Security Classification

DOCUMENT CONTROL DATA - R & D

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

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

3. REPORT TITLE

DEMONSTRATION OF IMPROVED RADIATION EMBRITTLEMENT RESISTANCE OF A533-B STEEL THROUGH CONTROL OF SELECTED RESIDUAL ELEMENTS

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

This is a summary report on one phase of a continuing problem.

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

J. Russell Hawthorne

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
May 29, 1970	33	7

8a. CONTRACT OR GRANT NO. NRL Problem M01-14 b. PROJECT NO. RR 007-11-41-5409 c. AEC-AT(49-5)-2110 USA-ERG-11-69 d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 7121 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

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

11. SUPPLEMENTARY NOTES Also sponsored by Army Nuclear Power Field Office, Ft. Belvoir, Va. and the U.S. Atomic Energy Commission	12. SPONSORING MILITARY ACTIVITY Department of the Navy (Office of Naval Research), Arlington, Va. 22217

13. ABSTRACT

A successful demonstration test of metallurgically controlled radiation embrittlement sensitivity has been conducted with a large commercial melt of A533-B steel. The 30-ton melt represents a scaleup from the 300-lb laboratory melts which provided the first evidence of the potential for very low sensitivity to radiation embrittlement at power reactor pressure vessel service temperatures (≈550°F, 288°C). The commercial-scale demonstration test was sponsored by the U.S. Atomic Energy Commission (AEC), Division of Reactor Development and Technology (DRDT), Fuels and Materials Branch, and depicts the composition specification approach to the development of optimum radiation resistance in structural steels.

The primary objective of special melt specifications and melt planning was the reduction of copper and phosphorus contents to the lowest possible level. Restrictions were also imposed on the content of other residual impurity elements with known or suspected influences on radiation embrittlement resistance. For a broad experimental analysis, the melt was split to provide material representing the primary melt analysis (0.03% Cu) and a melt modification (0.13% Cu). Plates representing each analysis were also split and sections individually heat-treated to Class 1 or Class 2 strength conditions. All procedures used were standard mill practices.

Radiation assessments showed the primary melt analysis to have very low sensitivity to radiation embrittlement at 550°F (288°C), thereby validating the composition specification approach for future melts. Transition temperature increases measured independently by Charpy-V (C_v) and dynamic tear (DT) test methods were 70°F (39°C) or less for fluences up

(over)

DD FORM 1473 1 NOV 65 (PAGE 1)

S/N 0101-807-6801

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Radiation embrittlement						
Scaleup demonstration melt						
A533-B steel						
Pressure vessel steel						
Radiation effects						
Charpy-V notch ductility						
Transition temperature						
Dynamic Tear (DT) properties						
Nuclear reactors						
Pressure containment						
Radiation sensitivity						

to 3.1×10^{19} n/cm^2 > 1 MeV. Based on DT results, the nil ductility transition (NDT) temperature of the Class 1 plate remained below 75°F (24°C) after 550°F (288°C) irradiation.

Results for the 0.13% Cu melt modification provided direct confirmation of the primary, highly detrimental influence of copper content on radiation embrittlement resistance. The C_v 30-ft-lb transition temperature increases for the Class 1 and Class 2 plates were 140° and 125°F (78° and 69°C), respectively, for a fluence of 2.8×10^{19} n/cm^2 > 1 MeV. The enhancement of radiation sensitivity by copper content appeared independent of the strength class.

Postirradiation DT characteristics of the primary melt analysis (Class 1 plate) were indicative of excellent fracture resistance at shelf level temperatures.

The A533-B scaleup demonstration test fully supports the principles for control of radiation embrittlement sensitivity developed in laboratory research. A summary of 550°F (288°C) radiation data for the ASTM A302-B reference plate and A533 standard production plate and weld metals places the results for the special melt in full perspective. The radiation embrittlement sensitivity of the primary melt analysis is shown to be only one third that of the reference plate and significantly less than that of A533 production materials.

CONTENTS

ABSTRACT

A successful demonstration test of metallurgically controlled radiation embrittlement sensitivity has been conducted with a large commercial melt of A533-B steel. The 30-ton melt represents a scaleup from the 300-lb laboratory melts which provided the first evidence of the potential for very low sensitivity to radiation embrittlement at power reactor pressure vessel service temperatures (≈550°F, 288°C). The commercial-scale demonstration test was sponsored by the U.S. Atomic Energy Commission (AEC), Division of Reactor Development and Technology (DRDT), Fuels and Materials Branch, and depicts the composition specification approach to the development of optimum radiation resistance in structural steels.

The primary objective of special melt specifications and melt planning was the reduction of copper and phosphorus contents to the lowest possible level. Restrictions were also imposed on the content of other residual impurity elements with known or suspected influences on radiation embrittlement resistance. For a broad experimental analysis, the melt was split to provide material representing the primary melt analysis (0.03% Cu) and a melt modification (0.13% Cu). Plates representing each analysis were also split and sections individually heat-treated to Class 1 or Class 2 strength conditions. All procedures used were standard mill practices.

Radiation assessments showed the primary melt analysis to have very low sensitivity to radiation embrittlement at 550°F (288°C), thereby validating the composition specification approach for future melts. Transition temperature increases measured independently by Charpy-V (C_v) and dynamic tear (DT) test methods were 70°F (39°C) or less for fluences up to 3.1×10^{19} n/cm^2 > 1 MeV. Based on DT results, the nil ductility transition (NDT) temperature of the Class 1 plate remained below 75°F (24°C) after 550°F (288°C) irradiation.

Results for the 0.13% Cu melt modification provided direct confirmation of the primary, highly detrimental influence of copper content on radiation embrittlement resistance. The C_v 30-ft-lb transition temperature increases for the Class 1 and Class 2 plates were 140° and 125°F (78° and 69°C), respectively, for a fluence of 2.8×10^{19} n/cm^2 > 1 MeV. The enhancement of radiation sensitivity by copper content appeared independent of the strength class.

Postirradiation DT characteristics of the primary melt analysis (Class 1 plate) were indicative of excellent fracture resistance at shelf level temperatures.

The A533-B scaleup demonstration test fully supports the principles for control of radiation embrittlement sensitivity developed in laboratory research. A summary of 550°F (288°C) radiation data for the ASTM A302-B reference plate and A533 standard production plate and weld metals places the results for the special melt in full perspective. The radiation embrittlement sensitivity of the primary melt analysis is shown to be only one third that of the reference plate and significantly less than that of A533 production materials.

PROBLEM STATUS

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

AUTHORIZATION

NRL Problem M01-14
RR 007-11-41-5409
AEC-AT(49-5)-2110
USA-ERG-11-69

Manuscript submitted May 12, 1970.

DEMONSTRATION OF IMPROVED RADIATION RESISTANCE OF A533-B STEEL THROUGH CONTROL OF SELECTED RESIDUAL ELEMENTS

INTRODUCTION

Variable sensitivity to radiation embrittlement has been revealed for many low-alloy pressure vessel steels (1). The A533 steel employed extensively in new commercial reactor vessel construction is no exception (2). Two and threefold differences in brittle-ductile transition temperature increases under equivalent exposure conditions have been documented for both A533 plate and weld metals. As a result, the advance prediction and possible control of variable sensitivity are of direct interest to reactor vessel operations as well as to future vessel design.

Laboratory studies for the understanding and minimization of steel embrittlement tendencies have revealed the strong influence of residual element content on radiation embrittlement characteristics at elevated service temperatures (3). As illustrated in Fig. 1, a low residual element content was found essential for a low radiation embrittlement sensitivity. Building on this research breakthrough, investigations of specific impurity elements using split laboratory melts subsequently revealed particularly detrimental influences of copper and phosphorus on irradiation resistance (3). The contributions of other suspect impurity elements, including S, Al, V, and N, have also been assessed experimentally. However, of those elements evaluated, none appear as highly potent as copper and phosphorus.

This report is concerned with the transfer of laboratory-scale findings to commercial-scale practice. The 30-ton A533-B steel melt to be described represents the first large-scale demonstration test of metallurgically controlled radiation embrittlement behavior. More specifically, the melt was conceived as a major test of industry's capability to provide tonnage quantities of steel with nuclear characteristics matching (or closely approaching) the excellent elevated-temperature radiation resistance shown consistently by high purity laboratory melts.

The AEC, DRDT, Fuels and Materials Branch, sponsored this scaleup demonstration test. The NRL prime contractor was Lukens Steel Company. The melt was made to NRL specifications by Latrobe Steel Company under subcontract to Lukens Steel. As planned, the melt would not reflect any unusual production techniques or procedures but would be fully representative of conventional (standard) commercial practices.

This report presents the initial findings on the radiation performance of 6-in.-thick plates from the 30-ton melt. Detailed specifications and complete mill history (melting, plate fabrication, and heat treatment) are also documented for the highly successful demonstration test.

