F (843°C) - 2 h, WQ; tempered 1025°F (552°C) - 4 h, AC; SRA 975°F (524°C) - 6 h, FC at 100°F/h (56°C/h) max.
FORGING		
12-6 PH (H1025)	4	Solution treated: 1900°F ±25°F (1038°C ±14°C) - 0.5 h, OQ; hardened 1025°F ±15°F (552°C ±8°C) - 4 h, AC
12-6 PH (H1100)	4	Solution treated; 1900°F ±25°F (1038°C ±14°C) - 0.5 h, OQ; hardened 1100°F ±15°F (593°C ±8°C) - 4 h, AC
WELD DEPOSIT		
A533-B-2 (S/A) (Demonstration Weld)	6	SRA 1150°F ±25°F (621°C ±14°C) - 8 h; FC to 600°F (316°C) at 90°F/h (50°C/h) max.
A543-1 (S/A)	6	Post-weld SRA: see Re-SRA of 6-in. A543-1 plate above
A543-1 (S/A) (NRL Code N40)	2.25	Post-weld SRA: 1150°F (621°C) - 8 h, FC
A543-1 (S/A) (NRL Code N43)	2.25	Post-weld SRA: 1150°F (621°C) - 8 h, FC
9Ni-4Co-.20C (GTA)	2	Post-weld SRA: see SRA of 9Ni-4Co-.20C plate above
12Ni-5Cr-3Mo (TIG)	4	Post-weld marage: 900°F (482°C) - 6 h, FC

*WQ—water-quenched; OQ—oil-quenched; FC—furnace-cooled; AC—air-cooled.

Table 3
Tensile Strength of Plates, Forgings, and Weld Deposits
Before and After 550°F (288°C) Irradiation

Material	Fluence* ($\times 10^{20}$ $n/cm^2 > 1$ MeV)		Test Temperature		0.2% Offset†‡ Yield Strength	Tensile Strength
	(Φ^{cs})	(Φ^{fs})	(°F)	(°C)	(ksi)‖	(ksi)
PLATE						
A302-B (ASTM Reference)	0	0	75	24	(A)¶ 70.1	92.0
					(T)** 70.3	92.0
			550	288	(A) 61.6	88.8
	1.9	2.0	250	121	95.5	111.7
			400	204	92.0	110.7
			550	288	89.5	109.7
	6.5	6.8	450	232	119.2	128.9
			550	288	116.7	124.2
A533-B (Demonstration Melt)	0	0	75	24	(A) 63.1	84.0
					(T) 64.8	84.5
			550	288	(T) 56.8	80.5
	2.4	2.5	250	121	84.5	96.5
			400	204	80.8	97.2
			550	288	77.8	97.2
(Class 2)	0	0	75	24	(A) 79.9	97.1
			400	204	(A) 70.1	90.5
	7.1	7.5	400	204	130.6	139.6
A543-1 (8-in.)	0	0	75	24	(A) 100.5	123.4
					(T) 106.5	124.2
			550	288	(A) 91.2	117.9
					(T) 96.0	118.7
	1.9	2.0	250	121	135.9	147.8
			400	204	134.1	149.3
			550	288	127.9	142.6
	6.6	7.0	400	204	183.0	.....
			550	288	173.8	178.8
	0.26	0.27	400	204	100.5††	120.4
A543-1 (6-in.)	0	0	75	24	(A) 99.7	115.4
					(T) 100.2	116.2
			550	288	(T) 79.5	96.5
	2.8	3.0	250	121	161.3	164.0
			400	204	154.8	159.6
			550	288	146.1	152.6
9Ni-4Co-.20C	0	0	75	24	(A) 189.6	206.2
					(T) 188.5	200.9
					(T)‡‡ 188.0	201.9
			550	288	(T) 165.8	180.5

Table 3 (cont'd)

Material	Fluence* (× 10^{20} n/cm^2 >1 MeV)		Test Temperature		0.2% Offset†‡ Yield Strength (ksi)‖	Tensile Strength (ksi)
	(Φ^{cs})	(Φ^{fs})	(°F)	(°C)		
PLATE (cont'd)						
					(T)‡‡ 159.6	172.3
	1.9	2.0	400	204	197.0	200.0
			500	260	192.0	197.7
FORGING						
12-6 PH (H1025)	0	0	75	24	(A) 152.6	154.8
					(T) 156.1	157.8
			550	288	(A) 123.7	125.2
	2.7	2.9	250	121	166.3	168.0
			400	204	157.1	159.3
			550	288	148.8	150.3
12-6 PH (H1100)	0	0	75	24	(A) 114.7	135.1
					(T) 116.7	135.6
	2.7	2.9	75	24	164.8	167.0
			250	121	153.1	156.1
			400	204	144.6	147.1
WELD DEPOSIT						
A533-B-2 (Demonstration Weld)	0	0	75	24	(A) 87.3	100.8
					(T) 84.8	96.2
			550	288	(A) 74.8	92.0
					(T) 71.6	90.5
	2.4	2.5	250	121	104.5	109.4
			400	204	95.7	107.9
			550	288	93.5	105.7
A543-1 (6-in.)	0	0	75	24	(A) 116.4	130.0
			550	288	(A) 102.5	111.8
	2.8	3.0	250	121	160.3	160.8
			400	204	156.1	158.6
			550	288	149.8	153.1
A543-1 (2.25-in., N40)	0	0	75	24	(A) 87.3	101.2
					(T) 88.2	101.9
			550	288	(A) 74.0	86.4
					(T) 71.4	86.2
	1.6	1.7	250	121	102.5	108.2
			400	204	98.7	104.5
			550	288	93.7	102.2
A543-1 (2.25-in.,	0	0	75	24	(A) 93.4	106.2
					(T) 95.6	107.7

Table 3 (cont'd)

Material	Fluence* (X 10^{20} n/cm^2>1 MeV) (Φ^{cs})	(Φ^{fs})	Test Temperature (°F)	(°C)	0.2% Offset†‡ Yield Strength (ksi)‖		Tensile Strength (ksi)
WELD DEPOSIT (cont'd)							
N43)			550	288	(A)	78.8	91.6
					(T)	78.4	92.0
	1.6	1.7	400	204		124.4	128.9
			550	288		117.9	122.4
9Ni-4Co-.20C	0	0	75	24	(A)	205.4	217.6
	1.9	2.0	500	260		218.1	220.1
			500	260		217.1	217.1
12Ni-5Cr-3Mo	0	0	75	24	(A)	182.0	186.7
					(T)	182.0	188.2
			400	204	(A)	154.1	160.1
	1.9	2.0	75	24		201.2	202.4
			400	204		171.5	176.3
			500	260		159.6	171.0

* Fluence $\Phi^{cs} > 0.1$ MeV = 2.15 X $\Phi^{cs} > 1.0$ MeV.
† 0.226-in.-diam. specimen unless noted.
‡ Single determination for irradiated condition.
‖ Multiply by 6.9 to obtain newtons per square meter X 10^6, MN/m^2.
¶ A = as fabricated.
** T = thermally conditioned at 550°F (288°C) out of reactor for 800 h (or 1000 h).
†† 600°F (316°C) irradiation.
‡‡ Thermally conditioned at 700°F (371°C) for 1000 h.
‖‖ Thermally conditioned at 550°F (288°C) for 1000 h.

