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Radiation-Embrittlement Resistance of Advanced NiCrMo Steel Plates, Forgings, and Weldments

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ABSTRACT

The 550° F(288° C) irradiation response characteristics of several NiCrMo steel plates, forgings, and weldments were evaluated. Primary objectives were to explore variable radiation-embrittlement tendencies and to assess notch ductility performance relative to that of the MnMoNi steel (ASTM Type A533-B) currently used in nuclear reactor vessel construction. The study was focused on ASTM Type A543 steel in Class 1 and Class 2 heat treatment conditions. Both submerged arc and electroslag weldments were evaluated. Irradiation embrittlement was indexed by the increase in Charpy-V 30 ft-lb transition temperature.

Results clearly demonstrate the promise of ASTM Type A543 plate and related A508 forging steels for advanced reactor applications. Both radiation-embrittlement resistance and preirradiation transition temperature characteristics were found superior to those of standard production A533-B. With only two exceptions, the A543 plates and A508 forgings exhibited sufficient resistance to a fluence of 4×10^{19} n/cm^2 >1 MeV to retain a subzero nil-ductility transition (NDT) temperature. Weld deposits generally had higher postirradiation transition temperatures than plates.

The significant variability in radiation resistance noted among A543 plates and weld deposits could be traced in most instances to composition differences, especially residual element content differences. Anomalous weld heat-affected-zone (HAZ) behavior relative to weld thickness location was observed. A progressive increase in irradiation response with an increase in copper content was found. Vanadium content appears detrimental to radiation resistance of NiCrMo plates, but not to NiCrMo forgings. Weld deposit results infer a harmful effect of nickel content when chromium content is low.

Notch ductility recovery by postirradiation heat treatment was also explored.

PROBLEM STATUS

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

AUTHORIZATION

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RADIATION-EMBRITTLEMENT RESISTANCE OF ADVANCED NiCrMo STEEL PLATES, FORGINGS, AND WELDMENTS

INTRODUCTION

Quenched-and-tempered MnMoNi steel, ASTM Type A533-B, is the current primary choice for new nuclear reactor vessel construction. Interest, however, is developing in the potential of higher strength, quenched-and-tempered, NiCrMo steels for future vessel fabrication. Design interest has been stimulated not only by the possibility for higher system pressures within a given size vessel but also by the possibility for a major system weight reduction through use of thinner vessels. As produced by modern methods, NiCrMo steels exhibit a higher yield strength without sacrifice of good preirradiation notch ductility. Unfortunately, a paucity of data exists by which to judge the relative radiation-embrittlement resistance of these steels. This investigation explores the irradiation response characteristics of several NiCrMo steel plates, forgings, and weldments.

The study focuses on ASTM Type A543 steel as the probable successor to Type A533-B steel for vessel fabrication. Type A543, in addition to having a higher yield strength than A533-B (85 ksi vs 50 ksi, Class 1 condition), offers a much lower preirradiation nil-ductility transition (NDT) temperature [$\leqslant -80^\circ$F(-62°C) vs $\geqslant -10^\circ$F(-23°C)]. Equally important, good radiation-embrittlement resistance was exhibited by an 8-in.-thick reference plate from an early commercial melt (1). Recently, however, melt-to-melt differences in radiation-embrittlement sensitivity have been recognized as typical for low-alloy steels (2-5). Also, significant differences in irradiation performance between weld deposits and plate have been observed, as illustrated in Fig. 1 (2,3,6). Contributing factors to variable radiation-embrittlement sensitivity are residual element (impurity) content and microstructure. The present study was specially tailored to test the variable radiation-embrittlement tendencies of NiCrMo steels and to assess the significance of such variability to overall radiation service potential.

MATERIALS

Materials selected for study represent different primary compositions, different melts of the same nominal composition, and different weldment types (submerged arc and electroslag). Subtle differences in chemical composition (Table 1) and heat treatment condition (Table 2) will be shown to be important to performance. All welds were produced by the Lukens Steel Corporation using standard commercial equipment and practices; however, most filter metals were specially tailored for improved radiation-embrittlement resistance using NRL specifications. Specified residual element content restrictions were based on earlier findings (2,6,7). Welding parameters and procedures for individual welds are outlined in Table 3. Materials of interest included a high-strength 10NiCrMoCo steel for exploring the potential for radiation-induced changes to normal metallurgical stability.

Note: This report is based on a paper to be delivered at the 2nd Inter. Conf. on Pressure Vessel Technology, San Antonio, Texas, Oct. 1-4, 1973.

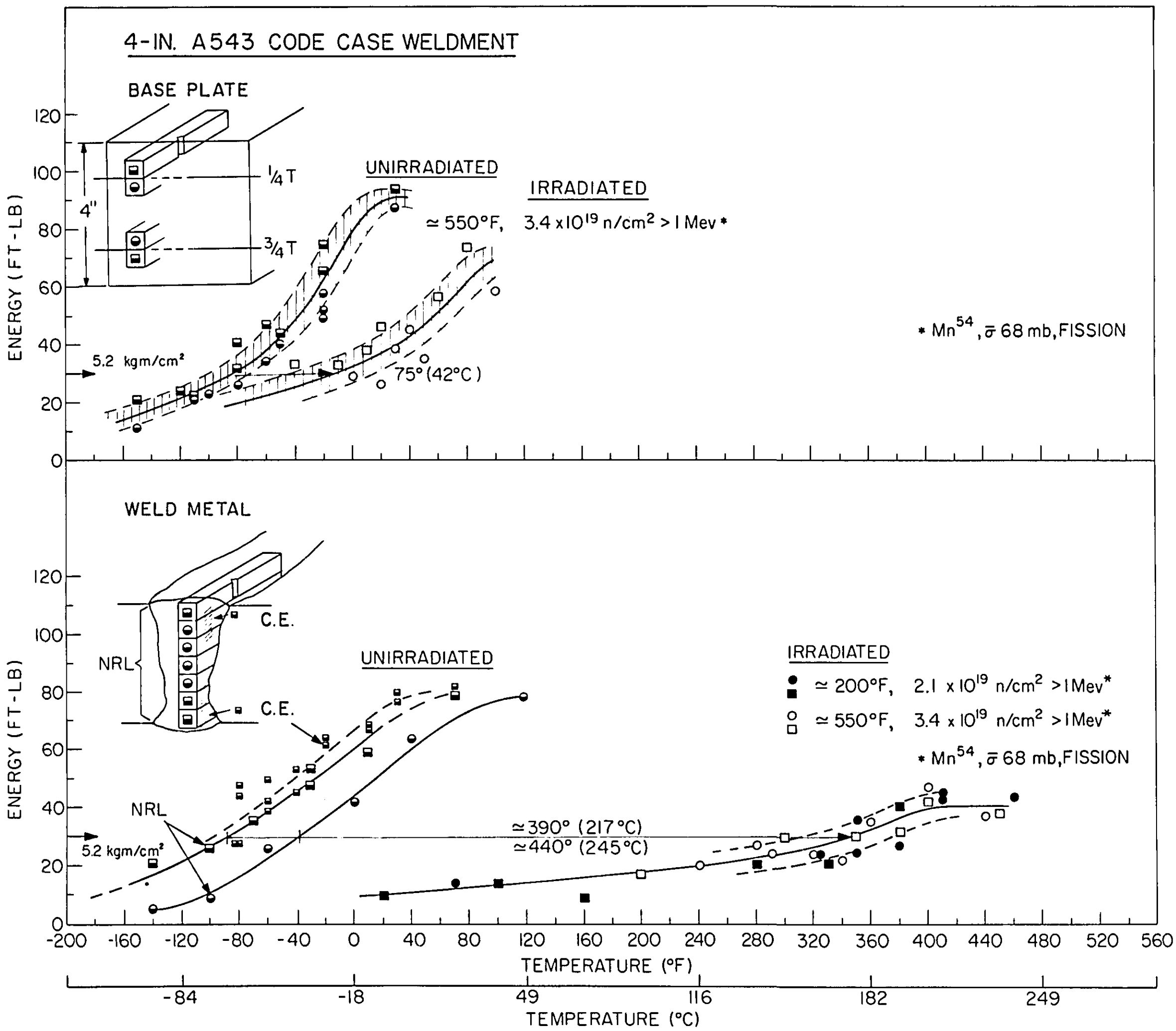

Fig. 1 — Notch ductility performance of a 4-in. A543 manual metal arc weldment prepared in support of ASME Code Case. Weld metal Charpy-V specimens were irradiated at 550°F(288°C) and at 200°F(93°C). (Ref. 2.)

Table 1
Chemical Compsoition and Strength of the NiCrMo Plates, Forgings, and Weld Deposits

Identification	Type	Thickness (in.)	Yield Strength* (ksi)	Tensile Strength (ksi)	Chemical Composition (wt-%) C	Mn	P	S	Si	Ni	Cr	Mo	Cu	V	Other
Plate 1†	A543-1	6	96.6	113.6	0.18	0.30	0.006	0.019	0.25	3.25	1.71	0.52	0.20	0.02	—
Plate 2†	A543-2	6	104.1	118.5	0.18	0.32	0.006	0.019	0.25	3.26	1.71	0.52	0.20	0.02	—
Plate 3	A543-2	5.5	100.5	116.5	0.18	0.31	0.004	0.010	0.22	3.00	1.56	0.42	0.12	0.004	0.030Al ¶
Plate 4	A543(mod)¶	4	109.0	120.7	0.10	0.79	0.005	0.011	0.28	3.36	0.90	0.41	0.04‡	0.09	—
Plate 5	10NiCrMoCo¶	2	184.9	199.4	0.13	0.04	0.005	0.005	0.025	10.4	2.07	1.01	0.03‡	—	7.96Co
Plate 6(ref)#	A543-1	8	95.2	118.4	0.17	0.32	0.011	0.016	0.25	3.37	1.92	0.50	0.05	0.02	0.02Al
Forging 1	A508-4¶	23.5	84.5**††	102.0**††	0.15	0.34	0.007	0.011	0.21	3.47	1.72	0.48	0.10‡	0.01	—
Forging 2	A508-5a	62	107.5	124.4	0.26‡‡	0.31	0.007	0.014	0.05	3.40	1.81	0.47	0.07	0.08	—
Weld Deposit															
Subarc S/A 1	A543-1 (2-1/4NiMnMo filler)	6	102.2	110.4	(AD) 0.09	1.16	0.006	0.007	0.56	2.40	0.09	0.49	0.03	0.01	<0.01Al
					(FW) 0.09	1.63	0.005	0.008	0.51	2.30	0.06	0.57	0.02	0.01	—
					(BP)	(From same melt and ingot as plates 1 and 2 above)									
Subarc S/A 2	A543-2 (2-1/4Cr1MoNi filler)	6	116.4	130.0	(AD) 0.10	0.84	0.006	0.008	0.35	0.83	2.40	1.10	0.01	0.02	—
					(FW) 0.11	1.34	0.006	0.009	0.24	1.00	2.51	1.03	0.025	0.01	—
					(BP)	(Plate 1 above)									
Electroslag E/S 1	A543-2 (2-1/4Cr1Mo filler)	6	93.8	108.1	(AD) 0.14	0.46	0.006	0.018	0.20	2.22	2.10	0.68	0.16	0.02	—
					(FW) 0.06	0.60	0.007	0.019	0.18	0.12	2.70	0.96	0.02	0.02	—
					(BP)	(Plate 2 above)									
Electroslag E/S 2	NiCrMo¶¶ (2-1/4Cr1Mo filler)	3.5	87.8	102.8	(AD)¶0.09	0.43	0.012	0.018	0.10	1.43	1.83	0.54	0.08	< 0.01	0.022Al
					(FW)	(Same filler for E/S weld 1 above)									
					(BP)¶0.19	0.30	0.010	0.015	0.09	2.48	1.24	0.31	0.13	0.003	0.016Al
Electroslag E/S 3	A543-1 (2-1/4Cr1Mo filler;lot 2)	8	94.2	104.0	(AD) 0.11	0.42	0.008	0.016	0.12	1.27	2.35	0.71	0.04	—	—
					(FW)¶0.07	0.52	0.008	0.018	0.18	0.02	2.79	0.95	0.03	—	0.071Al
					(BP)	(Plate 6 above)									

* 0.2% offset.
† Plates 1 and 2 from same melt and ingot.
‡ NRL Determination.
¶ Chemical composition courtesy of supplier.
# Reference plate from early commercial melt.
** Courtesy of supplier.
†† Specimen tangent to forging circumference.
‡‡ Out of specification.
AD = as deposited.
FW = filler wire.
BP = base plate.
¶¶ HY-80 plate.

