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Evaluation of Commercial Production A533-B Steel Plates and Weld Deposits with Extra-Low Copper Content for Radiation Resistance

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20. ABSTRACT (Continued)

allowable copper content. An overall objective was to develop information assisting the formulation of special specifications for steels for nuclear service and the delineation of associated embrittlement trends for reactor vessel design and operation. This report describes investigations on Series 3 materials, which represent optimum steelmaking practice, and a limitation on copper content of 0.06%Cu maximum. Previous investigations on Series 1 materials ($\geq$0.15%Cu) typical of nonimproved steel production (pre-1971) and Series 2 materials (0.10%Cu, max) representative of improved steel production (current practice) are also summarized.

Radiation resistance was assessed from Charpy-V (C_V) notch ductility changes with fluences of $\sim$ 5 to 7 $\times$ 10^{19} n/cm^2 $>$ 1 MeV. All Series 3 materials exhibited high resistance to radiation in terms of both transition temperature elevation and upper shelf degradation. Typically, the postirradiation C_v 41 J (30 ft-lb) transition-temperature elevation was less than 56°C (100°F). An independent effect of nickel content on radiation resistance was not observed for weld metal containing a high nickel content ($\approx$ 1% Ni) and an extra-low copper content (0.05%Cu).

Comparisons of Series 3 and Series 2 data trends revealed that the specification of an extra-low copper content (0.06%Cu, max) as opposed to a low copper content (0.10%Cu, max) does not provide a substantial increase in radiation resistance for A533-B materials for the fluence range investigated. Accordingly the study has confirmed that new ASTM and AWS supplemental specifications on copper content for nuclear service are sufficiently restrictive to optimize 288°C (550°F) radiation resistance of A533 plates and weld deposits for post projected vessel fluence conditions.

CONTENTS

EVALUATION OF COMMERCIAL PRODUCTION A533-B STEEL PLATES AND WELD DEPOSITS WITH EXTRA-LOW COPPER CONTENT FOR RADIATION RESISTANCE

INTRODUCTION

The NRC-CE-NRL Cooperative Program on Improved A533 Steel was established to define trends in radiation-induced change in notch toughness for commercial production A533-B materials with progressive reductions in allowable copper content. Three series of materials were investigated. Each series included plates, weld deposits, and weld heat-affected zone (HAZ) materials. The program builds on the findings of laboratory melt studies [1] which revealed that certain residual impurity elements, especially copper and phosphorus, have a particularly adverse effect on radiation resistance at reactor-vessel service temperatures (≈ 288°C, 550°F). Conversely, the reduction of these impurities to low levels was shown to produce a steel having high radiation resistance. Demonstration tests with a commercial-scale A533-B melt and A533-B weld clearly confirmed the laboratory melt findings [2,3]. The intent of the present study was to broaden and refine this base of information to assist the formulation of new American Society for Testing Materials (ASTM) and American Welding Society (AWS) specifications for improved (radiation resistant) steels and welding materials for nuclear service and to delineate trends in radiation performance for such materials for reactor-vessel design and operation. It is noted that Combustion Engineering (CE) and several other manufacturers have adopted the use of low-copper content materials for high fluence (vessel beltline) regions.

Materials selected for the cooperative study were:

Series 1 - Normal copper content (≥0.15%Cu),
Typical of nonimproved commercial steel production (pre-1971);

Series 2 - Low copper content (0.10%Cu maximum with 0.012%P maximum),
representing improved steel production (current practice);

Series 3 - Extra-low copper content (0.06%Cu maximum),
considered the practical lower limit for copper content control.

Findings for the Series 1 vs Series 2 materials have been reported [4]. The results clearly demonstrate that a major reduction in radiation sensitivity is achieved by a reduced copper content in commercial production A533 plate, weld, and weld HAZ materials. The improvement was evident both as a smaller increase in Charpy-V (C_v) transition temperature (Fig. 1) and as a smaller decrease in C_v upper shelf energy level with irradiation.

A specific objective of the Series 3 vs Series 2 material investigations, reported here, was to establish whether even greater radiation resistance is achieved by a very low copper content (optimum steelmaking practice) compared to a low copper content (improved practice only). This study of Series 3 materials completes the planned investigations on

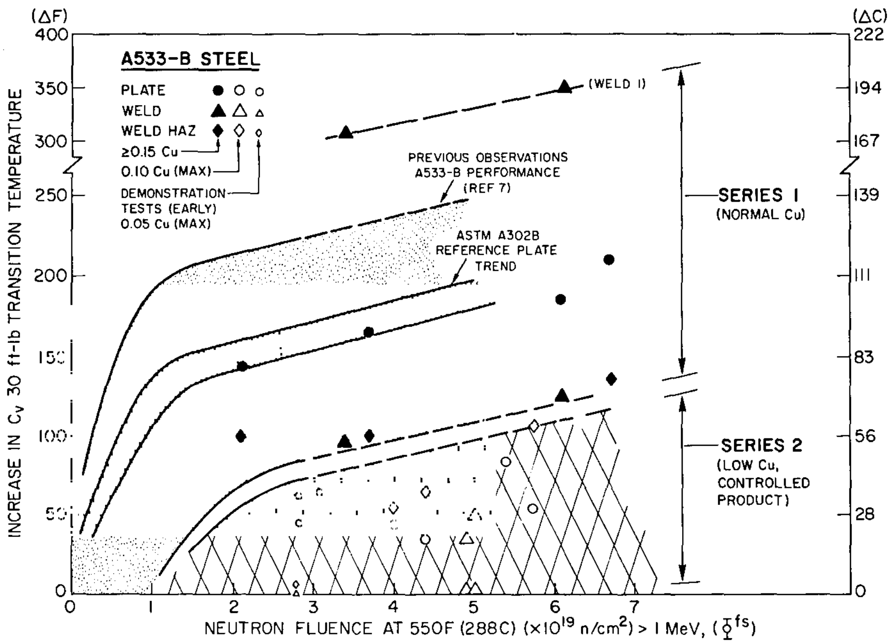

Fig. 1 - Summary of Charpy-V 40-J (30 ft-lb) transition-temperature changes with irradiation observed for Series 1 materials (large filled symbols) and Series 2 materials (large open symbols). A benefit to radiation-embrittlement resistance by a low copper content is clearly evident. Earlier determinations for extra-low copper content A533-B materials from commercial-scale demonstration tests are also given (small open symbols) [4].

notch ductility trends. A supporting investigation on tensile property trends with irradiation is under consideration. So that this document will be a single reference document, primary observations and results for the Series 1 and Series 2 materials are summarized in Appendix A.

MODIFIED PROGRAM PLAN

As described in the initial report [4], the program plan centered on the evaluation of C_V notch ductility before and after irradiation at 288°C (550°F) to two fluence levels: 2 to 3 $\times 10^{19}$ n/cm^2 $>$ 1 MeV and 4 to 5 $\times 10^{19}$ n/cm^2 $>$ 1 MeV (Table 1). Resistance to radiation exposure was to be judged in terms of the increase in C_V transition temperature, indexed to C_V 41-J (30 ft-lb) and C_V 68-J (50 ft-lb) energy levels, and in terms of the decrease in C_V upper-shelf energy level. This plan however was modified for the Series 3 materials because of the high radiation resistance observed for the Series 2 materials. Accordingly only high-fluence investigations were considered necessary to meet the program objectives.

For the Series 1 and Series 2 materials, but not for the Series 3 materials, the program plan included an investigation on postirradiation notch ductility recovery with a

Table 1 – Summary of Program Plan by Irradiation Experiment

Experiment	Specimen Type	Copper Level (%)	Target Fluence Level (10^{19} n/cm^2 > 1 MeV)	Number of Materials			Postirradiation Anneal*
				Plate	Weld	HAZ	
1	C_v	≥0.15	2 to 3	2	2	1	yes
2	C_v	≥0.15	~ 5	2	2	1	yes
3	C_v	0.10 (max)	2 to 3	2	2	2	yes
4	C_v	0.10 (max)	~ 5	2	2	1	yes
5	C_v	0.06 (max)	2 to 3	3	1	2	no
6	C_v	0.06 (max)	~ 5	3	1	2	no
7	Tensile	All Levels	~ 5	6	3	0	yes

*650°F (343°C) for 168 hr.

343°C (650°F) 168-hour heat treatment. A restoration of notch toughness by low-temperature heat treatment (annealing) has been suggested by the Code of Federal Regulations (10 CFR 50, Appendix G) as one possible means for periodically reducing the effects of radiation in service should the need rise. For the Series 3 materials, the degradation in fracture resistance was projected to be minimal, and postirradiation heat treatment would not be required for expected vessel fluence levels. Limited tests of the postirradiation heat treatment condition were nonetheless conducted with excess specimens to expand information on annealing response.

MATERIALS

The chemical compositions of the Series 3 materials together with those for the Series 2 (reference) materials are given in Table 2. Chemical compositions of the demonstration test materials [2, 3] and the Series 1 (nonimproved production) materials are also indicated for comparison. The Series 3 weld deposit was produced by the shielded metal arc (SMA) process. In contrast the Series 2 welds were made by the submerged arc (S/A) process. Likewise, the demonstration test weld and the Series 1 welds were by the S/A process. Welding parameters and materials are reported in Table 3. All six welds represent the use of standard commerical equipment and practices. Tensile properties are reported in Table 4.

For plates the C_v specimens were taken from the quarter-thickness location in two orientations: longitudinal (LT, parallel to the plate primary rolling direction) and transverse (TL, perpendicular to the plate primary rolling direction). However, except for plate 6, only the TL orientation was evaluated with irradiation. Weld metal C_v specimens were removed between the 1/8- and 7/8-thickness locations and were oriented perpendicular to the welding direction. The HAZ C_v specimens were also oriented perpendicular to the welding direction but had the specimen V-notch centered 0.8 mm (1/32 inch) in from the weld fusion line. The HAZ specimens were taken from the quarter-thickness location and oriented parallel to the parent plate LT orientation. In each case the plane of the specimen notch was made perpendicular to the plate (or weldment) surface.

Table 2 - Materials and Heat Treatment

Materials	Thickness		Chemical Composition (wt-%)										Heat Treatment*
	cm	in.	Cu	P	C	Mn	S	Si	Ni	Cr	Mo	Al	
Series 3: Extra-Low Copper Content													
Plate 5	24.5	9-5/8	0.02	0.009	0.20	1.24	0.011	0.23	0.70	0.05	0.61	0.027	1
Plate 6†	24.8	9-3/4	0.04	0.010	0.24	1.28	0.011	0.24	0.53	0.09	0.56	0.023	1
Plate 7	24.8	9-3/4	0.05	0.007	0.24	1.36	0.011	0.26	0.56	0.09	0.58	0.034	2
Weld 6 (SMA)	24.8	9-3/4	0.03	0.005	0.097	1.01	0.010	0.39	0.96	0.01	0.21	0.001‡	2
Series 2: Low Copper Content (Current Practice)													
Plate 3	24.8	9-3/4	0.09	0.009	0.20	1.29	0.017	0.22	0.58	-¶	0.57	0.027	1
Plate 4	22.9	9	0.09	0.011	0.21	1.38	0.018	0.28	0.66	-¶	0.52	0.02	1
Weld 3 (S/A)	24.8	9-3/4	0.07	0.010	0.15	1.15	0.010	0.25	0.12	0.04	0.59	0.004	2
Weld 4 (S/A)	22.9	9	0.05	0.004	0.15	1.25	0.010	0.19	0.09	0.06	0.62	<0.001	2
Series 1: Normal Copper Content													
Plate 1	25.4	10	0.17	0.009	0.23	1.29	0.015	0.21	0.56	0.10	0.57	0.027	1
Plate 2	25.4	10	0.24	0.008	0.25	1.40	0.011	0.23	0.62	0.11	0.59	0.02	1
Weld 1	25.4	10	0.36	0.015	0.14	1.38	0.012	0.22	0.78	0.07	0.55	0.02	2
Weld 2	25.4	10	0.20	0.016	0.13	1.11	0.013	0.17	0.04	0.05	0.53	0.004	2
NRL Demonstration Tests													
Plate [2]	15.2	6	0.03	0.008	0.17	1.22	0.008	0.19	0.58	0.06	0.50	0.015	3
Weld [3]	15.2	6	0.05	0.010	0.15	1.28	0.012	0.20	0.66	0.06	0.48	-¶	4

*Heat Treatment:
(1) Austenitized 871°C (1600°F) 4 hr and water quenched (WQ); tempered 649-677°C (1200-1250°F); stress-relief annealed 621°C (1150°F) 40 hr, furnace cooled (FC) to 316°C (600°F).
(2) Interstage stress-relief annealed 593-621°C (1100-1150°F) 1/4 hr minimum; postweld stress-relief annealed 621°C (1150°F) 40 hr, FC to 316°C (600°F).
(3) Austenitized 913°C (1675°F) 6 hr, WQ; reaustenitized 857°C (1575°F) 6 hr, WQ; tempered 677°C (1250°F) 6 hr, FC; stress-relief annealed 607°C (1125°F) 20 hr, FC.
(4) Post weld stress-relief annealed 621°C ± 14°C (1150° ± 25°F) 8 hr, FC to 316°C (600°F) at 50°C/hr (90°F/hr).