Code N43 represents a high copper content. Moderate fluence assessments of the 6-in.-thick A543 plates and the 6-in.-thick A543 weld deposits were also conducted earlier [7]. The experimental 12-6PH precipitation hardening alloy, the 9Ni-4Co-.20C alloy, and the 12Ni-5Cr-3Mo maraging alloy extend the preirradiation yield strength range and were selected in addition because of their particular hardening mechanism, alloying combination, and/or demonstrated promise in low-fluence irradiation experiments.

MATERIALS IRRADIATION

Specimen irradiations (standard C_v, 0.226-in.-diameter tension specimens) were conducted in the Advanced Test Reactor (ATR) in a water-cooled loop. The nominal irradiation temperature was 550°F (288°C); loop inlet and outlet temperatures were 535°F (279°C) and 565°F (296°C), respectively. Specimens of one material (8-in. A543-1 plate) were also irradiated at 600°F (316°C). Irradiation times for 550°F (288°C) exposures were either 360 or 1095 h; the irradiation time for the 600°F (316°C) exposure was 1771 h. Because of the vertical distribution of individual specimen groups relative to the fuel core, fluences varied among the materials. Similarly, fluxes varied between experiments.

Fluences greater than 1.0 MeV, based on a calculated neutron energy spectrum (Φ^{cs}) for the exposure facility, are given for each material irradiation.* The calculated spectrum fluence greater than 0.1 MeV is obtained by multiplying the Φ^{cs} fluence greater than 1.0 MeV by 2.15. Fluence determinations were based on analysis of iron neutron dosimeter wires included in each specimen group.

RESULTS

Tensile Properties

Yield and tensile strength properties of the materials before and after irradiation are summarized in Table 3. Test temperatures were selected to bracket C_v upper-shelf temperatures. Results for unirradiated, thermally conditioned specimens (550°F (288°C), 800 h nominal) are also shown. The thermal conditioning time purposely was made greater than the nominal radiation-exposure time to provide a stringent test of thermal stability. As noted, each alloy exhibited good thermal stability at 550°F (288°C) in the absence of irradiation. Post irradiation property changes thus are realistically assumed to be a result of neutron exposure only.

Figures 1 to 3 summarize the findings on yield strength change with irradiation by material type. Several observations are possible. First, a saturation of radiation effects is not evident from the data for several fluence levels for A302-B, A533-B, and A543-1 materials. Second, a linear relationship between yield strength and temperature exists for both irradiated and unirradiated conditions for the range 75°F (24°C) to 550°F (288°C), and this linear relationship essentially is unchanged except for the increase in yield strength. Third, the slope of the yield strength-vs-temperature trend is about the same for all A302-B, A533-B, and A543-1 materials evaluated but is somewhat less than the general slope of the trend in yield strength-vs-temperature for the high-strength alloys. All data patterns imply that accurate projections of yield strength behavior for temperatures in the 75° to 550°F (24° to 288°C) range should be possible from only limited postirradiation data.

Material intercomparisons indicate a significant detrimental effect of a high copper content on yield strength retention for Type A302-B, A533-B, and A543-1 materials. For the case of low copper content, plates and weld deposits of a given material type are shown to have the same increase in yield strength for a particular fluence. A greater yield strength increase is shown for A543 steel than for A302-B or A533-B steel. In contrast, the yield strength increase by irradiation for the high-strength materials is with one exception (12-6PH, H1100) equal to or less than that observed for the A302-B steel. Of special interest to pressure vessel applications is the observation that the yield strengths of the A302-B and A533-B plates and of the A533-B weld deposit were less than 110 ksi after a fluence of 2 to 2.5 × 10^{20} $n/cm^2 > 1$ MeV.

Radiation-induced changes in tensile strength paralleled but were less than yield strength changes (Table 3). Of primary importance, the materials generally exhibited some uniform strain hardening beyond the yield point for all fluence conditions evaluated.

*Data Tables 3 and 4 also list fluences ($n/cm^2 > 1.0$ MeV) based on a fission spectrum assumption.