MELT SPECIFICATIONS AND TWIN INGOT PROCESSING PLAN

General melt requirements on which actual melt specifications were founded are listed in Table 1. A 10-ton melt was considered a minimum for efficient working of the

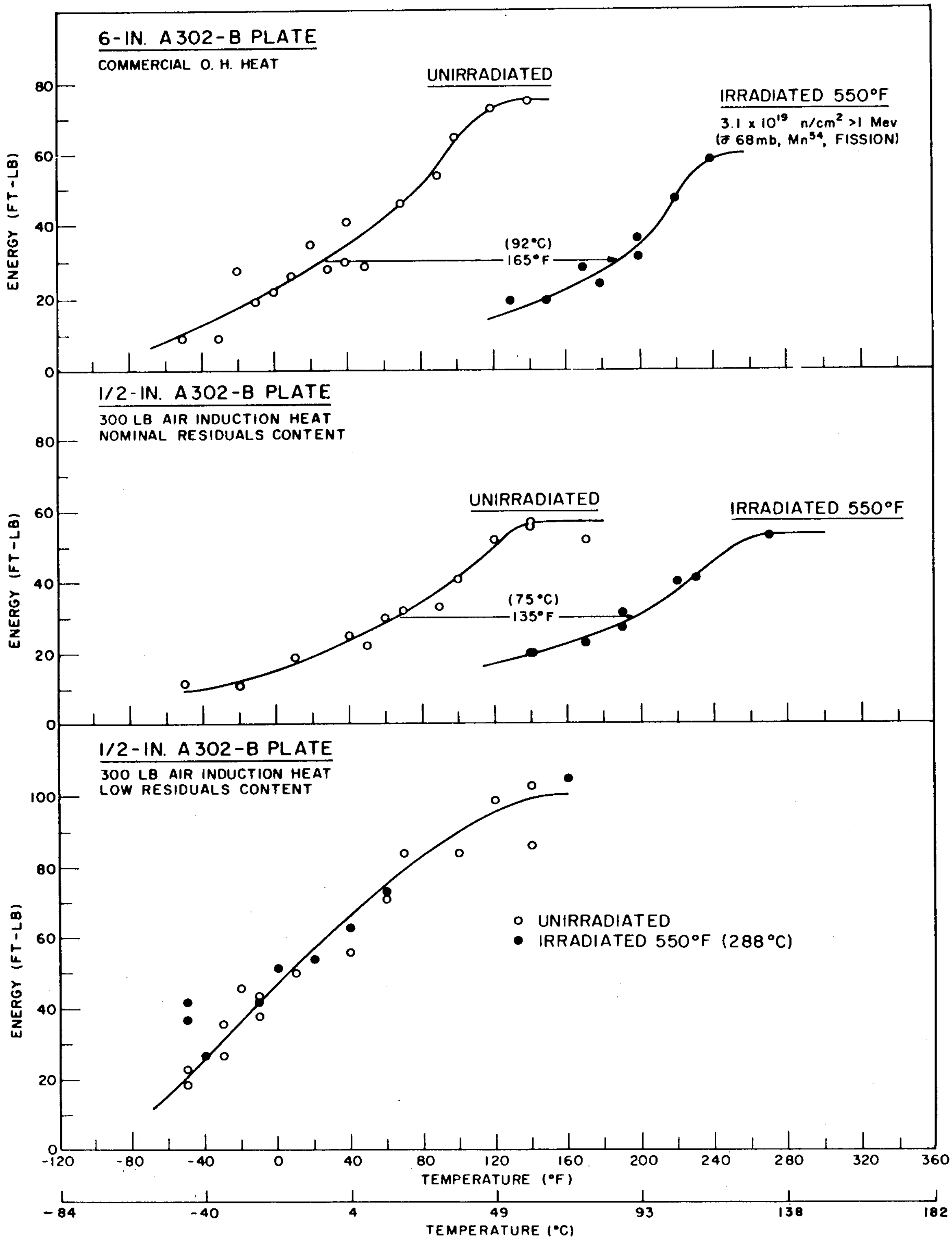


Fig. 1 - Comparison of radiation embrittlement sensitivities of one large commercial heat and two air induction heats of A302-B steel with nominal and low residual element contents based on Charpy-V notch ductility following 550°F (288°C) irradiation (3)

Table 1
General Melt and Melt Processing Requirements

Composition	A533 Grade B steel
Melt size	10 ton (min)
Melt type	Electric furnace air melt, fine grain practice
Melt charge	Selected scrap and/or hot metal
Slag process	Double slag
Ladle treatment	Vacuum degas
Ingot size	18-in.-thick ingot for 3:1 reduction (min)
Plate size	6.0-in. gage
Rolling ratio	Approximately 1:1 (aim)

heat. This minimum melt size was also dictated by the limited availability of small-capacity electric furnaces. Plate gage and the desired ingot reduction ratio defined the minimum ingot size. Double-slagging and vacuum-degassing treatments were consistent with the basic aim of reducing the total impurities content to the lowest possible level.

Composition specifications for the special melt, as given by the purchase order, are summarized in Table 2. Ranges for C, Mn, Si, Ni, and Mo contents are those limits specified by the ASTM Standard Specification for A533 Grade B steel. The balance of listed composition restrictions are special purity requirements imposed by NRL on elements with known (or suspect) influences on radiation performance. Maximum allowable values for the two elements of primary concern, copper and phosphorus, served to guide melt shop planning of the furnace charge; however, their reduction was to proceed on a best efforts basis.

To insure a maximum yield of information from this scaleup effort, special steps were added to normal melt handling and plate processing sequences. Special plans included the splitting of the melt between two ingot molds, thereby permitting a study of the effects of two impurity copper contents. The planned copper doping addition to one ingot (0.13% Cu) was to represent the approximate copper purity level of "best" current production A533-B melts. Plans also called for the splitting of each prime plate into two sections after the final austenitizing treatment, but before tempering, to permit a direct comparison of Class 1 and Class 2 strength conditions. Thus, a total of four plate sections were secured for radiation assessments rather than one large plate representing a single composition and single heat-treatment condition. Complete purchase order specifications are given in Appendix A.

The stepwise melt plan and ingot processing sequence through to final tempering treatments are illustrated schematically in Fig. 2. The 3-1/2:1 ingot reduction ratio exceeded the required minimum reduction. Note that pur copper shot was added (gradually) to the first ingot mold* (during the pour) in order to take advantage of higher ladle

*Consistent with purchase specifications, this ingot is identified as ingot 2.

Table 2
Chemical Composition: Specifications and NRL Check Analyses

Determination	Chemical Composition (wt-%)										
	C	Mn	Si	Ni	Mo	Cu	P	S	As	Sb	Sn
Melt purchase specifications											
Ladle	0.25 max	1.15–1.50	0.15–0.30	0.40–0.70	0.45–0.60	0.08 max	0.007 max	0.007 max	0.01* max	0.01* max	0.02* max
Check	—	1.10–1.55	0.13–0.32	0.37–0.73	0.41–0.64	0.10 max	0.010 max	†	0.01* max	0.01* max	0.02* max
Ingot 1 (Av of Plates A and B)	0.17	1.22	0.19	0.58	0.50	0.03	0.008	0.008	<0.03	<0.01	0.02
Ingot 2 (Copper Mod.) (Av of Plates C and D)	0.17	1.21	0.20	0.56	0.50	0.13§	0.008	0.007	<0.03	<0.01	<0.02

*As + Sb + Sn + Bi ⩽ 0.05 max.
†P + S ⩽ 0.022 max.
‡Total aluminum by spectrographic analysis (Courtesy Lukens Steel).
§Copper added to ingot 1 during pour.

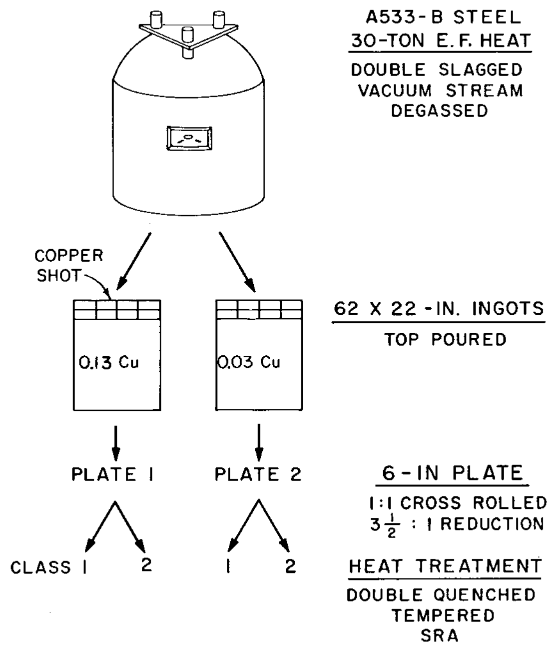


Fig. 2 - Schematic plan of processing of special commercial heat of A533-B steel for radiation sensitivity studies

temperatures and higher ladle head pressure for best mixing. Significant details of melt and ingot processing are given in Appendix B.

HEAT-TREATMENT PROCEDURES

Primary heat-treatment procedures employed for the individual plate sections are outlined in Table 3. The double-quench, temper, and thermal-stress-relief sequence is typical of the heat-treatment history of plate forming welded nuclear reactor vessels. Complete heat-treatment procedures are given in Appendix C together with a synopsis of mill test results including nondestructive examinations. It should be noted that the heat treatment histories of the Class 1 plate sections from ingots 1 and 2 were identical and that the thermal histories of the Class 2 plate sections were also identical. Mill tests of plate sections B and D after the first (1200°F, 649°C) temper indicated that their strengths were below the Class 2 required minimum. These two plates were subsequently reaustenitized, quenched, and tempered at a lower temperature (1150°F, 621°C) whereupon repeat mill tests following a 10-hr stress relief indicated acceptable Class 2 properties. Averages of mill tensile property determinations are included in Appendix C.

Drop weight tests by the mill indicated that all plate sections passed the nil ductility transition (NDT) temperature requirement of +10°F (-12°C) maximum.

PREIRRADIATION PROPERTIES

Chemical Composition

Individual chemical compositions of ingots 1 and 2 as determined by surveys of plate sections A and B and plate sections C and D are given in Table 2. With the exception of As, Sb, Sn, and Bi, the determinations are based on wet chemistry methods. Values given for As, Sb, Sn, and Bi are approximate limits based on spectrographic comparisons with reference standards. Results for ingot 1 indicate that the melt composition

Table 3
Heat Treatment of Individual Plate Sections

Plate Section	Strength Specification	Heat Treatment
Section A (ingot 1) Section C (ingot 2)	Class 1 (50-ksi (min) Y.S.)	Austenitized at 1675°F (913°C) for 6 hr, water quenched;* reaustenitized at 1575°F (857°C) for 6 hr, water quenched; tempered at 1250°F (677°C) for 6 hr, furnace cooled; stress relief annealed at 1125°F (607°C for 20 hr, furnace cooled
Section B (ingot 1) Section D (ingot 2)	Class 2 (70-ksi (min) Y.S.)	Same double-quench treatment as class 1 above; tempered at 1200°F (649°C) for 6 hr, furnace cooled; stress relief annealed at 1125°F (607°C) for 20 hr, furnace cooled; reaustenitized at 1575°F (857°C) for 6 hr, water quenched; tempered at 1150°F (621°C) for 6 hr, furnace cooled; stress relief annealed at 1100°F (593°C) for 10 hr, furnace cooled

*Dip quenched in agitated water (typical).

conformed fully to purchase order check analyses requirements (Table 2). Significantly, the copper content of ingot 1 was well below the allowable check test value and met the more stringent ladle analysis maximum as well. Phosphorus and sulfur contents satisfied check test specifications but were above ladle analysis requirements. As expected, the analyses for ingots 1 and 2 were matched except for copper content.