†Parent plate for weld 6.
‡Soluble aluminum.
¶Not determined.

Table 3 - Welding Materials and Parameters

	Welds 1 through 4	Weld 6
Flux	Linde 0091	—
Joint	Straight sided with backing plate	Straight sided with backing plate
Electrode diameter	4.75 mm (3/16 in.)	4.75 mm (3/16 in.)
Preheat temperature	121°C (250°F) min	149°C (300°F) min
Interpass temperature	260°C (500°F) max	260°C (500°F) max

	Weld 1	Weld 2	Weld 3	Weld 4	Weld 6
Filler type	High Mn/ Mo/ Ni	High Mn/ Mo	High Mn/ Mo	High Mn/ Mo	E8018-C3
Process*	S/A	TS/A	TS/A	S/A	SMA
Electrode connection†	ac	ac	ac	ac	dcrp
Travel speed: mm/s	5.5‡	9.3‡	9.3‡	5.5¶	4.4¶
ipm	13	22	22	13	10.5

*S/A = submerged arc process, TS/A = tandem submerged arc process, and SMA = shielded metal arc process.
†ac = alternating current and dcrp = direct current reverse polarity.
‡Heat input range not available.
¶ Heat input range 1.2 to 1.5 kj/mm (30 to 37 kj/inch).

Table 4 - Tensile Properties of Series 3 Plates and Weld Deposits

Material	Copper (wt-%)	Yield Strength* (0.2% offset)		Tensile Strength		Reduction in Area (%)	Elongation in 1 inch (%)
		MN/m^2	ksi	MN/m^2	ksi		
Plate 5	0.02	469	68†	593	86	68	28
		386	56‡	565	82	60	23
Plate 6	0.04	462	67†	600	87	65	26
		386	56‡	586	85	64	22
Plate 7	0.05	469	68†	600	87	67	25
		386	56‡	559	81	64	23
Weld 6	0.03	476	69†	552	80	74	28
		407	59‡	545	79	73	23

*Transverse orientation; duplicate tests: 24°C (75°F) specimens 5.74 mm (0.226 in.) in diameter; 288°C (550°F) specimens 5.74 mm or 6.40 mm (0.226 in. or 0.252 in.) in diameter.
†24°C (75°F), crosshead rate 1.27 mm (0.05 in.)/min.
‡288°C (550°F), crosshead rate 1.27 mm (0.05 in.)/min.

The nil-ductility transition (NDT) temperature for the unirradiated condition was determined from drop-weight specimens (ASTM Type P-3) that were taken either at the quarter-thickness location (plate) or through the thickness (weld deposit).

For this investigation, CE provided all source materials, specimens, documented chemical compositions, and preirradiation properties. NRL conducted all material irradiations and postirradiation property assessments.

MATERIAL IRRADIATION

Series 3 materials were irradiated in the Union Carbide Research Reactor (UCRR) D-3 fuel lattice position and in the University of Buffalo Reactor (UBR) B-4 fuel lattice position. Experiment 1 (UCRR) with plate 5 and HAZ 5 samples was irradiated to average fluences of 4.8×10^{19} and 5.3×10^{19} n/cm^2 > 1 MeV; experiment 2 (UBR), containing all materials except HAZ 5, reached fluences of 4.9 to 6.1×10^{19} n/cm^2 > 1 MeV, depending on the particular experiment subsection.

Fluence determinations (Φ^{cs} = calculated spectrum fluence; Φ^{fs} = fission spectrum (assumed) fluence) were based on measurements with iron neutron-dosimeter wires included in each experiment specimen array. The duration of irradiation was approximately 1500 hours for the UCRR experiment and approximately 1900 hours for the UBR experiment. Irradiation temperatures were monitored continously by means of multiple thermocouples in each specimen array.

RESULTS

Irradiated Condition

Data developed for the six Series 3 materials are presented in Figs. 2 to 7 and are summarized in Table 5. Consistent with the low copper (and low phosphorus) contents, all of the materials exhibited excellent resistance to radiation in terms of both transition temperature retention and upper-shelf retention. For example, plates 5, 6, and 7 depicted C_v 41-J (30 ft-lb) transition-temperature increases on the order of only 36 to 42°C (65 to 75°F). In Figs. 2 and 4 a "double transition" behavior by plates 5 and 6 before irradiation is seen to be reproduced in the irradiated condition. In Fig. 2 (upper graph) the measured increase in the C_v 68-J (50 ft-lb) transition temperature ignores the postirradiation double transition to project a maximum radiation effect. In Fig. 4 the postirradiation double transition occurs below C_v 68-J. This occurrence acts to magnify the difference between C_v 41-J vs C_v 68-J transition temperature elevations. In Fig. 6 plate 7 does not show the double transition tendency.

Conventional assessments of transition-temperature elevation with irradiation could not be made for HAZ 5 (Fig. 3) because of data scatter. For HAZ 6 (Fig. 5) the indicated transition temperature elevations are considered approximations only. However the postirradiation data for both heat affected zones fall consistently to the left of the postirradiation curve for the parent plate in the transition regime; this relationship would suggest that the HAZ is not the limiting material in weldments. (In the absence of postirradiation LT orientation data for plate 5, it can be assumed that the LT vs TL orientation

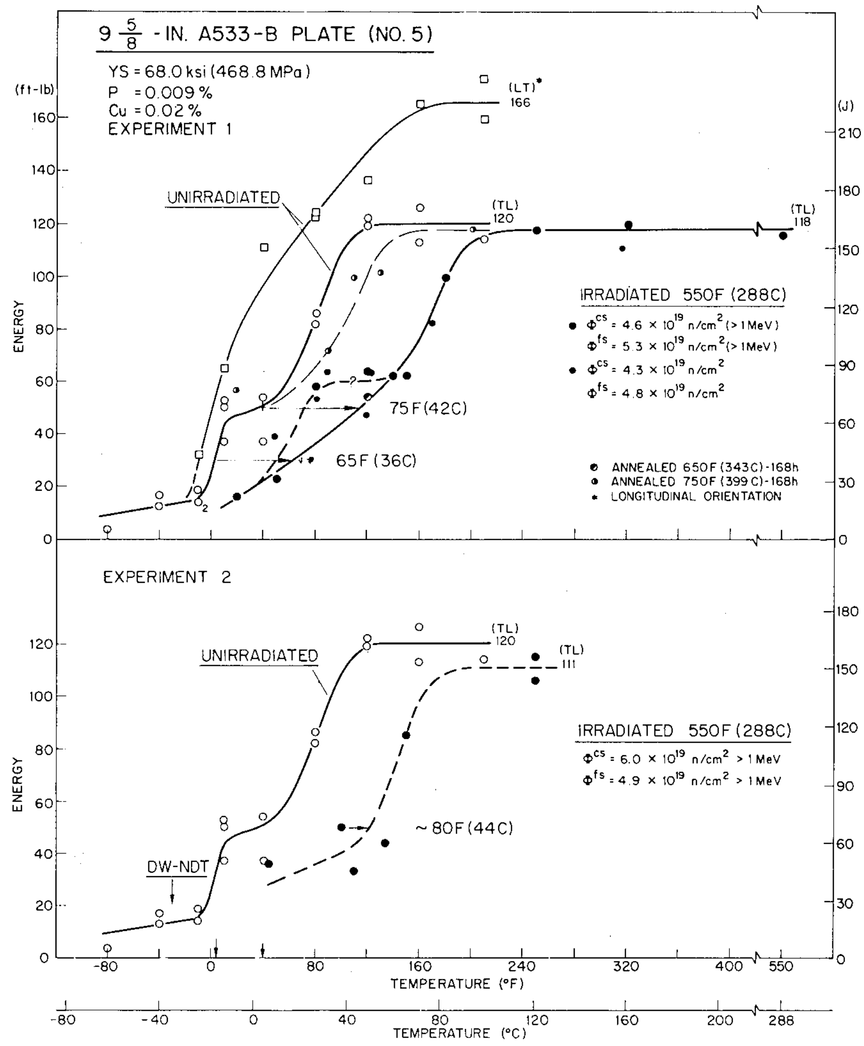

Fig. 2 - Notch ductility of plate 5 (Series 3) before and after 288°C (550°F) irradiation to two fluence levels. In this figure and in Figs. 3 through 7 open and filled symbols refer to unirradiated and irradiated conditions respectively.

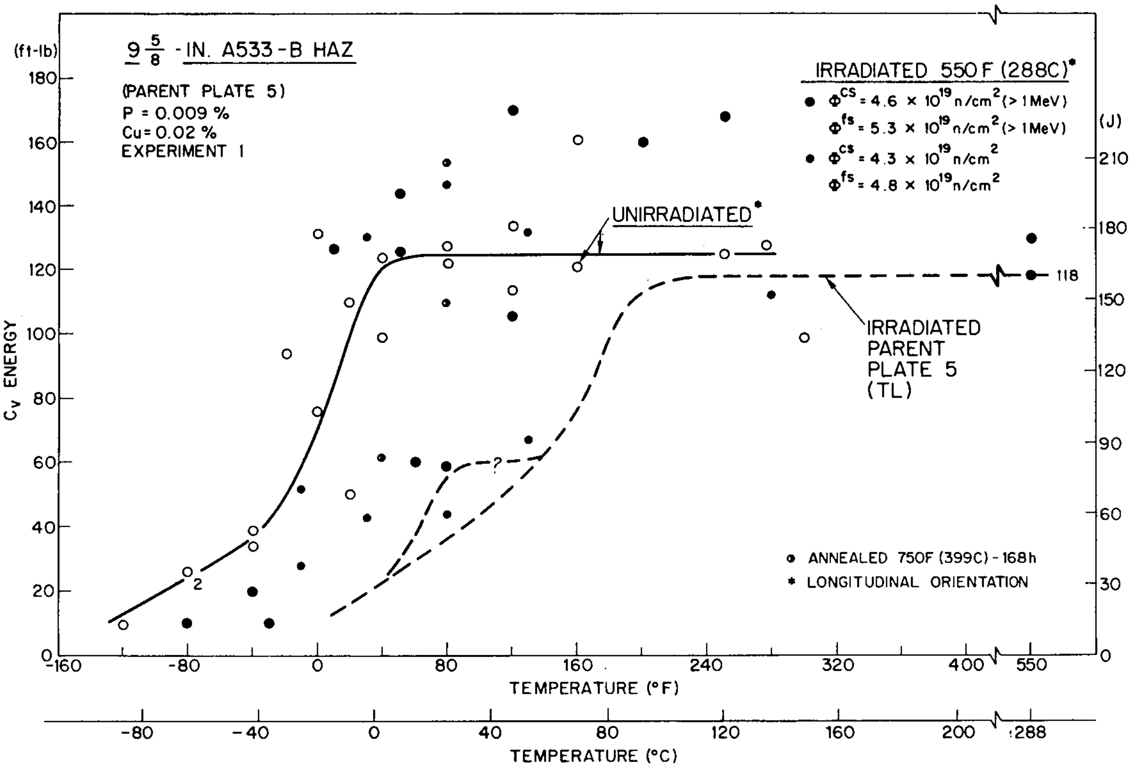

Fig. 3 - Notch ductility of HAZ 5 before and after irradiation. The notch ductility of the parent plate (TL orientation, Fig. 2) after irradiation is also indicated (dashed curve).