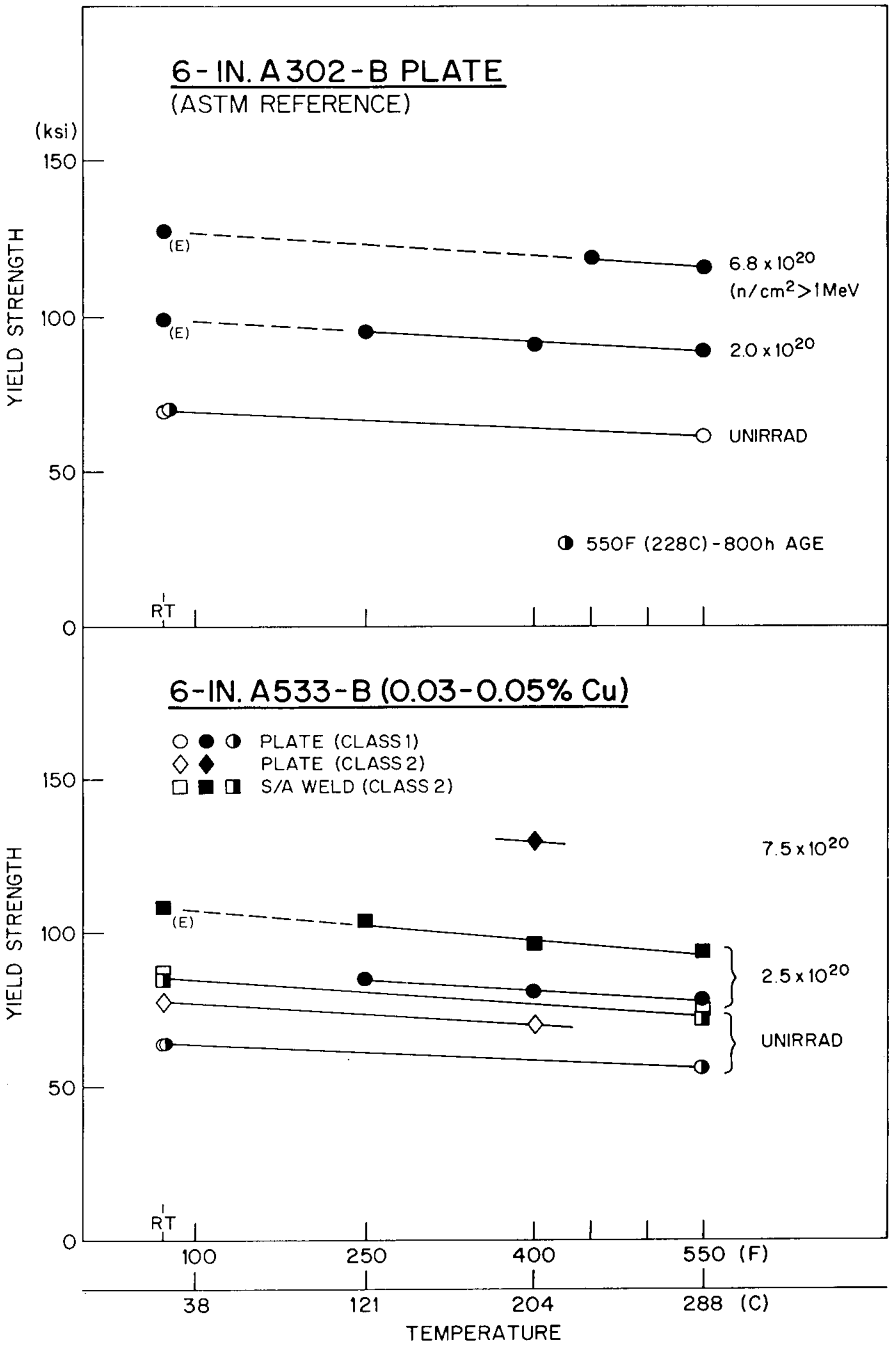

Fig. 1 — Increase in elevated-temperature yield strength with 550°F (288°C) irradiation for the A302-B (ASTM Reference) plate and for low-copper-content A533-B plates and weld deposits from commercial-scale demonstration tests. Results for specimens thermally conditioned at 550°F (288°C) are also shown (half-filled symbols).

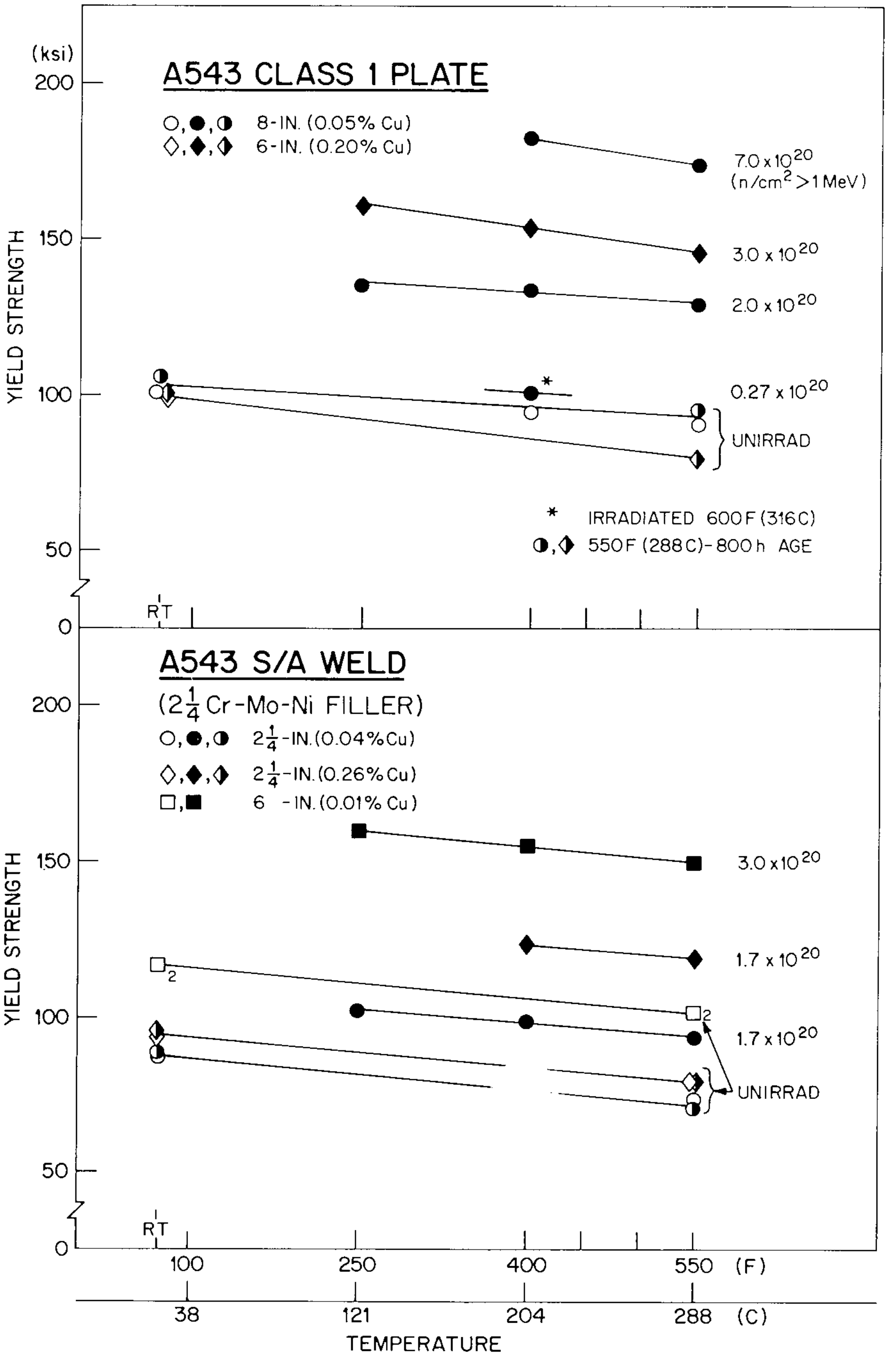

Fig. 2 — Increase in elevated-temperature yield strength with 550°F (288°C) irradiation for A543 Class 1 plates and submerged arc-weld deposits. Half-filled symbols refer to 550°F (288°C) thermal control tests. A 600°F (316°C) irradiation determination for one A543 plate is also shown.