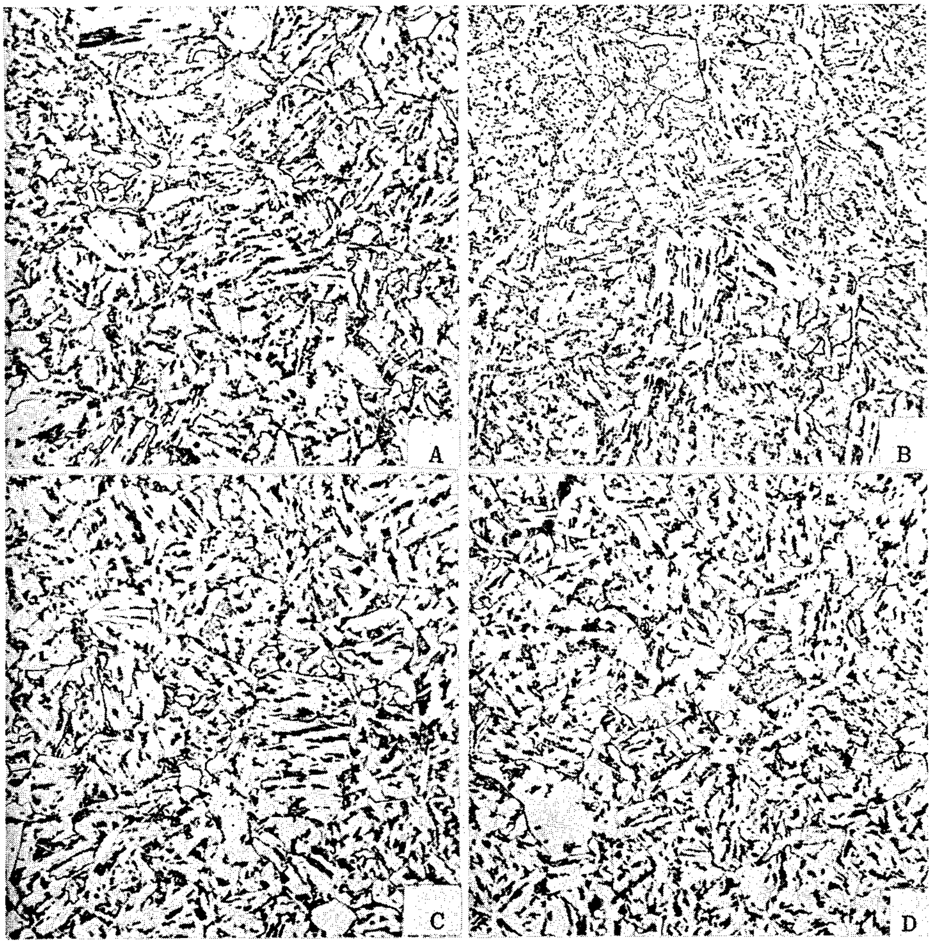
Referring to Appendix B, NRL and Latrobe analyses of dip test samples (ingot hot-top samples) were in close agreement except for manganese content. Similarly, NRL and Lukens Steel check test results (plate samples) were in good agreement, although Lukens' values for copper and phosphorus were slightly higher.

Spot checks at two sampling positions in each plate (approximately 3 and 7 ft from the bottom ingot end) and at two test depths through the thickness (surface and 1/4T to 1/2T) did not show composition differences suggestive of marked alloy or trace-element segregation. Average copper content values for ingots 1 and 2 were, respectively, 0.03% ± 0.01% and 0.13% ± 0.01%. The average phosphorus content value for both ingots 1 and 2 was 0.008% ± 0.001%. The reported spread in values represents a confidence level of 85% or better.

Microstructure

Typical microstructures at the quarter plate thickness location are shown in Fig. 3. The structures have been classified as tempered upper bainite and give some small evidence of banding. Plate from both ingots 1 and 2 exhibited a duplex prior austenitic grain structure. The grain size of plate section A (0.03% Cu) was rated as ASTM 7-8 and finer; the grain size of plate section C (0.13% Cu) was rated as ASTM 8 and finer.

The close similarity of structures of Class 1 plate sections and of Class 2 plate sections has an important bearing on radiation effects comparisons described below.



a. Plate section A: class 1, 0.03% Cu
b. Plate section B: class 2, 0.03% Cu
c. Plate section C: class 1, 0.13% Cu
d. Plate section D: class 2, 0.13% Cu

Fig. 3 - Microstructures of plate sections A, B, C, and D (quarter-thickness location). Structures appear very similar irrespective of the copper content variation. Tempered upper bainite (X500; nital + picral etchant).

Tensile Properties

Results of through thickness tension tests of each plate section are summarized in Table 4. The sampling area was located on the plate centerline approximately 3 ft above the bottom ingot end. The results confirm that the strength and ductility of all four plate sections were within required ASTM limits for the respective A533-B strength classes.

Through-thickness properties gradients noted in Table 4 are considered quite small for the type and size of plates involved. Properties at the 1/4T and 3/4T locations are well matched in all cases. The slight difference in strength levels possibly may be a reflection of the flat quenching procedure used.

Table 4
Tension Test Properties of 6-in. Plate Sections A, B, C, and D

Plate Section	Nominal Copper Content (Wt-%)	Test Orientation*	Yield Strength (0.2% Offset)† (ksi)				Tensile Strength‡ (ksi)			
			Surface	1/4T	3/4T	1/2T	Surface	1/4T	3/4T	1/2T
A (Class 1)	0.03	RW	68.9	66.9	66.8	61.1	88.0	86.3	86.3	85.1
		WR	66.9	66.1	64.5	64.2	88.2	86.5	86.2	85.2§
C (Class 1)	0.13	RW	70.5	68.2¶	67.9	67.6	89.7	87.8¶	87.8	87.5
		WR	70.9	68.3	68.2	68.4	90.6	87.7	87.7	87.7
B (Class 2)	0.03	RW	87.2	79.9	77.1	76.2	103.2	97.1	95.3	95.0
		WR	80.2	78.7	74.7	74.1	103.3	96.4	94.8	94.0
D (Class 2)	0.13	RW	97.8	87.2¶	86.2	81.0	113.1	103.9¶	103.9	99.2
		WR	91.2	83.3	83.0	78.0	113.4	104.5	104.3	99.7

Plate Section	Nominal Copper Content (Wt-%)	Test Orientation*	Reduction of Area (%)				Elongation in 1-inch (%)			
			Surface	1/4T	3/4T	1/2T	Surface	1/4T	3/4T	1/2T
A (Class 1)	0.03	RW	73.2	70.9	70.4	66.7	28.7	28.7	28.9	28.4
		WR	74.0	71.7	71.7	70.7	28.4	29.7	29.1	28.3
C (Class 1)	0.13	RW	73.2	70.0¶	70.4	67.3	27.4	27.7¶	28.2	26.7
		WR	73.6	71.2	71.3	70.0	28.5	28.1	28.9	26.9
B (Class 2)	0.03	RW	72.6	66.0	70.0	64.8	25.3	25.8	28.0	27.0
		WR	72.8	68.5	69.4	69.2	25.8	26.8	26.0	27.8
D (Class 2	0.13	RW	69.1	67.9¶	65.8	63.1¶	23.8	24.9¶	24.1	23.2
		WR	69.8	68.2	66.2	64.6	23.8	25.3	25.0	24.8

*RW — Longitudinal; WR — Transverse.
†Average of two specimen tests.
‡0.252 × 1.750 inch gage length tensile specimens.
§Slag inclusion visible in failure region.
¶Single determination only.

Assessments of the longitudinal (RW) and transverse (WR) plate directions also showed only small differences in properties. The observed correspondence between test orientations is indicative of the high degree of cross rolling (1:1 aim) used in plate fabrication.

Noting that the Class 2 plate sections, B and D, were heat-treated together, comparisons of test data for these two sections suggest some influence of copper content on general strength level in this heat-treatment condition. Plate section D with 0.13 Cu exhibited both a 5 to 10 ksi higher yield strength and a 5 to 10 ksi higher tensile strength than plate section B with 0.03% Cu. However, strength differences between the corresponding Class 1 plate sections were insignificant.

Notch Ductility Properties

Drop Weight Test Assessments — The NDT temperatures listed in Table 5 were determined by ASTM Method E-208 using type P-3 drop weight test specimens (2 by 5 by 5/8 in.). Through-thickness surveys of the Class 1 plate sections revealed very good uniformity throughout. Quarter-thickness position NDT temperatures were -20°F (-29°C). Surveys of the Class 2 plate sections also revealed good uniformity with the exception of the bottom surface layer. The marked differences between top and bottom surface determinations in this case undoubtedly resulted from the flat quenching procedure and the smaller total volume of metal (≈50% less) involved when these particular sections were repeat-quenched. Quarter-thickness position NDT temperatures of sections B and D were 0°F (-18°C) and 10°F (-12°C), respectively.

Quarter-thickness position determinations verified that the maximum NDT temperature requirement (+10°F, -12°C) was met in all cases. Copper content did not appear to influence NDT temperature characteristics of either the Class 1 or Class 2 plate sections.

Charpy-V Assessments — Charpy-V (C_v) notch ductility characteristics of the individual plate sections are summarized and compared to NDT performance in Table 5. As with NDT determinations, relatively good agreement in properties is observed between Class 1 plate sections, between Class 2 plate sections, and between one-quarter and three-quarter-thickness locations of a given section. Unlike NDT determinations, however, C_v 30-ft-lb transition temperatures show a distinct gradient from plate surface to plate center with the greater change occurring between the quarter-thickness and mid-thickness positions. Since the NDT temperature did not vary appreciably with test depth while the C_v curve did, the C_v energy level approximating the NDT temperature differed with thickness position. Energy 'fix' values (Table 5) vary from as high as 65 to 95 ft-lb (surface locations) to as low as 25 to 30 ft-lb (center location). Radiation-effects assessments to be described were indexed to 30-ft-lb transition temperature behavior to allow direct comparisons with the bank of existing data on commercially produced A533 and A302 steels. The choice of a higher index was considered but would not have altered the reported analysis appreciably due to generally consistent transition temperature characteristics.

