RAOIATION EFFECTS INFORMATION GENERATEO ON THE ASTM REFERENCE CORRELATION-MONITOR STEELS

DS 54

AMERICAN SDCIETY FOR TESTING AND MATERIALS

RADIATION EFFECTS INFORMATION

05-054000-35

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Sponsored by
ASTM Committee E-10 on
Radioisotopes and
Radiation Effects
AMERICAN SOCIETY FOR
TESTING AND MATERIALS

ASTM DATA SERIES PUBLICATION DS 54
Prepared by J. R. Hawthorne

List price $9.75
05-054000-35

AMERICAN SOCIETY FOR TESTING AND MATERIALS
1916 Race Street, Philadelphia, Pa. 19103

Library of Congress Catalog Card Number: 74-79014

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Printed in Baltimore, Md.
July 1974

Foreword

This volume is yet another splendid example of scientific and engineering progress that can be achieved through voluntary cooperation. It is typical of the programs conducted under the auspices of ASTM which lead to the world respected voluntary consensus ASTM standards.

ASTM Committee E-10 on Radioisotopes and Radiation Effects is commended for developing this program, conducting the surveillance, and compiling the resulting data. The information generated from the continuing monitoring of the effects of radiation on reference steels is of immense value to those who must design and operate nuclear reactors. The foresight of the committee in developing such cooperative research points the way to the solution of the world's energy problems.

W. T. Cavanaugh
Managing Director, ASTM

Related ASTM Publications

Analysis of Reactor Vessel Radiation Effects Surveillance Programs, STP 481 (1970), $26.00 (04-481000-35)

Irradiation Effects on Structural Alloys for Nuclear Reactor Applications, STP 484 (1971), $49.25 (04-484000-35)

Effects of Radiation on Substructure and Mechanical Properties of Metals and Alloys, STP 529 (1973), $49.50 (04-529000-35)

Contents

J. R. Hawthorne [1]

Radiation Effects Information Generated on the ASTM Reference Correlation-Monitor Steels

REFERENCE: Hawthorne, J. R., *Radiation Effects Information Generated on the ASTM Reference Correlation-Monitor Steels, ASTM DS 54,* American Society for Testing and Materials, 1974.

ABSTRACT: A survey is made of radiation effects information generated on the first four correlation-monitor materials provided by ASTM to radiation research and reactor surveillance programs. The survey was performed for Subcommittee 2 of ASTM Committee E-10 on Radiation Effects and includes a review of the worldwide distribution and use of the reference materials since 1960. The reference plates were those originally donated to ASTM by the U. S. Steel Corporation. Individual plates are identified as 6-in. A302-B steel, 4-in. A212-B steel, 3-in. Ni-Cr-Mo (HY-80) steel, and 2-in. T-1 steel.

The report presents extensive tabulations of data as provided by the recipient laboratories. In addition, trends in radiation effects behavior with respect to tensile properties, Charpy-V (C_v) notch ductility properties and postirradiation annealing response are identified and discussed. Nil-ductility transition (NDT) temperature behavior and dynamic tear (DT) test performance relative to C_v behavior are also identified for the A302-B and A212-B reference plates.

The report is intended as a reference document for the evaluation and analysis of data developed by on-going reactor vessel surveillance programs and a source for data and data trends by which to assess the performance of new structural steels and to compare the effects of diverse reactor environments.

KEY WORDS: radiation effects, steels, evaluation, structural steels, pressure vessels, reactors, neutron irradiation, thermal reactors (nuclear)

Introduction

The progressive increase in strength and reduction in notch ductility of low-alloy steels as a result of neutron exposure are now well recognized nuclear service phenomena. Substantial progress has also been made toward the understanding and the prediction of irradiation effects to such steels. The ASTM

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recognition, a decade ago, of the need for incorporating a few, well-documented reference steels in radiation research and power reactor surveillance programs undoubtably contributed to this technical progress. Such recognition stemmed from the dual concern for variable radiation embrittlement behavior among steels and for the potential for (and extent of) radiation response variations with differing nuclear environment conditions (flux intensity, neutron spectrum). An additional concern was the proper definition of the nuclear environment with respect to the significant, that is, damaging, neutron energy levels. It was projected that the use of correlation-monitor materials would help resolve such questions.

Four well-documented structural steel plates provided to the Society in 1960 by the U. S. Steel Corporation for radiation effects programs have been distributed to several United States and European organizations. Distribution of the reference materials has been under the auspices of Subcommittee 2 of Committee E-10 on Radiation Effects. This paper represents an effort to survey the use of the reference materials and to gather radiation effects data generated to date. The report is intended as: (1) a reference document for the evaluation and analysis of data developed by on-going reactor vessel surveillance programs, and (2) a source for data and data trends by which to assess the relative performance of new structural materials and to compare the effects of diverse reactor environments. In addition, survey findings help weigh the continuing need for reference materials by future research and surveillance programs. It is noted that the original stock of reference materials now stands largely depleted.

Compositions of the four reference plates donated by U. S. Steel include A-302-B steel (6 in.), A212-B steel (4 in.), Ni-Cr-Mo (3 in. HY-80), and T-1 steel[2] (2 in.). Of these the A302-B composition received the most interest and effort.

Consistent with aims of this report, data analyses will be developed only for the definition and illustration of data trends and not to the extent of assessing the engineering significance of such trends.

Materials

Compositions and heat treatments of the individual reference plates are given in Tables 1 and 2, respectively [*1,2*].[3] Preirradiation mechanical properties are listed in Table 3 [*1*]. Charpy V-notch (C_V) transition behavior and drop weight nil-ductility transition (NDT) temperature are compared in Figs. 1-4. Only minor variations in C_V properties across individual plates have been recorded. Of the four plates, the quenched and tempered Ni-Cr-Mo plate showed the most pronounced variation in C_V behavior with test location (see Figs. 4 and 5) [*3*]. Through-thickness determinations by tensile [*4*], C_V, and drop weight test

[2] United States Steel Corporation proprietary steel designation.
[3] The italic numbers in brackets refer to the list of references appended to this paper.

TABLE 1–*Chemical composition of reference steel plates* [1], *weight percent.*

Plate	Thickness in.		C	Mn	P	S	Si	Ni	Cr	Mo	Cu	V[a]	Ti[a]	B[a]	Sn	N	Al, total	Al, insoluble
A302-B	6	ladle	0.20	1.31	0.013	0.023	0.23	0.18	...	0.48	0.18	...	...	...	...	...	...	...
(Heat A0421)		check	0.24	1.34	0.011	0.023	0.23	0.18	0.11	0.51	0.20	<0.001	0.015	0.0001	0.037	0.008	0.040	0.002
A212-B	4	ladle	0.27	0.77	0.013	0.035	0.21	0.20	...	...	0.26	...	...	...	...	...	0.069	0.004
(Heat A0456)		check	0.26	0.80	0.012	0.036	0.22	0.28	0.12	0.034	0.26	<0.001	<0.001	0.0003	0.023	0.007	0.069	0.004
Ni-Cr-Mo	3	ladle	0.14	0.22	0.011	0.015	0.20	2.98	1.57	0.54	...	...	...	...	...	...	...	...
(Heat 74L204)		check	0.14	0.20	0.011	0.015	0.18	3.01	1.61	0.50	0.065	0.005	0.005	<0.0005	0.005	0.008	0.037	0.006
T-1	2	ladle	0.16	0.90	0.015	0.015	0.26	0.71	0.55	0.45	0.23	0.05	...	0.004	...	...	...	...
(Heat 68P281)		check	0.16	0.89	0.014	0.012	0.24	0.66	0.55	0.40	0.21	0.045	0.003	0.0043	0.026	0.005	0.035	0.005

[a]Estimated wherever (<) precedes the reported value.

TABLE 2–*Heat treatment of reference steel plates* [1,2].

Plate	Heat Treatment
A302-B (6 in.)	austenitized at 1650°F (899°C) 6 h, water quenched to 300°F (149°C); tempered at 1200°F (649°C) 6 h, air cooled (heated to 1200°F at 63°F (35°C) per hour maximum)
A212-B (4 in.)	austenitized at 1650°F (899°C) 4 h, water quenched to 300°F (149°C); tempered at 1175°F (635°C) 4 h, air cooled (heated to 1175°F at 63°F (35°C) per hour maximum)
Ni-Cr-Mo (3 in.)	austenitized at 1650°F (899°C) 3 h, water quenched; tempered at 1175°F (635°C) 3 h, (air cooled)
T-1 (2 in.)	austenitized at 1700°F (927°C) 2 h, water quenched; tempered at 1150°F (621°C) 2 h, air cooled re-tempered at 1166°F (630°C) 2 h, (air cooled)

methods indicated the good properties uniformity essential for standard reference materials (see Figs. 6-12).

Assessments of preirradiation plane strain fracture toughness (K_{Ic}) have been performed for the A302-B plate only (Fig. 13)[5]. Similar determinations on the remaining plates are not planned by any participating laboratories. Assessments of preirradiation notch toughness by the dynamic tear (DT) test method[4] have been performed for the A302-B and A212-B plates only (Fig. 14).

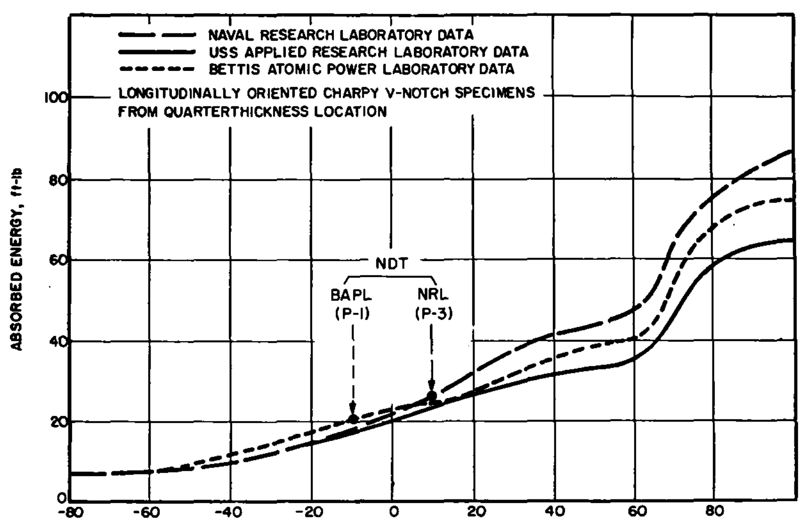

FIG. 1–*Charpy V-notch transition curves for 6-in.-thick plate of ASTM A302-B steel* [1]. *The drop weight NDT temperature is also shown.*

[4]MIL Standard 1601 (Bureau of Ships).