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

Identification	Type	Thickness (in.)	Heat Treatment*	
Plate 1	A543-1	6	Austenitized	1675°F(913°C) — 7.5 hr, WQ;
			Reaustenitized	1575°F(857°C) — 7.5 hr, WQ;
			Tempered	1160°F(627°C) — 6 hr, WQ;
			Stress relief annealed (SRA)	1050°F(566°C) — 2 hr, AC;
			Postweld SRA:	1135°F(613°C) — 6 hr, AC.
Plate 2	A543-2	6	Same preweld heat treatment as plate 1;	
			Postweld Heat Treatment:	
			Austenitized	1675°F(913°C) — 6 hr, WQ;
			Reaustenitized	1575°F(857°C) — 6 hr, WQ;
			Tempered	1160°F(627°C) — 6 hr, WQ;
			SRA (first)	1100°F(593°C) — 6 hr, FC;
			SRA (second)	1160°F(627°C) — 6.5 hr, fan cooled†.
Plate 3	A543-2	5.5	Austenitized	1650°F(899°C), WQ;
			Reaustenitized	1600°F(871°C), WQ;
			Tempered	1120°F(604°C), WQ.
Plate 4	A543(mod)	4	Austenitized	1660°F(904°C) — 2 hr, WQ;
			Reaustenitized	1550°F(843°C) — 2 hr, WQ;
			Tempered	1180°F(638°C) — 2 hr, WQ.
Plate 5	10NiCrMoCo	2	Austenitized	1650°F(899°C) — 2 hr, WQ;
			Reaustenitized	1550°F(843°C) — 2 hr, WQ;
			Aged	950°F(510°C) — 10 hr, WQ.
Plate 6	A543-1(Ref)	8	Austenitized	1650°F(899°C) — 8 hr heating and 2 hr hold, water quenched for 17 min;
			Reaustenitized	1500°F(816°C) — 8 hr heating and 2 hr hold, water quenched for 17 min;
			Tempered	1185°F(640°C) — 8 hr heating and 2 hr hold, water quenched cold.
Forging 1	A508-4	23.5	Heat treatment not available	
Forging 2	A508-5	62 (diam.)	Austenitized	1550°F(843°C) — 10 hr equalize and 30 hr hold, water (spray) quenched;
			Reheated to	1140°F(616°C) in 30 hr;
			Tempered	1140°F(616°C) — 10 hr equalize and 30 hr hold, AC.
Weld Deposit				
Subarc S/A 1	A543-1 (2-1/4NiMnMo filler)	6	Postweld SRA:	1135°F(613°C) — 6.5 hr, fan cooled†.
Subarc S/A 2	A543-2 (2-1/4Cr1MoNi filler)	6	Postweld SRA:	1135°F(613°C) — 6 hr, AC
Electroslag E/S 1	A543-2 (2-1/4Cr1Mo filler)	6	Postweld Heat Treatment: see postweld heat treatment listed for plate 2 above.	
Electroslag E/S 2	NiCrMo (2-1/4 Cr1Mo filler)	3.5	Postweld Heat Treatment:	
			Austenitized	1675°F(913°C) — 3.5 hr, WQ;
			Reaustenitized	1575°F(857°C) — 3.5 hr, WQ;
			Tempered	1160°F(627°C) — 3.5 hr, WQ;
			SRA (single)	1100°F(593°C) — 3.5 hr, AC.
Electroslag E/S 3	A543-1 (2-1/4Cr1Mo filler)	8	Postweld Heat Treatment:	
			Austenitized	1675°F(913°C) — 8 hr, WQ;
			Reaustenitized	1650°F(899°C) — 8 hr, WQ;
			Tempered	1200°F(649°C) — 8 hr, WQ;
			SRA (single)	1065°F(574°C) — 8 hr, AC.

* Austenitizing temperatures are ±25°F(15°C); tempering and stress relief temperatures are ±15°F(8°C) unless noted otherwise.

† Fan cooled — 1135°F(613°C) to 600°F(316°C) in 70 min.

WQ = quenched in agitated water.
AC = cooled in still air.
FC = furnace cooled.

Table 3
Welding Parameters and Procedures for Individual Welds

Parameter/Procedure	Submerged Arc Weld		Electroslag Weld		
	S/A 1	S/A 2	E/S 1	E/S 2	E/S 3
Base Plate	A543-1	A543-1	A543	NiCrMo (HY80)	A543
Weld Procedure	Tandem electrodes	Tandem electrodes	Twin electrodes*	Single electrode	Twin electrodes†
Filler Type (noncopper clad)	2-1/4NiMnMo (Arcos: IP 2915	2-1/4Cr1MoNi (Special; Arcos: 23706)	2-1/4Cr1Mo (Arcos: D1141 A521)	2-1/4Cr1Mo (Arcos: D1141 A521)	2-1/4Cr1Mo (Arcos: D2062 A521)
Electrode size	1/8 in. diam.	5/32 in. diam.	1/8 in. diam.	1/8 in. diam.	1/8 in. diam.
Flux	Linde 0091‡	Linde 0091‡	Arcos BV	Arcos BV (50%) Arcos V (50%)	Arcos BV
Joint Design	Double U; 2:1 ratio	Double U; 2:1 ratio	Square Edge; Gap 1-1/8 in. to 1-1/4 in.	Square Edge; Gap 1-1/4 in. to 1-5/8 in.	Square Edge; Gap 1-1/4 in. to 1-5/8 in.
Electrode Connection	Scott connection (ac-ac, 90° phase shift)	Scott connection (ac-ac, 90° phase shift)	ac	ac	ac
Current	550 amp (lead); 500 amp (trail)	550 amp (lead); 500 amp (trail)	600 amp (each wire)	600 amp	525-600 amp (each wire)
Voltage	25 V (lead) 30 V (trail)	25 V (lead) 30 V (trail)	50 V	50 V	36-38 V
Travel or Oscillation	31 ipm	31 ipm	2-in. with 5-s dwell	3/4-in. with 3-s dwell	2-5/8-in. with 3.5 s dwell
Slag Depth	—	—	2 in.	2 in.	1-3/4 in.
Preheat Temperature	300°F(149°C)	300°F(149°C)	none	none	none
Interpass Temperature (maximum)	300°F(149°C)	300°F(149°C)	—	—	—
Postweld Heat Treatment	1135°F(613°C)-6.5 hr fan cooled	1135°F(613°C)-6 hr still-air cooled	(see Table 2)	(see Table 2)	(see Table 2)

*Electrode spacing 3 in.

†Electrode spacing 4-3/8 in.

‡Flux (65 × 200) baked at 700° F(371° C) for 2 hr in 2-in.-deep pans prior to use.

Standard Charpy-V (C_v) specimens were utilized for all determinations of irradiation response. Unless noted otherwise, specimens were taken with their long dimension parallel to the primary working direction for plates and forgings, and perpendicular to the welding direction for weld deposits. The specimen notch was oriented perpendicular to the material surface, except for weld HAZ specimens. Here the specimen notch was oriented parallel to the weldment surface and centered on the weld fusion line revealed by etching. Proper notch placement was verified after final machining by re-etching. For selected weld deposits, pre-irradiation assessments also included 5/8-in.-thick dynamic tear (DT) and drop weight (DW) determinations. The DT specimen notch was oriented perpendicular to the weldment surface and was sharpened after machining by the pressed knife edge technique described in Ref. 8.

MATERIAL IRRADIATION

Material irradiations were conducted in the Union Carbide Research Reactor (UCRR) in the D-3 fuel lattice position. For representation of average service conditions of power reactor vessels, a nominal exposure temperature of 550°F(288°C) was used*. Specimen temperatures during irradiation were monitored continuously by thermocouples. Neutron exposures were determined from iron wire neutron detectors (^{54}Fe (n,p) ^{54}Mn reaction) included in the specimen arrays. Fluences Φ (n/cm^2 >1 MeV) are described for an assumed fission spectrum in the exposure facility and for a calculated spectrum neutron energy distribution. Fission spectrum fluences, while less accurate, are necessary for making data comparisons against published trends for A533.

EXPERIMENTAL RESULTS AND DISCUSSION

A543 Plates and A508 Forgings

Figures 2-4 compare the pre/postirradiation performances of the A543 plates and A508 forgings. Property changes are summarized in Fig. 5 and in Table 4. It will be noted that A543 plates 1 and 2 served, respectively, as base plates for submerged arc weld 2 and electroslag weld 1.

Before irradiation, each of the plates and forgings exhibited very good notch ductility. The C_v upper shelf level typically exceeded 95 ft-lb and, except for plate 1, the C_v 30 ft-lb transition temperature was below −100°F(−79°C)†. The 8-in. reference plate (plate 6, Table 4) by comparison developed an upper shelf of 72 ft-lb and a 30 ft-lb transition at −130°F(−90°C). Prior assessments of the A543 reference plate and of two other A543 plates indicated the 30 ft-lb transition to be a reasonable approximate of the drop weight NDT temperature (1,9). Accordingly, the selection of the 30 ft-lb index to assess plate irradiation response was not fully arbitrary.

The poorer C_v 30 ft-lb transition performance of plate 1 [−70°F(−57°C)] relative to plate 2 [−200°F(−129°C)] bears special mention since both plates were from the same melt and ingot. The 130°F difference in transition temperature is believed to be the result of two factors: (a) a difference in cooling rate from postweld stress relief (still-air cooled vs accelerated cooled), and (b) a difference in total austenitizing and quenching heat treatment cycles (two

*The 10NiCrMoCo plate was also irradiated at 800°F(427°C) for special assessments of properties stability

†The C_v 30 ft-lb (5.2 kg - m/cm^2) temperature is often used as a convenient arbitrary index of brittle/ductile transition for pre/postirradiation comparisons of low-alloy steel performance.