Average C_v shelf energy values included in Table 5 attest to the general high-purity level of the melt. Shelf levels of the Class 1 plate sections are in good agreement; differences in shelf level of the Class 2 plate sections can be ascribed to the small difference in yield strength. Data scatter at shelf level temperatures as well as in the transition region was somewhat pronounced but did not exceed typical scatter for large commercial melts. Data scatter in the shelf region may have been enhanced by the 1:1 cross rolling practice as well as by the better-than-average melt cleanliness. Photomacrographs of full-thickness sections of the Class 1 materials are given in Fig. 4.

Dynamic Tear Test Assessments — Dynamic tear (DT) test shelf level determinations for the transverse (WR) orientation are compared in Table 5. The specimens were of the standard size: 1-5/8 by 7 by 5/8 in. Differences noted between plate surface and mid-thickness locations are considered small. In view of the nominal 1:1 cross rolling ratio and general melt cleanliness, only slightly higher values would be expected for the longitudinal (RW) test orientation. Shelf values of plate sections A and C significantly exceed values determined for other commercially produced A533-B Class 1 plates (≈1100 ft-lb versus 750 to 850 ft-lb), perhaps for the same reasons.

The DT energy transition curves developed for plate section A are given in Fig. 5. Results are considered representative of through-thickness variations observed for the remaining sections. Typically, DT transition curves are displaced to the right of corresponding C_v curves due to the inherent fracture characteristics of the larger DT specimen.

Table 5
Notch Ductility Characteristics of 6-in. Plate Sections A, B, C, and

Plate Section	Nominal Copper Content (wt-%)	Drop Weight NDT Temperature (°F)				Charpy-V 30-ft-lb Transition Temperature* (°F)				
		Surface† (Top)	Surface† (Bottom)	1/4 and 3/4T	1/2T	Surface (Top)	Surface (Bottom)	1/4 and 3/4T	1/2T	Sur (T
A (Class 1)	0.03	-30	-40	-20	-20	-100	-100	-75	-15	9
C (Class 1)	0.13	-30	-30	-20	-20	-105	-105	-80	-10	9
B (Class 2)	0.03	0	-90	0	0	-95	-120	-85	-15	8
D (Class 2)	0.13	0	-50	10	10	-85	-115	-55	10	6

Plate Section	Nominal Copper Content (wt-%)	Approximate Charpy-V Energy Shelf (ft-lb)			Dynamic Tear Test Energy Shelf WR Orientation (ft-lb)		
		Surface	1/4 and 3/4T	1/2T	Surface	3/4T	1/2T
A (Class 1)	0.03	150	140	120	1260	1130	1020
C (Class 1)	0.13	>145	135	≈115	1180	1060	940
B (Class 2)	0.03	125	125	110	1140	1100	970
D (Class 2)	0.13	110	110	110	1010	1090	870

*Longitudinal (RW) test orientation.
†Weld bead on rolled surface.

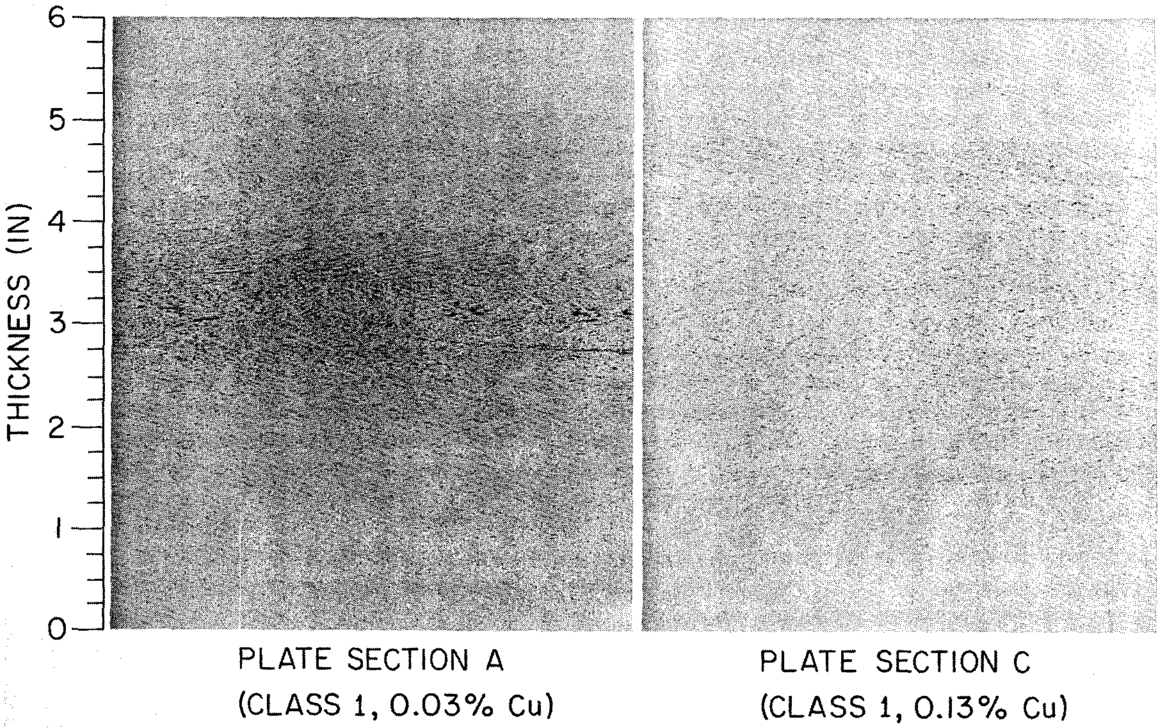


Fig. 4 - Macrostructures of Class 1 plate sections of the primary melt analysis and the copper melt modification. The difference in inclusion distribution may reflect the ingot pouring sequence. Plate section C represents the first ingot cast (highest ladle temperature).

Note that the drop weight NDT indexes the beginning of the temperature range through which DT energy absorption rises to the condition of maximum ductility.

RADIATION INVESTIGATIONS

The initial radiation experiment, conducted with C_v specimens of all four plate sections, was designed to compare the effects of copper content and strength class on radiation performance as well as to determine if low radiation embrittlement sensitivity had indeed been secured by the special melt specifications. The experiment was performed at 550°F (288°C) in the Union Carbide Research Reactor (UCRR) using a fully instrumented assembly.

Subsequent radiation experiments contained DT specimens whereby radiation effects on fracture resistance characteristics could be explored quantitatively. By including C_v specimens in each of the reactor units, a partial assessment of the correspondence of C_v and DT test methods for the irradiated case was also achieved. The DT-C_v specimen irradiations were conducted in the UCRR at 550°F (288°C) and in the Engineering Test Reactor (ETR) at <300°F (149°C). The ETR experiments were not instrumented but depended on low-melting-point alloys for peak temperature determinations. The DT-C_v assessments have been completed for one plate section, A; systematic assessments of companion sections are still underway.

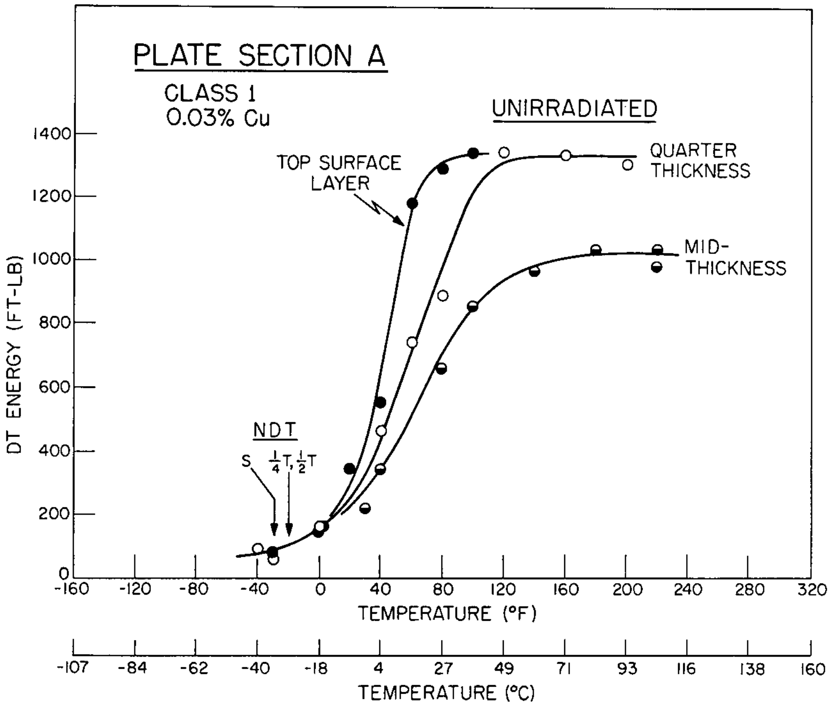


Fig. 5 - The DT test performance of plate section A at surface, quarter, and midthickness positions. The 1-5/8-by-7-by-5/8-in. specimens were oriented in the transverse (WR) test direction. Corresponding NDT temperatures determined by drop weight tests are also indicated.

Neutron fluence values, based on an assumed fission spectrum neutron energy distribution and the $^{54}Fe(n,p)^{54}Mn$ reaction, are given for UCRR and ETR experiments. The fission-averaged ^{54}Fe cross section was taken as 68 mb. Neutron fluence values based on a calculated neutron spectrum and the related ^{54}Fe averaged cross section of 82.6 mb are also reported for the UCRR experiments. Spectrum calculations for the ETR facility are not yet available. Detailed techniques for translating fission spectrum fluence values into calculated spectrum fluence values are outlined elsewhere (4,5).

Initial Determination of Radiation Resistance

The C_v specimens for this 550°F (288°C) radiation assessment were taken from the quarter-thickness location of plate sections A, B, C, and D. Specimens within each material group represented the longitudinal (RW) and transverse (WR) test orientations. The experiment was exposed in the UCRR F-5 fuel core facility and received a fluence (fission spectrum) of 2.8×10^{19} n/cm^2 > 1 MeV. The corresponding calculated spectrum fluence value [Φ^{cs}(F-5 facility) = $\Phi^{fs} \times 98.26/114$] was 2.4×10^{19} n/cm^2 > 1 MeV.