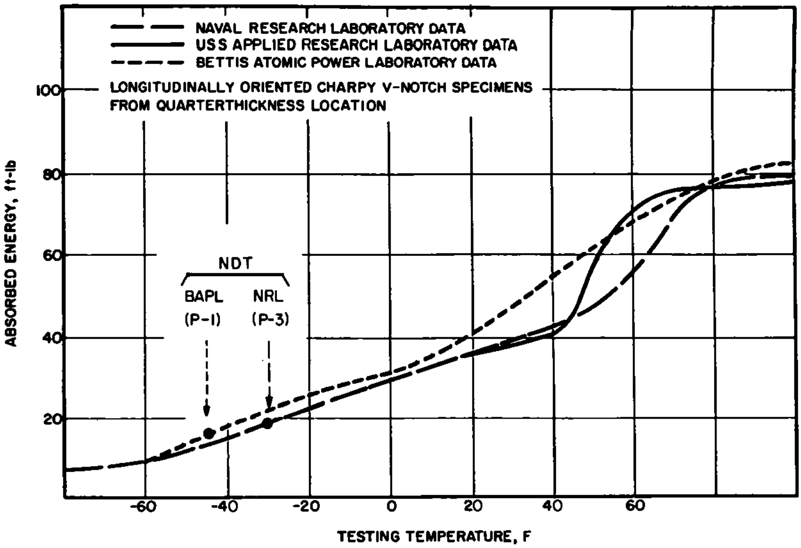

FIG. 2—*Charpy V-notch transition curves for 4-in.-thick plate of ASTM A212-B steel* [1]. *The drop weight NDT temperature is also shown.*

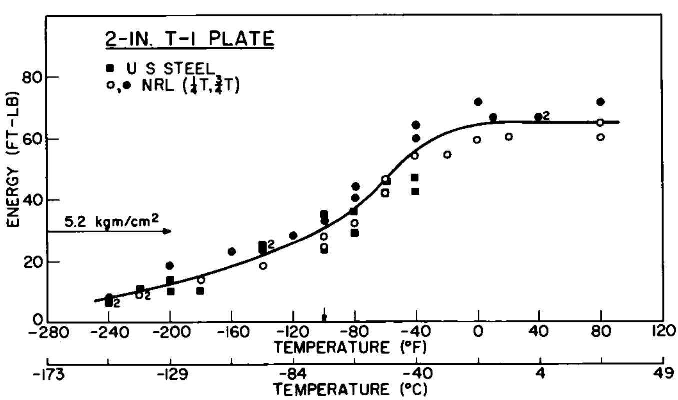

FIG. 3—*Charpy V-notch transition curve for 2-in.-thick plate of T-1 steel.*

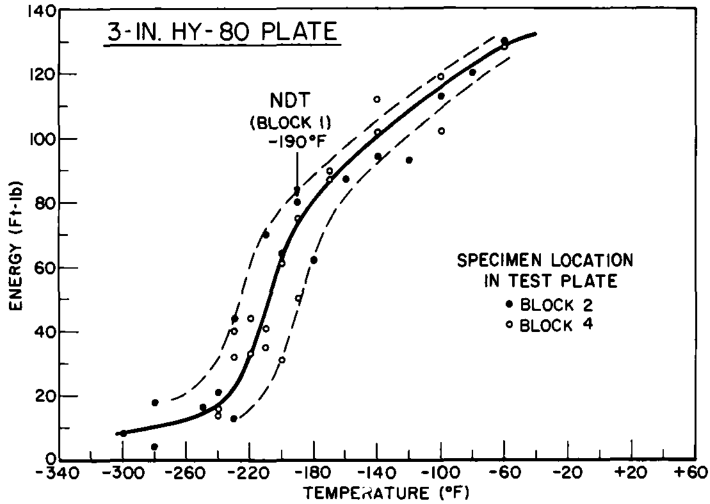

FIG. 4*a–Charpy V-notch transition curve for 3-in.-thick plate of HY-80 steel. The drop weight NDT temperature is also shown* [3].

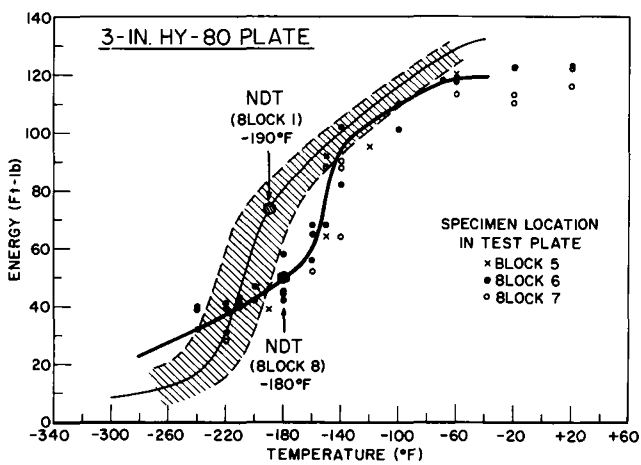

FIG. 4*b–Notch ductility of 3-in.-thick HY-80 steel showing variations in Charpy-V and drop weight NDT performance across the plate* [3].

TABLE 3—*Preirradiation mechanical properties of reference steel plates* [1].

Plate	Test[a] Orientation	Yield Points, psi	Tensile Strength, psi	Elongation, % in 2 in.	Reduction of Area, %	C_v Energy at +10°F(-12°C)	NDT °F(°C)	Hardness[b]	Austenitic Grain Size (ASTM No.)
A302-B	L	67 870	92 800	23.0	65.0	27-28-29	+10[c](-12)	Rb92-93	7
(6 in.)	T	69 270	93 180	24.0	57.1	18-20-22	-10[d](-23)		
A212-B	L	47 980	76 080	32.0	64.2	38-38-40	-30[c](-34)	Rb80-82	6.5
(4 in.)	T	55 580	80 850	28.0	61.1	28-29-32	-45[d](-43)		
Ni-Cr-Mo	L	88 620[e]	104 100	25.0	73.3	(97,118,118)[f]	-180[c](-118)	Rc21-22	9
(3 in.)	T	90 360[e]	105 600	25.5	70.8	...			
T-1	L	115 000[e]	123 850	18.0	61.2	55, 59, 60	...[g]	Rc24-25	8
(2 in.)	T	...	...	...	...	69, 70, 74			

[a] L = longitudinal (*RW*-parallel major plate dimension).
T = transverse (*WR*-perpendicular major plate dimension).
[b] One and three quarter thickness locations.
[c] Naval Research Laboratory determination with 2 by 5 by 5/8-in. drop weight specimens.
[d] Bettis Atomic Power Laboratory determination with 3 1/2 by 14 by 1-in. drop weight specimens.
[e] 0.2% offset yield strength.
[f] C_v energy at -120°F (-85°C).
[g] Not determined.

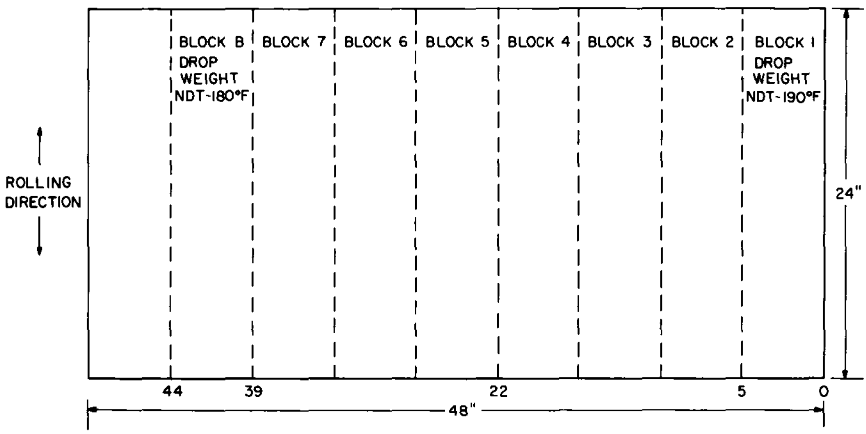

FIG. 5–*Diagram showing location of various sampling sections in HY-80 steel plate* [3].

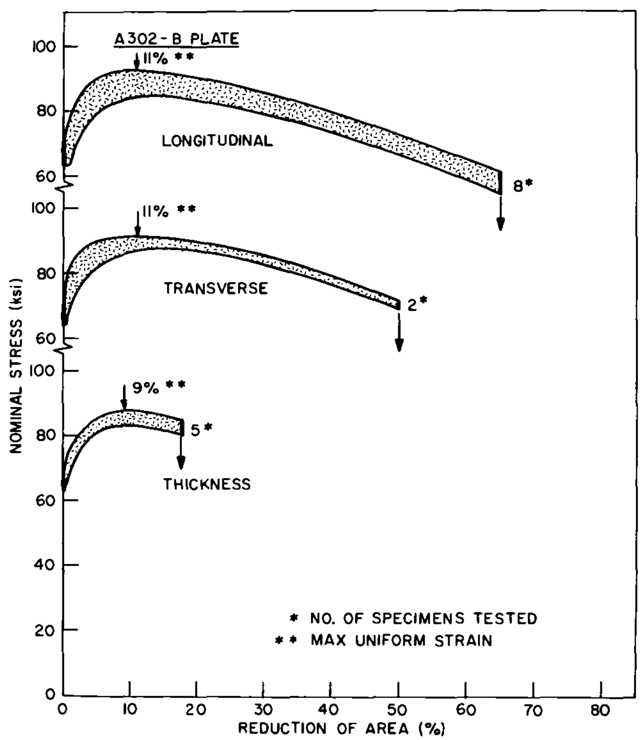

FIG. 6–*The nominal stress-reduction of area data bands for A302-B steel plate for the specimen orientation indicated* [4]. *Longitudinal orientation data band represents 1/4T, 1/2T, and 3/4T test locations.*