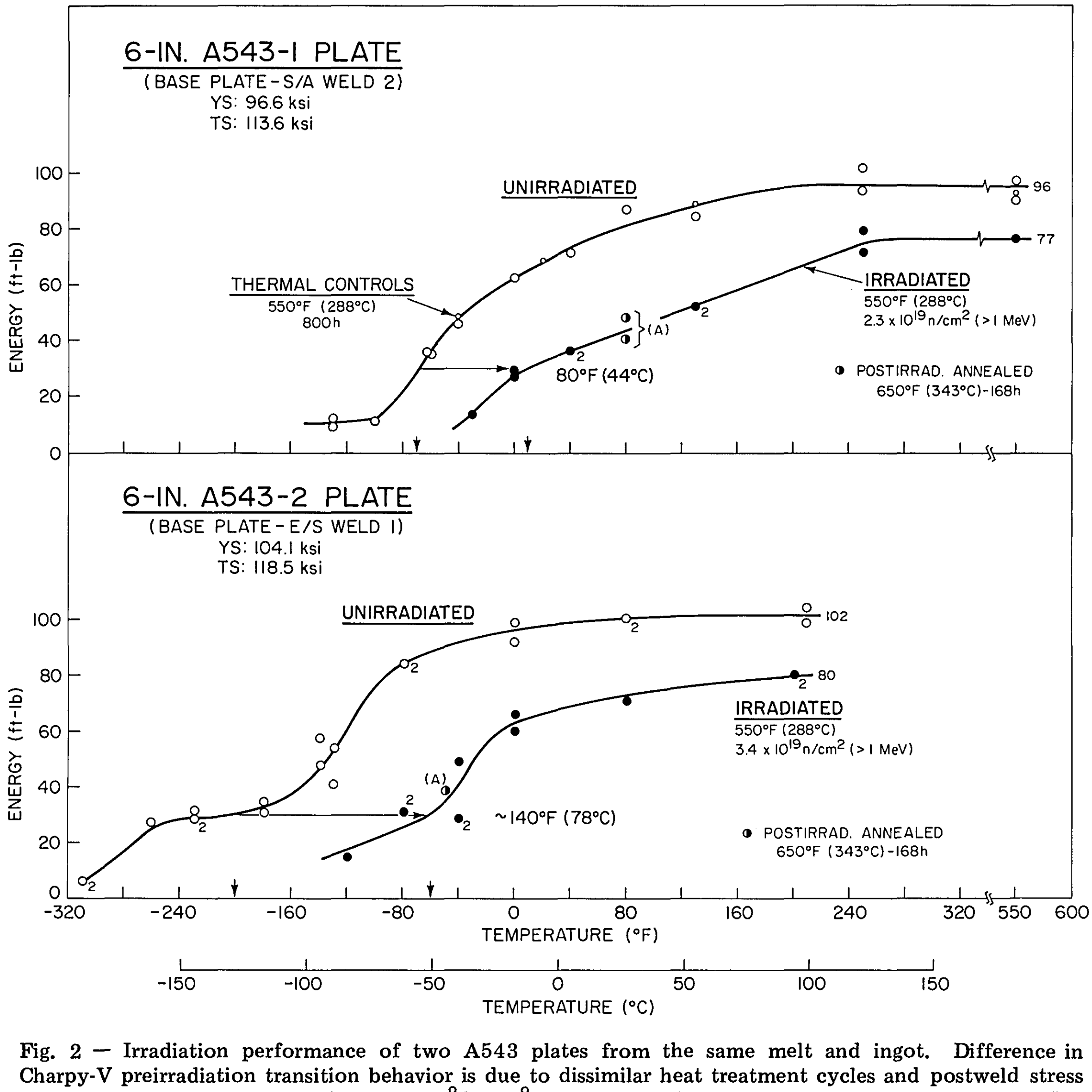

Fig. 2 — Irradiation performance of two A543 plates from the same melt and ingot. Difference in Charpy-V preirradiation transition behavior is due to dissimilar heat treatment cycles and postweld stress relief cooling rates. Limited data for 650°F(343°C) postirradiation heat treatment are also shown. Calculated spectrum fluences Φ^{cs} >1 MeV are 2.0 X 10^{19} n/cm^2 (upper graph) and 3.0 X 10^{19} n/cm^2 (lower graph).

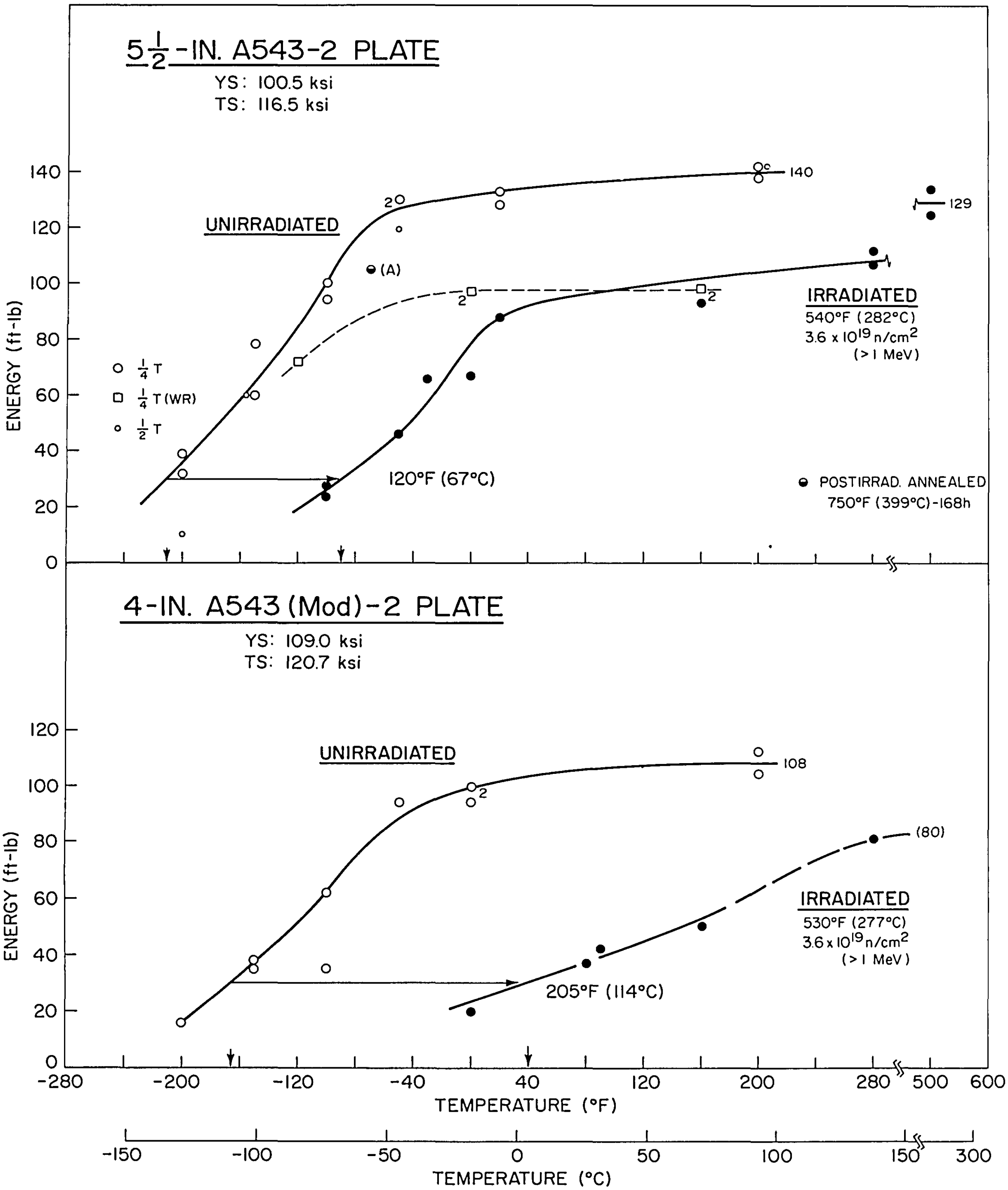

Fig. 3 — Irradiation performance of two A543 Class 2 plates (simultaneous exposure). Higher radiation-embrittlement sensitivity of the A543 (mod) composition plate (lower graph) is believed due to vanadium alloying (0.08%V). Calculated spectrum fluence Φ^{cs} >1 MeV = 3.1 X 10^{19} n/cm^2.

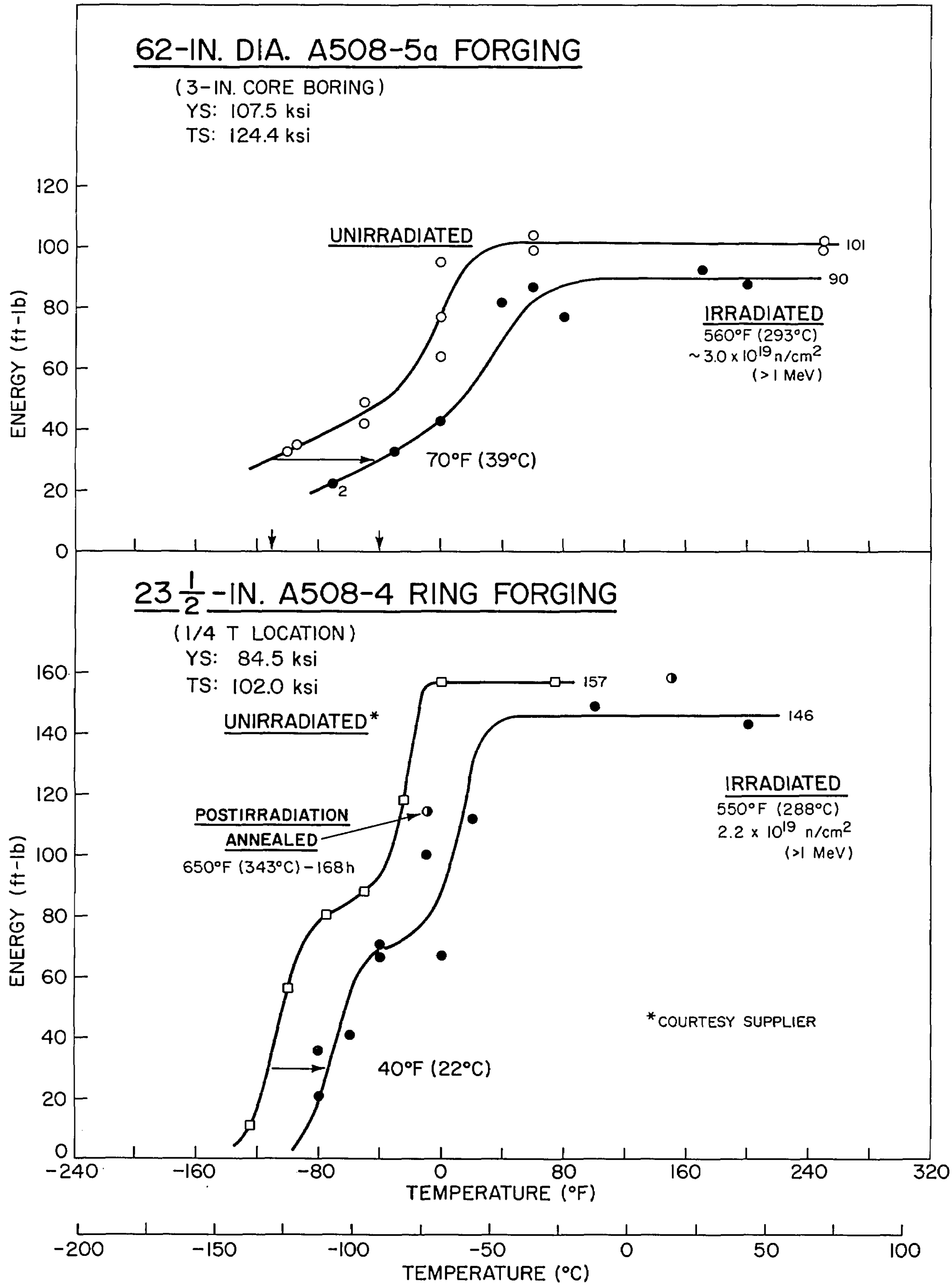

Fig. 4 — Irradiation performance of two A508 forgings. The A508-5a forging does not depict an adverse effect of 0.08% vanadium alloying on radiation resistance as noted for the A543 (mod) plate (see Fig. 3). Calculated spectrum fluence Φ^{cs} >1 MeV = 2.6 X 10^{19} n/cm^2 (upper graph) and 1.9 n/cm^2 (lower graph).