Postirradiation results are shown in Fig. 6. Closed data points refer to the longitudinal orientation; half-filled points refer to the transverse orientation. Results for unirradiated specimens aged at 550°F (288°C) for 700 hours, corresponding to the reactor experiment thermal history, are also shown (open points). Thermal control data in each case are indicative of good properties stability at this temperature.

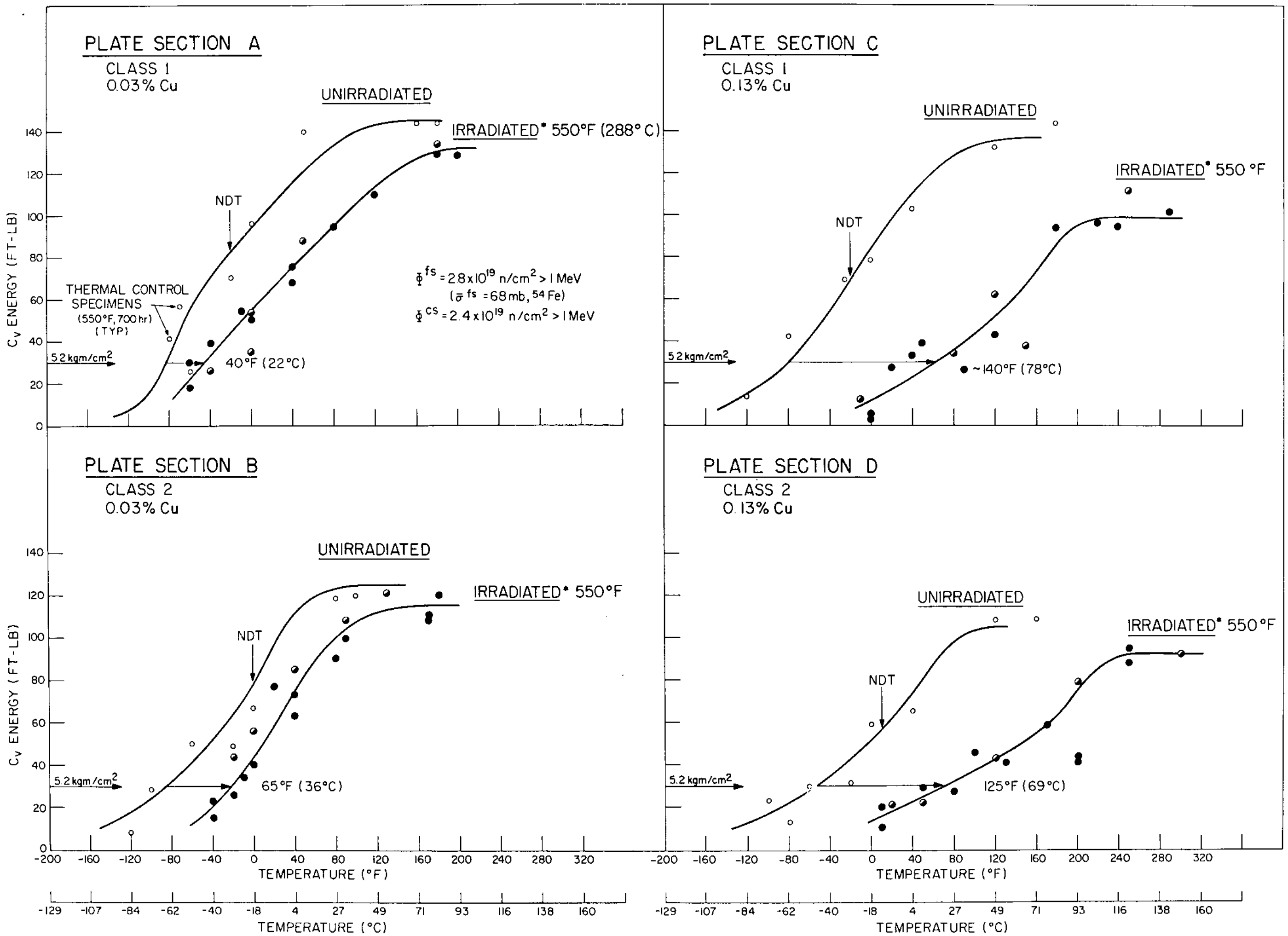


Fig. 6 - Charpy-V (C_V) assessments of the radiation embrittlement resistance of plate sections A, B, C, and D at 550°F (288°C). Very low sensitivity to radiation embrittlement is indicated for the primary melt analysis represented by plate sections A and B. The melt modification which increased copper content to 0.13% is seen to have a strong detrimental effect on radiation performance. The calculated spectrum neutron fluence value, 2.4×10^{19} n/cm^2 > 1 MeV, was derived from the conversion: Φ^{cs} (UCRR F-5 facility) = $\Phi^{fs} \times 98.26/114$

The immediate observation from Fig. 6 is the high radiation embrittlement resistance of the primary melt composition as represented by plate sections A and B. The data also indicate that the radiation resistance of the melt does not depend on the heat-treatment condition, i.e., strength Class 1 or Class 2. The difference in values for sections A and B should be considered insignificant in view of the general level of data scatter for the pre- and postirradiation conditions.

Radiation would be expected to have a similarly small effect on drop weight test performance (6). NDT temperatures below room temperature would be projected for this exposure condition.* In terms of reactor service, the fluence of 2.8×10^{19} n/cm^2 equals or exceeds most water reactor vessel lifetime projections. The transition temperature increases recorded for plate sections A and B thus indicate that a very low 550°F (288°C) radiation embrittlement sensitivity has indeed been achieved by "specification."

Results for plate sections C and D, given in Fig. 6c and 6d, signify that an elevation in copper content to 0.13% appreciably degrades the radiation embrittlement resistance of A533 steel. The average radiation embrittlement sensitivity of the copper-modified melt composition, as depicted by these plate sections, appears more than double that of the primary melt analysis. It is reemphasized that, for a given strength class, a direct comparison of results is fully valid due to the identical melt processing, heat treatment, and irradiation history of the materials. Results of this experiment indicate that the effectiveness of copper content toward enhancing the sensitivity of A533-B does not depend highly on the particular strength class (1 or 2). This observation is supported by data compilations for A533 production plates having a wide range of copper contents (2).

Dynamic Tear Investigations

The primary objectives of DT investigations were the verification of C_v test indications concerning the 550°F (288°C) radiation embrittlement resistance of the primary melt analysis, the assessment of relative <300°F (149°C) radiation resistance of both the primary melt analysis and the copper-modified analysis, and finally, the assessment of DT shelf level retention with 550°F (288°C) and <300°F (149°C) radiation exposure. Shelf determinations were of particular interest as an indication of resistance to fracture for the condition of maximum ductility.

Dynamic tear and C_v specimens for the irradiation series were taken from the quarter-thickness location and were oriented in the transverse (WR) test direction only. Postirradiation assessments of plate section A only have been completed. Combined results for the 550°F (288°C) UCRR irradiation and the <300°F (149°C) ETR irradiation are presented in Fig. 7. The upper graph compares C_v results for the pre- and postirradiation conditions; the lower graph gives corresponding DT results. Note that the C_v and DT energy scales are in the ratio of 1:10.

The fluence received by the 550°F (288°C) UCRR DT irradiation was C_v 3.1×10^{19} n/cm^2 > 1 MeV, slightly higher than the fluence received by the similar experiment. The corresponding calculated spectrum neutron fluence value was 2.7×10^{19} n/cm^2 > 1 MeV based on the 0.870 conversion factor for the D-3 core facility. The C_v 30-ft-lb transition temperature increase of 70°F (39°C) agrees well with the initial determination for plate section A (Fig. 6). For comparisons of C_v-versus-DT results, the midenergy range transition temperature increase was taken as a more appropriate index of irradiation performance. In Fig. 7, the two independent determinations are found in close

†A direct determination of NDT temperature increase will be possible with drop weight specimens of plate section A currently being irradiated in the Big Rock Point Power Reactor.