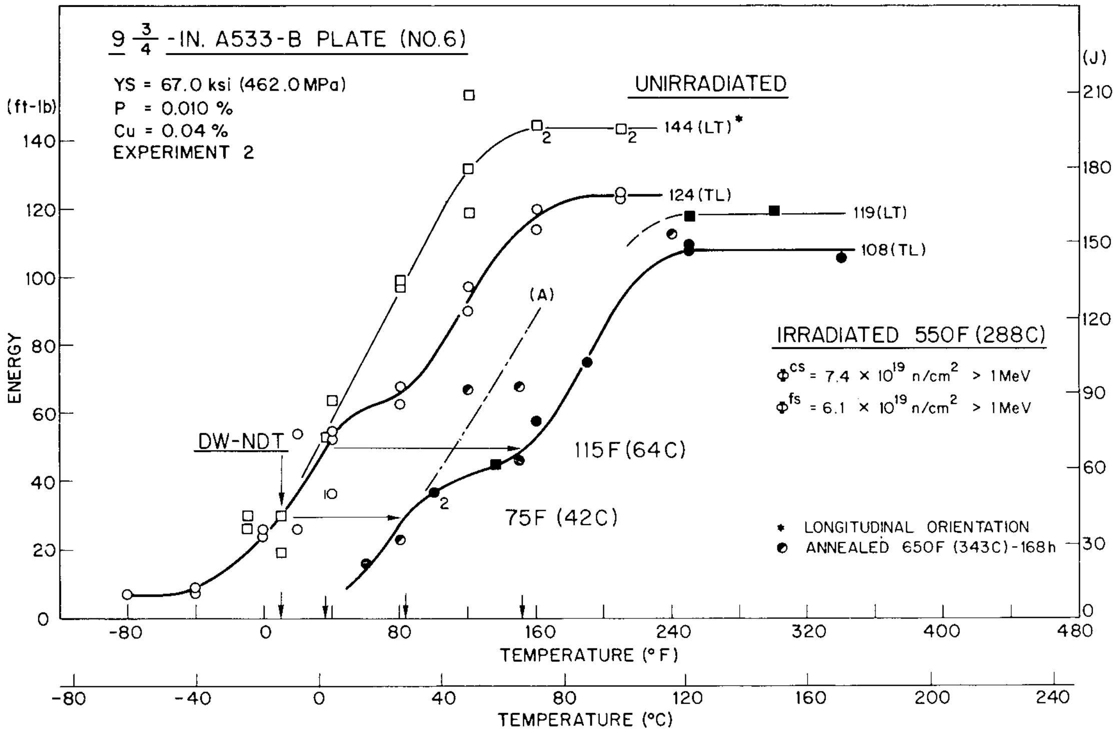

Fig. 4 - Notch ductility of plate 6 before and after irradiation. Limited data for the postirradiation annealed condition (half-filled symbols) are also shown.

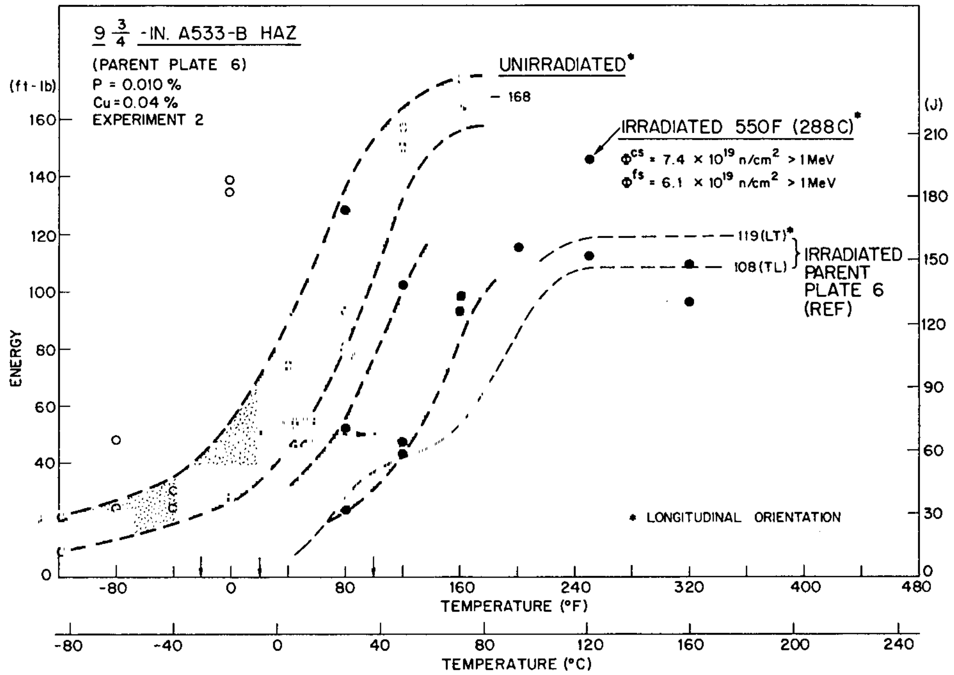

Fig. 5 - Notch ductility of HAZ 6 before and after irradiation. The notch ductility of the parent plate (LT and TL orientations, Fig. 4) after irradiation is also indicated.

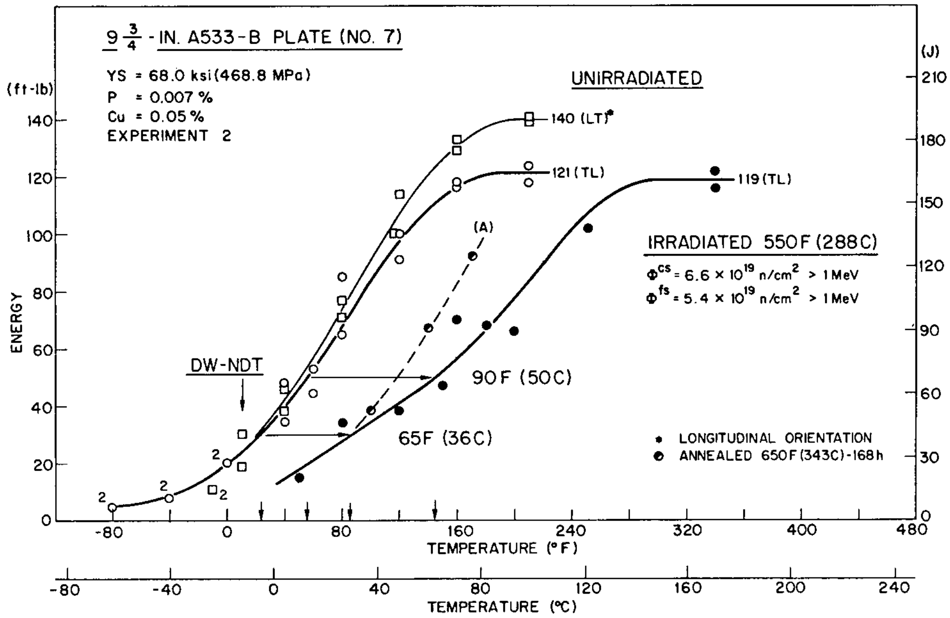

Fig. 6 - Notch ductility of plate 7 before and after irradiation. Limited data for the postirradiation annealed condition are also shown.

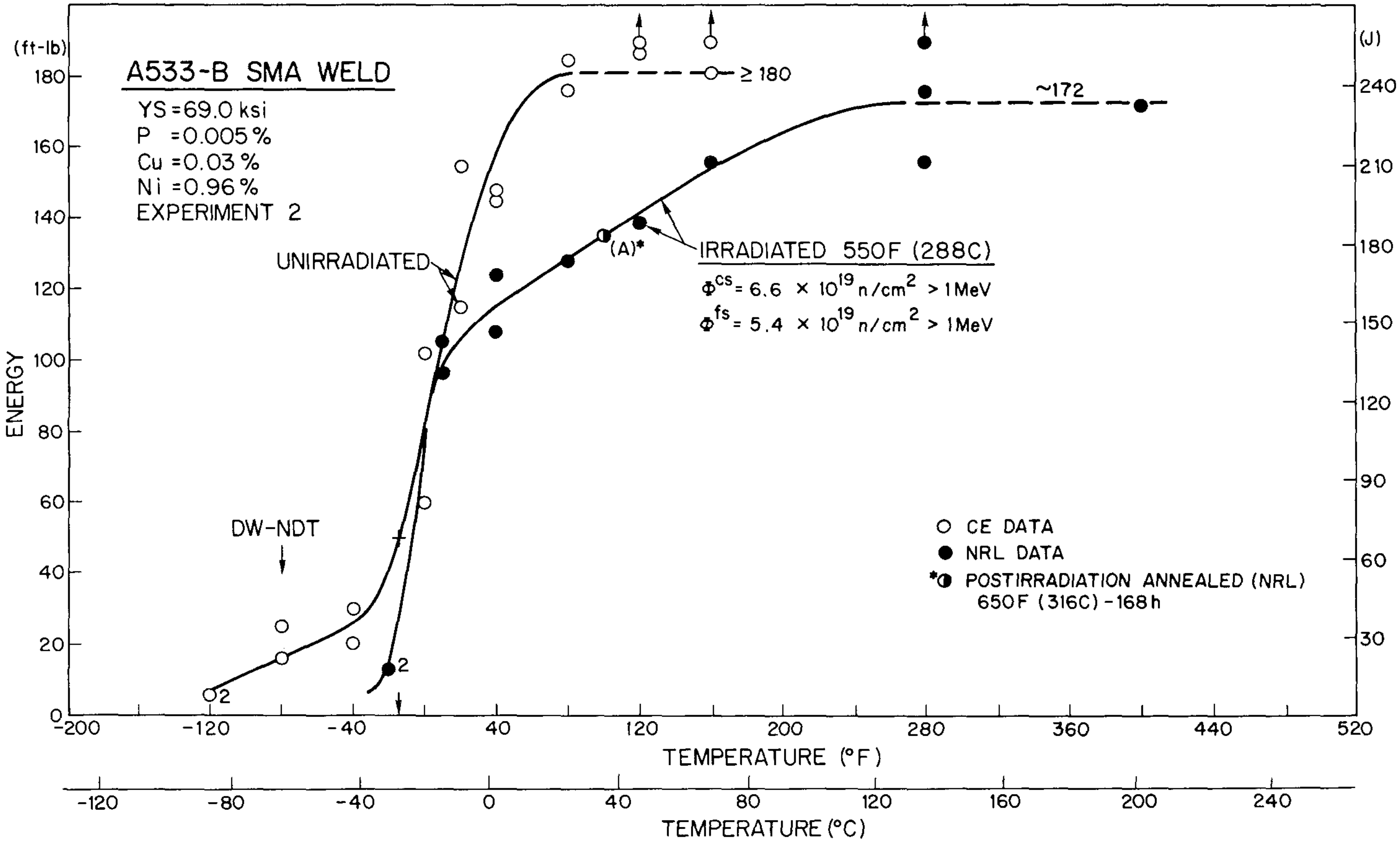

Fig. 7 - Notch ductility of weld 6 (SMA) before and after irradiation. One datum for the postirradiation annealed condition is also shown.

Table 5 — Notch Ductility Properties of Plates, Weld Deposits, and Weld Heat Affected Zones As Fabricated and After 288°C (550°F) Irradiation

As Fabricated*

Material	Nil-Ductility Transition		C_v Energy at NDT		C_v Transition: 41-J Index (30 ft-lb)		C_v Transition: 68-J Index (50 ft-lb)		C_v Upper-Shelf Energy	
	°C	°F	J	ft-lb	°C	°F	°C	°F	J	ft-lb
Plate 5	-34	-30	19	14	-18	0	4	40	163 (226)†	120 (166)†
HAZ 5†	-	-	-	-	-51	-60	-29	-20	≈170	≈125
Plate 6	-18	0	41	30	-12	10	2	35	168 (196)†	124 (144)†
HAZ 6†	-	-	-	-	-29	-20	-7	20	≈228	≈168
Plate 7	-12	10	33	24	-7	20	13	55	164 (190)†	121 (140)†
Weld 6 (SMA)	-62	-80	22	16	-34	-30	-26	-15	≥245	≥180

Irradiated Condition

Material	Fluence ($\times 10^{19}$ n/cm^2 > 1 MeV)		C_v Transition: 41-J Index (30 ft-lb)			C_v Transition: 68-J Index (50 ft-lb)			C_v Upper-Shelf Energy			
	Φ^{cs}	Φ^{fs}	°C	°F	ΔF	°C	°F	ΔF	J	ft-lb	ΔJ	Δft-lb
Plate 5	4.6	5.3	18	65	65	46	115	75	160	118	3	2
	6.0	4.9	—§	—§	—§	≈49	≈120	80	151	111	12	9
HAZ 5	4.6	5.3	<10	<50	<110	<21	<70	<90	—§	—§	—§	—§
Plate 6¶	7.4	6.1	29	85	75	66	150	115	146	108	22	6
HAZ 6	7.4	6.1	21	~70	~90	38	100	80	156	115	72	53
Plate 7	6.6	5.4	29	85	65	63	145	90	161	119	3	2
Weld 6 (SMA)	6.6	5.4	-26	-15	15	-23	-10	5	234	~172	≥11	≥ 8

*TL orientation except where noted.
†LT orientation.
§Not established (high data scatter).
¶LT orientation C_v upper shelf (postirradiation condition = 161 J (119 ft-lb).

relationship is generally maintained with irradiation.) In the upper-shelf regime, HAZ vs parent plate relationships are less clear. The data for HAZ 6 vs plate 6 suggest a somewhat greater radiation reduction in upper shelf and a lower postirradiation upper-shelf value for the HAZ. A parallel comparison for HAZ 5 was not possible for lack of plate 5 LT orientation data. For both HAZ 5 and HAZ 6 postirradiation upper shelf is not reduced below that for the parent-plate TL orientation.