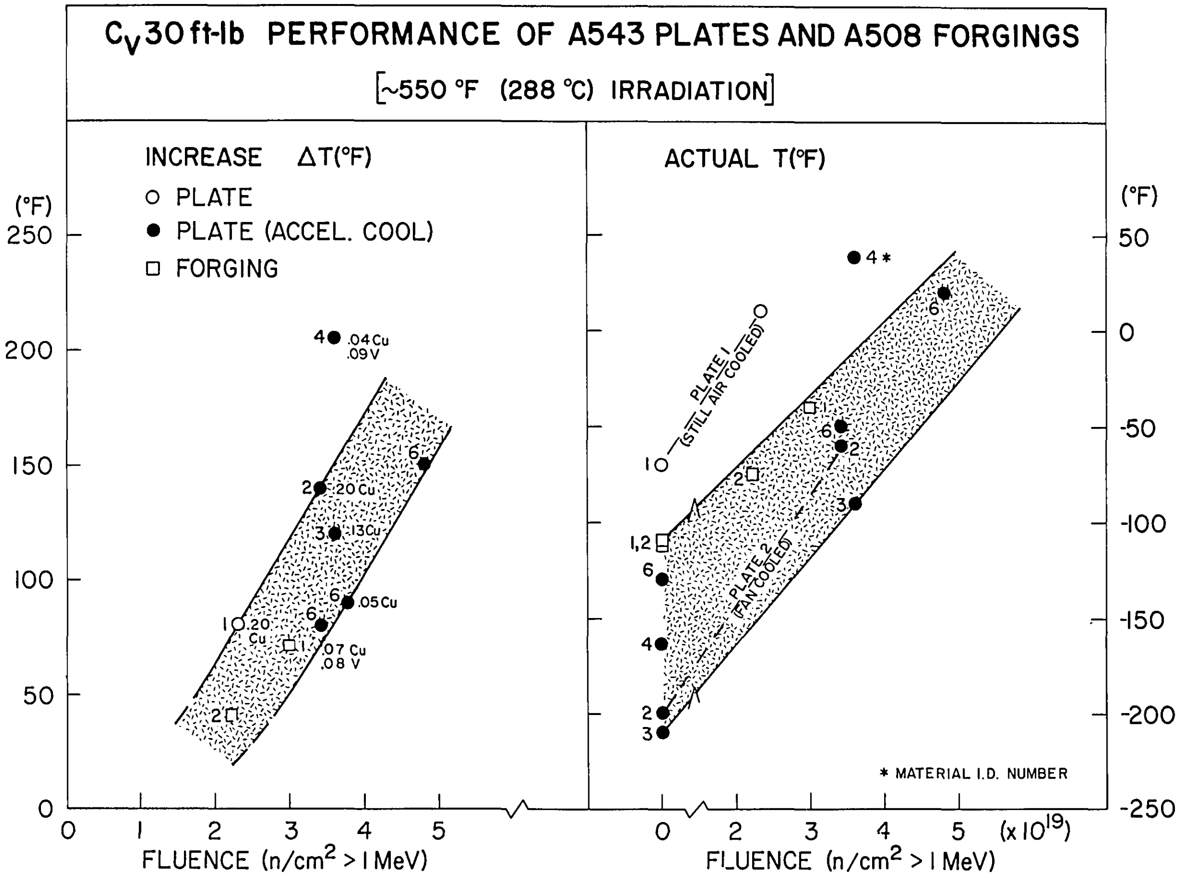

Fig. 5 — Summary of Charpy-V 30 ft-lb transition behavior of A543 plates and A508 forgings with irradiation. Capability for a Φ^{fs} = 4 X 10^{19} n/cm^2 >1 MeV (Φ^{cs} = 3.5 X 10^{19} n/cm^2 >1 MeV) without loss of a subzero transition temperature is indicated, except for two atypical plates (no. 1 and 4). Radiation sensitivity is shown to increase with copper content.

Table 4
Summary of Notch Ductility Properties Before and After Irradiation*

Identification		Type	Fluence 10^{19} n/cm^2 >1 MeV		C_v 30-ft-lb Transition						C_v Upper Shelf			DT Upper Shelf‡	NDT‡	
					Initial		Irrad.		Increase		Initial	Irrad.	Decr.	Initial	Initial	
			Φ^{fs}	Φ^{cs}†	°F	°C	°F	°C	Δ°F	Δ°C	(ft-lb)	(ft-lb)	Δ(ft-lb)	(ft-lb)	°F	°C
Plate	1	A543-1	2.3	2.0	− 70	− 57	10	− 12	80	44	96	77	19			
		HAZ(1)¶	2.3	2.0	−125	− 87	− 40	− 40	85	47	94	>80	<14			
		HAZ(2)¶	2.3	2.0	− 70	− 57	− 25	− 32	45	25	86	84	< 5			
	2	A543-2	3.4	3.0	−200	−129	− 60	− 51	140	78	102	80	22			
	3	A543-2	3.6#	3.1	−210	−134	− 90	− 68	120	67	140	129	11			
	4	A543(mod)	3.6**	3.1	−165	−109	40	4	205	114	108	>80	28			
	5	10NiCrMoCo	3.3		<−200	<−129	<−200	<−129	—	—	100	82	18			
			4.3††	3.7	<−200	<−129	−160	−107	~100	~56	100	122	(+)22			
	6(1)	A543-1 (ref.)	3.4	3.7	−130	− 90	− 50	− 46	80	44	72	61	11	550	−110	− 79
			3.8	4.3	−130	− 90	− 40	− 40	90	50	72	63	9			
			4.8	5.4	−130	− 90	20	− 7	150	83	72	53	19			
Forging	1	A508-4	2.2	1.9	−115	− 82	− 75	− 59	40	22	157	146	11			
	2	A508-5a	~3.0‡‡	2.6	−110	− 79	− 40	− 40	70	39	101	90	11			
Weld Deposit																
Subarc	S/A 1	A543-1 (2-1/4-NiMnMo filler)	3.6	3.1	− 50	− 46	60	16	110	61	140	108	32	1350	− 80	− 62
	S/A 2	A543-2 (2-1/4-CrMoNi filler)	3.6	3.1	− 5	− 21	40	4	45	25	102	102	0	690	− 10	− 23
Electroslag¶¶	E/S 1	A543-1(C)	3.4	3.0	− 40	− 40	100	38	140	78	65	51	14	590	− 80	− 62
		(O)			− 85	− 65	20	− 7	105	58	⩾ 89	71	⩾ 18			
	E/S 2	NiCrMo	3.0	2.6	− 95	− 71	− 45	− 43	50	28	87	77	10			
	E/S 3	A543-1	—		− 50	− 46	—	—	—	—	90	—	—			

* 550°F(288°C) irradiation, except as noted.
† Φ^{cs} — fluence for calculated neutron spectrum:
multiply by 2.0 for Φ^{cs} >0.1 MeV, except for plate 6;
multiply by 2.1 for Φ^{cs} >0.1 MeV for plate 6.
‡ 5/8-in.-thick specimen.
¶ Thickness layer.
\# 540°F(282°C) irradiation.
** 530°F(277°C) irradiation.
†† 800°F(427°C) irradiation.
‡‡ 560°F(293°C) irradiation.
¶¶ 2-1/4Cr1Mo filler.
(C) = centerline location;
(O) = offset location.

vs four cycles). To distinguish between these effects, the performance of a third plate from the same melt and ingot as plates 1 and 2 can be referenced (9). In this case, two heat treatment cycles and an accelerated cool from postweld stress relief yielded a −130°F(−90°C) transition temperature. Accordingly, it is considered that the slow cooling and resultant temper embrittlement of plate 1 led to a transition temperature elevation of 60°F(33°C), whereas the higher number of heat treatment cycles and resultant microstructure refinement of plate 2 caused a transition temperature reduction of 70°F(39°C). Unwelded plates 3 and 4 were accelerated cooled from tempering (Table 2). As may be noted from Fig. 5, a lower preirradiation transition temperature is advantageous by providing greater tolerance for radiation-induced embrittlement.

Comparing pre/postirradiation behavior, several general and specific observations can be made. First, in Fig. 5, comparable trends in transition temperature increase are noted for both A543 plates and A508 forgings. Of major importance is the observation that all but two of the materials appear capable of withstanding a fluence of 4×10^{19} n/cm^2 without loss of a subzero transition temperature. The exceptions are plate 1 and plate 4. The exceptional behavior of plate 1 is clearly the result of a high preirradiation transition temperature. Plate 4, on the other hand, is clearly an example of "high" radiation-embrittlement sensitivity. Significantly, the trend performance of plate 1 parallels that of plate 2. This infers that the irradiation response of A543 (and of other NiCrMo steels) is independent of the cooling rate used from postweld stress relief or, in other terms, of the degree of temper embrittlement introduced prior to irradiation. Results of a recent study (10) support this assessment. Jointly, the data indicate that radiation and temper embrittlement are independent processes producing cumulative effects.

The high 550°F(288°C) radiation sensitivity of plate 4 is believed to be caused by its "high" vanadium content. As indicated, this plate represents a modified A543 composition, with the primary modifications being in manganese content (above specification), chromium content (below specification), and vanadium content (intentionally added). The consideration of vanadium content as the responsible factor stems from an earlier observation of radiation-sensitive behavior by 5NiCrMoV plates. Paralleling the performance of plate 4, plates from separate melts exhibited transition temperature increases of 230°F(128°C) and 235°F(131°C) for a fluence of 3.4×10^{19} n/cm^2 at 550°F(288°C). A contribution of vanadium to sensitivity development was suspected and subsequently confirmed using split laboratory melts (plate) with and without 0.08 percent vanadium additions (2). Significantly, an effect of vanadium content on forging performance is not indicated (Fig. 5). Forging 2, although containing 0.08 percent vanadium for example, did not exhibit an abnormally high radiation-embrittlement sensitivity. Elsewhere (11), comparisons of a series of experimental 3-1/2NiCrMoV forgings did not show an influence of 0.11 to 0.12 percent vanadium on irradiation behavior. In fact, four forgings containing low phosphorus and copper contents exhibited essentially no embrittlement after 550°F(288°C) irradiation to a fluence of 3.1×10^{19} n/cm^2. The consistent difference in the vanadium effect observed between plates and forgings may be due to inherent material processing differences or, as suggested by results for the split laboratory melts (2), to differences in nitrogen content. Chemical analyses are being extended to test the latter possibility.

Dissimilarities in copper content also are partly responsible for the variable radiation-embrittlement resistance observed in Fig. 5. The detrimental contribution of this element to radiation-sensitivity development, like that of phosphorus, is well established (2,4,6,7). A progressive increase in radiation-embrittlement sensitivity with increasing copper content is indicated jointly by the 8-in. reference plate (0.05 percent Cu), by plate 3 (0.13 percent Cu), and by plates 1 and 2 (0.20 percent Cu). Of special interest, it would appear that variable copper content has less of an influence on A543 steel than on A533-B steel, as will be indicated below. Tentatively, it is proposed that the copper contribution to sensitivity development is microstructure dependent, with the copper content having less of an influence on a tempered martensite structure (A543) than on a tempered upper bainite structure (A533-B).

Postirradiation heat treatment response is discussed separately below.

Weldments

Pre/postirradiation performances of the submerged arc and electroslag weldments are graphed in Figs. 6-10. Comparisons to plate performances can be made in Table 4.