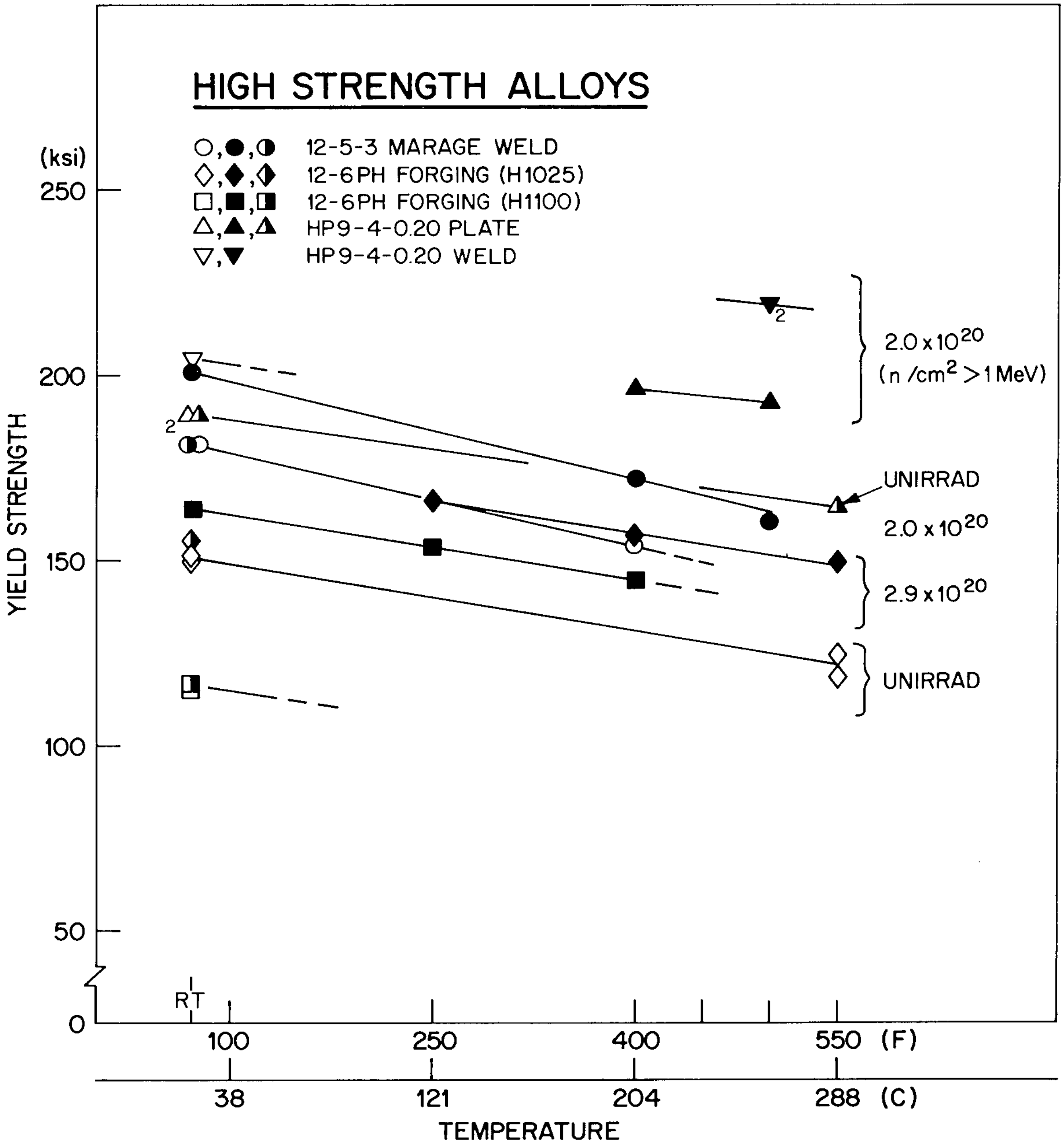

Fig. 3 — Increase in elevated-temperature yield strength with 550° F (288° C) irradiation exhibited by the high-strength materials. Half-filled symbols refer to 550° F (288° C) thermal control tests.

Charpy-V Upper-Shelf Properties

Charpy-V upper-shelf determinations for the plates, forgings, and weld deposits are summarized in Table 4. For the preirradiation condition, upper-shelf temperatures for most of the materials ranged from 80°F (27°C) to 250°F (121°C). After irradiation, most upper-shelf temperatures were between 250°F (121°C) and 400°F (204°C). Two notable exceptions were the A543 plates. Here, a difference in heat-treatment condition (non-temper embrittled vs temper embrittled) and a difference in radiation embrittlement sensitivity (low vs high copper content) combined to produce a very large difference in postirradiation upper-shelf temperatures. Because of limited specimen numbers, a confirmation of upper-shelf development for the 6-in. A543-1 plate at 500°F (260°C) (the highest test temperature) was not possible. Upper-shelf temperature definition for the 9Ni-4Co-.20C weld deposit is also approximate. With reference to the 12Ni-5Cr-3Mo maraging weld, C_v energy absorption was found to gradually increase between 80°F (27°C) and 500°F (260°C) both before and after irradiation. In the previous section it was noted that this weld also showed the greatest decrease in yield strength with increasing temperature.

Large differences in postirradiation upper-shelf energy were observed. Eight material conditions resulted in upper-shelf energy values of 50 ft-lb or higher; six material conditions resulted in upper-shelf values less than 50 ft-lb. Charpy-V specimens from both plate and forging materials were oriented in the longitudinal test direction. Preirradiation assessments of the A533-B and 9Ni-4Co-.20C plates and of the 12-6PH forgings revealed only small directional property differences; however, the A302-B and A543-1 plates showed much lower shelf energy levels in the transverse orientation than in the longitudinal orientation. Directionality differences can be highly significant to projections of probable fracture mode as indicated below.

RAD Assessments of Upper-Shelf Toughness

The Ratio Analysis Diagram (RAD), developed at NRL, provides a simple graphical method for assessing metal fracture resistance in the upper-shelf-level condition. The development of the RAD and its foundation in fracture mechanics are discussed in detail elsewhere [5]. Figure 4 shows the RAD with results of this investigation entered. Primary coordinates are dynamic tear (DT) upper-shelf energy, yield strength (σ_{ys}), and plane strain fracture toughness (K_{Ic}). The C_v energy scale was indexed to the DT scale by experimental correlation. Figure 5 indicates the good correspondence between C_v and DT upper-shelf energies for pre- and postirradiation conditions observed in one study [8]. The RAD is zoned by lines of constant K_{Ic}/σ_{ys} ratio into plastic, elastic-plastic, and linear elastic fracture regimes. The elastic-plastic regime is bounded by ratio lines respectively determined by: B (material thickness) = 1.0 $(K_{Ic}/\sigma_{ys})^2$ and B = 2.5 $(K_{Ic}/\sigma_{ys})^2$. Accordingly, the position of the elastic-plastic regime varies with material thickness.