Influence of Weld Deposit Nickel Content

The performance of weld 6 is of special interest (Fig. 7) because certain experimental data [1, 4, 5] have raised suspicions of a detrimental contribution of nickel content to radiation sensitivity. The data in question pertain largely to high copper (>0.20%Cu) weldments of A533-B steel. One interpretation of the data (NRL) was a reinforcement by nickel of the primary copper effect rather than an independent contribution of nickel to radiation sensitivity for amounts up to 1%Ni [1, 4, 5]; that is, an independent effect of nickel was considered unlikely. An independent effect of nickel for amounts in this range, on the other hand, has been projected by other investigators. In view of the broad usage and importance of weld metal containing about 1%Ni in nuclear vessel construction, clarification of the existence and mode of a nickel contribution to radiation performance is essential. In Fig. 7 the high radiation resistance exhibited by weld 6 (extra-low Cu) clearly demonstrates that nickel does not significantly contribute separately to radiation embrittlement sensitivity for chemistries representative of an extra-low copper content. Supporting evidence is provided by the NRL demonstration test weld which contained 0.6%Ni and 0.05%Cu [3]. Accordingly the original concern for the use of high-nickel weldments in high-fluence applications can be dismissed, provided that an extra-low copper content (≤0.05%) is specified. The results of Fig. 7 however do *not* resolve the hypothesis of a synergistic effect of nickel content to reduced radiation resistance for the alternate situation of a high-copper weld. Here the possibility of an interaction of nickel with copper suggested by the NRL analysis still remains.

Postirradiation Annealed Condition

Limited results for the 343°C (650°F) postirradiation heat-treated condition are presented in Figs. 4 and 6 for plates 6 and 7 respectively. The 168-hour heat treatment did not achieve significant recovery in C_v 41-J (30 ft-lb) transition temperature and produced only limited recovery in the C_v 68-J (50 ft-lb) temperature. A high degree of recovery was not expected, however, in view of similar results for the Series 2 materials [4]. In contrast a 399°C (750°F) 168-hour postirradiation heat treatment produced almost full recovery for plate 5 (Fig. 2, upper graph). Comparable tests of 399°C (750°F) heat treatment response were not performed for the Series 2 materials.

Charpy-V Lateral Expansion vs Energy Relationships

The reference nil-ductility temperature (RT_{NDT}) described by the ASME Code Section III [6] for assessing fracture toughness is established from drop weight-NDT, C_v 68-J (50 ft-lb), and C_v 0.9 mm (35 mils) lateral expansion transition temperature information. Trends in C_v lateral expansion vs C_v energy absorption after irradiation accordingly were explored and are presented in Figs. 8 through 13. (Results for the Series 1 and Series 2 materials were not available at the time of publication of Reference 4.)

Four observations are possible from the respective data trends. First, the general direction of the radiation effect is to decrease the slope of the trend curve. Accordingly materials tend to shift from RT_{NDT} limitation based on C_v energy absorption to a limitation based on C_v 0.9 mm (35 mils) lateral expansion. An example of this shift is illustrated in Fig. 9. Second, the data trend curves vary less with fluence for the more radiation resistant materials, as would be expected. Third, the slope of the HAZ trend

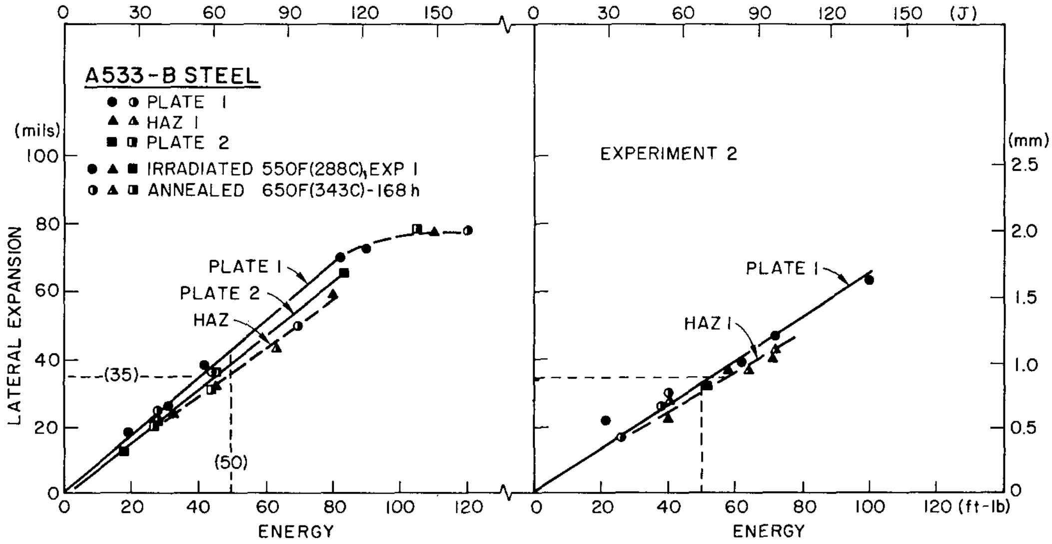

Fig. 8 - Charpy-V lateral expansion vs energy absorption trends observed for plate 1, HAZ 1, and plate 2 (Series 1) after irradiation and after postirradiation heat treatment. In this figure and in Figs. 9 through 12 "Experiment 2" refers to the high fluence condition.

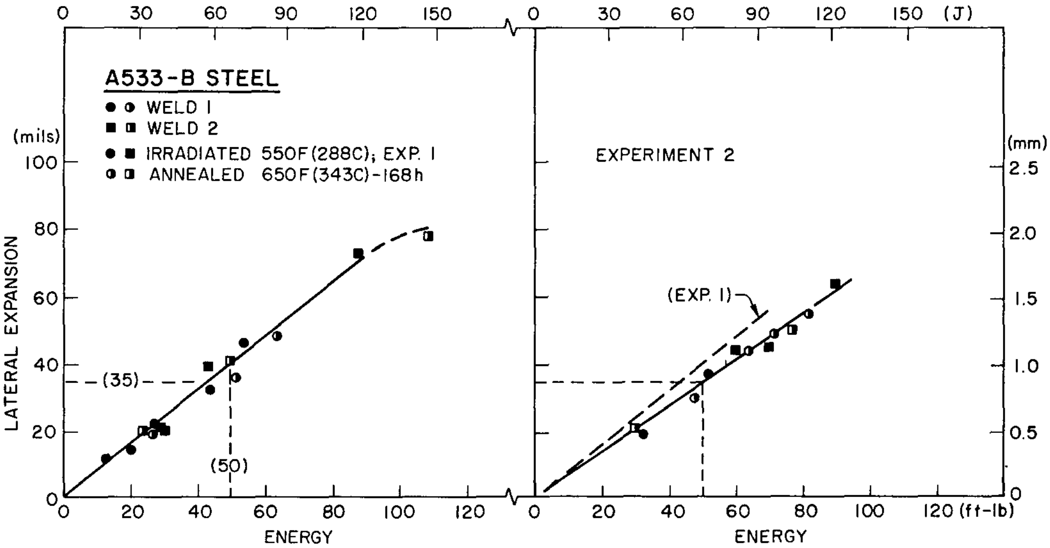

Fig. 9 - Charpy-V lateral expansion vs energy absorption trends observed for weld 1 and weld 2 (Series 1) after irradiation and after postirradiation heat treatment.

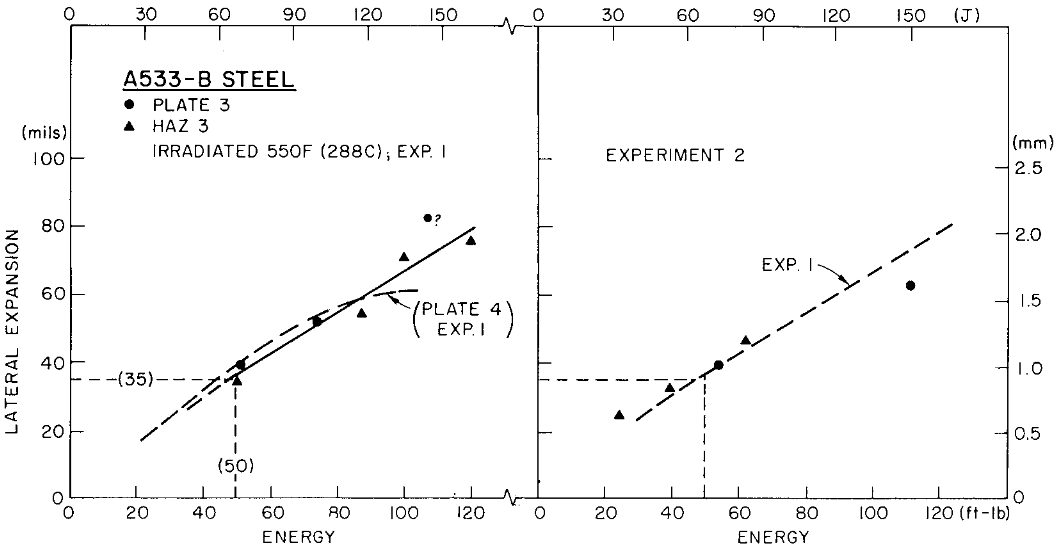

Fig. 10 - Charpy-V lateral expansion vs energy absorption trends observed for plate 3 and HAZ 3 (Series 2) after irradiation. In the left-hand graph the dashed curve reproduces the trend for plate 4 (Experiment 1) from Fig. 11.

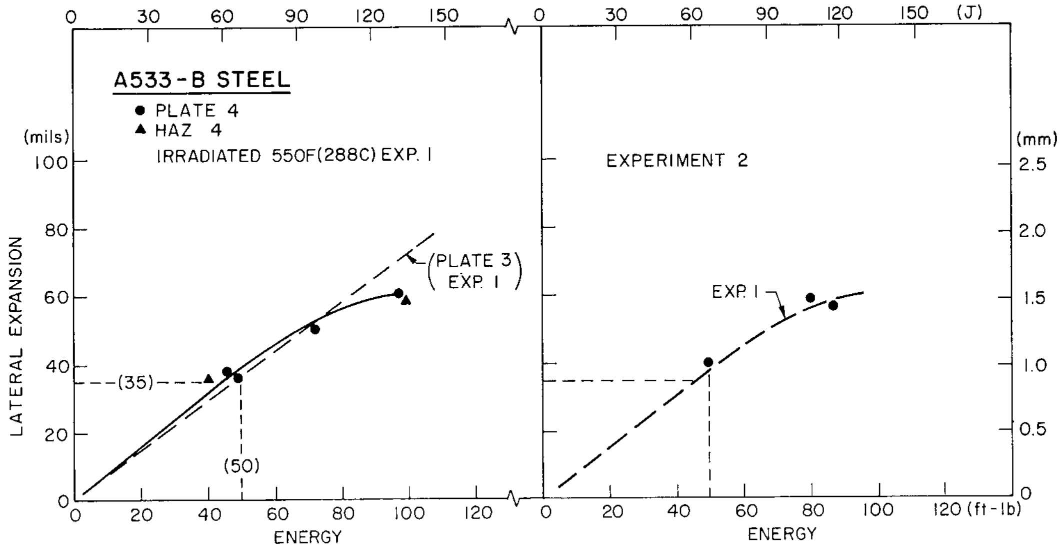

Fig. 11 - Charpy-V lateral expansion vs energy absorption trends observed for plate 4 and HAZ 4 (Series 2) after irradiation. The trend for plate 3 (Experiment 1) from Fig. 10 is also shown in the left-hand graph.

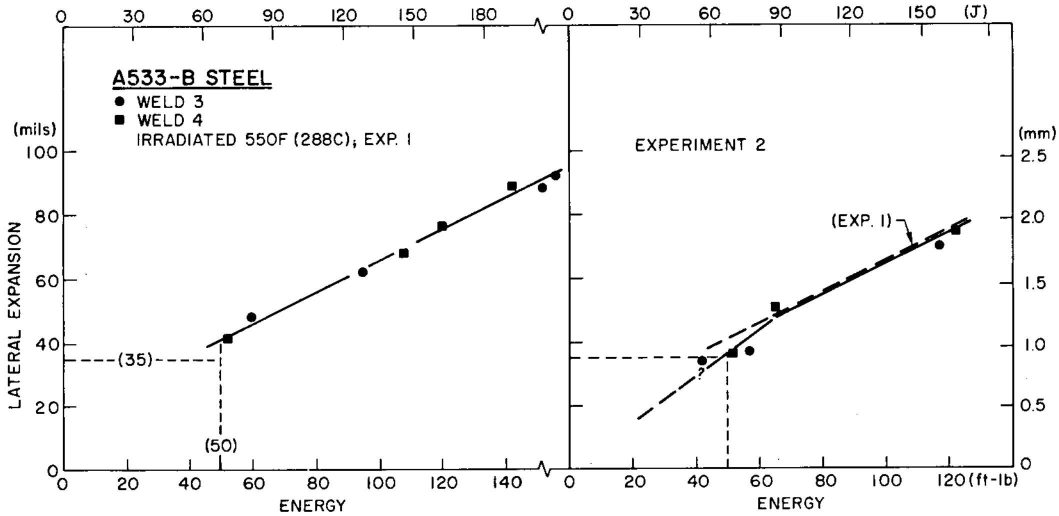

Fig. 12 - Charpy-V lateral expansion vs energy absorption trends observed for weld 3 and weld 4 after irradiation. Note the apparent inflection in the trend curve at approximately 88 J (65 ft-lb).