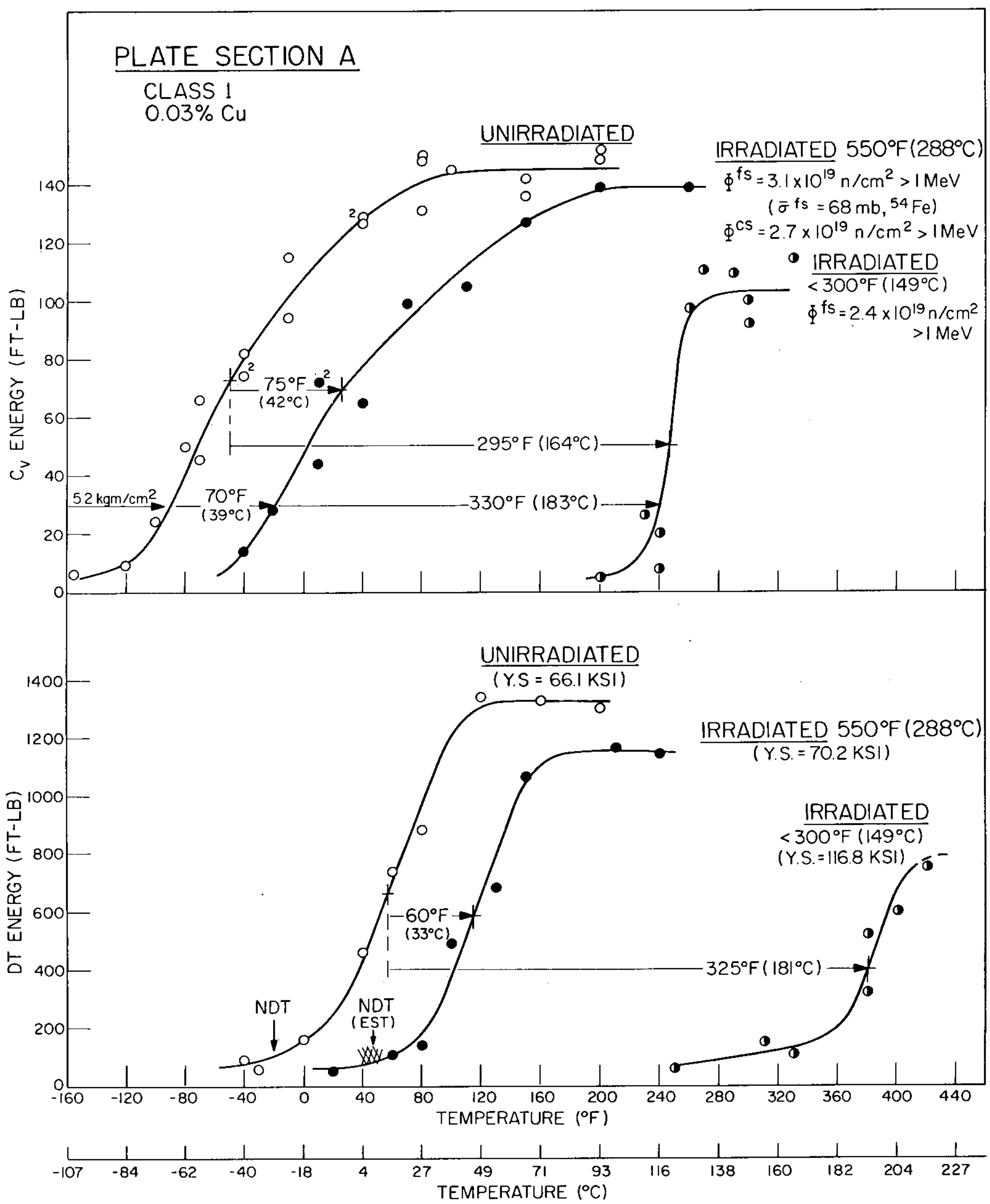


Fig. 7 - Comparison of C_v and DT test performance of plate section A at the quarter-thickness location. Good agreement of midenergy range transition temperature increases is found for both low-temperature and elevated-temperture radiation assessments.

agreement, 75°F (39°C) C_v versus 60°F (33°C) DT. Noting that the NDT temperature marks the toe of the DT curve, estimates would place the postirradiation NDT temperature between 40° and 50°F (4° to 10°C) for the stated exposure condition. This estimate based on DT performance is in good agreement with the original estimate based on C_v results.

Specimens contained in the <300°F (149°C) ETR experiment received an average fluence (fission spectrum) of 2.4×10^{19} n/cm^2 > 1 MeV. From Fig. 7, midenergy range transition temperature increases determined by the respective test methods again appear in good agreement. As expected, radiation-induced changes with the low exposure temperature were much more pronounced. Consistent with experimental findings for high-purity laboratory heats (3), the primary melt analysis appears about as sensitive to low-temperature irradiation as the ASTM A302-B reference plate. In effect, residual element restrictions serve to optimize elevated-temperature radiation embrittlement resistance but have little or no effect on steel embrittlement characteristics at low (below 300°F) exposure temperatures.

Apparent DT shelf and yield strength characteristics of UCRR and ETR exposure conditions are suggestive of excellent fracture resistance at shelf level temperatures. As noted in Fig. 7, changes in shelf level and yield strength with 550°F (288°C) exposure were very small. Accordingly, fracture resistance features were not impaired to a significant extent. In the case of the ETR exposure, an exact determination of shelf level was not obtained but the level clearly exceeded 600 ft-lb. At the measured yield strength of 116.8 ksi, a shelf level of this magnitude, according to the Ratio Analysis Diagram (RAD) (7), precludes plane strain fracture in thin or thick section (up to 12 in.). Overall shelf level performance characteristics of the primary melt analysis thus complement well its transition temperature performance at elevated irradiation temperatures.

DISCUSSION

Experimental results from the individual radiation assessments have confirmed the success of the scaleup effort. The overall yield of significant new information was also gratifying.

To place the radiation embrittlement resistance of the primary melt analysis in full perspective, the results for plate sections A and B have been entered on a summary plot of 550°F (288°C) radiation data for standard production A533 plate and weld metals and the ASTM A302-B reference plate (Fig. 8). The potential benefit of low-copper and low-phosphorus contents in steels for nuclear applications is immediately visible. The radiation embrittlement sensitivity of the primary melt analysis appears only one third that of the ASTM A302-B reference plate and significantly less than that of the "best" A533 production materials. It will be noted that, within the series of production materials, those with the best radiation resistance also had the lowest copper and phosphorus contents (2). Data points for the 0.13% Cu melt modification, if added, would fall just below the ASTM A302-B reference trend line. Thus, the significance of copper content relative to radiation embrittlement resistance cannot be denied.

Purity specifications used for the scaleup demonstration were proven attainable with conventional melting techniques and good commercial practices. In this regard, it is considered that a reduction of allowable phosphorus content below the 0.010 check test maximum would be beneficial in terms of radiation performance. Surveys of phosphorus content did not reveal appreciable segregation; thus, a tighter check specification may be both realistic as well as beneficial to performance.

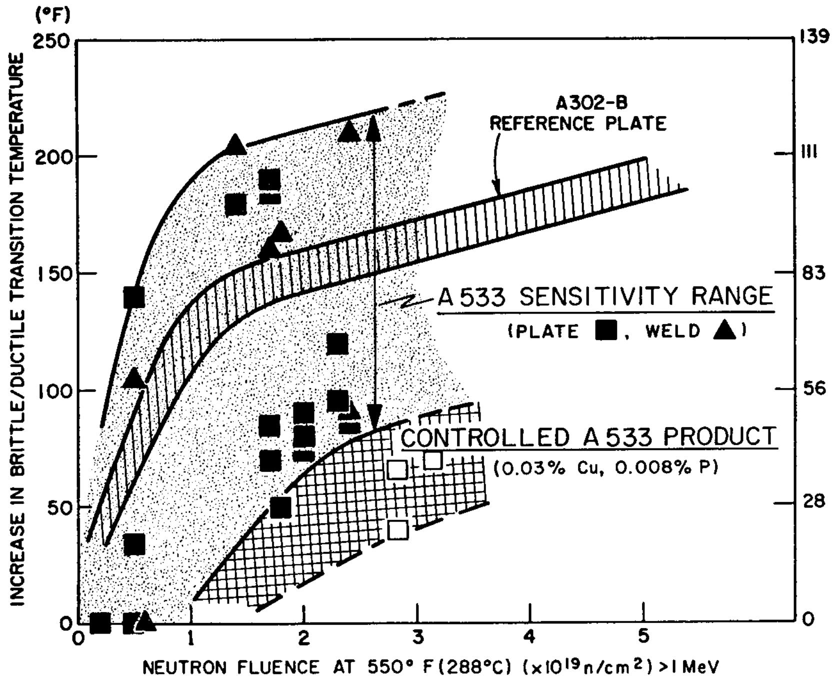


Fig. 8 - Increase in C_v 30-ft-lb transition temperature with neutron exposure at 550°F (288°C). The performance of plate sections A and B representing the primary melt analysis (open data points) is compared to the performance of the ASTM A302-B reference plate and conventional A533 materials representative of current reactor vessel construction. The benefit of controlled copper and phosphorus contents is readily apparent.

To provide material duplicating the primary melt analysis specification in the beltline region of a large reactor vessel, the additional cost to the reactor builder has been estimated at 35 to 40 thousand dollars. The cost premium is, by comparison, but a small percentage of the 2 to 2.5 million dollar projection of total vessel cost and an even smaller part of the approximately 100 million dollar overall cost for a large nuclear power plant.

The continuing research effort has undertaken the development of companion weld metals having matching radiation embrittlement resistance characteristics. One study involves the submerged arc welding process and plate from the special melt (low-copper plate section A). Looking toward longer-range vessel requirements, other studies are engaged in the improvement of higher strength steels, including A543, A517-E, and A542 (plate and weld metals). Simultaneously, studies of radiation-effects mechanisms have been initiated to reveal the processes by which copper and other impurity elements alter radiation embrittlement sensitivity. The effort includes a determination of the significance of trace impurities at internal surfaces (particle-matrix interfaces, grain boundaries, etc.) and the investigations of heterogeneous nucleation of defect aggregates on impurity solute atoms.

CONCLUSIONS

The first, large-scale demonstration of metallurgically controlled radiation embrittlement sensitivity has been conducted and has proven highly successful. All research objectives for the 30-ton A533-B steel melt were attained. The commercial melt, sponsored by the U.S. Atomic Energy Commission, Division of Reactor Development and Technology, Fuels and Materials Branch, demonstrates industry's capability to produce, in quantity, steel having low radiation embrittlement characteristics approaching the optimum radiation resistance of steel produced in the laboratory.

The 30-ton melt did not require unusual production techniques or procedures to satisfy NRL special specifications to optimize radiation resistance. The NRL specifications were primarily concerned with the maximum concentrations of certain residual elements having known or suspected influences on radiation performance. The reduction of copper and phosphorus contents to the lowest possible level was stressed. Experimental results have verified this "composition approach" to the development of maximum radiation embrittlement resistance in reactor structural steels.

According to plan, the A533-B melt was split and plates representing the primary melt analysis (0.03% Cu, 0.008% P) and a melt modification (0.13% Cu) were produced. Specific observations from radiation assessments of the 6-in.-thick plates using the C_v and DT test methods were as follows:

1. The primary melt analysis (0.03% Cu, 0.008% P) exhibited very low sensitivity to radiation embrittlement at 550°F (288°C). Charpy-V 30-ft-lb transition temperature increases for Class 1 and Class 2 plates were 40° and 65°F (22° and 36°C), respectively, for a neutron fluence of 2.8×10^{19} n/cm^2 > 1 MeV. Low radiation embrittlement sensitivity characteristics were confirmed separately by dynamic tear radiation assessments.

2. The melt modification (0.13% Cu) appeared about twice as sensitive to radiation embrittlement at 550°F (288°C) as the primary melt composition (0.03% Cu), a clear and specific demonstration of the highly detrimental influence of copper content on radiation resistance at elevated temperature. Charpy-V 30-ft-lb transition temperature increases for Class 1 and Class 2 plates were 140° and 125°F (78° and 69°C), respectively, for the radiation exposure identified in 1 above.

3. The enhancement of radiation embrittlement sensitivity by copper content does not depend on Class 1 or Class 2 strength conditions.