RAD assessments indicate that, among the materials investigated, only the A533-B plate and weld deposit would exhibit plastic fracture behavior (very high-toughness, plastic overload required for failure) in 6-in.-thick section after a fluence of 2.5×10^{20}. It is important to note that this evaluation assumes uniform material properties through

Table 4
Charpy-V Upper Shelf Performance of Plates, Forgings, and Weld Deposits
Before and After 550 F (288 C) Irradiation

Material	Fluence* (× 10^{20} n/cm2 >1 MeV)		C_v Upper-Shelf Energy (ft-lb)		Postirradiation C_v Upper-Shelf Temperature (approx.)		Temperature Range Postirradiation Tests	
	(Φ_{cs})	(Φ_{fs})	Unirradiated	Irradiated	(°F)	(°C)	(°F)	(°C)
PLATE								
A302-B (ASTM Reference)	1.6 6.5	1.7 6.8	81 81	56 33†	< 340 440	<171 227	340-430 350-600	171-221 177-316
A533-B-1 (Demonstration Melt)	2.4	2.5	140	99	~ 350	~ 177	200-520	93-271
A543-1 (8-in.)	1.6	1.7	72	46	< 200	< 93	200-380	93-193
A543-1 (6-in.)	2.8	3.0	96	23	⩾ 550	⩾ 288	250-550	121-288
9Ni-4Co-.20C	2.0	2.1	76‡	55	< 400	< 204	140-520	60-271
FORGING								
12-6 PH (H1025)	2.6	2.7	102‖	104	⩽ 380	⩽ 193	200-440	93-227
12-6 PH (H1100)	2.6	2.7	131¶	110	< 300	< 149	300-440	149-227
WELD DEPOSIT								
A533-B-2 (Demonstration Weld)	2.4	2.5	127**	82	⩽ 320	⩽ 160	140-500	60-260
A543-1 (6-in.)	2.8	3.0	102	45	~ 380	~ 193	250-550	121-288

Table 4 (cont'd)

Material	Fluence* (× 10^{20} n/cm^2 >1 MeV)		C_v Upper-Shelf Energy (ft-lb)		Postirradiation C_v Upper-Shelf Temperature (approx.)		Temperature Range Postirradiation Tests	
	(Φcs)	(Φfs)	Unirradiated	Irradiated	(°F)	(°C)	(°F)	(°C)
WELD DEPOSIT (cont'd)								
A543-1 (2.25 in.) (NRL Code N40)	1.2	1.3	81	58	~ 280	~ 138	180-400	82-204
A543-1 (2.25 in.) (NRL Code N43)	1.0	1.1	68	43	< 420	< 216	420-500	216-260
9Ni-4Co-.20C	1.9	2.0	⩾ 80††	46	⩾ 500	⩾ 260	500	260
12Ni-5Cr-3Mo	0.96	1.0	84‡‡	66	~ 500	~ 260	80-500	27-260

* Fluence, Φ^{cs} >0.1 MeV = 2.15 × Φ^{cs} >1 MeV.
† 600°F (316°C) irradiation.
‡ Upper-shelf level at 500°F (260°C); upper-shelf level to 300°F (149°C) was 62 ft-lb.
‖ Upper-shelf level between 200°F (93°C) and 400°F (204°C).
¶ Upper-shelf level at 400°F (204°C); upper-shelf level to 200°F (93°C) was 124 ft-lb.
** Upper-shelf level at 550°F (288°C); upper-shelf level to 200°F (93°C) was 118 ft-lb.
†† Weld deposit exhibited 80 ft-lb at 250°F (121°C) and rising.
‡‡ Weld deposit exhibited 71 ft-lb at 200°F (93°C) and gradual rise to 84 ft-lb at 500°F (260°C).