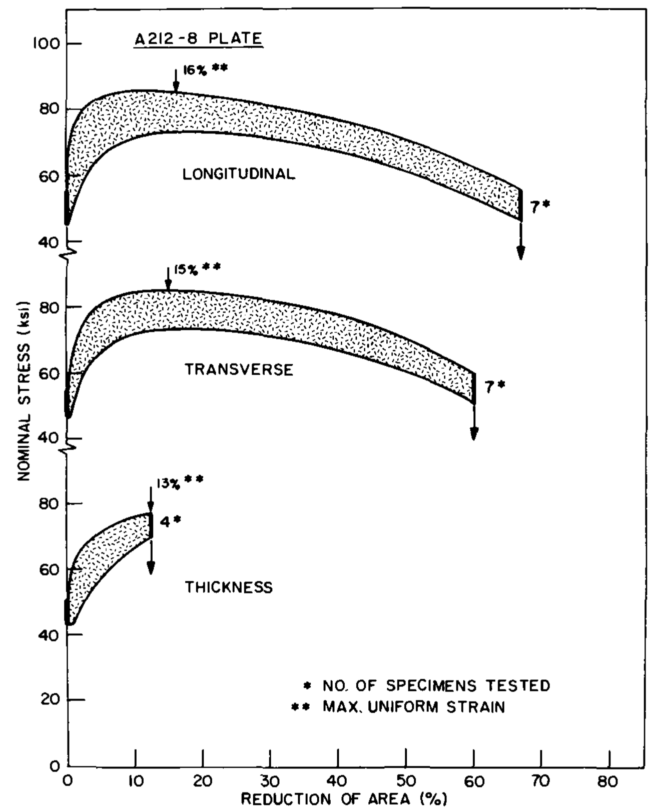

FIG. 7—*The nominal stress-reduction of area data bands for A212-B steel plate for the specimen orientations indicated* [4]. *Longitudinal orientation data band represents 1/4T, 1/2T, and 3/4T test locations.*

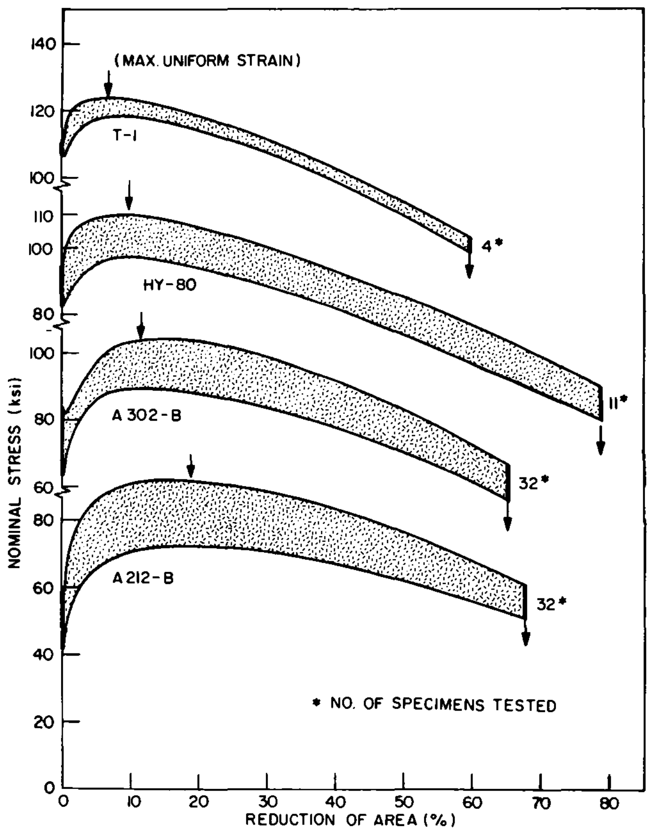

FIG. 8–*Nominal stress-reduction of area data bands for the four ASTM reference steel plates* [4].

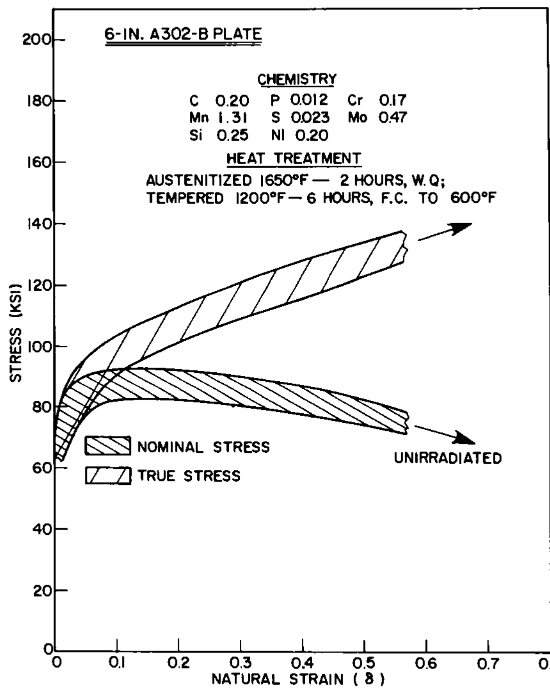

FIG. 9–*True stress-natural strain and nominal stress-natural strain maximum and minimum data envelopes for a second lot of unirradiated specimens of A302-B steel plate* [4].

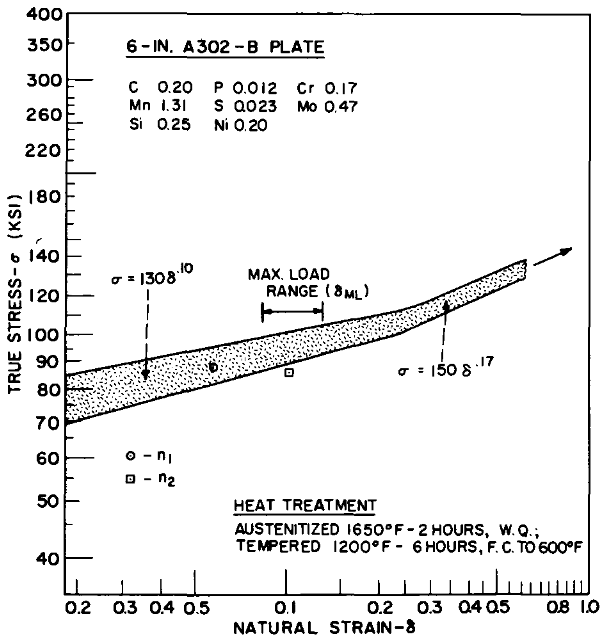

FIG. 10—*True stress-natural strain data envelope for a second lot of unirradiated specimens of A302-B steel plate in ln-ln coordinates* [4].

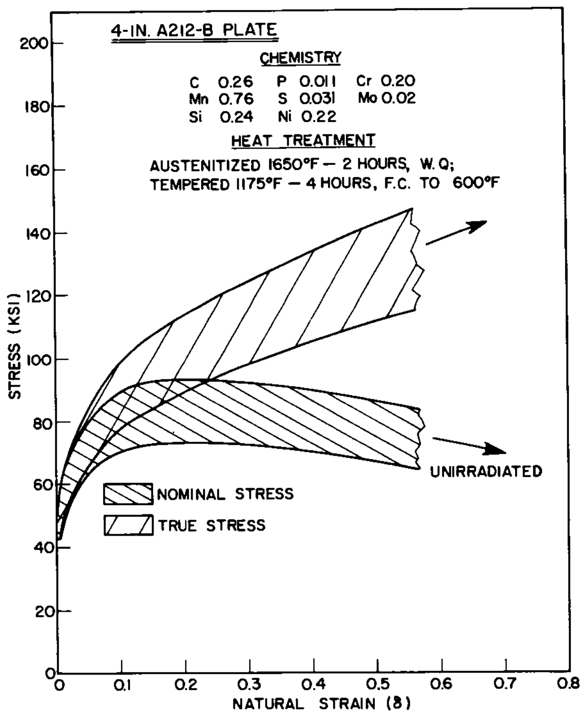

FIG. 11—*True stress-natural strain and nominal stress-natural strain maximum and minimum data envelopes for one set of unirradiated specimens of A212-B steel plate* [4].

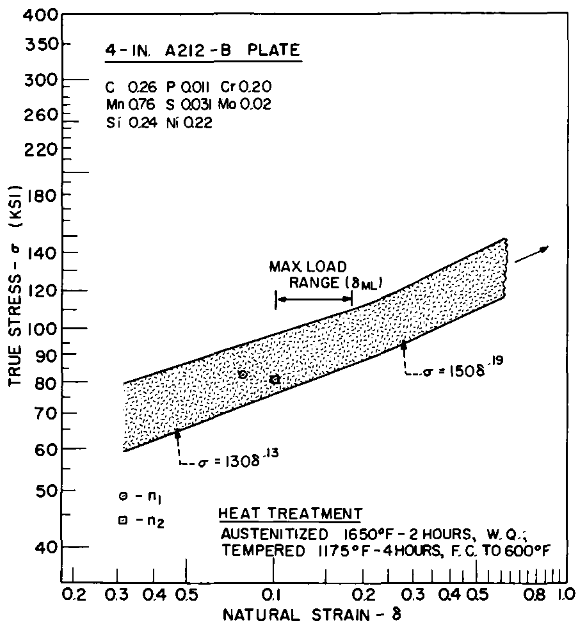

FIG. 12–*True stress-natural strain data envelope for one set of unirradiated specimens of A212-B steel plate in ln-ln coordinates* [4].

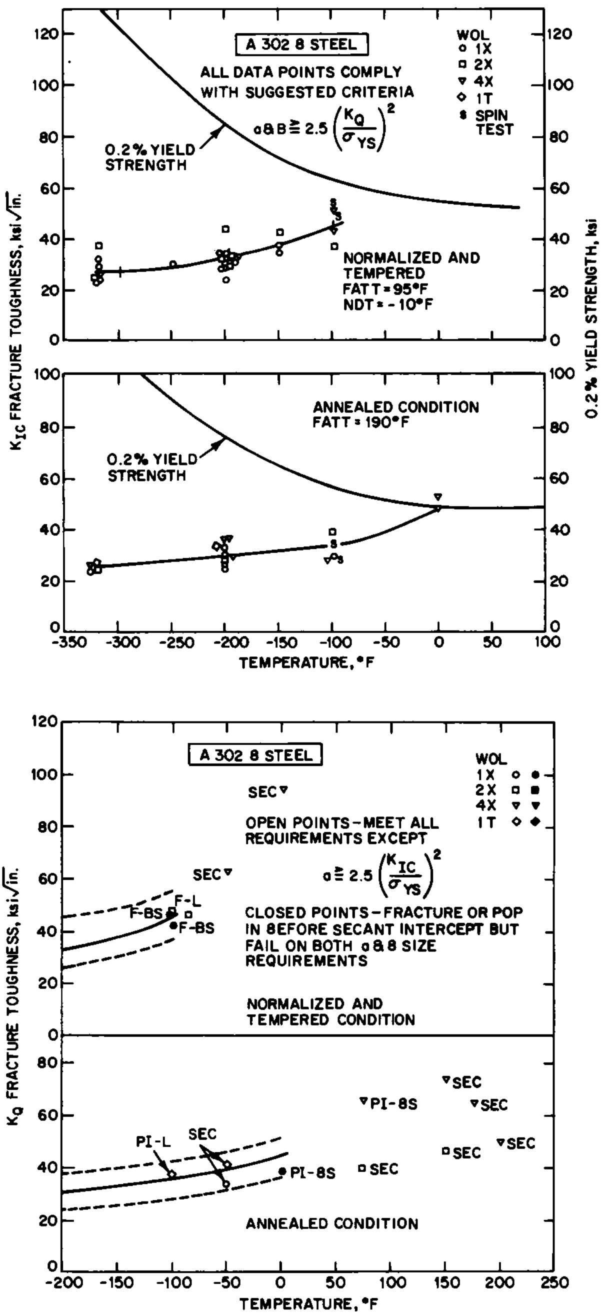

FIG. 13—*Plane strain fracture toughness of 6-in.-thick plate of A302-B steel*[5].