4. Residual-element restrictions are shown to maximize elevated-temperature radiation embrittlement resistance but have little or no effect on low (less than 300°F, 149°C) temperature irradiation characteristics. As expected, radiation embrittlement sensitivity of the primary melt analysis (0.03% Cu, 0.008% P) at <300°F (149°C) was about equal to that of the ASTM A302-B reference plate (0.21% Cu, 0.013% P).

5. The simultaneous exposure of DT and C_v specimens of the primary melt analysis produced comparable increases in midenergy range transition temperature.

6. The DT performance after low- and elevated-temperature exposure suggests excellent retention of fracture resistance at shelf level temperatures for the primary melt analysis Class 1 plate. The DT shelf retention coupled with observed yield strength behavior suggests that the development of plane strain fracture even in thick section components exposed to fluences of at least 2.4×10^{19} n/cm^2 > 1 MeV is highly unlikely.

7. The nil ductility transition temperature of the primary melt analysis Class 1 plate after irradiation at 550°F (288°C) to 3.1×10^{19} n/cm² > 1 MeV was below 75°F (24°C) according to postirradiation DT test results.

8. The A533-B scaleup demonstration fully supports the principles of radiation embrittlement sensitivity control developed in the laboratory.

ACKNOWLEDGMENTS

The scaleup demonstration test was sponsored by the U.S. Atomic Energy Commission, Division of Reactor Development and Technology, Fuels and Materials Branch. The advice and support of A. VanEcho, AEC coordinating officer, and the continuing support of this agency are deeply appreciated.

The author thanks R. H. Sterne, G. Martini, and S. G. Johnson of Lukens Steel Company and J. V. Alger of the U.S. Steel Corporation for the helpful discussions concerning melt shop options and capabilities in aid of advance melt planning.

The author also thanks W. S. Pellini and L. E. Steele for their consultation and support throughout the course of this investigation. Personal efforts and contributions of individual members of the NRL Reactor Materials Branch, which insured the success of radiation experiment operations, are acknowledged with gratitude.

REFERENCES

1. Steele, L.E., Hawthorne, J.R., and Gray, R.A., Jr., "Neutron Irradiation Embrittlement of Several Higher Strength Steels," NRL Report 6419, Sept. 7, 1966; ASTM STP 426:346-370 (1967)

2. Hawthorne, J.R., and Potapovs, U., "Initial Assessments of Notch Ductility Behavior of A533 Pressure Vessel Steel with Neutron Irradiation," NRL Report 6772, Nov. 22, 1968; ASTM STP 457:113-134 (1969)

3. Potapovs, U., and Hawthorne, J.R., "The Effect of Residual Elements on 550°F Irradiation Response of Selected Pressure Vessel Steels and Weldments," NRL Report 6803, Nov. 22, 1968; Nucl. Appl. 6 (No. 1):27-29 (1969)

4. Serpan, C.Z., Jr., and Steele, L.E., "Neutron Spectral Considerations Affecting Projected Estimates of Radiation Embrittlement of the Army SM-1A Reactor Pressure Vessel," NRL Report 6474, Sept. 30, 1966

5. Serpan, C.Z., Jr., and Hawthorne, J.R., "Yankee Reactor Pressure Vessel Surveillance: Notch Ductility Performance of Vessel Steel and Maximum Service Fluence Determined from Exposure During Cores II, III, and IV," NRL Report 6616, Sept. 29, 1967; Trans. ASME (Series D, J. Basic Eng.) 89:897-910 (1967)

6. Hawthorne, J.R., and Steele, L.E., "The Effect of Neutron Irradiation on the Charpy V and Drop-Weight Test Transition Temperatures of Various Steels and Weld Metals," NRL Report 5479, May 27, 1960

7. Pellini, W.S., "Evolution of Engineering Principles for Fracture-Safe Design of Steel Structures," NRL Report 6957, Sept. 23, 1969

Appendix A

PURCHASE SPECIFICATIONS FOR SPECIAL 30-TON A533-B STEEL MELT

GENERAL

A single heat of ASTM A533 Grade B steel shall be air-melted, vacuum-stream-degassed, and cast into two 62-in.-wide-by-22-in.-thick ingot molds. Each mold will be top poured and filled to a height of approximately 77 in. One ingot shall contain 0.08% (maximum) Cu; the other ingot shall contain 0.13% (aim)* Cu. Each ingot shall be cross-rolled to 6.0-in.-thick plate using an L/T rolling ratio of approximately 1:1 (aim). Two 96-in.-by-48-in.-by-6.0-in. (thickness) patterns shall be cut from each plate using the pattern layout given in Fig. A1. The primary direction of rolling shall be parallel to the 96-in. pattern dimension. Pattern orientation with respect to the top and centerline of the ingot shall be retained with suitable reference markings.

Patterns from ingot 1 (0.08% (maximum) Cu) shall be designated plates A and B; patterns from ingot 2 (0.13% Cu) shall be designated plates C and D. The pattern size is exclusive of edge allowances. Each plate edge shall be at least 1T away from the initial as-quenched plate edge surfaces. Three of the four plate edges shall be at least 1T away from the initial as-quenched and tempered plate edge surfaces. Edge allowances for plate and test dropouts (Fig. A1) shall not be removed until after the tempering treatment.

CHEMICAL COMPOSITION

The additional special restrictions on melt analysis for ASTM A533 Grade B are given in Table A1.

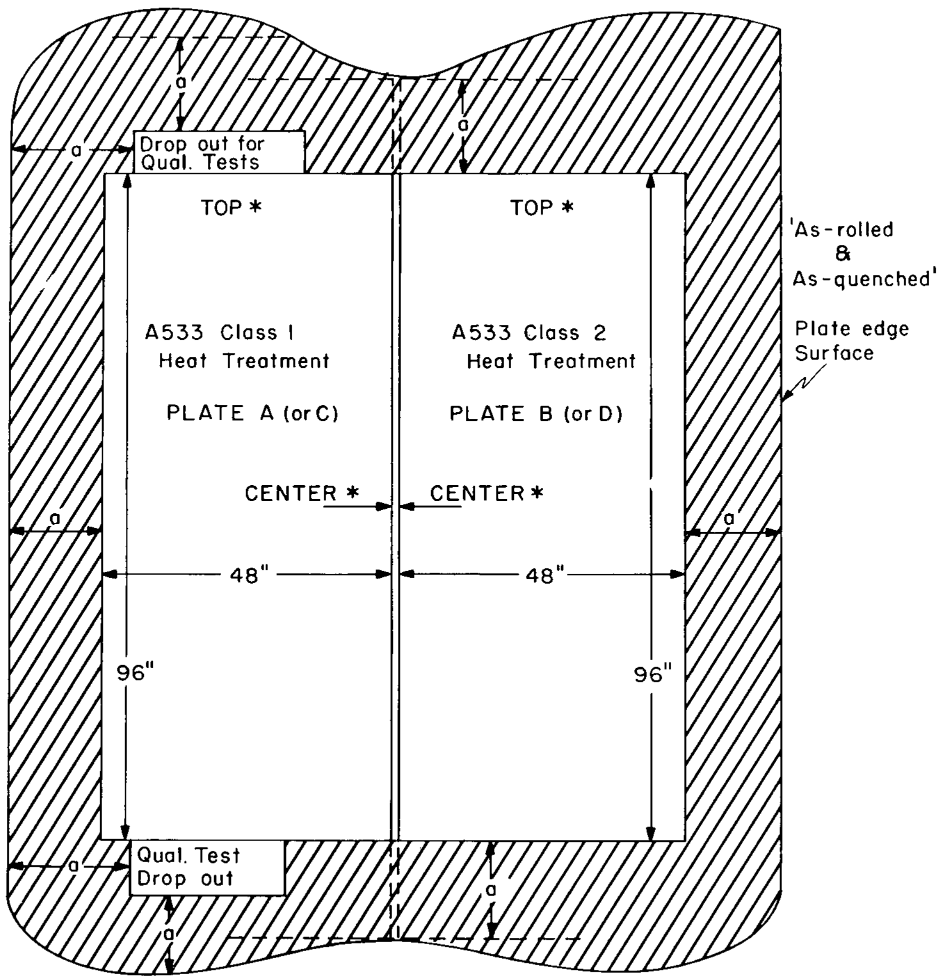
Table A1

Determination	Composition (wt-%, maximum)								
	Cu*	P	S	P + S	As	Sb	Sn	Bi	As + Sb + Sn + Bi
Ladle	0.08	0.007	0.007	0.012	0.01	0.01	0.02	0.02	0.05
Check (Plates A & B)	0.10	0.010	—	0.022	0.01	0.01	0.02	0.02	0.05

*Ingot 2 'ladle' maximum was 0.16% Cu.

Chemistry and heat treatment shall be in accordance with best fine grain practice.

*Achieved by ingot addition of pure copper shot.



* REQUIRED PLATE ORIENTATION MARKINGS
a 6-INCH (IT) MINIMUM EDGE ALLOWANCE (TYPICAL)

Fig. A1 - Plate pattern layout

HEAT TREATMENT

Plates A and C — Heat treat by double quenching and tempering treatments to meet ASTM A533 Grade B Class 1 specifications: 50,000-psi minimum yield strength (0.2% offset), 80,000 to 100,000 psi tensile strength, and 20.0% minimum elongation in 2 in.

Plates B and D — Heat treat by double quenching and tempering treatments to meet ASTM A533 Grade B Class 2 specifications: 70,000 psi minimum yield strength (0.2% offset), 90,000 to 115,000 psi tensile strength, and 18.0% minimum elongation in 2 in.

REQUIRED QUALIFICATION TESTS

Qualification tests over and above those destructive and nondestructive tests required by ASTM A533 Grade B (firebox quality) steel specifications are:

1. Destructive tests: All destructive qualification tests must be a minimum of 1T away from the initial quenched and tempered plate edge surfaces.

   Drop Weight Tests — Drop weight tests of each plate shall be performed in accordance with ASTM Method E-208-66T. Each plate shall meet the NDT requirement of +10°F (or lower) at the quarter-thickness location. Specimens shall be oriented with their long dimension perpendicular to the primary rolling direction of the plate. Specimens shall be sawcut with the surface on which the weld bead is to be placed parallel to and centered on the quarter-thickness plane of the plate. The body of the specimen shall be located toward the center of the plate.