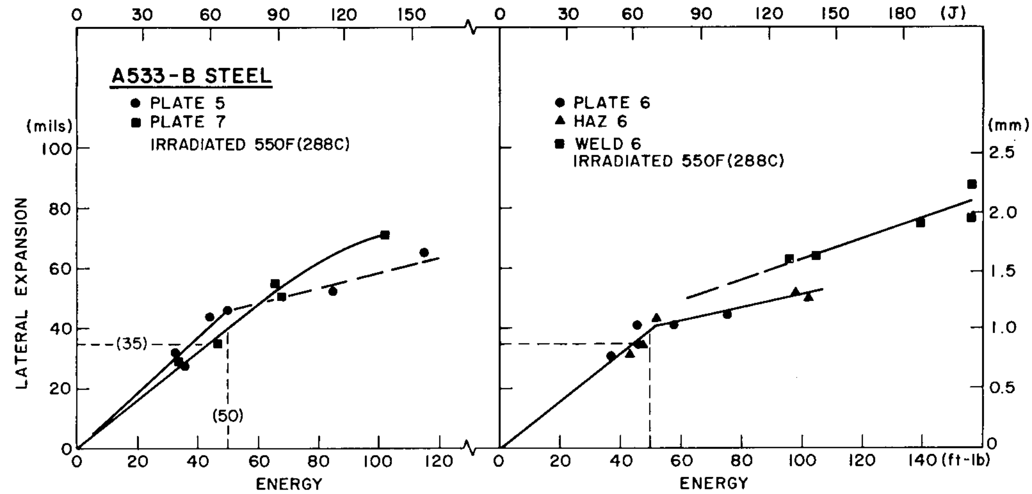

Fig. 13 - Charpy-V lateral expansion vs energy absorption trends observed for plate 5 and plate 7 (left-hand graph) and plate 6, HAZ 6, and weld 6 (right-hand graph) from Series 3 after irradiation. Note the inflection in the trend curves in the range of 68 to 82 J (50 to 60 ft-lb).

curve is equal to or less than the slope of the parent plate trend curve. Last, a distinct inflection in the slope of the trend curves is noted for the Series 2 and Series 3 materials but not for the Series 1 materials in the interval of C_v 1.0 to 1.5 mm (40 to 60 mils) lateral expansion, i.e., below the C_v upper-shelf regime. The significance of the C_v 68-J (50 ft-lb) and C_v 0.9 mm (35 mils) lateral expansion indices to each other and thus to RT_{NDT} would appear to be a function of copper content or general impurity content. This apparent relationship cannot be explained at this time.

A final observation is that the use of the C_v 68-J (50 ft-lb) index for postirradiation RT_{NDT} determinations over the full range of fluence service seems adequate for A533-B weldments. That is, the use of this single index rather than both the C_v 68-J (50 ft–lb) and 0.9 mm (35 mils) lateral-expansion indices will not introduce large errors in RT_{NDT} estimations for this steel.

DISCUSSION

The C_v 41-J (30 ft-lb) transition-temperature increases determined for the Series 3 materials are compared in Fig. 14 to the previously reported data for Series 1 and 2 materials. Significantly, the magnitude of radiation-induced property change indicated for the extra-low copper content materials (Series 3 materials and demonstration test materials) is comparable to that for the low-copper content materials (Series 2). The study thus has shown that a further reduction in maximum allowable copper content from 0.10%Cu max (ASTM specification) to 0.06%Cu max (best steelmaking practice) will not substantially improve 288°C (550°F) radiation resistance, at least not for plate and HAZ materials. For weld deposits, the effect of a reduction in permissible copper content from 0.10%Cu to 0.06%Cu could not be tested fully because copper content differences among the welds were too small. That is, individual copper contents were 0.07, 0.05 and 0.03%Cu. In addition, the transition temperature increase for the 0.07%Cu weld was only 28°C (50°F) vs < 11°C (20°F) for the 0.05%Cu and 0.03%Cu welds (high-fluence condition). Overall, the latter welds exhibited the highest radiation resistance of the materials investigated.

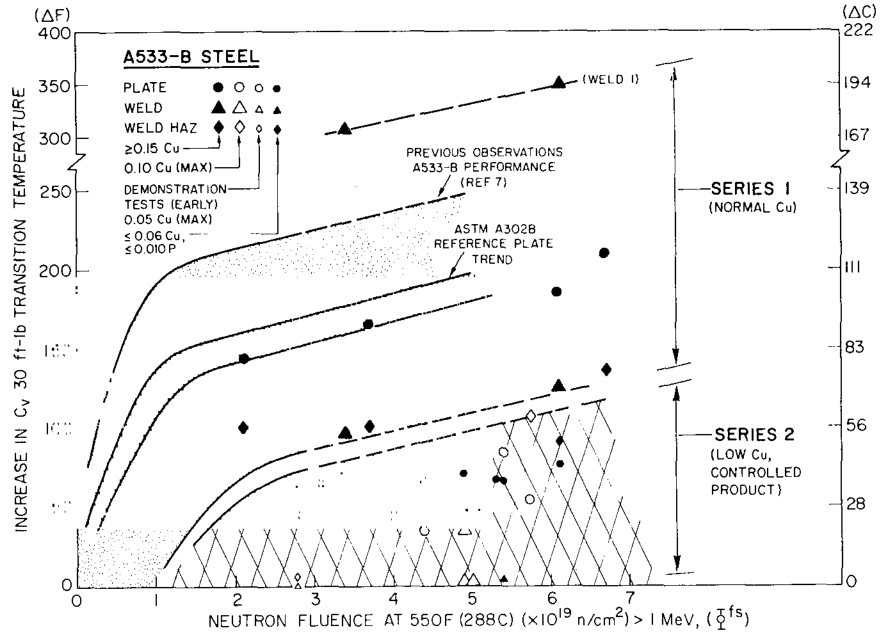

Fig. 14 - Summary of Charpy-V transition temperature observations for Series 3 materials (small filled symbols) superimposed on graph of Fig. 1. An entry (datum) for HAZ 5 was precluded by high data scatter. The results demonstrate comparable radiation resistance in materials with 0.06%Cu max and 0.10%Cu max contents, respectively representing best steelmaking practice vs current improved practice.

New ASTM specifications for A533-B and A508-2 steels [7, 8] outline optional supplemental requirements on the heat analysis for reactor beltline applications consisting of 0.10%Cu max, 0.012%P max, 0.015%S max, and 0.05%V max. The supplemental requirements note that vanadium and sulfur can affect the upper-shelf energy level and thus are limited by specification. New (and pending) AWS specifications for bare carbon-steel electrodes and bare low-alloy steel electrodes and fluxes for submerged arc welding [9, 10] provide the following supplemental requirements for fillers for nuclear applications: 0.08% Cu max, 0.010%P max, 0.013%S max, and 0.05%V max. It is expected that for most projected applications and fluence levels the specifications will serve the needs of industry for radiation resistant vessel materials. However, differences are permitted in the case of the ASTM specifications between the heat and product analysis. Accordingly actual plate or forging compositions should be reviewed to verify that the product will feature the expected level of radiation resistance for the application.

CONCLUSIONS

Radiation assessments of the Series 3 materials (extra-low copper content) by the NRC-CE-NRL Cooperative Program have resulted in the following primary observations and conclusions:

- The specification of extra-low copper content (0.06%Cu max) as opposed to a low copper content (0.10%Cu max) does not substantially improve 288°C (550°F) radiation resistance for A533-B steel materials for fluences up to $\approx 5 \times 10^{19}$ n/cm^2 $>$ 1 MeV.

- All plate, weld, and HAZ materials of Series 3 exhibited very low sensitivity to radiation-induced change in C_v notch ductility in terms of transition temperature elevation and upper-shelf energy degradation. Typically C_v 41-J (30 ft-lb) transition temperature elevations were less than 56°C (100°F) and shelf-energy degradations were 13% or less with fluences (Φ^{cs}) of ~ 5 to 7×10^{19} n/cm^2 $>$ 1 MeV.

- The weld deposit showed the best radiation resistance of the Series 3 materials. The weld HAZ in general exhibited a ductile/brittle trensition no higher than that of the parent plate. Somewhat poorer upper-shelf retention by the HAZ is suggested by the data.

- Nickel in amounts up to 1% does not contribute separately to radiation effects sensitivity in extra-low copper content ($\leq$ 0.05%) A533 weld deposits.

- Postirradiation annealing of extra-low copper content A533 plates at 343°C (650°F) for 168 hours is not particularly effective toward radiation effects recovery; however annealing responses of Series 3 steels were only of academic interest because of their high radiation resistance.

- The trend of 288°C (550°F) irradiation is to decrease the slope of the curve of C_v lateral expansion vs C_v energy absorption. Accordingly materials tend to shift from an RT_{NDT} limitation based on energy absorption to a limitation based on lateral-expansion behavior.

- An inflection in the postirradiation C_v lateral expansion vs energy trend was observed below the upper-shelf energy regime for Series 2 and Series 3 materials but not for Series 1 (normal copper content) materials.

- The indexing of postirradiation RT_{NDT} from the C_v 68-J (50 ft-lb) transition temperature alone appears adequate for A533-B plates and welds for fluences up to 5×10^{19} n/cm^2 > 1 MeV.

ACKNOWLEDGEMENTS

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Appendix A

PREVIOUSLY REPORTED RESULTS FOR NORMAL-COPPER (SERIES 1) AND LOW-COPPER (SERIES 2) MATERIALS

INTRODUCTION

This appendix summarizes data and primary observations for the Series 1 and Series 2 materials previously reported [4]. An overview of the Cooperative Program and its specific research objectives for the Series 1 and 2 materials is given in the first three sections and Table 1 of the main text.

MATERIALS

The chemical compositions and heat treatment conditions of the Series 1 and 2 materials are given in Table 2. Welding parameters and materials are provided in Table 3.

Charpy-V specimens for the investigations were cut in the manner described herein for the Series 3 materials. With one exception (plate 1), only the TL orientations of the plates* were evaluated with irradiation. Preirradiation NDT temperatures were determined using drop-weight test specimens (ASTM Type P-3) taken from the quarter-thickness location in plate and through the thickness in weld deposits.

MATERIALS IRRADIATION

The materials were irradiated in the Union Carbide Research Reactor (UCRR) using B-3 and D-3 fuel lattice positions. Irradiation exposures were approximately 1200 to 1400 hours in duration for the "low" fluence experiments (2 to 3×10^{19} n/cm^2; Table 1) and of approximately 2400 to 2600 hours in duration for the "high" fluence experiments (4 to 5×10^{19} n/cm^2). In general, neutron fluences of individual experiments somewhat exceeded those levels called for by the program plan (Table 1).

The reactor exposure of experiment 3 was not fully satisfactory in that a temporary loss of temperature control to one of three specimen sections involving welds 3 and 4 resulted in an overheating of that section to 427°C (800°F) for 5.5 hours at a point 43% through the total exposure. A "repeat experiment" subsequently performed in lieu of the "high" fluence experiment confirmed the indications of the initial experiment, demonstrating that the midcycle anneal was of little consequence to the performance of welds 3 and 4.

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*Since Reference 4 was issued, the designation for the transverse orientation WR has been succeeded by the identification TL. Similarly the designation for the longitudinal orientation RW has been replaced by the designation LT.

RESULTS

Experimental results for the Series 1 and 2 materials in preirradiation, postirradiation, and 343°C (650°F) postirradiation heat-treated conditions are shown in Figs. A1 through A11. Notch ductility properties are listed in Table A1. Preirradiation tensile properties are listed in Table A2.