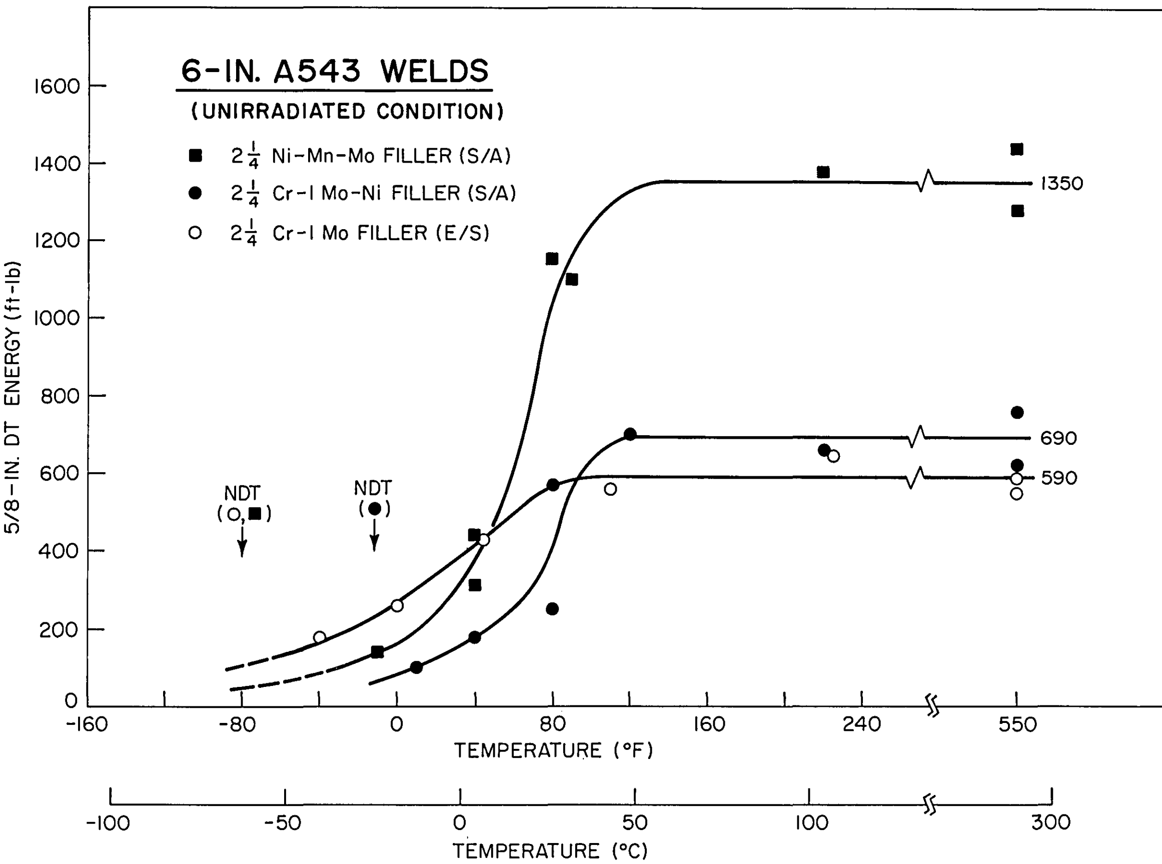

Fig. 6 — Preirradiation drop weight and dynamic tear test performances of three representative welds. Best overall notch ductility is shown by submerged arc (S/A) weld 1 (2-1/4NiMnMo filler). The A543-1 reference plate, by comparison, exhibited a −110°F(−79°C) drop-weight NDT temperature and a 550 ft-lb dynamic tear upper shelf energy.

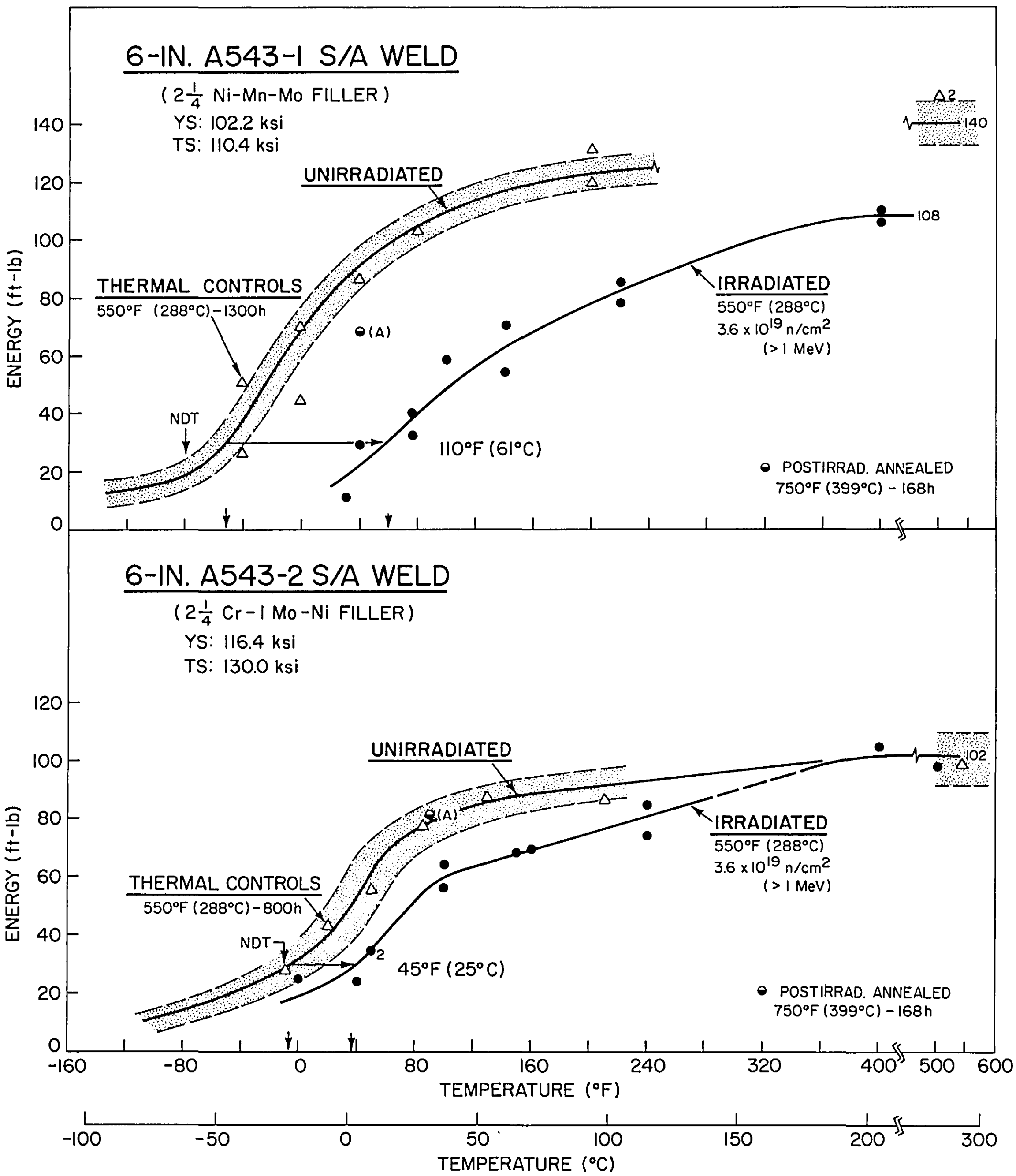

Fig. 7 — Irradiation performance of submerged arc welds 1 and 2 (simultaneous exposure). The superior notch ductility of weld 1 (upper graph) relative to weld 2 (lower graph) appears lost on irradiation through greater embrittlement sensitivity. Note that the C_v 30 ft-lb transition temperature approximates well the drop weight NDT temperature. (Φ^{cs} >1 MeV = 3.1 X 10^{19} n/cm^2.)

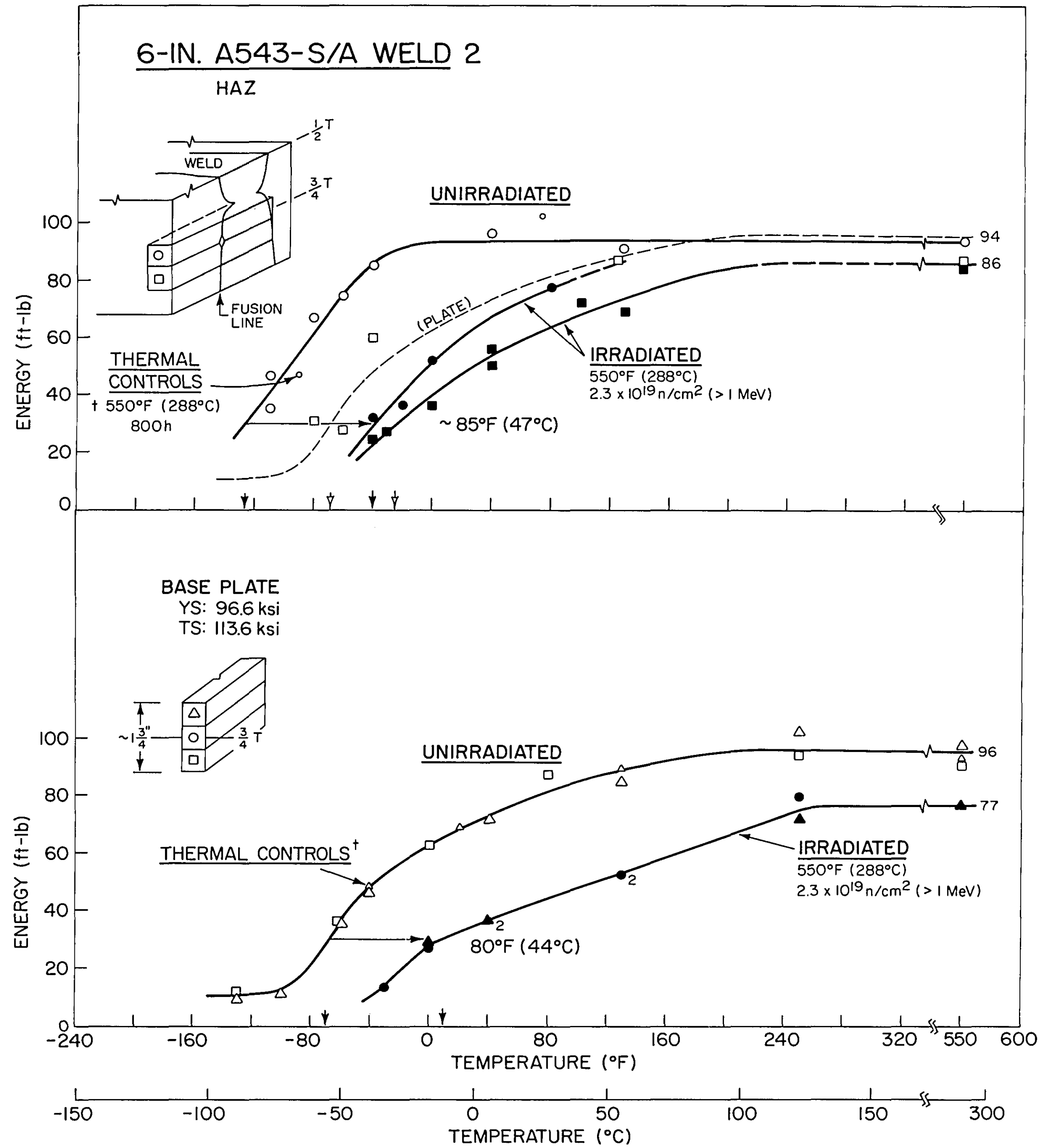

Fig. 8 — Notch ductility of the weld heat affected zone (HAZ) (upper graph) vs base plate (lower graph) of submerged arc weld 2. The dashed curve (upper graph) references preirradiation plate behavior. Superior pre- and postirradiation performance is indicated for the HAZ; however, performance variability as a function of thickness location is anomalous. (Φ^{cs} >1 MeV = 2.0 X 10^{19} n/cm^2.)