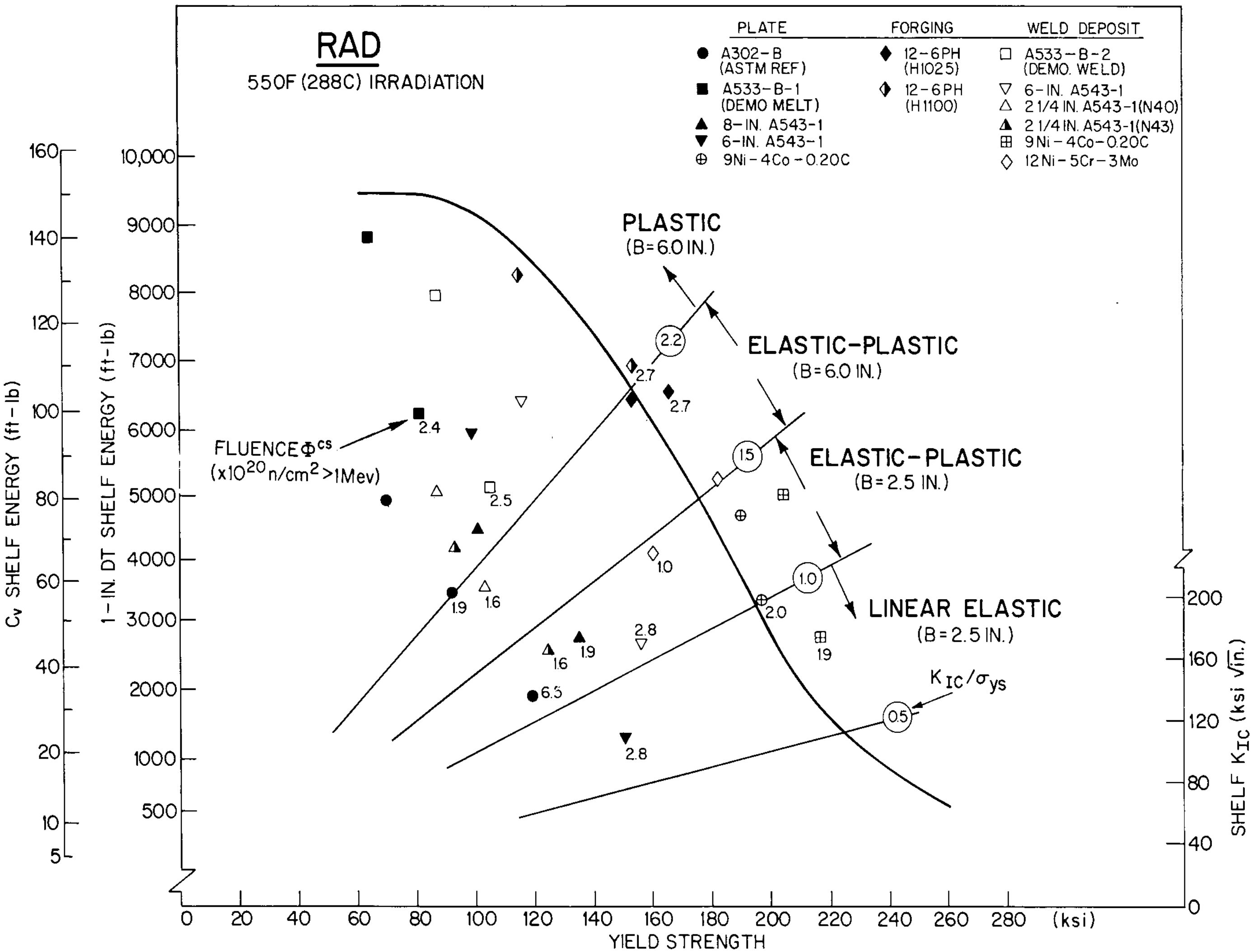

Fig. 4 — The Ratio Analysis Diagram (RAD) illustrating the pre- and postirradiation upper-shelf toughness performance of the several materials. Data points for the low-copper-content A533-B plate and weld deposit (commercial-scale demonstration tests) indicate retention of plastic fracture behavior in thick sections after 2.5×10^{20} $n/cm^2 > 1$ MeV at 550°F (288°C).

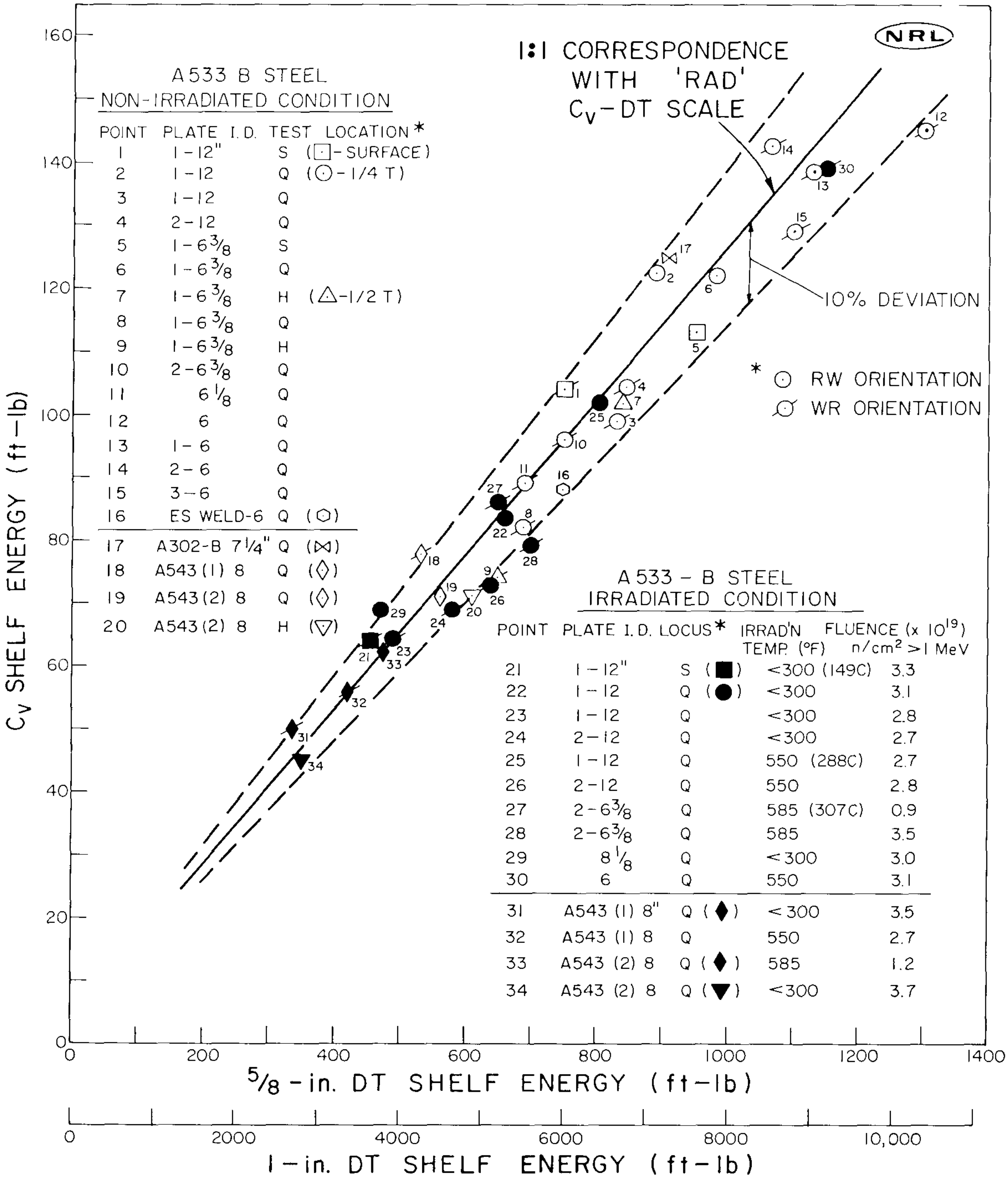

Fig. 5 — Pre- and postirradiation comparisons of Charpy-V and Dynamic Tear upper-shelf energies from numerous plates of A533-B. Comparisons are also illustrated for two plates of A543 steel, an A302-B plate, and an A533 electroslag weld [8].

the thickness after irradiation. At a 2.0 × 10^{20} fluence level, the A302-B plate would also appear to have potential for plastic fracture behavior with respect to the longitudinal orientation; however, the transverse orientation probably would exhibit elastic-plastic behavior (intermediate toughness) for the reason given in the preceding section. Elastic-plastic behavior, nonetheless, is quite acceptable for many if not most service applications. Obviously, both the A533-B and A302-B materials profit by having postirradiation yield strength levels of less than 110 ksi. In this regard, surprisingly high thick-section fracture resistance is depicted for the experimental 12-6PH alloy. The H1025 and H1100 conditions show plastic or high elastic-plastic toughness for a fluence of 2.7 × 10^{20}. In contrast, both A543 plates and two of the three A543 weld deposits appear to offer elastic-plastic fracture characteristics after irradiation only in thinner (2.5-in.) section sizes. The general toughness of the other materials is about comparable to that of the A543 plates. From the above analysis, it is evident that the RAD is well suited to the ready evaluation of shelf toughness for both pre- and postirradiation conditions.