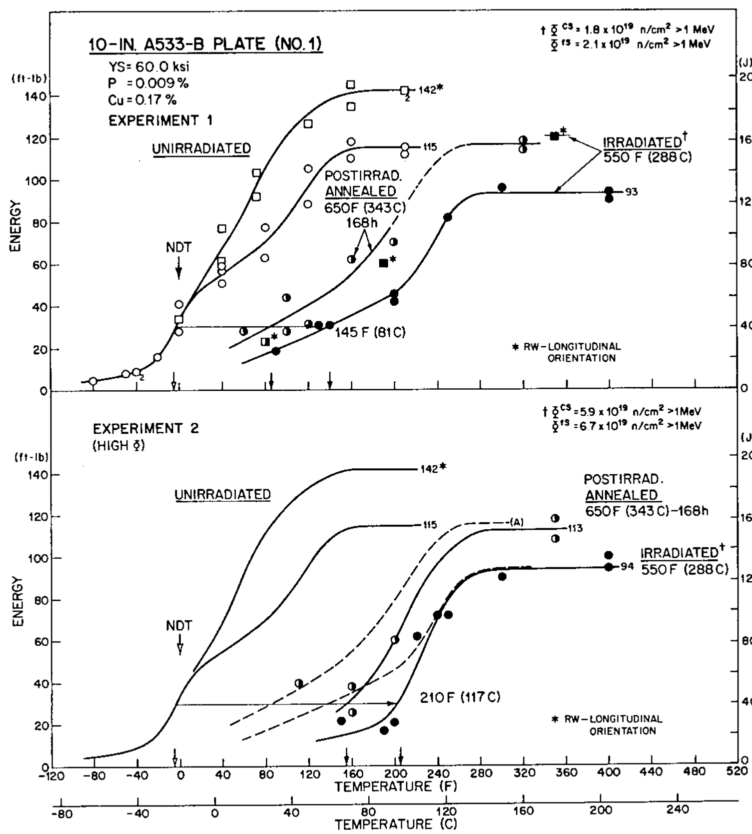

Fig. A1 - Notch ductility of plate 1 (Series 1) before and after 550°F (288°C) irradiation. In this figure and in Figs. A2 through A11, open and filled symbols refer to unirradiated and irradiated conditions respectively; half-filled symbols refer to the 650°F (343°C) postirradiation annealed condition. Also by convention results for the low-fluence and the high-fluence experiments are given in top and bottom graphs respectively. In some figures, curves for the irradiated and postirradiation annealed (A) condition in the top graph are repeated as dashed curves in the bottom graph for quick comparisons.

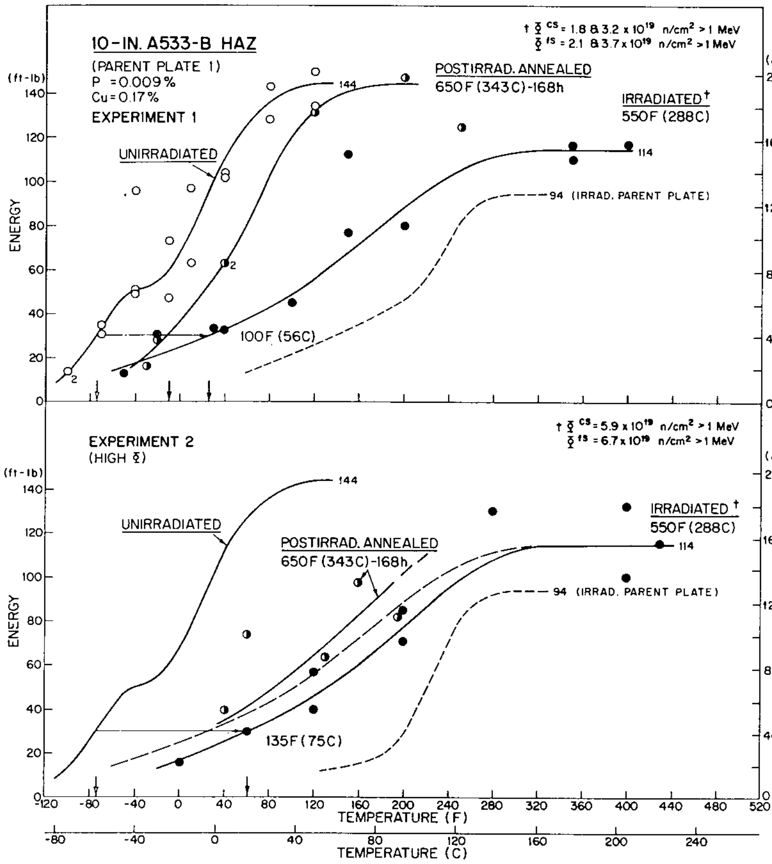

Fig. A2 - Notch ductility of HAZ 1 (Series 1) before and after irradiation. The notch ductility of the parent plate (WR orientation, Fig. A1) after irradiation is also indicated.

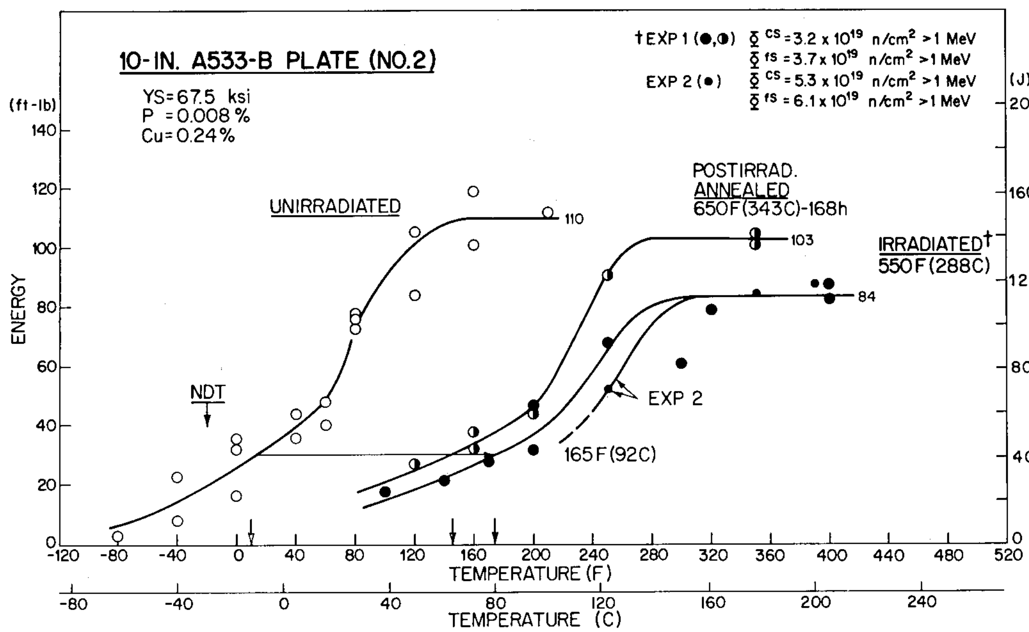

Fig. A3 - Notch ductility of plate 2 (Series 1) before and after irradiation to a low fluence. Limited data from a high-fluence experiment (small filled symbols) are also shown.

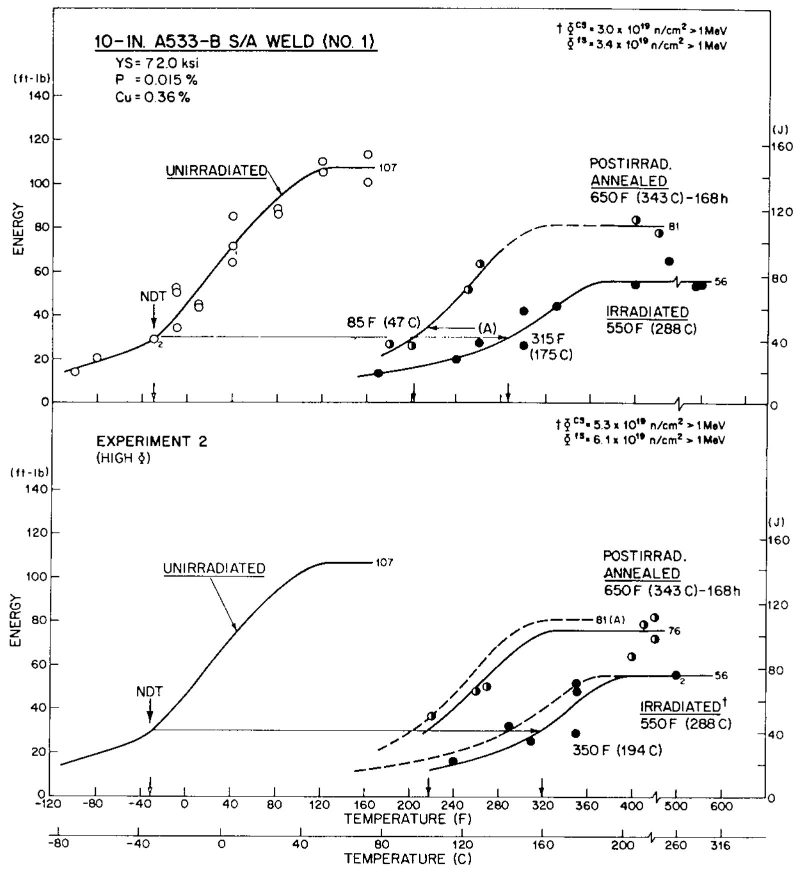

Fig. A4 - Notch ductility of weld 1 (Series 1) before and after irradiation.

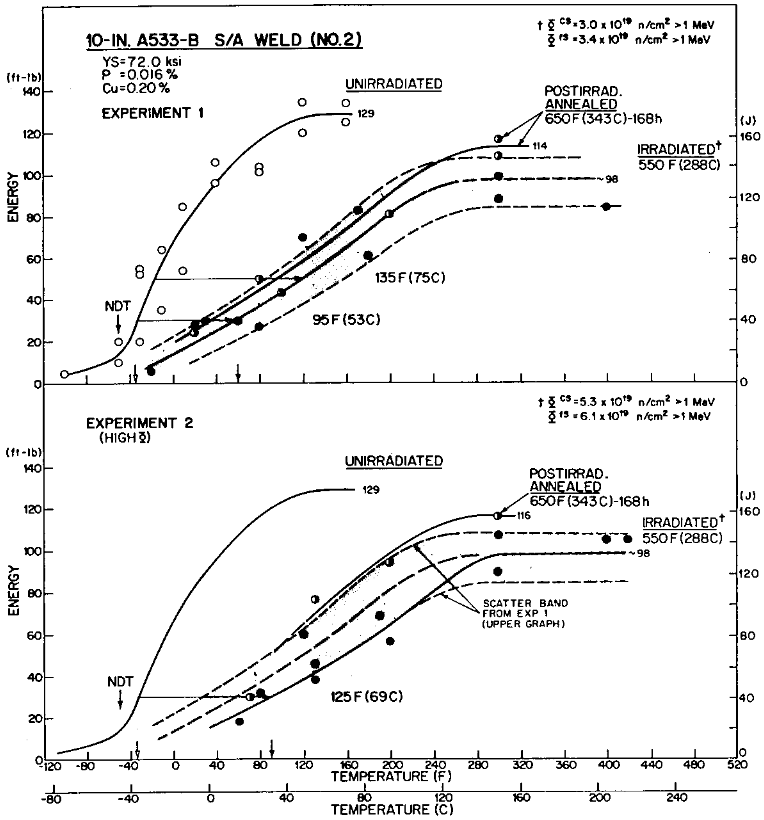

Fig. A5 - Notch ductility of weld 2 (Series 1) before and after irradiation.

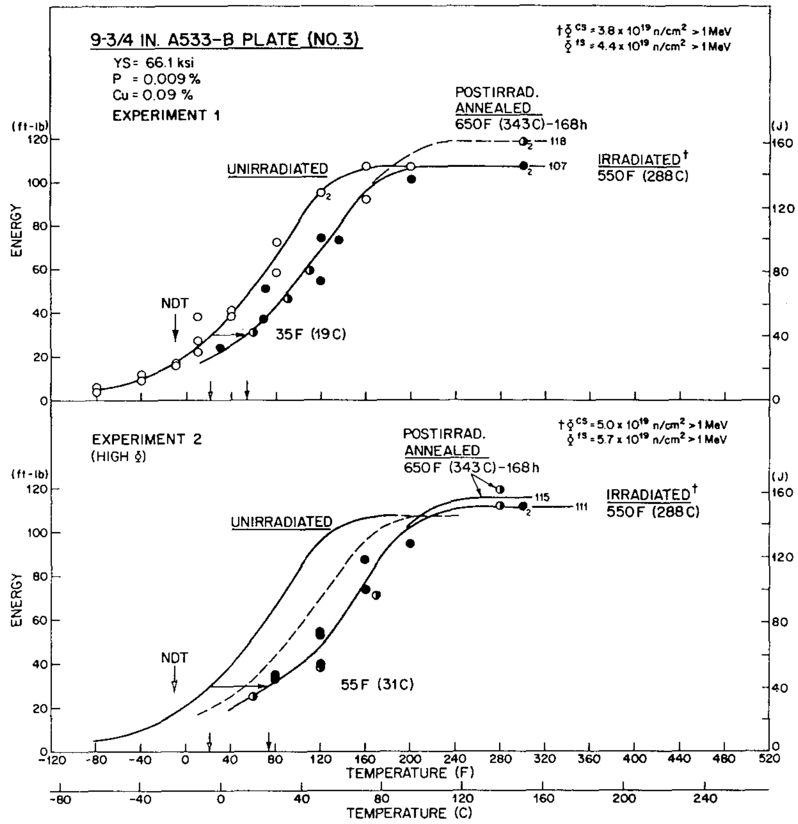

Fig. A6 - Notch ductility of plate 3 (Series 2) before and after irradiation. Note the anomalous increase in C_v upper shelf energy with postirradiation annealing.