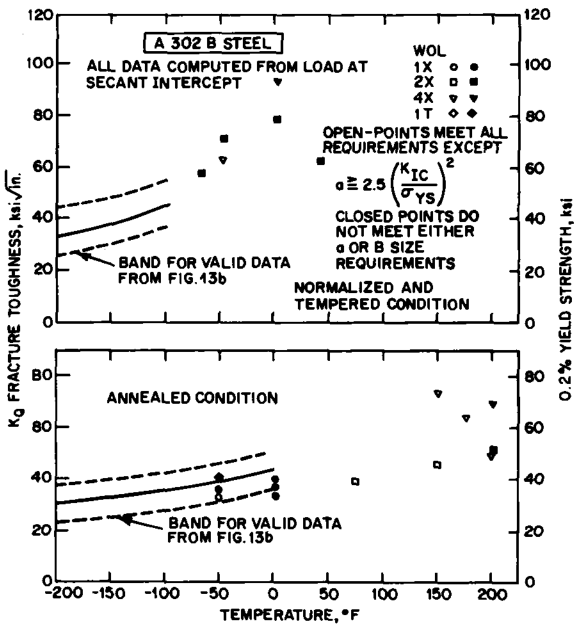

FIG. 13–(*Continued*)

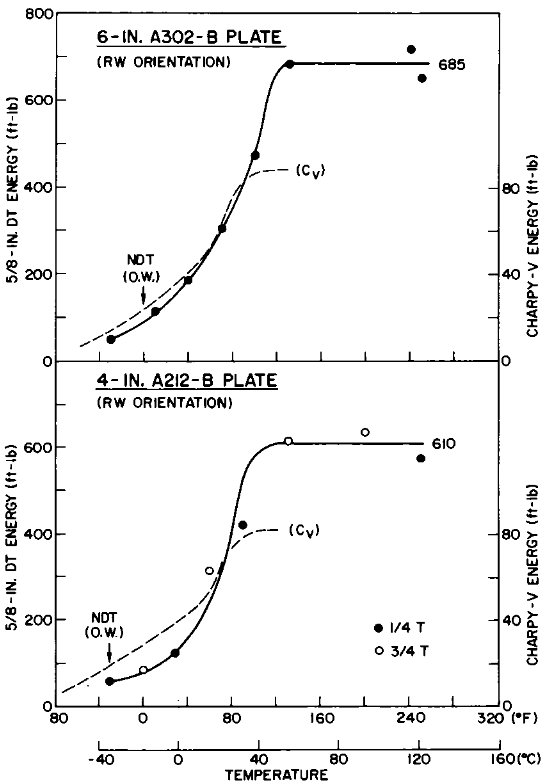

FIG. 14–*The 5/8-in. DT test performance of the 6-in. A302-B plate and 4-in. A212-B plate. Drop weight NDT and Charpy-V* (C_V) *performances are also shown.*

Survey of Materials Distribution

Distribution of the correlation-monitor materials prior to 1962 was summarized by Landerman [*2*] at the 1962 ASTM Symposium on Radiation Effects on Metals and Neutron Dosimetry. Figures 15-18 from his report indicate the material recipients and the relative size and location of their respective test sections. As noted, several laboratories had considerable interest in and had extensive plans for the A302-B and A212-B materials. Interest in these particular compositions was a reflection of the materials of reactor vessel construction at that time. By comparison, the higher strength Ni-Cr-Mo and T-1 materials carried only nominal interest.

Table 4 summarizes correlation-monitor material requests received by the Subcommittee prior to and after 1962. The shaded areas in Figs. 15-18 represent the amount of stock involved in post-1962 requests. It is evident that requirements for reference material diminished appreciably after 1962, particularly in radiation effects research studies. The extent of the Naval Research Laboratory (NRL) use of three of the four materials is only a reflection of several special research studies[5] and the application of relatively large test specimens. On the other hand, repeat requests for material by reactor vendors

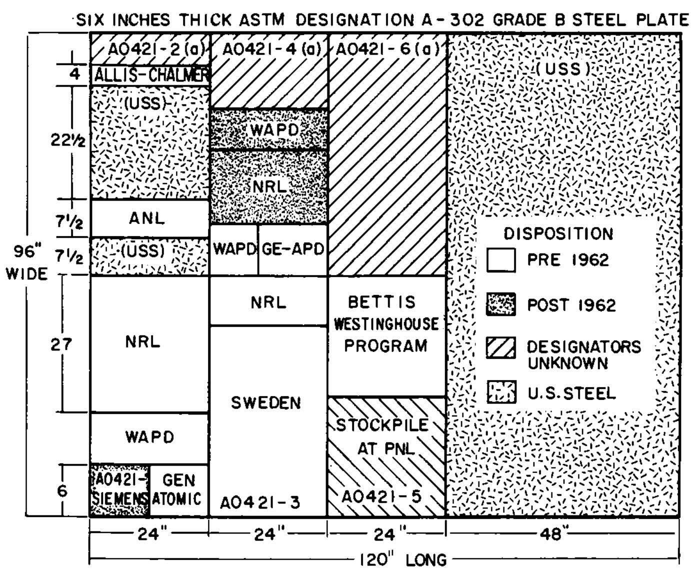

FIG. 15–*The 6-in.-thick plate of A302-B steel showing the location of stock used for test specimens and details regarding cutting and marking plate sections for irradiation program* [2]. *(Shaded areas indicate stock involved in post-1962 requests.)*

[5] Special studies have included postirradiation annealing response studies, through wall embrittlement studies, and studies of modified neutron spectrum effects.

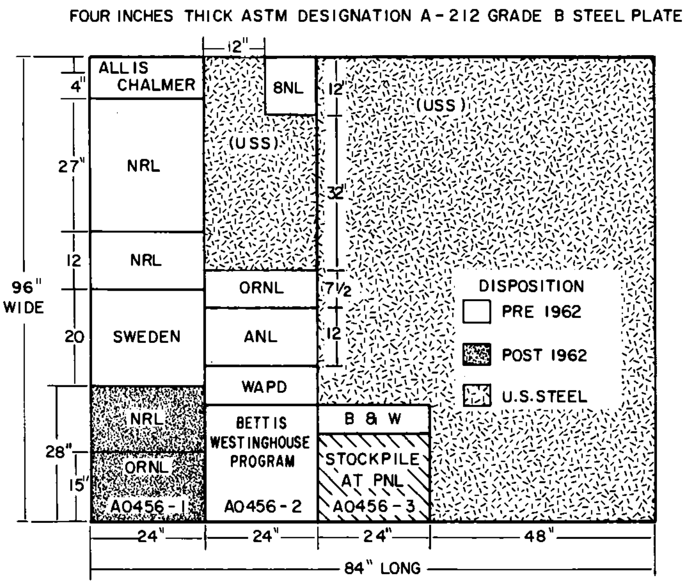

FIG. 16–*The 4-in.-thick plate of A212-B steel showing the location of stock used for test specimens and details regarding cutting and marking plate sections for irradiation program* [2]. *(Shaded areas indicate stock involved in post-1962 requests.)*

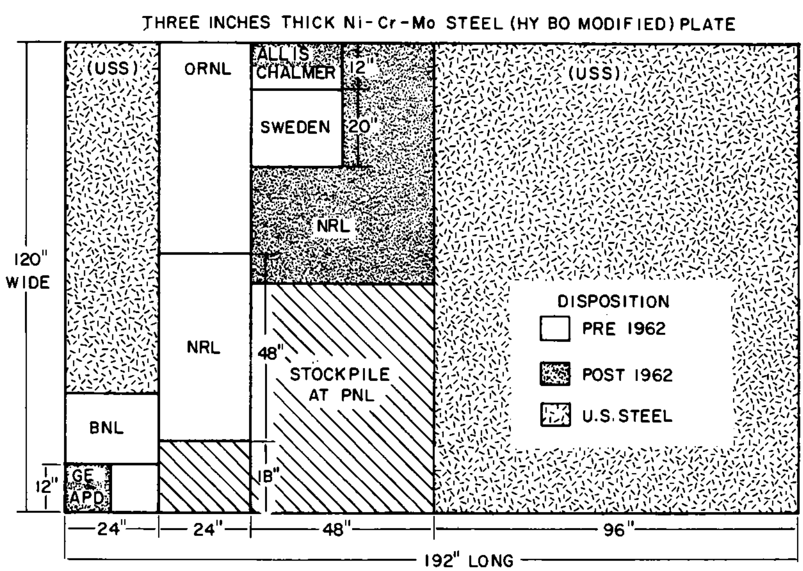

FIG. 17–*The 3-in.-thick plate of HY-80 steel showing the location of stock used for test specimens and details regarding cutting and marking plate sections for irradiation program* [2]. *(Shaded areas indicate stock involved in post-1962 requests.)*

TABLE 4–*Recipients of reference steel plates.*

Plate	Period	Organization	Plate Section Size, in. (approximate)
A302-B (6 in.)	(6/59 to 6/62)	Westinghouse Electric Corporation (Bettis Atomic Power Laboratory)	24 by 24
		Oak Ridge National Laboratory (Solid State Division)	24 by 7 1/2
		Naval Research Laboratory (Metallurgy Division)	24 by 27 24 by 12
		Allis Chalmers Company (Nuclear Power Department)	18 by 4
		Westinghouse Electric Corporation (Atomic Power Department)	24 by 12 12 by 12
		Aktiebolaget Atomenergie (Metallurgy Department)	1 plate section[a]
		General Dynamics Corporation (General Atomics Division)	12 by 6
	6/62 to present	General Electric Company (Atomic Products Division)	(1) 12 by 12 (2) 1 plate section[a]
		Naval Research Laboratory (Metallurgy Division)	24 by 15
		General Electric Company (Richland, Washington)	24 by 24 (stockpile)
		Siemens-Schuchertwerke-AG	12 by 6 section
A212-B (4 in.)	(6/59 to 6/62)	Westinghouse Electric Corporation (Bettis Atomic Power Laboratory)	24 by 24
		Oak Ridge National Laboratory (Solid State Division)	24 by 7-1/2
		Argonne National Laboratory (Reactor Engineering Division)	24 by 12
		Naval Research Laboratory (Metallurgy Division)	(1) 24 by 27 (2) 24 by 12
		Brookhaven National Laboratory (Metallurgy Division)	(1) 12 by 12 (2) 10 by 5
		Allis Chalmers Company (Nuclear Power Department)	18 by 4