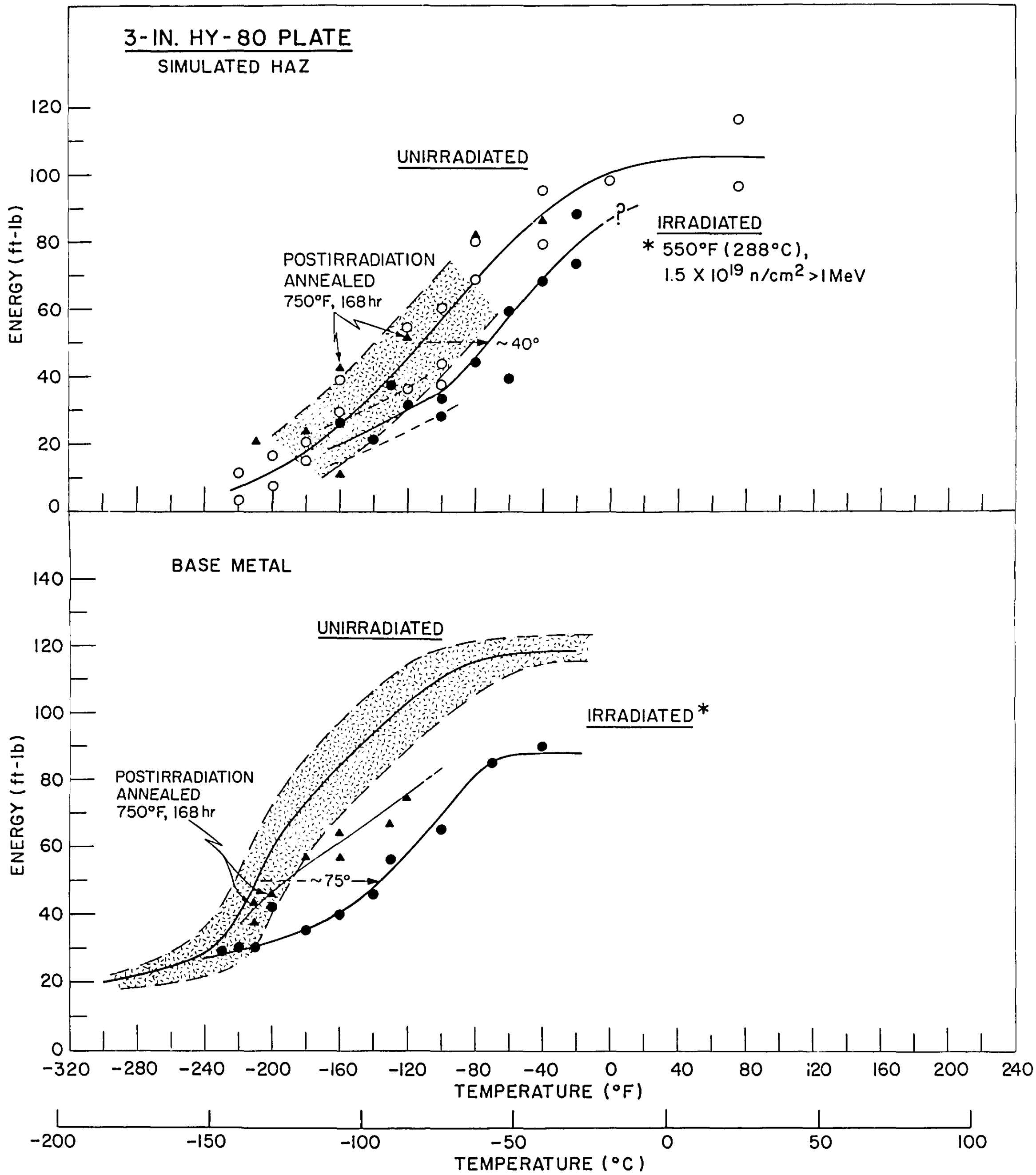

Fig. 9 — Notch ductility of a simulated weld heat affected zone (HAZ) (upper graph) vs base metal (lower graph) of a NiCrMo (HY-80) plate. The HAZ simulation was accomplished on the RPI hot-ductility tester (GLEEBLE) and employed thermal cycles duplicating the maximum grain-coarsened region (13). The difference in preirradiation transition behavior of HAZ vs base metal reflects a difference in cooling rate after heat treatment. (Φ^{cs} >1 MeV = 1.7 X 10^{19} n/cm^2.)

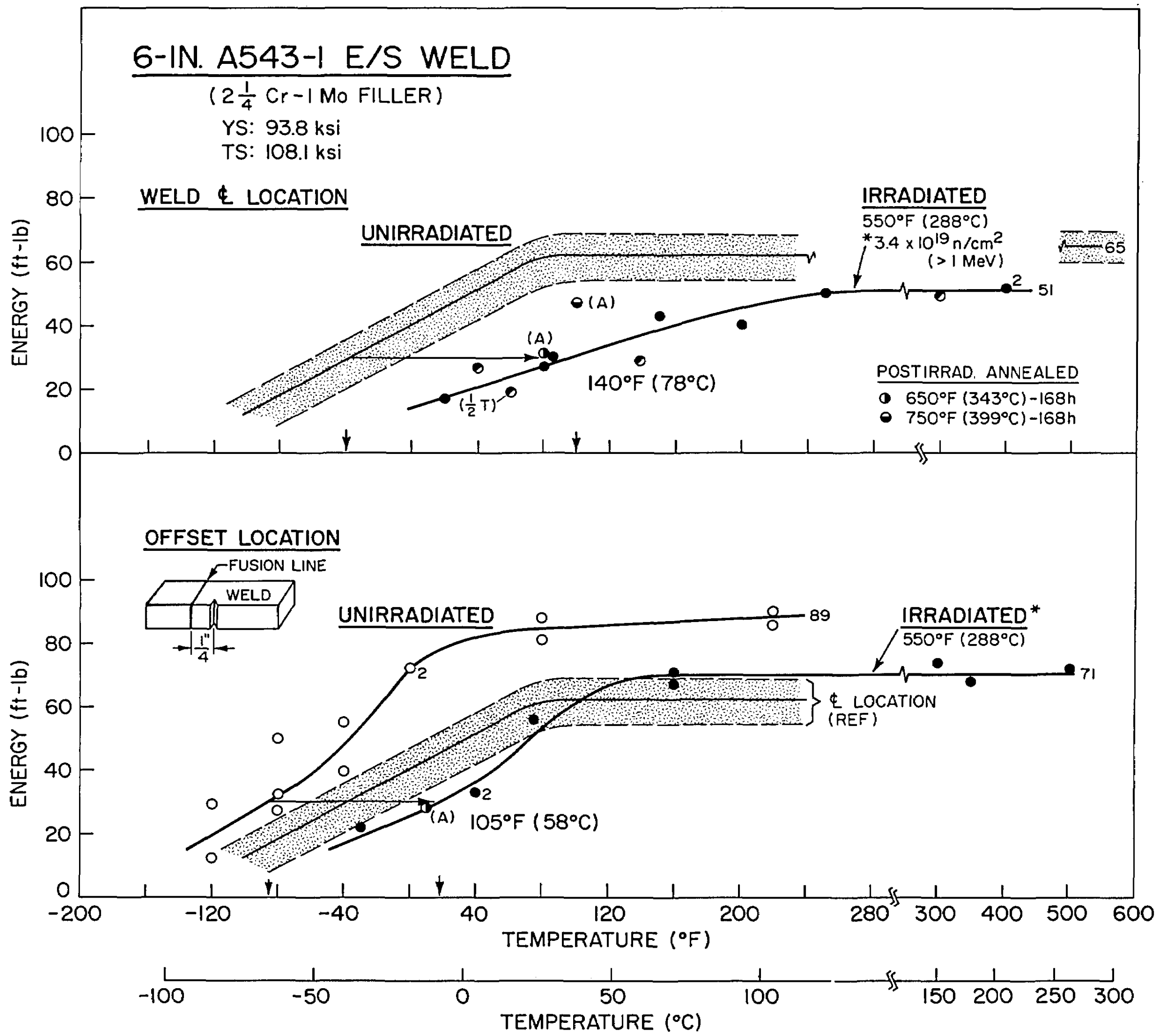

Fig. 10 — Irradiation performance of electroslag weld 1 at two locations across the weld width. Poorer notch ductility is shown for the weld centerline location (upper graph). (Φ^{cs} >1 MeV = 3.0 X 10^{19} n/cm^2.)

Figure 6 compares the DW and DT performances of submerged arc (S/A) welds 1 and 2 and of electroslag (E/S) weld 1. In terms of both DW-NDT temperature and DT upper shelf energy level, submerged arc weld 1 (2-1/4NiMnMo filler) depicts a much better preirradiation notch ductility than submerged arc weld 2 (2-1/4CrMoNi filler). The NDT performance of electroslag weld 1 surprisingly was better than that of submerged arc weld 2. However, differences in postweld heat treatment cooling rates again could be the responsible factor. From Table 4 it is noted that the NDT temperatures of the three weld deposits are approximated well by their C_v 30 ft-lb transition temperatures. Accordingly, the use of the C_v 30 ft-lb index to assess and compare weld deposit radiation-embrittlement tendencies appears justified.

Simultaneous irradiation of submerged arc welds 1 and 2 revealed a 2:1 difference in radiation-embrittlement sensitivity as observed in Fig. 7. Clearly, the initial NDT advantage of weld 1 is lost on irradiation by virtue of its higher radiation-sensitivity level. The results are taken to infer a detrimental effect of high nickel content on irradiation response when the chromium content is low (<1 percent Cr). Concern for a nickel contribution to radiation sensitivity was voiced earlier (2,6,9). Other evidence in support of the above analysis can be cited (12). Additional investigations to validate the proposed contribution of nickel to radiation-sensitivity development appear in order if high-nickel-content weld metals are to be selected for nuclear components.

The low radiation-embrittlement sensitivity of submerged arc weld 2 has special significance since the weld represents a commercial-scale demonstration of an experimental filler composition. The sensitivity level was comparable to that shown by 2-1/4-in.-thick submerged arc welds produced in the laboratory using a different welding procedure (single electrode, dc reverse polarity).

The irradiation assessment made of the weld HAZ and base plate companion to submerged arc weld 2 is illustrated in Fig. 8. The fluence was lower than that received by the weld deposit (Fig. 7). However, for an equivalent fluence level, the HAZ appears to offer better postirradiation notch ductility than either the parent plate or the weld deposit. As noted, a difference in HAZ preirradiation performance and radiation embrittlement sensitivity was observed as a function of thickness layer. Plate specimens taken immediately adjacent to these locations did not show comparable variability. Accordingly, an anomaly is indicated. Welding procedures and sequences were well documented; the anomaly can only be attributed at this time to a change in weld beads deposited per layer opposite the respective HAZ locations, coupled with the slow cool used from stress relief. Regardless, the observation of greatest importance is that, for the temper embrittled condition, the performance of the HAZ at least equalled the performance of the parent plate both before and after irradiation. Also indicative of a general trend, similar transition temperature responses have been observed for simulated weld HAZ and plate specimens of NiCrMo (HY-80) steel (Fig. 9) (13). Simulation was accomplished on the Rensselaer Polytechnical Institute (RPI) hot-ductility tester (Gleeble). Thermal cycles simulated HAZ development (maximum grain-coarsened region) in a 1-in. plate and depicted welding with a 74 kJ/in. heat input and 150°F(66°C) preheat. In this case, a difference in cooling rate after heat treatment (HAZ, slow cooled at 50°F (28°C)/hr, vs plate, air cooled) resulted in an appreciable difference in preirradiation transition temperatures.