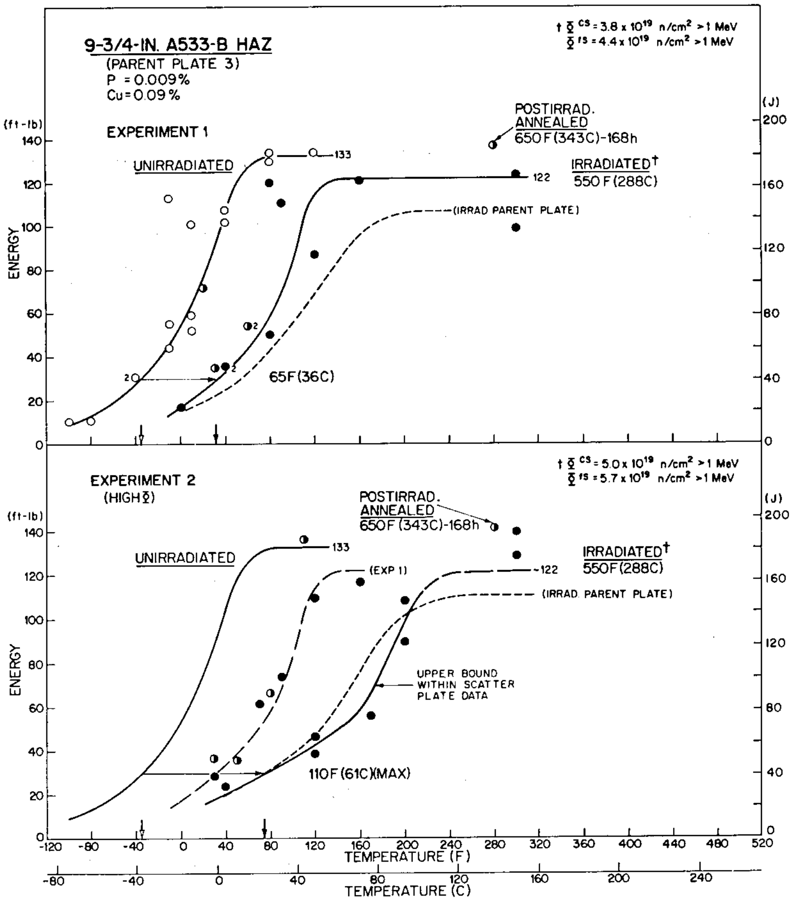

Fig. A7 - Notch ductility of HAZ 3 (Series 2) before and after irradiation. The notch ductility of the parent plate (WR orientation, Fig. A6) after irradiation is also indicated.

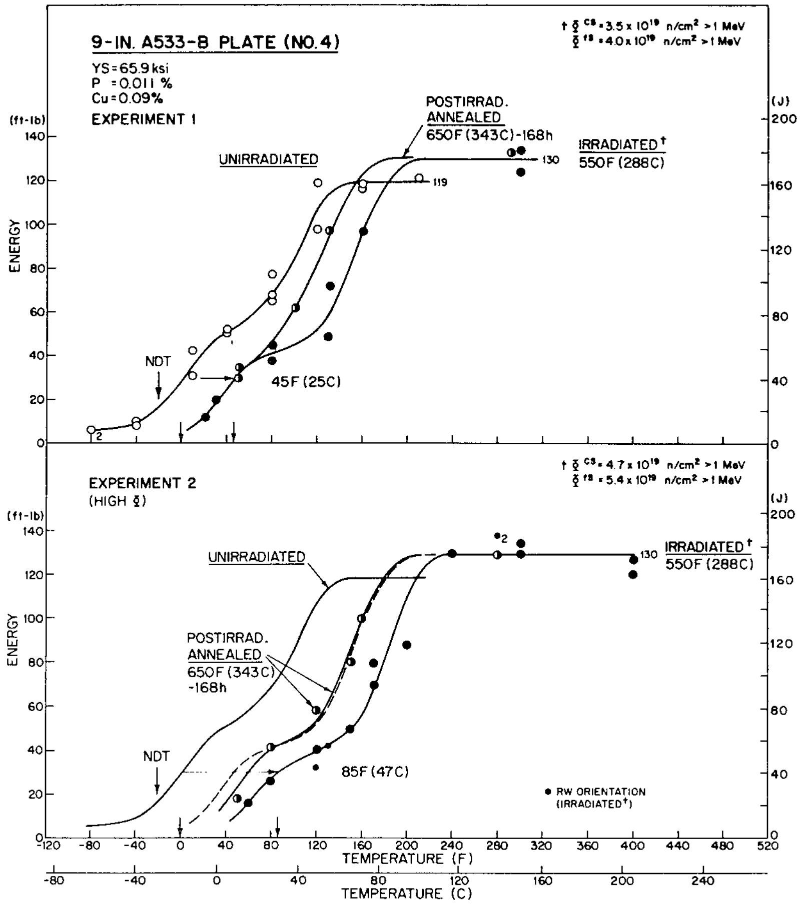

Fig. A8 - Notch ductility of plate 4 (Series 2) before and after irradiation.

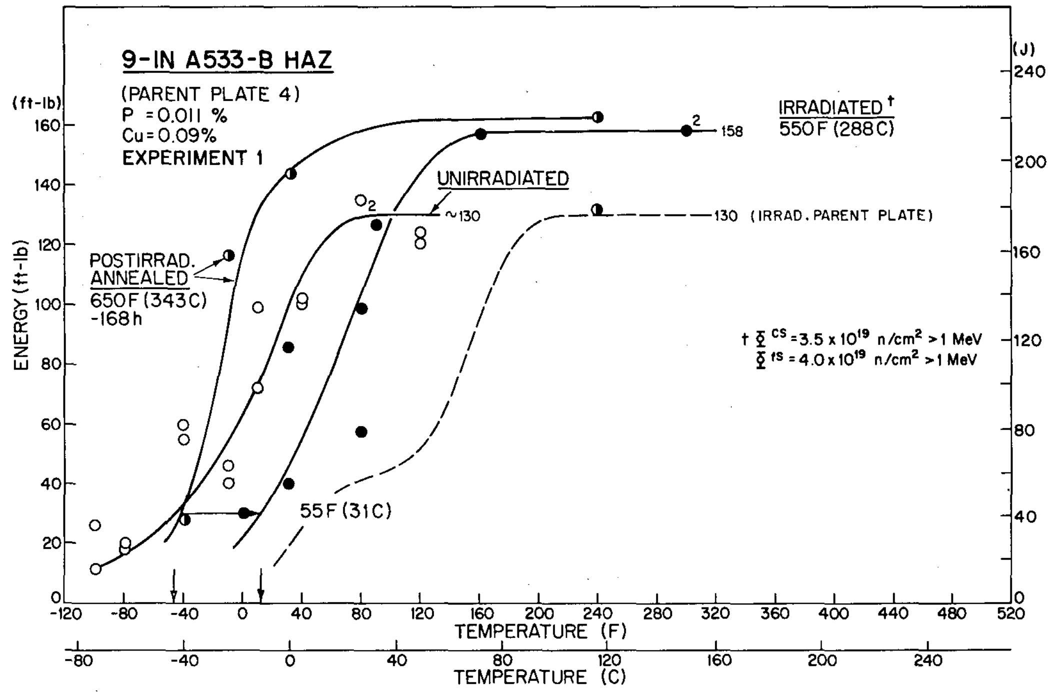

Fig. A9 - Notch ductility of HAZ 4 (Series 2) before and after irradiation to a low fluence. The notch ductility of the parent plate (WR orientation, Fig. A8) after irradiation is also indicated.

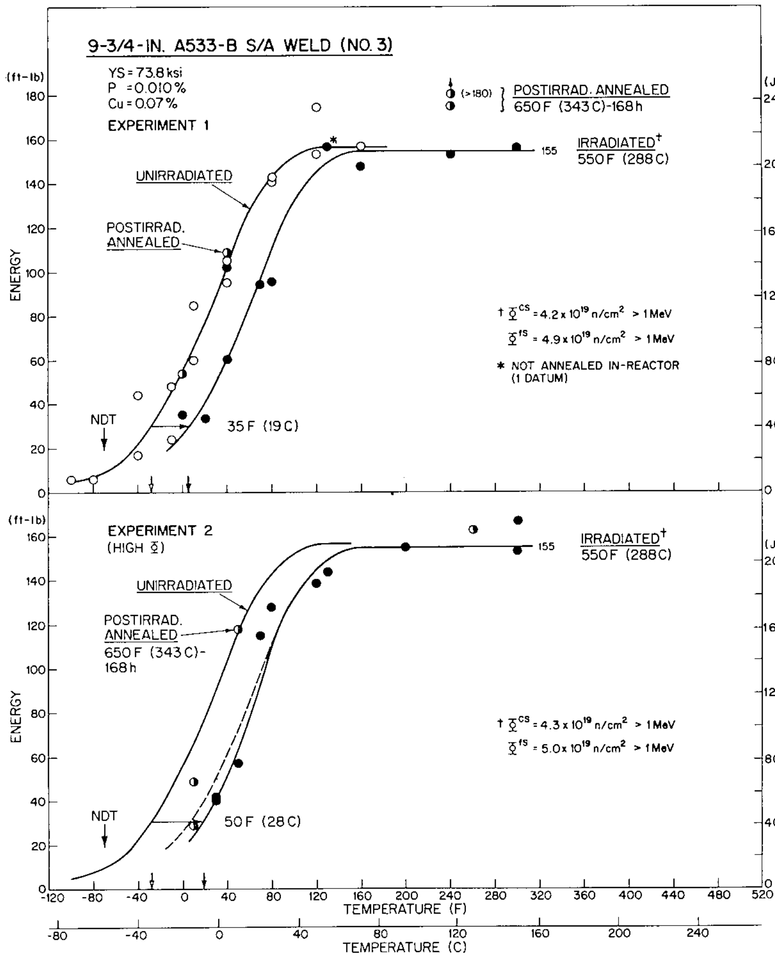

Fig. A10 – Notch ductility of weld 3 (Series 2) before and after irradiation. In this case, the low-fluence exposure included a midcycle 800°F (427°C) 5-1/2-hr anneal except for one specimen tested at 120°F (49°C).

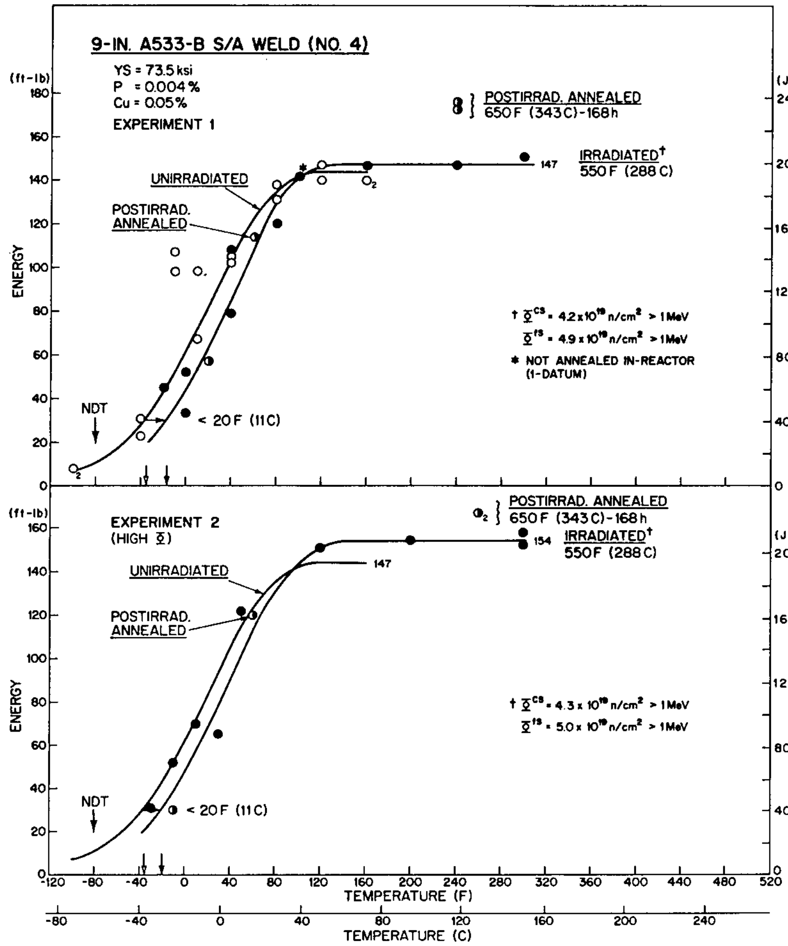

Fig. A11 - Notch ductility of weld 4 (Series 2) before and after irradiation. The low-fluence exposure included a midcycle 800°F (427°C) 5-1/2-hr anneal except for one specimen tested at 100°F (38°C).