		Westinghouse Electric Corporation (Atomic Power Department)	24 by 8 1/2
		Aktiebolaget Atomenergi (Metallurgy Department)	1 plate section[a]
		Babcock & Wilcox Company (Atomic Energy Division)	24 by 6
	(6/62 to present)	Naval Research Laboratory (Metallurgy Division)	24 by 12
		General Electric Company (Richland, Wash.)	24 by 18 (stockpile)
		Oak Ridge National Laboratory (Solid State Division)	1 plate section[a]
Ni-Cr-Mo (3 in.)	(6/59 to 6/62)	Oak Ridge National Laboratory (Solid State Division)	24 by 60
		Naval Research Laboratory (Metallurgy Division)	24 by 48
		Brookhaven National Laboratory (Metallurgy Division)	12 by 12 10 by 5
		Allis Chalmers Corporation (Nuclear Power Department)	24 by 4
		Aktiebolaget Atomenergi	1 plate section[a]
	(6/62 to present)	Naval Research Laboratory (Metallurgy Division)	(1) 24 by 30 (2) 24 by 72
		General Electric Company (Richland, Washington)	20 ft^2 (stockpile)
		General Electric Company (Atomic Products Division)	1 plate section[a]
T-1 (2 in.)	(6/59 to 6/62)	Oak Ridge National Laboratory (Solid State Division)	24 by 54
		Naval Research Laboratory (Metallurgy Division)	24 by 48
		Aktiebolaget Atomenergi (Metallurgy Division)	1 plate section[a]
	(6/62 to present)[b]	Naval Research Laboratory (Metallurgy Division)	(1) 24 by 30 (2) 24 by 72

[a]Section size not recorded.
[b]None placed in archive material stockpile.

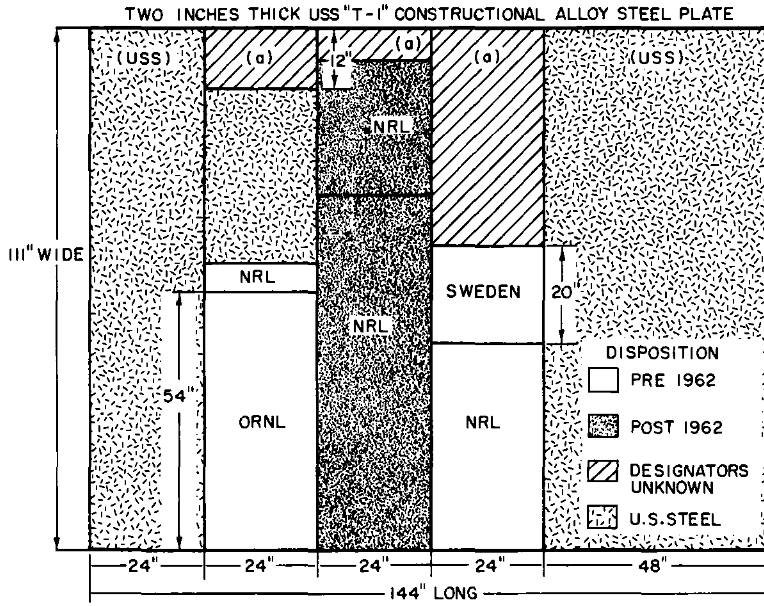

FIG. 18–*The 2-in.-thick plate of T-1 steel showing the location of stock used for test specimens and details regarding cutting and marking plate sections for irradiation program* [2]. *(Shaded areas indicate stock involved in post-1962 requests.)*

for surveillance programs indicated a continuing need of correlation-monitor materials. To explain the former, observations of heat-to-heat variability in radiation embrittlement sensitivity enforced a need to evaluate other plates of similar composition. A second factor responsible for decreasing requests for the correlation-monitor materials is the present selection of A533-B steel over A302-B for new reactor construction.[6] Fortunately, this change coincided approximately with the depletion of the A302-B reference steel plate stock. Subcommittee 2 has acquired a replacement correlation-monitor material, 12-in.-thick A533-B Class 1 plate,[7] from the Atomic Energy Commission (AEC) Heavy Section Steel Technology (HSST) program for future surveillance studies. Requests for this material can be obtained by writing the ASTM E-10 Subcommittee.

Survey of Material Usage

To survey actual usage of the correlation-monitor plates, the form questionnaire, Appendix I, was addressed to all laboratories having received one or more plate sections. Survey results are indicated in Table 5. The response level was

[6] A533-B steel is a nickel-modified A302-B steel with a quench and temper heat treatment.

[7] AEC HSST Plate 02.

TABLE 5–*Organizations responding to reference steel questionnaire.*

Organization	Questionnaire Answered	Reference Steel Received				Data Developed			
		A302-B	A212-B	Ni-Cr-Mo	T-1	A302-B	A212-B	Ni-Cr-Mo	T-1
Westinghouse Electric Corporation (Bettis Atomic Power Laboratory)	yes	X	X	...	...	yes	yes	...	...
Oak Ridge National Laboratory	yes	X	X	X	X	no	no	no	no
Argonne National Laboratory	yes	...	X	...	...	...	yes	...	...
Naval Research Laboratory	yes	X	X	X	X	yes	yes	yes	yes
Brookhaven National Laboratory	yes	...	X	X	...	...	yes	yes	...
Allis Chalmers Company	no	X	X	X	...	...	...	...	...
Westinghouse Electric Corporation (Atomic Power Department)	yes	X	X	...	...	yes	yes	...	...
Aktiebolaget Atomenergie	no	X	X	X	X	...	...	...	...
Babcock & Wilcox Company	yes	...	X	...	...	...	no	...	...
General Dynamics Corporation (General Atomics Division)	yes	X	...	...	...	yes	...	...	...
General Electric Company (Atomic Products Division)	yes	X	...	X	...	yes	...	no	...
General Electric Company (Richland, Wash.)	yes	X	X	X	...	no	no	no	...
Siemens-Schuchertwerke-AG	yes	X	...	...	...	no	...	...	...

approximately 90 percent. In some instances where inquiries elicited no reply the research activity stands disbanded, or cognizant individuals have left the organization.

The survey clearly indicates that planned efforts by some major laboratories did not reach fruition. In terms of interest Table 5 may be somewhat misleading in that past interest of major reactor vendors in the correlation-monitor materials may not be truly indicative of their interest in vessel surveillance programs. For example, in-house reference materials have been adopted by some, and materials from the AEC HSST program are being used by others. Moreover, it must be kept in mind that the utility owner makes the ultimate decision on the nature and extent of surveillance in any one reactor plant. For guidance in this decision there is ASTM Recommended Practice for Surveillance Tests for Nuclear Reactor Vessels (E 185-73).

Of the various material recipients, NRL probably has developed the most comprehensive set of information on postirradiation mechanical properties for the case of test reactor and power reactor irradiations. The most extensive information on the reference materials resulting from just power reactor surveillance programs has or (ultimately) will stem from Westinghouse Electric Corporation (Nuclear Energy Systems (NES)) efforts.

Postirradiation Properties—Trend Determinations

General postirradiation mechanical properties trends are illustrated in Figs. 19-53. The trends reflect significant effects of exposure temperature, fluence level, steel composition, and microstructure. On the other hand, neither a strong dose rate dependence nor an effect of applied stress on irradiation responses has been revealed by research involving these and other steels. Similarly, stress relief annealing or prior temper embrittlement have not been found to exert an appreciable individual influence on irradiation behavior.

In viewing trend performance, it must be kept in mind that neutron spectrum conditions can influence apparent material response. Specifically, thermal neutrons under certain conditions (high-thermal neutron population compared to the fast neutron population) can account for a significant portion of the observed embrittlement and strength increase. In typical light water moderated test reactor environments, however, the fast neutron spectrum has an overriding effect.

Tensile Properties

Tensile properties changes with cumulative radiation exposure at low temperature ($<300°F$, 149°C) are illustrated for the four steels in Figs. 19-35. The general effects of neutron exposure are shown as increased strength and reduced ductility. Yield strengths normally rise faster than ultimate tensile strengths; percent uniform elongation values decrease more significantly than percent reduction of area values.

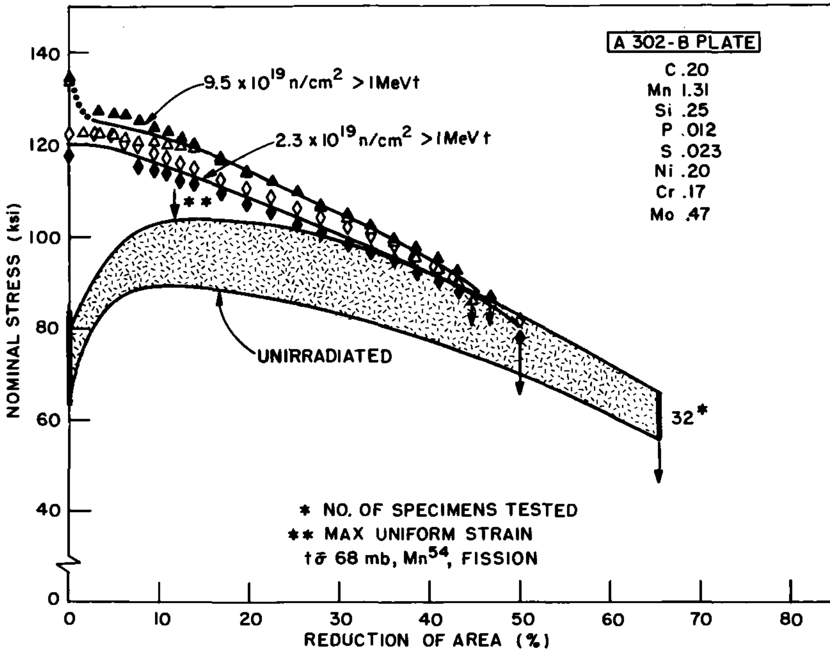

FIG. 19—*Comparative nominal stress-reduction of area curves for A302-B steel plate after indicated neutron radiation exposures at <250°F (121°C)* [4].