Findings for the electroslag welds are presented in Figs. 10 and 11. Figure 10 shows the performance of an electroslag weld made in a high-copper-content plate (0.20 percent Cu). Two weld sampling locations were used: (a) quarter-thickness location — specimen notch

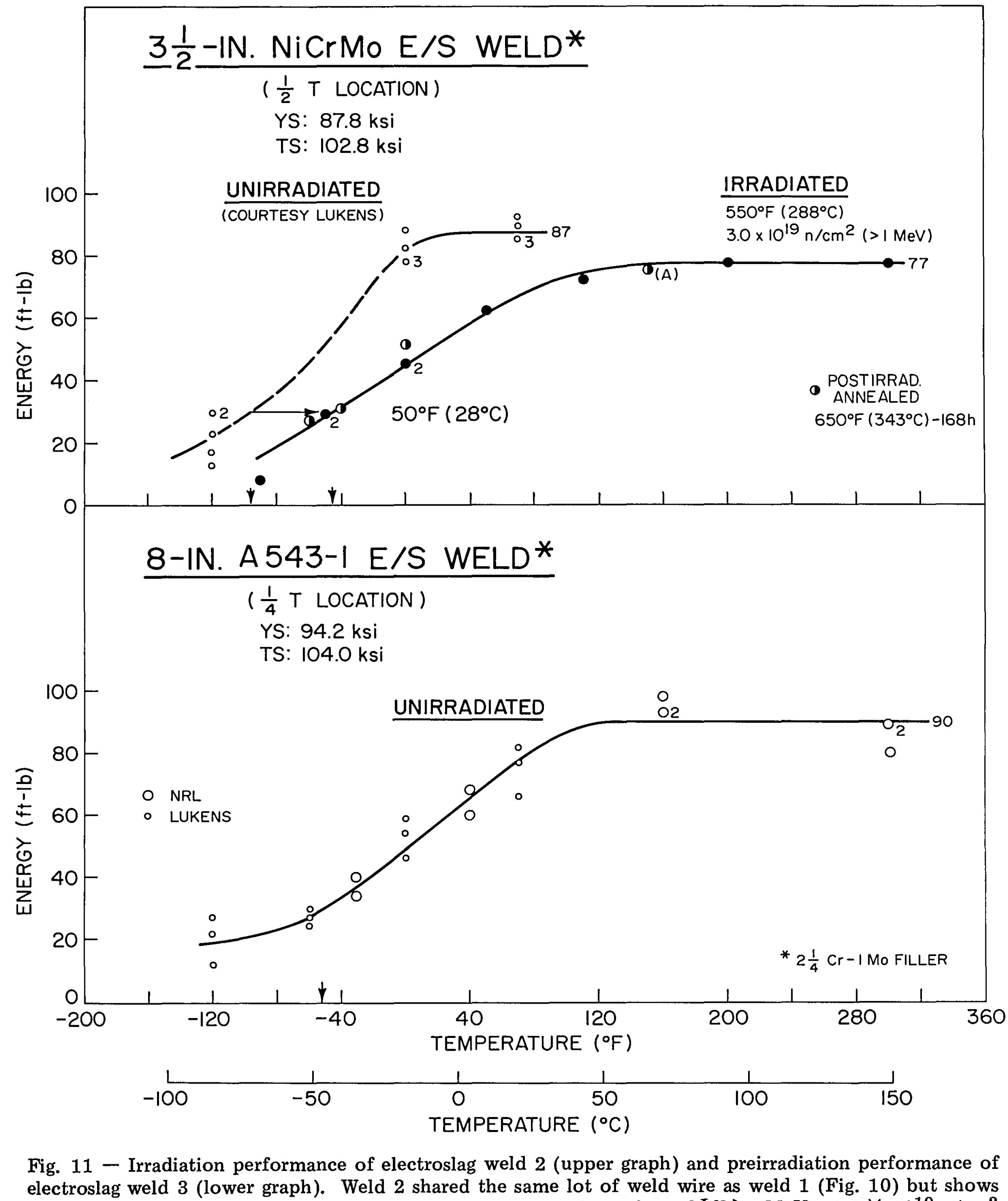

Fig. 11 — Irradiation performance of electroslag weld 2 (upper graph) and preirradiation performance of electroslag weld 3 (lower graph). Weld 2 shared the same lot of weld wire as weld 1 (Fig. 10) but shows lower radiation sensitivity because of a lower-copper-content base plate. [Φ^{cs} >1 MeV = 2.6 X 10^{19} n/cm^2 (upper graph).]

placed on weld centerline, and (b) quarter-thickness location — specimen notch placed 1/4 in. away from weld fusion line. The aim in comparing centerline and offset locations was to determine the overall significance to pre/postirradiation performance of inherent microstructure differences and potential impurities segregation during solidification. As noted, the centerline location describes much poorer notch ductility than the offset location before and after irradiation. Also, a somewhat higher radiation embrittlement sensitivity is depicted. Accordingly, the centerline location should be the focus of attention for irradiation assessments.

Figure 11 (upper graph) describes the performance of an electroslag weld made in a medium-copper-content plate (0.13 percent Cu). This weld and electroslag weld 1 (Fig. 10) were both made with a low-copper-content filler wire. Weld deposit copper contents at the centerline* were 0.09 and 0.16 percent, nonetheless, because of plate melt-back during welding. The results for both welds provide a clear example of the benefit of reduced copper content to radiation-embrittlement resistance. The necessity for having low-copper filler wire and low-copper parent plate for optimum radiation resistance is also most apparent. It is noted that the radiation resistances of electroslag weld 2 (Fig. 11) and submerged arc weld 2 (Fig. 7) are generally comparable.

The 8-in.-thick electroslag weld of Fig. 11 (lower graph) represents a low-copper-content plate/filler combination which currently is undergoing exploratory irradiation. Preirradiation properties are shown to be comparable to those of electroslag weld 1 (Fig. 10).

Postirradiation Heat Treatment Response

Embrittlement relief by postirradiation heat treatment was also explored where specimen numbers permitted. Two heat treatments were evaluated: (a) 650°F(343°C) for 168 hr, and (b) 750°F(399°C) for 168 hr. The heat treatment temperatures were selected to represent, respectively, design capabilities of current reactors and reactor vessels and projected capabilities using external (nonnuclear) heat sources. For either type of operation, a minimum heat treatment of 168-hr duration is considered realistic and practical. Embrittlement relief by in-service annealing has been successfully demonstrated with the Army SM-1A reactor vessel A350-LF1, Mod. steel (14,15).

Data presented in individual figures, though limited, demonstrate that a 650°F(343°C) heat treatment following 550°F(288°C) irradiation service is largely ineffective. Little if any transition temperature recovery was observed for the plates and weld deposits. A 750°F (399°C) heat treatment, on the other hand, produced noticeable recovery in all cases. A capability for embrittlement relief by an in situ heat treatment is thus demonstrated. However, the procedure would be difficult to apply at best because of the high-temperature and external heating requirements.

10NiCrMoCo Plate

Results for a special investigation with the 10NiCrMoCo steel plate are given in Fig. 12. The 800°F(427°C) assessment was designed primarily to explore the possibility for an influence of radiation on metallurgical stability in a high-temperature environment. The

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*In a separate study involving a MnMoNi electroslag weld deposit, the copper content gradient across the deposit to within 1/4 in. of the weld fusion line was found to be less than 0.02% Cu.

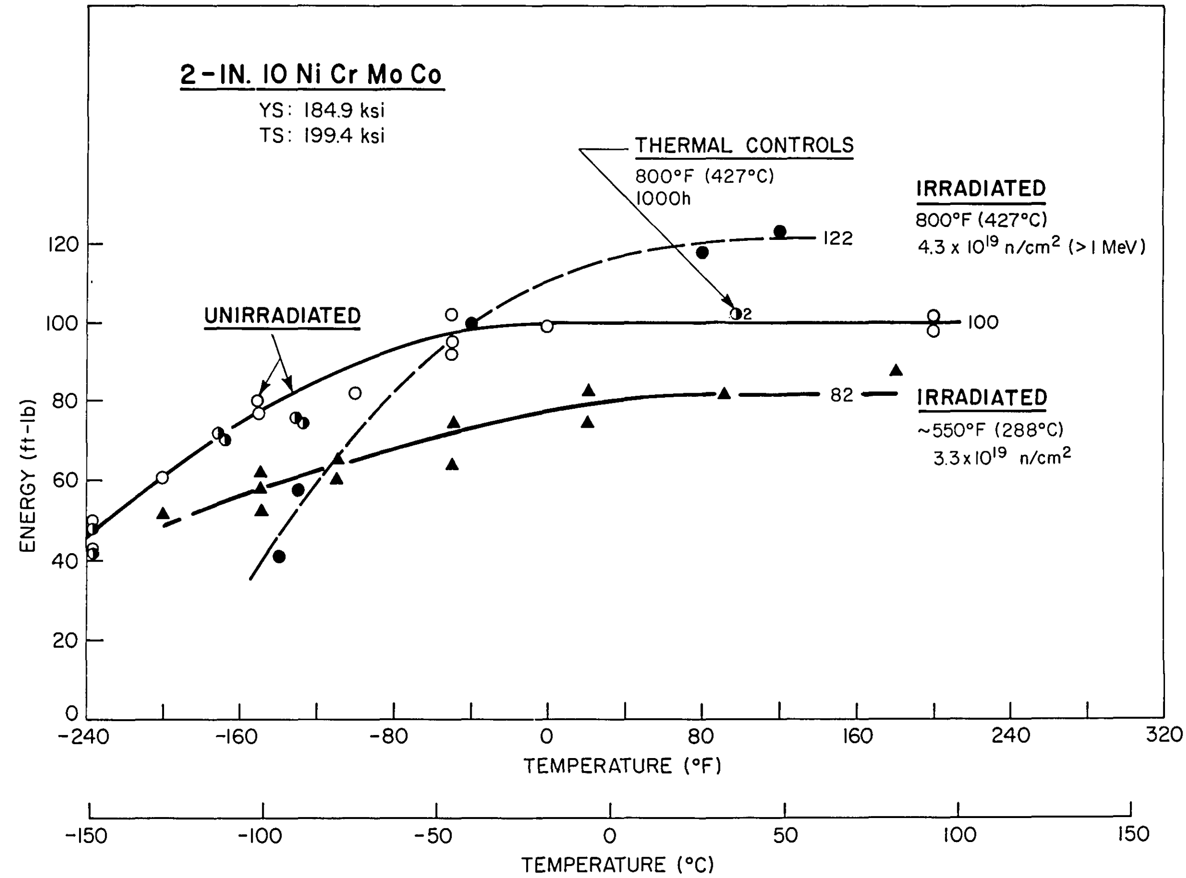

Fig. 12 — Notch ductility of a high-strength 10 NiCrMoCo plate with 800°F(427°C) irradiation vs 800°F(427°C) thermal conditioning and with 550°F(288°C) irradiation. The anomalous increase in upper shelf level by irradiation at the higher temperature was accompanied by a 12 point decrease in Rockwell-C hardness to indicate a radiation-induced change in metallurgical stability.

plate was originally hardened (aged) at 950°F(510°C). Thermal conditioning at 800°F (427°C) for 1000 hr showed stable strength and notch ductility properties in the absence of irradiation. After irradiation, good notch toughness retention with 1200-hr irradiation was observed. However, a significant increase in C_V upper shelf energy was noted, along with a 12-point decrease in Rockwell-C hardness. Upper shelf and hardness changes with 550°F(288°C) irradiation, on the other hand, were in the expected (opposite) direction. Accordingly, irradiation at the higher temperature appears to have affected metallurgical stability. Specifically, the results suggest a radiation-induced extension of the alloy hardening mechanism to this temperature whereby an overaged condition was produced. Therefore, depending on the alloy, the results point out a need for caution in the use of high-strength complex steels in radiation environments at temperatures below, but approaching, the normal temperature range for metallurgical changes. (The effect of irradiation on temper embrittlement resistance was discussed in a preceding section.)