Table A1a — Notch Ductility Properties of Plates, Weld Deposits, and Weld Heat Affected Zones As Fabricated

Material	NDT		C_v Energy at NDT		C_v Transition Temperature				C_v Upper-Shelf Energy	
					41-J Index (30 ft-lb)		68-J Index (50 ft-lb)			
	°C	°F	J	ft-lb	°C	°F	°C	°F	J	ft-lb
Series 1 Materials: Normal Copper Content										
Plate 1	−18	0	46	34	−21	− 5	− 4	25	156	115
HAZ 1	—	—	—	—	−59	−75	−40	−40	196	144
Plate 2	−29	−20	27	20	−12	10	16	60	~149	~110
Weld 1	−34	−30	39	29	−34	−30	−15	5	145	107
Weld 2	−46	−50	20	15	−37	−35	−26	−15	175	129
Series 2 Materials: Low Copper Content										
Plate 3	−23	−10	23	17	− 7	20	16	60	141	104
HAZ 3	—	—	—	—	−37	−35	−21	− 5	181	133
Plate 4	−29	−20	23	17	−18	0	4	40	161	119
HAZ 4	—	—	—	—	−43	−45	−26	−15	~176	~130
Weld 3	−57	−70	12	9	−34	−30	−21	− 5	≥214	≥157
Weld 4	−62	−80	14	10	−37	−35	−26	−15	196	144

Table A1b — Notch Ductility Properties of the Materials in Table A1a After 288°C (550°F) Irradiation

Material	Fluence* (10^{19} n/cm² > 1 MeV)		C_v Transition Temperature								C_v Upper-Shelf Energy			
			41-J Index (30 ft-lb)				68-J Index (50 ft-lb)							
	Φ^{cs}	Φ^{fs}	°C	°F	Δ°C	Δ°F	°C	°F	Δ°C	Δ°F	J	ft-lb	ΔJ	Δft-lb
Series 1 Materials														
Plate 1	1.8	2.1	60	140	81	145	99	210	103	185	126	93	30	22
	5.9	6.7	93	205	117	210	104	220	108	195	127	94	29	21
HAZ 1	2.5†	2.9†	− 4	25	56	100	38	100	78	140	155	114	41	30
	5.9	6.7	16	60	75	135	57	135	97	175	~155	~114	~ 41	~ 30
Plate 2	3.2	3.7	79	175	92	165	107	225	92	165	114	84	~ 35	~ 26
	5.3	6.1	~ 91	~195	~103	~185	~118	~245	~103	~185	117	86	~ 33	~ 24
Weld 1	3.0	3.4	141	285	175	315	174	345	189	340	76	56	69	51
	5.3	6.1	160	320	194	350	188	370	208	375	76	56	69	51
Weld 2	3.0	3.4	16	60	53	95	49	120	75	135	~133	~ 98	~ 42	~ 31
	5.3	6.1	32	90	69	125	71	160	97	175	~133	~ 98	~ 42	~ 31
Series 2 Materials														
Plate 3	3.8	4.4	13	55	19	35	32	90	17	30	145	107	(+) 4	(+) 3
	5.0	5.7	24	75	31	55	52	125	36	65	151	111	(+)10	(+) 7
HAZ 3	3.8	4.4	− 1	30	36	65	21	70	42	75	165	122	15	11
	5.0	5.7	24	75	61	110	60	140	81	145	~165	~122	~ 15	~ 11
Plate 4	3.5	4.0	7	45	25	45	46	115	42	75	176	130	(+)15	(+)11
	4.7	5.4	29	85	47	85	66	150	61	110	176	130	(+)15	(+)11
HAZ 4	3.5	4.0	− 12	10	31	55	2	35	28	50	215	158	(+)34	(+)25
Weld 3	4.2	4.9	− 15	5	19	35	− 1	30	19	35	211	155	~ 0	~ 0
	4.3	5.0	− 7	20	28	50	4	40	25	45	211	155	~ 0	~ 0
Weld 4	4.2	4.9	− 29	− 20	≤ 11	≤ 20	− 15	5	11	20	200	147	~ 0	~ 0
	4.3	5.0	− 29	− 20	≤ 11	≤ 20	− 15	5	11	20	209	154	(+)14	(+)10

*$\Phi^{cs} > 0.1$ MeV = 2.0 $\Phi^{cs} > 1$ MeV.

†Average fluence; the actual values varied between two groups of specimens.

Table A1c — Notch Ductility Properties of the Materials in Table A1a in the Postirradiation Annealed Condition [343°C (650°F) for 168 hr]

Material	Fluence Level	C_v Transition-Temperature: 41-J Index (30 ft-lb) Δ°C	Δ°F	68-J Index (50 ft-lb) Δ°C	Δ°F	C_v Upper-Shelf Recovery (%)
Series 1 Materials						
Plate 1	Low	31	55	33	60	100
	High	28	50	17	30	100
HAZ 1	Low	19	35	44	80	100
	High	22	40	28	50	— ‡
Plate 2	Low	17	30	11	20	75
Weld 1	Low	47	85	56	100	49
	High	56	100	61	100	~ 39
Weld 2	Low	14	25	14	25	52
	High	17	~ 30	39	~ 70	58
Series 2 Materials						
Plate 3	Low	Nil	Nil	Nil	Nil	— †
	High	Nil	Nil	Nil	Nil	— †
HAZ 3	Low	Nil	Nil	Nil	Nil	100
	High	— ¶	— ¶	— ¶	— ¶	— ¶
Plate 4	Low	Nil	Nil	17	30	— †
	High	14	25	22	40	— †
HAZ 4	Low	Full	Full	Full	Full	— †
Weld 3	Low	Full	Full	Full	Full	— †
	High	Full	Full	Full	Full	— †
Weld 4	Low	— ‡	— ‡	— ‡	— ‡	— †
	High	— ‡	— ‡	— ‡	— ‡	— †

‡Not established.
†No loss in upper shelf occurred after irradiation.
¶High data scatter.

Table A2 — Tensile Properties of Plates and Weld Deposits

Material	Cu (wt-%)	Yield Strength* (0.2% Offset)		Tensile Strength		R.A. (%)	Elong. in 1-in. (%)
		MN/m²	ksi	MN/m²	ksi		
Series 1 Materials: Normal Copper Content							
Plate 1	0.17	428†	61.3†	599	85.8	69.0	14.5
		419‡	60.0‡	599	85.8	70.0	13.0
		383§	54.8§	576	82.5	65.0	11.0
Plate 2	0.24	470†	67.3†	631	90.3	66.6	13.5
		472‡	67.5‡	634	90.8	70.0	12.0
		419§	60.0§	613	87.8	62.5	10.5
Weld 1	0.36	465†	66.6†	624	89.3	68.0	13.5
		503‡	72.0‡	646	92.5	70.0	12.0
		451§	64.5§	596	85.3	60.0	9.5
Weld 2	0.20	523†	74.8†	613	87.8	73.8	15.5
		503‡	72.0‡	603	86.3	72.5	12.5
		440§	63.0§	583	83.5	70.0	11.0
Series 2 Materials: Low Copper Content							
Plate 3	0.09	446†	63.9†	597	85.4	66.5	14.0
		462‡	66.1‡	599	85.8	63.5	13.5
		411§	58.8§	574	82.2	60.8	11.0
Plate 4	0.09	453†	64.8†	604	86.5	68.6	13.5
		460‡	65.9‡	611	87.4	69.3	14.5
		430§	61.6§	607	86.9	65.0	11.5
Weld 3	0.07	497†	71.1†	604	86.4	71.4	12.5
		516‡	73.8‡	603	86.3	71.7	13.0
		458§	65.5§	587	84.0	67.2	12.3
Weld 4	0.05	506†	72.4†	601	86.0	71.1	11.5
		513‡	73.5‡	600	85.9	72.6	13.5
		458§	65.5§	578	82.7	67.7	12.5

*Transverse orientation, duplicate tests: 24°C (75°F), 5.7-mm-diam (0.226-in.-diam) specimens; 288°C (550°F), 5.7- or 6.4-mm-diam (0.266- or 0.252-in.-diam specimens.

†24°C (75°F): 0.13-mm/min (0.005 in./min) crosshead rate.

‡24°C (75°F): 1.27-mm/min (0.05-in./min) crosshead rate.

§288°C (550°F): 1.27-mm/min (0.05-in./min) crosshead rate.

Preirradiation Condition

Several preirradiation determinations (Tables A1a and A2) important to postirradiation evaluations were as follows:

- The yield-strength range of the plates was slightly lower than that of the weld deposits, but the tensile-strength ranges of both material types were about the same.
- Weld deposits on balance exhibited better notch ductility than plates. Weld NDT temperatures were consistently lower than those of plates. Charpy-V upper-shelf energy levels, with one exception, equaled the levels found for the LT orientation of plates.
- Charpy-V assessments of plate LT vs TL orientations revealed only small differences overall.
- The C_v 41-J (30 ft-lb) transition temperature, selected as an arbitrary index for pre-postirradiation comparisons, equaled or was a conservative estimate of individual drop-weight NDT temperatures (plate TL orientation and weld deposit).
- Weld HAZ data generally described a lower C_v transition than the parent plate but an equivalent C_v upper shelf level.

Postirradiation Condition

General observations reported for the 288°C (550°F) irradiation condition (Table A1b) includes the following:

- The comparison of Series 2 and Series 1 materials clearly demonstrates a benefit of reduced copper and phosphorus content to radiation resistance. The Series 2 materials typically exhibited smaller radiation-induced increases in 41-J (30 ft-lb) transition temperatures, lower actual 41-J (30 ft-lb) transition temperatures, and higher postirradiation upper-shelf levels than Series 1 (normal copper content) materials.
- The C_v 41-J (30 ft-lb) transition temperatures of the Series 2 materials were below 32°C (90°F) after high-fluence irradiation (4 to 5 × 10^{19} n/cm^2).
- Weld 1 showed the highest transition temperature increase of all Series 1 materials and the greatest upper-shelf energy reduction, consistent with its relative copper content (highest). In contrast the best overall performance among Series 1 materials was demonstrated by HAZ 1.
- Postirradiation upper-shelf levels for HAZ 1, HAZ 3, and HAZ 4 were equal to projections for the parent plates in the same test orientation.

Postirradiation Heat-Treated Condition

The half-filled symbols in Figs. A1 through A11 depict data for the 343°C (650°F) 168-hour postirradiation heat-treated condition. In view of the relative changes in notch ductility produced by irradiation, recovery obtainable by postirradiation annealing was considered to be of engineering interest primarily for Series 1 materials. Additional observations on annealing response were the following:

- Series 1 materials, with the exception of plate 2, exhibited 25 to 38% recovery in the C_v 41-J (30 ft-lb) transition temperature.
- Weld 1 (high-fluence condition) which exhibited the greatest change in properties with irradiation, showed 29% or 56°C (100°F) recovery with annealing.
- Upper-shelf recovery by annealing was significant in many cases and generally appeared to be the same for high- and low-fluence conditions.
- Recovery in C_v 68-J (50 ft-lb) transition temperature was equal to or greater than observed recovery in C_v 41-J (30 ft-lb) transition temperature.

CONCLUSIONS

Primary conclusions drawn from the investigations with Series 1 and Series 2 materials were reported as follows:

- A major reduction in radiation sensitivity is achieved in commercial-production A533-B plates and weld deposits with reduced copper content (0.10%Cu max.) compared to normal copper content (≥0.15%Cu). The reduction in radiation sensitivity is evident in a smaller transition temperature increase and in a smaller upper-shelf energy decrease with irradiation.
- Proposed ASTM and AWS specifications placing restrictions on copper, phosphorus, and sulfur contents for nuclear-grade A533-B plates and weld deposits appear justified and well formulated for nuclear service applications.
- Low copper materials of this investigation compare well in performance with extra-low copper content materials from earlier demonstration tests. It is speculated that extra-low copper content materials (Series 3) will exhibit only a small additional increase in radiation embrittlement resistance at moderate fluence levels over the performance of low copper content materials (Series 2).
- Low copper content weld metals tend to show higher radiation resistance than low copper content plates. The performance of weld HAZ relative to parent plate appears mixed; however, the notch ductility of the HAZ after high-fluence exposure appeared equal to, if not better than, the notch ductility of the parent plate.

- Postirradiation 343°C (650°F) 168-hour heat treatment effects were most pronounced in normal copper materials, where upper-shelf reductions and transition-temperature shifts were greatest after 288°C (550°F) irradiation. Upper-shelf levels after annealing are 103 to 157 J (76 to 116 ft-lb) (40% or more recovery), whereas transition temperature recovery is 14 to 56°C (25 to 100°F) (25 to 35%). For the range of fluence levels investigated, notch ductility recovery was not appreciably governed by exposure level.

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