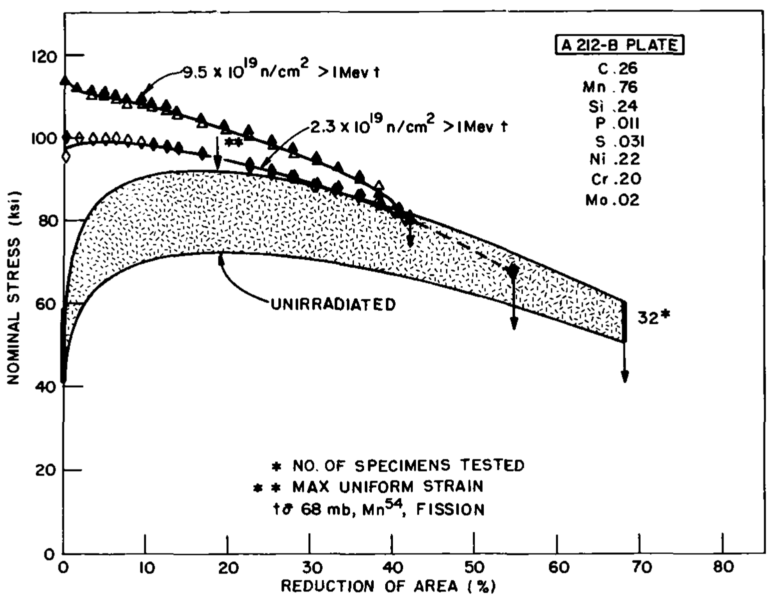

FIG. 20—*Comparative nominal stress-reduction of area curves for A212-B steel plate after indicated neutron radiation exposures at <250°F (121°C)* [4].

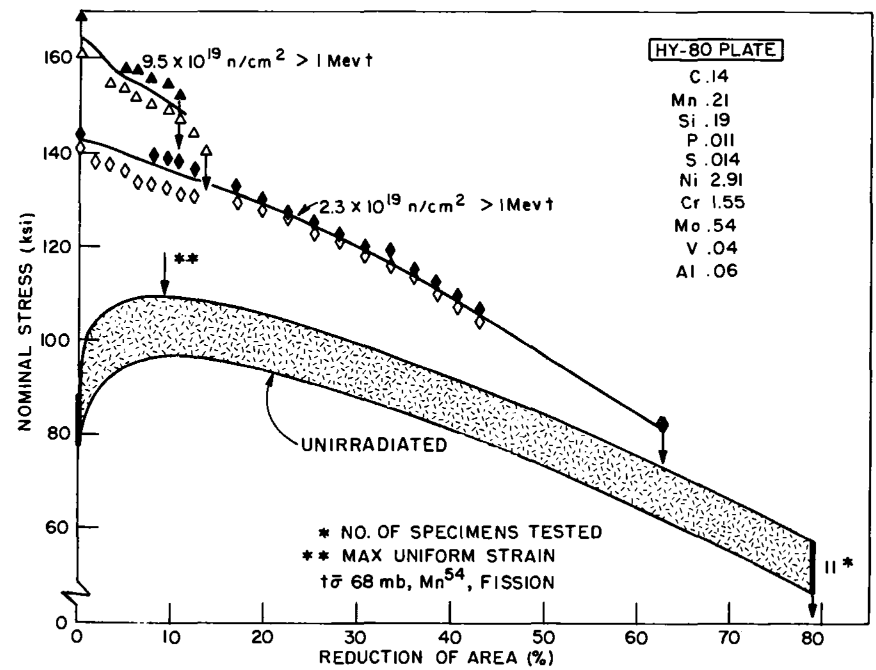

FIG. 21–*Comparative nominal stress-reduction of area curves for HY-80 steel plate after indicated neutron radiation exposures at <250°F (121°C)* [4].

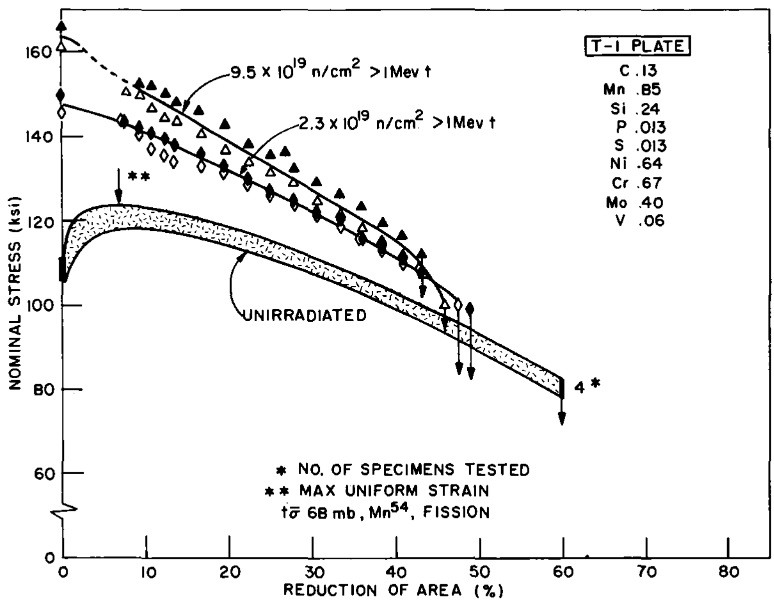

FIG. 22–*Comparative nominal stress-reduction of area curves for T-1 steel plate after indicated neutron radiation exposures at <250°F (121°C)* [4].

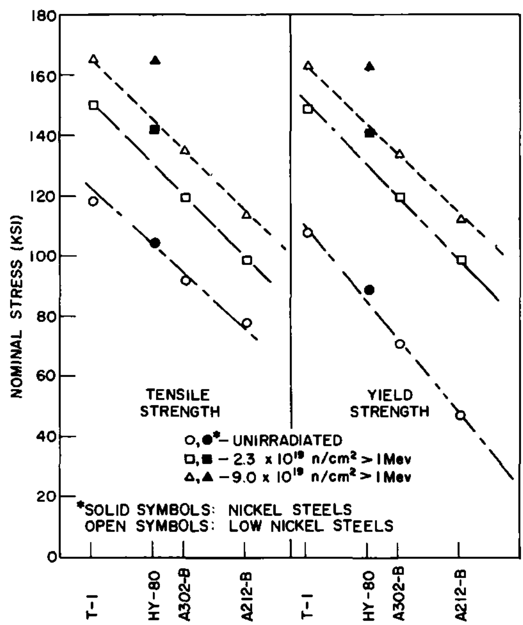

FIG. 23–*The tensile and yield strengths for the four ASTM reference steel plates after neutron radiation at <250°F (121°C) to the fluence levels indicated* [4].

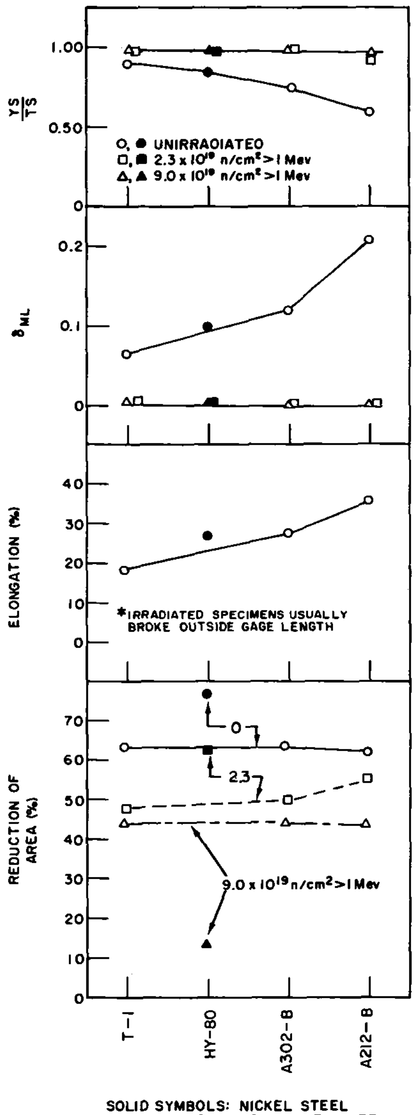

FIG. 24—*Additional strength and ductility properties for the four ASTM reference steel plates after neutron irradiation at <250°F (121°C) to the indicated fluence levels* [4].

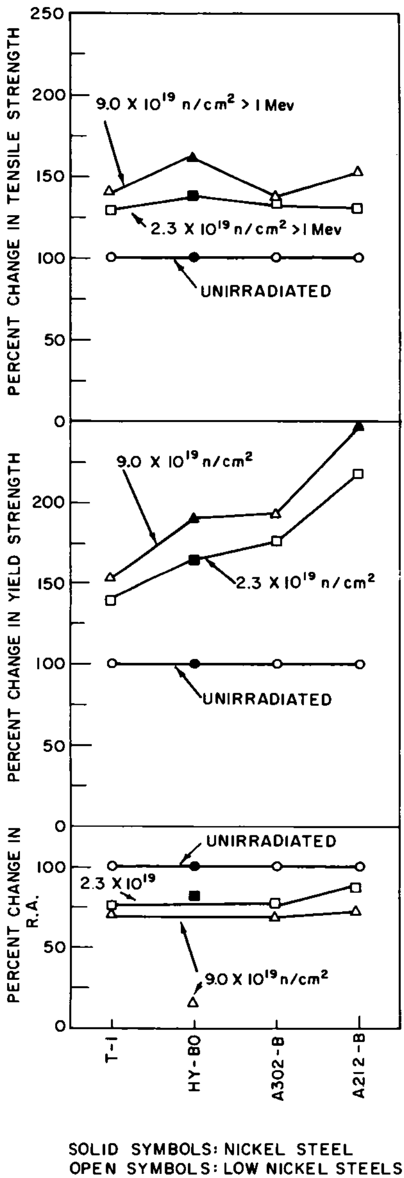

FIG. 25—*The percent change in the tensile and yield strengths and reduction of area with indicated neutron exposures at* <*250°F (121°C)* [4].