Upper Shelf-vs-Yield Strength Trend With Fluence

In a previous study [9], trends in C_v upper-shelf energy vs yield strength change with neutron fluence were established for the A302-B plate and for the 8-in. A543-1 plate for the low temperature (<300°F, 149°C) irradiation condition. The data trends are reproduced in Figs. 6 and 7. The filled points represent data for individual <300°F (149°C) radiation experiments; the numbers adjacent to individual points indicate fluence in 10^{19} n/cm^2 >1 MeV. Here the indicated yield strength is that measured at 75°F (24°C), not at the C_v upper-shelf temperature as in the case of Fig. 4. In each figure, results from a moderate-fluence, 550°F (288°C) irradiation experiment (open circle) are also indicated. Because of the superposition of the respective data points on the <300°F (149°C) trend lines it was suggested that the shelf energy vs yield strength change with 550°F (288°C) irradiation follows the same damage path as described for <300°F (149°C) irradiation conditions. The results of the present study, as shown in Figs. 6 and 7 (open squares), clearly support the initial assumption. As noted, thermal processes at the higher irradiation temperature serve well to reduce the primary irradiation effect.

DISCUSSION

A comparison of the observed trends in tensile properties behavior with 550°F (288°C) irradiation against those for <300°F (149°C) irradiation [6,9,10] reveals several important differences. A reduction in radiation effect with a 550°F (288°C) exposure temperature is most evident (Figs. 6 and 7). In addition, however, it is found that the decrease in yield strength with increasing test temperature is not as rapid as that observed following <300°F (149°C) irradiation. Additional trend differences relate to the yield strength to tensile strength ratio. In Table 3, some retention of uniform strain hardening (ratio less than 1) with 550°F (288°C) irradiation was indicated even with high fluence. In contrast, a yield strength-to-tensile strength ratio of 1 was produced by fluences as low as 2.4 × 10^{19} n/cm^2 at <300°F (149°C) for the A302-B plate and for other steels investigated. Trend differences therefore suggest care in the extrapolation of data for one irradiation temperature to another, significantly higher or lower, temperature.

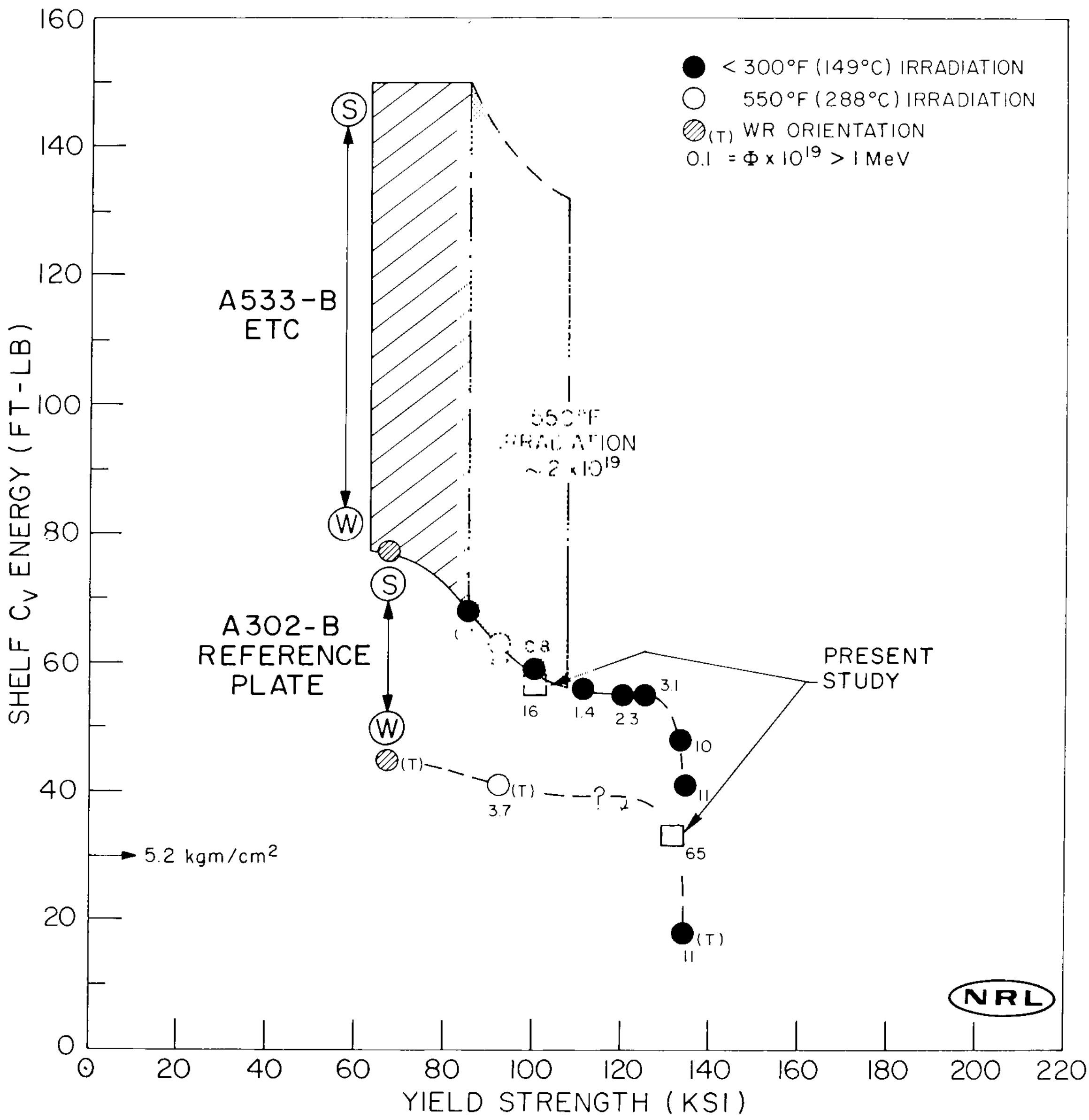

Fig. 6 — Trend in Charpy-V shelf-energy reduction vs yield strength increase for the neutron-irradiated ASTM A302-B reference plate and A533 plate and weld metals. Shaded enclosures for A533 steel represent data for multiple grades and strength classes of thick-section material before and after irradiation at 550° F (288° C) [9]. High fluence, 550° F (288° C) irradiation determinations by the present study are also shown (open-square symbol).