   Tensile Tests — Tensile tests will be performed at the top and bottom of the plate, in accordance with the ASTM A-20 specification.

2. Nondestructive Tests:

   Ultrasonic — The plates shall be sonically sound and inspected in accordance with ASME Code Case 1338-4, Alternate 1, 100%.

Certified copies of results of all destructive and nondestructive tests performed for qualification and acceptance of each of the four plates, A, B, C and D, shall be furnished.

Appendix B

MELT AND INGOT PROCESSING DETAILS

MELT IDENTIFICATION

Latrobe Steel Company heat V22403

MELT TYPE

Basic electric double-slag, fine-grain practice

FURNACE

Swindel, 30-ton trunnion type with induction stirrers (17 prior heats on top and bottom linings)

FURNACE CHARGE

100% scrap, low-phosphorus automobile fender punchings (S 0.022% maximum; P 0.007%; Cr, Ni, Mn < 0.02%; Cu 0.04%). Nickel to spec. with electrolytic nickel. Molybdenum to spec. with ferromolybdenum. Manganese to spec. with electrolytic manganese.

FURNACE ORDER SHEET SPECIFICATIONS

Elements	Low (%)	High (%)	Aim (%)	Working Aim (%)
C	0.18	0.21	0.20	0.19
Si	0.15	0.30	0.24	0.24+
Mn	1.20	1.40	1.30	1.45
S	0.006	LAP	S + P = 0.012 max	LAP
P	0.006	LAP		LAP
Cr	0.05	0.10	0.05 max	LAP
V	–	0.02	LAP	LAP
Mo	0.45	0.60	0.55	0.53
Ni	0.40	0.70	0.55	0.55
Cu	–	0.08	LAP	LAP
Sn	–	0.02	LAP	LAP
As	–	0.01*	LAP	LAP
Sb	–	0.01*	LAP	LAP
Bi	–	0.02	LAP	LAP

*Total 0.05 max.

MELT SCHEDULE

Charge	1600 hr
Back charge	1730 hr
First slagging*	1845 hr
Second slagging*	2000 hr
Tapped heat	2205 hr (3070°F furnace, 2960°F ladle)
Commenced vacuum degassing	2210 hr
Commenced pouring ingot 1	2225 hr
Completed pouring ingot 2	2240 hr

*Lanced heat in advance of slagging operation.

MELT SAMPLING

Sample Identification		Composition (wt-%)								
		C	Si	Mn	S	Cr	Mo	Ni	Cu	V
After melt-in and oxygen	(P-1)	0.04	—	—	0.017/ 0.018	—	—	—	—	—
After first slagging	(P-2)	0.127	0.10	1.02	0.009	0.02	0.37	0.41	0.044	0.01
	(P-3)	0.120	0.10	1.03	0.006	0.02	0.38	0.41	0.034	—
After second slagging	(P-4)	0.143	0.09	1.04	0.006	0.01	0.38	0.41	0.044	0.01
Ladle	(P-5)	0.18	0.20	1.37	0.006	0.06	0.53	0.56	0.03 (0.12*)	0.01

*28-lb copper shot added to ingot 2 to bring content to approximately 0.13%.

INGOT TYPE

Big-end-up, top-poured plug mold (62 by 22 by 77 in. (height to hot-top junction)).

INGOT SAMPLING

Ingot No. 1 (28,580 lb) (Composition (wt-%))											
	C	Mn	P	S	Ni	Cr	Mo	Si	Cu	Al	Others
Dip test (Latrobe)	0.176	1.38	0.006	0.006	0.56	0.06	0.53	0.20	0.124	—	*
Dip test (NRL)	0.16	1.20	0.007	0.006	0.55	0.07	0.49	0.18	0.12	—	—
Check test (Lukens) Ingot top	0.20	1.29	0.010	0.010	0.56	0.06	0.51	0.20	0.16	0.016	—
Check test (Lukens) Ingot bottom	0.19	1.30	0.010	0.009	0.57	0.06	0.52	0.20	0.16	0.016	—
Ingot No. 2 (28,650 lb) (Composition (wt-%))											
Dip test (Latrobe)	0.182	1.37	0.006	0.006	0.56	0.06	0.53	0.20	0.034	—	*
Dip test (NRL)	0.16	1.20	0.007	0.006	0.55	0.07	0.51	0.18	0.05	—	—
Check test (Lukens) Ingot top	0.19	1.26	0.010	0.009	0.56	0.06	0.52	0.20	0.05	0.013	—
Check test (Lukens) Ingot bottom	0.18	1.26	0.011	0.008	0.54	0.06	0.51	0.20	0.05	0.016	—

*As + Sb + Sn + Bi < 0.05%.

INGOT PROCESSING

Ingots were given a full anneal after stripping, then slow cooled to below 600°F. Surfaces were inspected and any major surface defects were removed by grinding. Ingots were heated to 2300° to 2350°F and tandem-rolled on Lukens 140/206 mills directly to 6-in. gage, following the ingot to plate sequence outlined schematicaly in Fig. B1. The plates finished rolling above 1600°F and were buried in sand. The L/T ratios from ingot to plate were 1.03:1 (plate length/ingot length ÷ plate width/ingot width = 1.03).

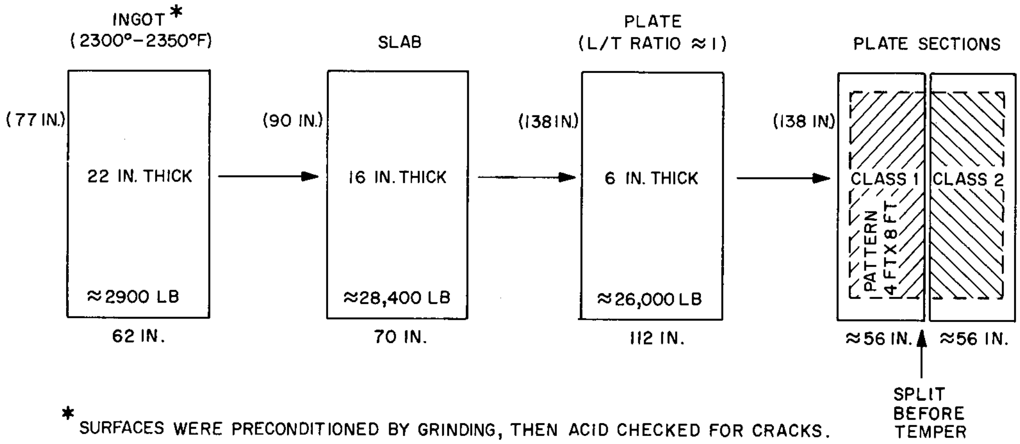


Fig. B1 - Ingot-to-plate processing sequence

Appendix C

PLATE HEAT TREATMENT, QUALIFICATION AND INSPECTION

HEAT TREATMENT

Both 6-in. gage plates were heated to 1675° ± 25°F, held for 6 hr, and water (dip) quenched, then reheated to 1575° ± 25°F, held for 6 hr, and water (dip) quenched. Following stress relief at 1050° ± 25°F for 6 hr and air cooling, both plates were split in half longitudinally by gas cutting. (Orientation of each plate section relative to the parent plate was retained by suitable heat-resistant reference markings). After gas cutting, all four plate sections were stress relieved at 1050° ± 25°F for 6 hr and air cooled.

Plate section A from ingot 1 (low copper) and plate section C from ingot 2 (high copper) were tempered for Class 1 properties at 1250° ± 25°F. Plate section B from ingot 1 and plate section D from ingot 2 were tempered for Class 2 properties at 1200° ± 25°F. All tempered sections were then stress relieved at 1125° ± 25°F for 20 hr. Furnace cooling to 600°F was used consistently with tempering and the final stress relief treatment.

Mechanical tests revealed that Class 2 requirements were not met by plate sections B and D. These sections were requenched from 1575° ± 25°F after 6 hr at temperature, tempered at 1150° ± 25°F for 6 hr, air cooled, stress relieved at 1100°F for 10 hr, and water quenched. After gas cutting to size, plate sections B and D plus test sections received a final stress relief at 1050° ± 25°F for 6 hr, followed by furnace cooling to below 600°F.

STRENGTH QUALIFICATION TESTS

Tensile tests were conducted on specimens oriented with their central axis lying in the plate section top 1/4T plane. Properties based on the duplicate tests are given in Table C1.

ULTRASONIC INSPECTION TESTS

All four plates were ultrasonic tested to ASME Code Case 1338-4 Alternate 1, search after heat treatment but before final cutting. The instrument was calibrated on a 3/4-in.-diameter flat-bottom hole drilled in a 6-in.-gage calibration block to a depth of 10% of the gage. An ingot top end indication of massive size was noted in both parent plates (ingot 1 and 2). A smaller (but slightly above specification) indication was noted about 1/4 of the plate length from the ingot bottom end of plate 1. Nondestructive test reports included plots of all indications for evaluation and reference.

Table C1
Quarter-Thickness Tensile Properties of 6-in.-Thick Plate Sections

Plate Section	Strength Specification	Test* Orientation	Ingot Location	Yield Strength (0.2% offset†) (ksi)	Tensile‡ Strength (ksi)	Elongation (%)	Reduction of Area (%)
Section A (ingot 1)	Class 1	L	Top	66.9	87.7	27	68.5
		L	Bottom	59.2	84.1	27	67.7
		T	Top	67.3	87.3	25	69.2
		T	Bottom	63.6	83.5	27	68.1
Section C (ingot 2)	Class 1	L	Top	64.9	91.0	27	68.2
		L	Bottom	63.6	85.0	27	68.0
		T	Top	68.2	90.0	27	68.2
		T	Bottom	64.8	85.9	27	68.0
Section B (ingot 1)	Class 2	L	Top	79.2	98.2	25	65.8
		T	Top	78.9	98.0	25	65.9
		T	Bottom	81.5	98.5	25	66.2
Section D (ingot 2)	Class 2	L	Top	88.7	107.4	24	64.1
		T	Top	87.1	104.7	24	64.4
		T	Bottom	81.0	96.7	25	65.8

*L — Parallel to ingot and plate long axis.
T — Transverse to ingot and plate long axis.
†0.505-in.-diameter tension test specimens.
‡Average of duplicate tests.