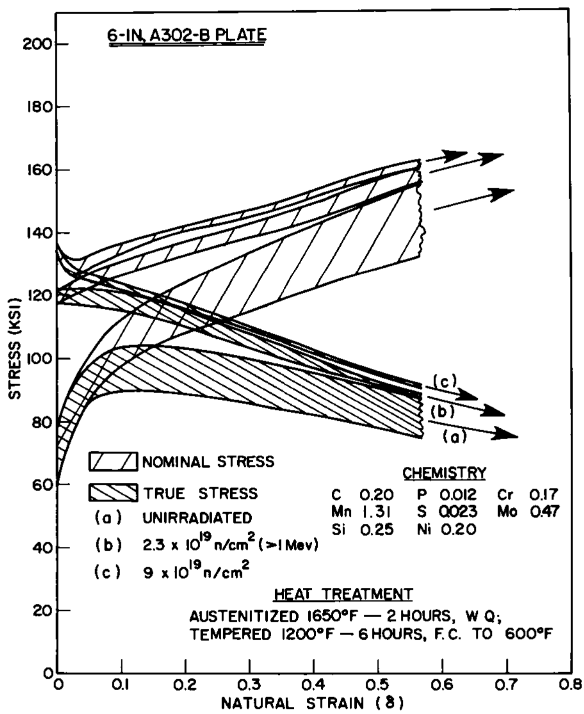

FIG. 26*a*–*True stress-natural strain and nominal stress-natural strain maximum and minimum data envelopes for A302-B steel plate for indicated radiation exposures at <250°F (121°C)* [4].

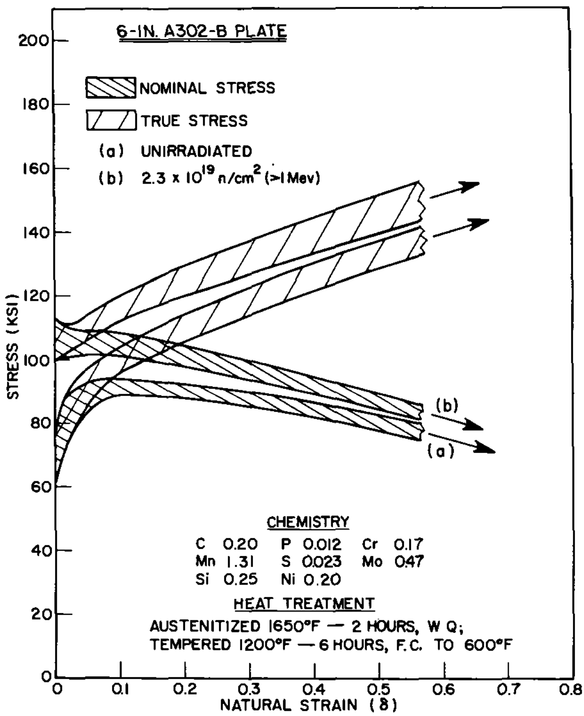

FIG. 26*b*–*True stress-natural strain and nominal stress-natural strain maximum and minimum data envelopes for a third lot of specimens of A302-B steel plate. The indicated radiation exposure was at <250°F (121°C)* [4].

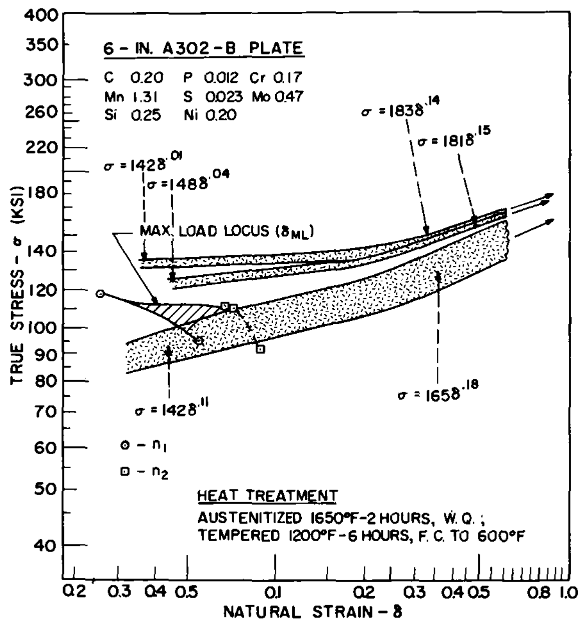

FIG. 27a–*True stress-natural strain data envelopes for A302-B steel plate in ln-ln coordinates. The analytic expression for each curve segment is given for true stress in ksi* [4].

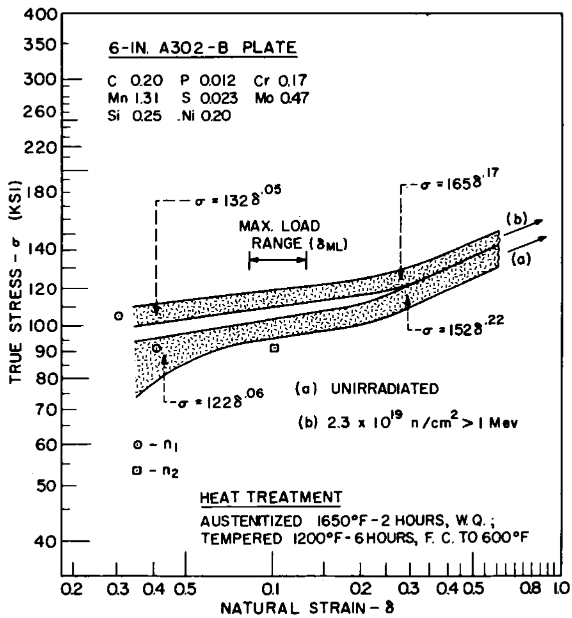

FIG. 27*b*–*True stress-natural strain data envelopes for a third lot of specimens of A302-B steel plate in ln-ln coordinates. The indicated radiation exposure was at <250°F (121°C). The analytic expression for each curve segment is given for true stress in ksi* [4].

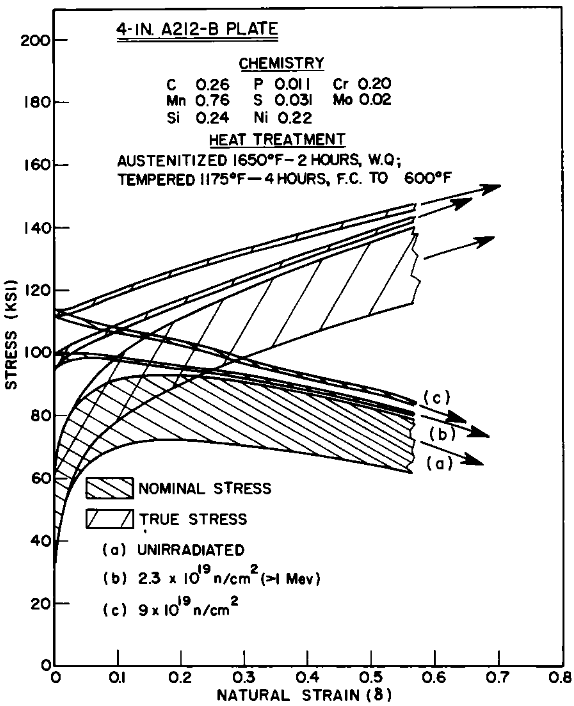

FIG. 28—*True stress-natural strain and nominal stress-natural strain maximum and minimum data envelopes for A212-B steel plate for indicated radiation exposures at <250° F (121° C)* [4].

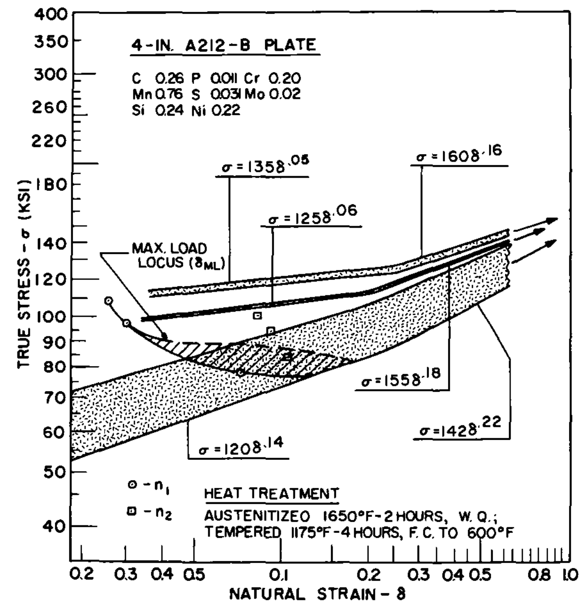

FIG. 29—*True stress-natural strain data envelopes for A212-B steel plate in ln-ln coordinates. The analytic expression for each curve segment is given for true stress in ksi* [4].

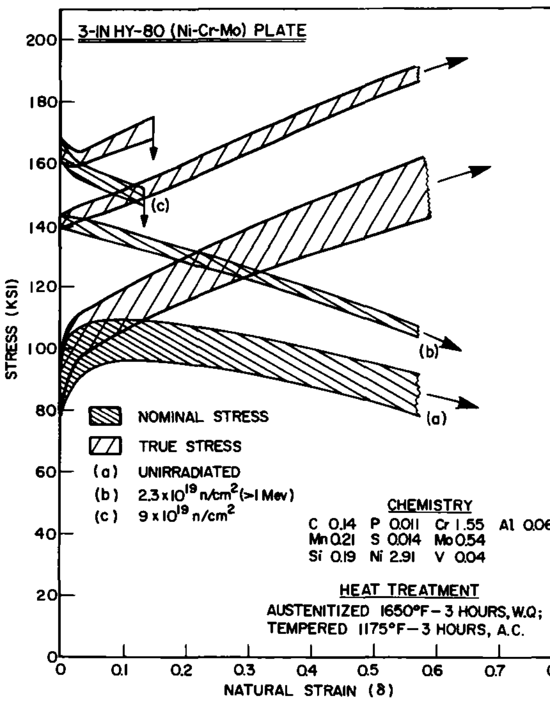

FIG. 30—*True stress-natural strain and nominal stress-natural strain maximum and minimum data envelopes for HY-80 steel plate for indicated radiation exposures at* <*250°F (121°C)* [4].

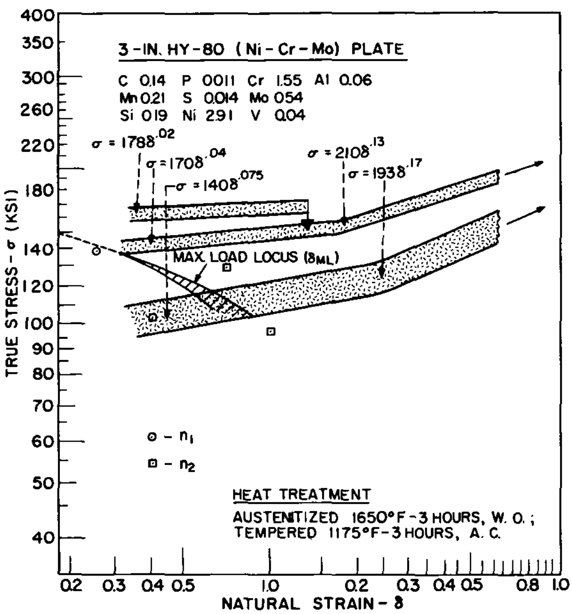

FIG. 31–*True stress-natural strain data envelopes for HY-80 steel plate in ln-ln coordinates. The analytic expression for each curve segment is given for true stress in ksi* [4].