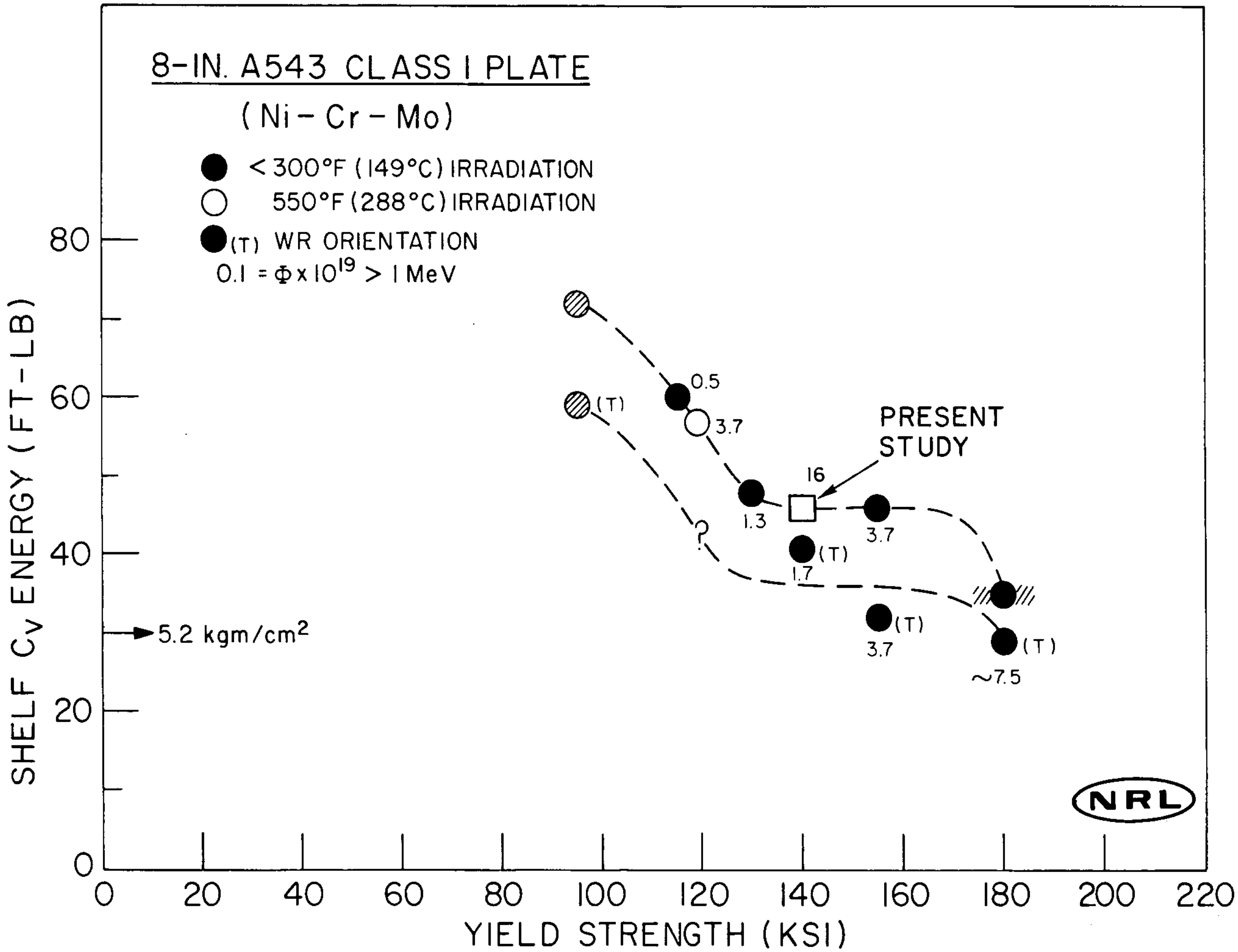

Fig. 7 — Trend in Charpy-V shelf-energy reduction vs yield strength increase of the 8-in. A543 Class 1 plate with neutron irradiation [9]. A high fluence, 550°F (288°C) irradiation determination by the present study is also shown (open-square symbol).

The high upper-shelf toughness retention demonstrated for the A533-B plate and weld deposit was expected and is a clear example of the need for minimizing copper, phosphorus, and sulfur impurities in reactor vessel steels, as proposed by new ASTM and AWS specifications. The evidence against copper content in the low- to medium-strength steels is well established; however, the experimental 12-6PH alloy that showed high upper-shelf toughness after irradiation also includes 3% copper in its composition specification for hardening. The H1025 and H1100 heat-treatment conditions vary in the amount of copper precipitation in the fully martensitic matrix. Niobium, also specified, serves as an inhibitor to copper precipitation during aging. For these two conditions, the results suggested a difference in irradiation effect depending on heat treatment. The mechanisms of copper-enhanced radiation embrittlement in lower strength bainitic alloys have been studied and described [11]. It is proposed that the current understanding of the copper content effect might be refined further by studies with the 12-6PH material, based on the above observations.

Finally, material performance in thick-section components will be influenced to an important degree by the through-thickness toughness gradient normally produced (or modified by) irradiation. Although the nature of the toughness gradient produced from neutron flux attenuation has been explored in detail [12-13], the full significance to thick-section (6-in.) fracture performance is only now being explored. Based on present technology, the estimates of material fracture behavior reported here are felt to be quite conservative.

CONCLUSIONS

Primary conclusions and observations of this investigation are as follows:

1. A linear relationship between yield strength and temperature in the range 75°F (24°C) to 550°F (288°C) is typical for all material types investigated for both 550°F (288°C) irradiated and nonirradiated conditions. The linear relationship, except for the yield strength increase, is unchanged by irradiation to fluences at least as high as 3×10^{20} n/cm^2 and possibly as high as 6×10^{20} to 7×10^{20} n/cm^2.

2. Approximately the same trend in yield strength vs temperature is exhibited by A302-B, A533-B and A543-1 materials (plates and weld deposits). A somewhat different trend appears to be typical of higher strength materials.

3. High ($\geqslant$0.15%) copper content has a significant detrimental effect on the yield strength response of A302-B/A533-B and A543 materials to 550°F (288°C) irradiation. Differences in yield strength response due to alloying composition were also observed.

4. A capability for some uniform strain hardening was exhibited by all materials investigated, irrespective of the level of neutron exposure at 550°F (288°C).

5. Large differences in postirradiation shelf-energy level were typical; however, high-fluence irradiation did not reduce the upper-shelf energy level of eight materials or material conditions to a level below 50 ft-lb.

6. RAD procedures readily qualify postirradiation upper-shelf level toughness behavior. Plastic fracture capabilities after high fluence (2.5×10^{20} n/cm^2) were determined for low-copper A533-B plate and weld deposits in thick (6-in.) section sizes. High post-irradiation fracture resistance was also determined for an experimental 12-6PH alloy of higher yield strength.

7. The findings for two steels, A302-B and A543-1, confirm an earlier predicted trend for C_V upper-shelf energy vs yield strength change with increasing fluence at 550°F (288°C).

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