IRRADIATION RESPONSE RELATIVE TO A533 STEEL

Figure 13 summarizes the transition temperature responses of the various plates, forgings, and weld deposits with reference to the performance of standard production A533 plates and welds. With one exception (plate 4), the data points lie in or below the lower third of the A533 trend band. Accordingly, average radiation-embrittlement resistance clearly exceeds that of conventional A533 materials. The poor performance of plate 4 has been discussed and could be avoided in practice. From Table 4 the greater radiation-embrittlement resistance observed for the A543 and A508 materials compared to standard production A533 plates can be attributed, in part, to a lower phosphorus content (0.006% P versus 0.012-0.015% P for A533). The range of copper contents depicted, on the other hand, encompasses that of those A533 plates whose performance defines the lower half of the trend band of Fig. 13.

The demonstrated level of radiation-embrittlement resistance, coupled with low pre-irradiation transition temperature characteristics, presents a particularly attractive combination for radiation service. The potential of A543 steel as a successor to A533 steel for future vessel fabrication appears well enhanced by the experimental findings herein.

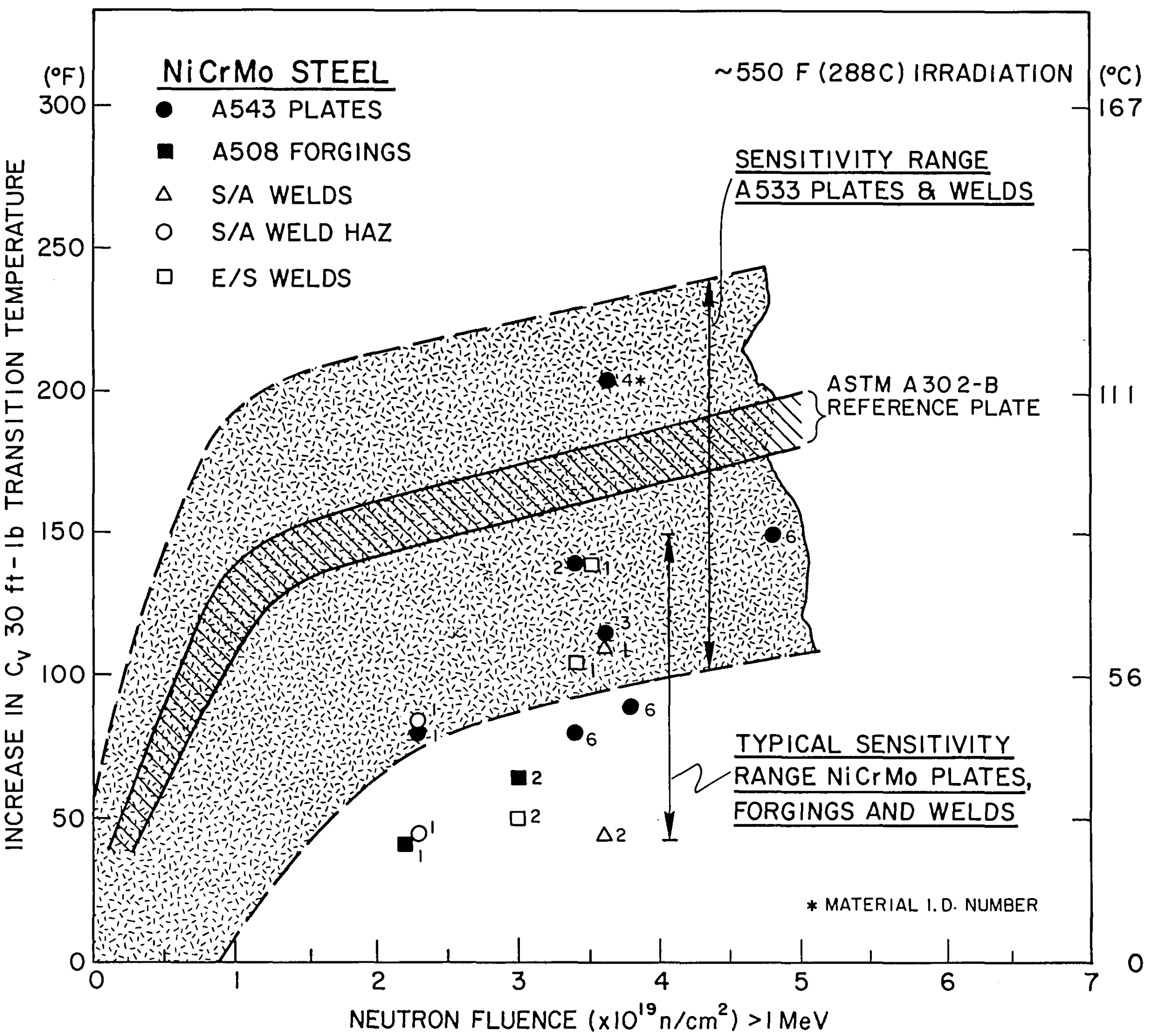

Fig. 13 —Determination of superior radiation-embrittlement resistance of A543 plates, A508 forgings, and companion weld metals compared to standard production A533 plates and welds. The NiCrMo plates and forgings present an attractive combination of good radiation-embrittlement resistance and generally low preirradiation transition temperatures for advance reactor service.

Continued development of NiCrMo steel irradiation performance trends is suggested. In particular, further investigation of filler metal capabilities is advisable. A need for alternate filler metals with low preirradiation NDT temperature characteristics [-100°F (-73°C)] is indicated. However, as noted, best preirradiation filler performance need not equate to best postirradiation performance.

Finally, it is encouraging that guidelines developed at NRL for improved radiation-embrittlement resistance in lower strength steels have equal applicability to the improvement of A543 plate and A508 forging compositions and associated weld metals. The guidelines, emphasizing the need for lower copper and phosphorus contents, recently were adopted commercially for improving A533 plates and weld fillers.

SUMMARY AND CONCLUSIONS

The promise of selected NiCrMo steels for advanced reactor vessel applications has been demonstrated. Generally superior radiation embrittlement resistance, as well as superior preirradiation transition temperatures (Charpy-V 30-ft-lb index), were observed relative to the performance of A533 plates and welds of current usage. With only two exceptions, the A543 plates and A508 forgings examined showed sufficient resistance to a fluence of 4×10^{19} n/cm^2 >1 MeV to retain a subzero transition temperature. Weld deposits typically had higher postirradiation transition temperatures than parent plates.

Specific observations and assessments were as follows:

1. Significant variability in irradiation response was demonstrated by A543 plates and weld deposits. Variable radiation resistance could be traced either partially or completely to differences in composition, especially residual element (impurity) content.

2. Radiation-embrittlement resistance described by A508 forgings was comparable to the average resistance for A543 plates.

3. Copper content is detrimental to the radiation resistance of A543 plates and weld deposits. A progressive increase in radiation sensitivity with increasing copper content was observed for the range of 0.05 to 0.20 percent Cu.

4. Vanadium content appears detrimental to the radiation resistance of NiCrMoV plates, but not to NiCrMoV forgings. The occurence of the vanadium effect may be dependent on material processing and/or nitrogen content.

5. Duplicate submerged arc welds showed a NiMnMo filler to be twice as sensitive to radiation embrittlement as a CrMoNi filler. A detrimental effect of nickel content for the case of low chromium content (<1 percent Cr) is proposed. Further study of the nickel influence on radiation sensitivity is warranted.

6. Superior postirradiation notch ductility was found for the HAZ of a submerged arc weld (fusion line location) compared to the parent plate. Postirradiation HAZ performance relative to that of weld deposit, however, should be determined on an individual weldment basis because of composition and initial property differences.

7. Anomalous differences in preirradiation transition temperature and in radiation-embrittlement sensitivity were found for a weld HAZ relative to weld thickness location. Anomalous behavior could be attributed only to some variation in local microstructure.

8. A postirradiation heat treatment of 650°F(343°C) for 168 hr following 550°F (288°C) irradiation is not effective for transition temperature recovery in NiCrMo plates and weld deposits. However, significant recovery was observed with a 750°F(399°C), 168-hr heat treatment in all cases.

9. Temper embrittlement developed on slow cooling a 0.20-percent copper content plate from 1135°F(613°C) did not appear to influence subsequent 550°F(288°C) radiation sensitivity level.

10. Results for a 10NiCrMoCo steel plate indicate that radiation exposure can induce (or promote) metallurgical instabilities at temperatures below that where instabilities are expected.

From the results of this study, the commercial production of advanced NiCrMo steels with uniformly high resistance to 550°F(288°C) radiation embrittlement should be possible. The primary requirements would appear to be proper control (minimization) of selected residual elements identified previously as being detrimental to irradiation performance for lower strength steels and filler metals.

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13. ABSTRACT

The 550°F(288°C) irradiation response characteristics of several NiCrMo steel plates, forgings, and weldments were evaluated. Primary objectives were to explore variable radiation-embrittlement tendencies and to assess notch ductility performance relative to that of the MnMoNi steel (ASTM Type A533-B) currently used in nuclear reactor vessel construction. The study was focused on ASTM Type A543 steel in Class 1 and Class 2 heat treatment conditions. Both submerged arc and electroslag weldments were evaluated. Irradiation embrittlement was indexed by the increase in Charpy-V 30 ft-lb transition temperature.

Results clearly demonstrate the promise of ASTM Type A543 plate and related A508 forging steels for advanced reactor applications. Both radiation-embrittlement resistance and preirradiation transition temperature characteristics were found superior to those of standard production A533-B. With only two exceptions, the A543 plates and A508 forgings exhibited sufficient resistance to a fluence of 4×10^{19} n/cm^2 >1 MeV to retain a subzero nil-ductility transition (NDT) temperature. Weld deposits generally had higher postirradiation transition temperatures than plates.

The significant variability in radiation resistance noted among A543 plates and weld deposits could be traced in most instances to composition differences, especially residual element content differences. Anomalous weld heat-affected-zone (HAZ) behavior relative to weld thickness location was observed. A progressive increase in irradiation response with an increase in copper content was found. Vanadium content appears detrimental to radiation resistance of NiCrMo plates, but not to NiCrMo forgings. Weld deposit results infer a harmful effect of nickel content when chromium content is low.

Notch ductility recovery by postirradiation heat treatment was also explored.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Forgings						
Neutron irradiation						
NiCrMo steel						
Notch ductility						
Nuclear reactors						
Pressure vessels						
Radiation effects						
Radiation embrittlement						
Radiation sensitivity						
Trace elements						
Weldments						

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