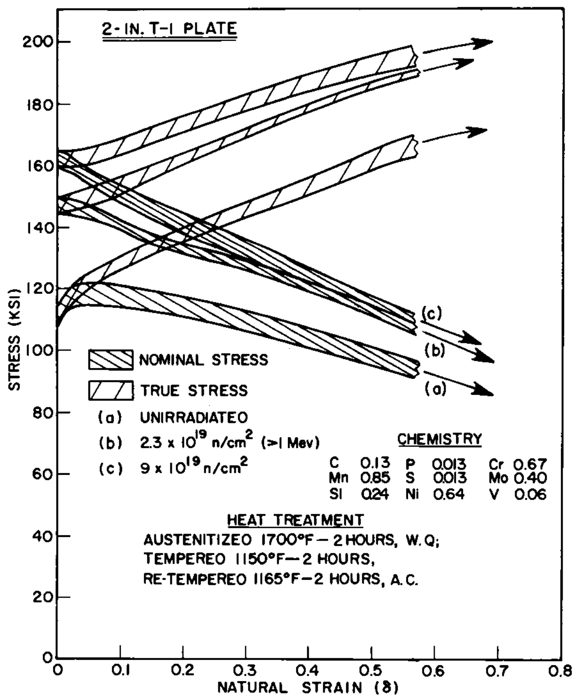

FIG. 32–*True stress-natural strain and nominal stress-natural strain maximum and minimum data envelopes for T-1 steel plate for indicated radiation exposures at* <*250°F (121°C)* [4].

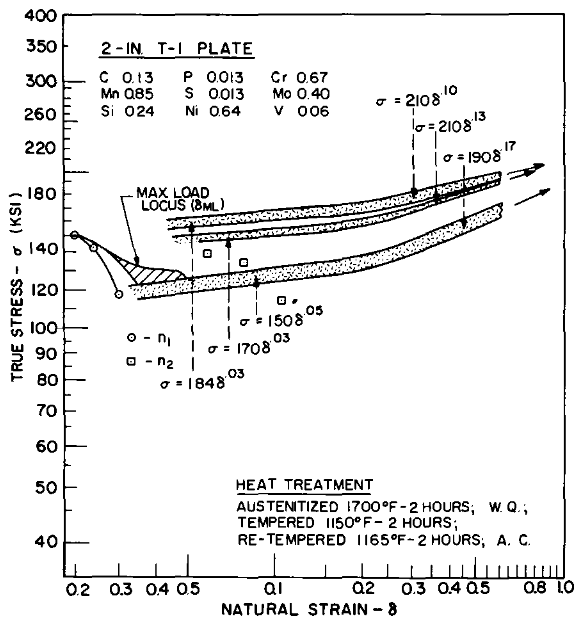

FIG. 33–*True stress-natural strain data envelopes for T-1 steel plate in ln-ln coordinates. The analytic expression for each curve segment is given for true stress in ksi* [4].

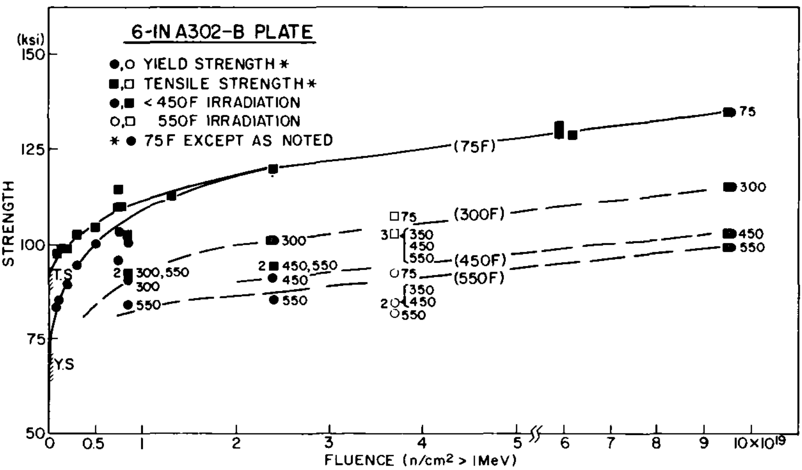

FIG. 34–*Yield and tensile strength of A302-B steel plate as a function of fluence for various exposure temperatures.*

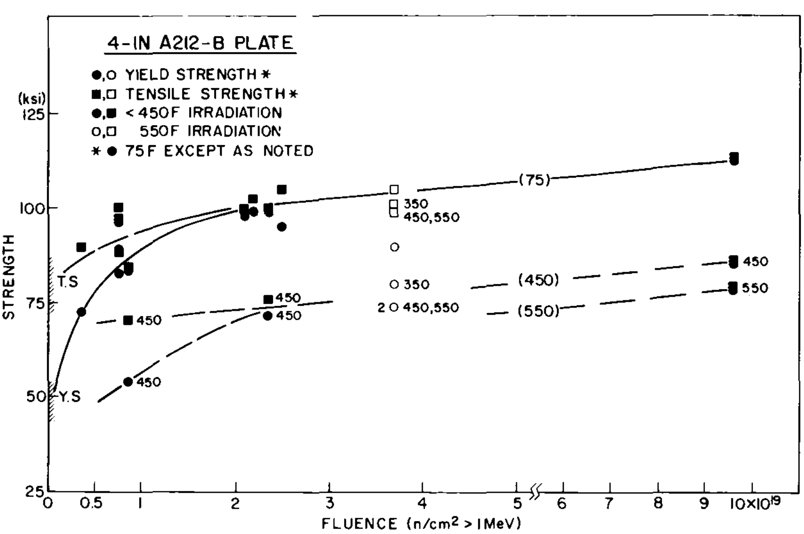

FIG. 35–*Yield and tensile strength of A212-B steel plate as a function of fluence for various exposure temperatures.*

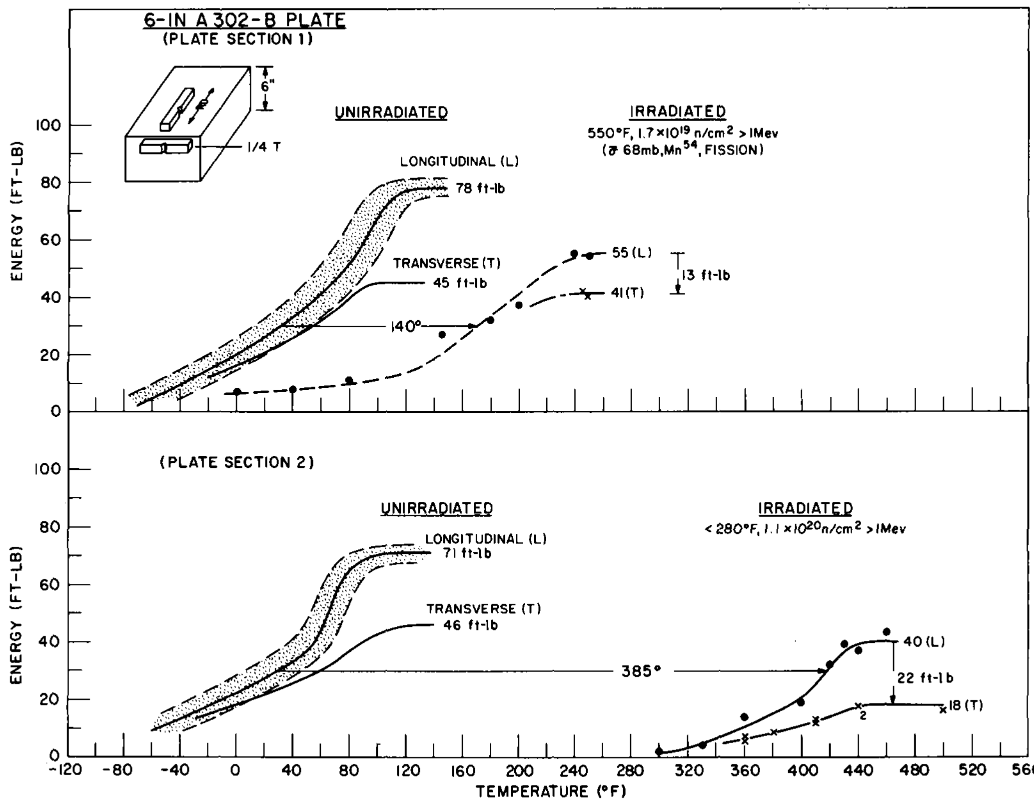

FIG. 36–*Notch ductility performance of the ASTM reference A302-B steel plate in the RW and WR orientations with irradiation exposure at 550°F (288°C) and at low (<280°F, 138°C) temperatures* [7].

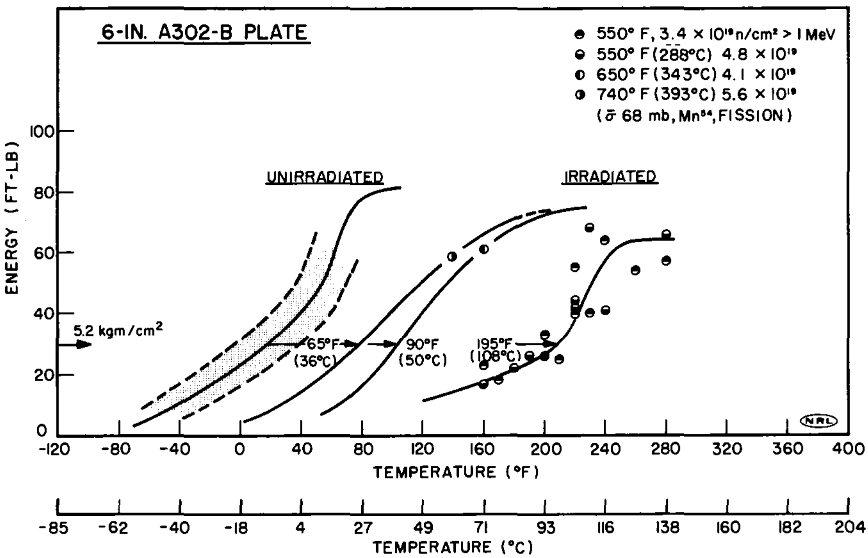

FIG. 37—*High-temperature/high-fluence irradiation response of the ASTM A302-B reference plate* [8].

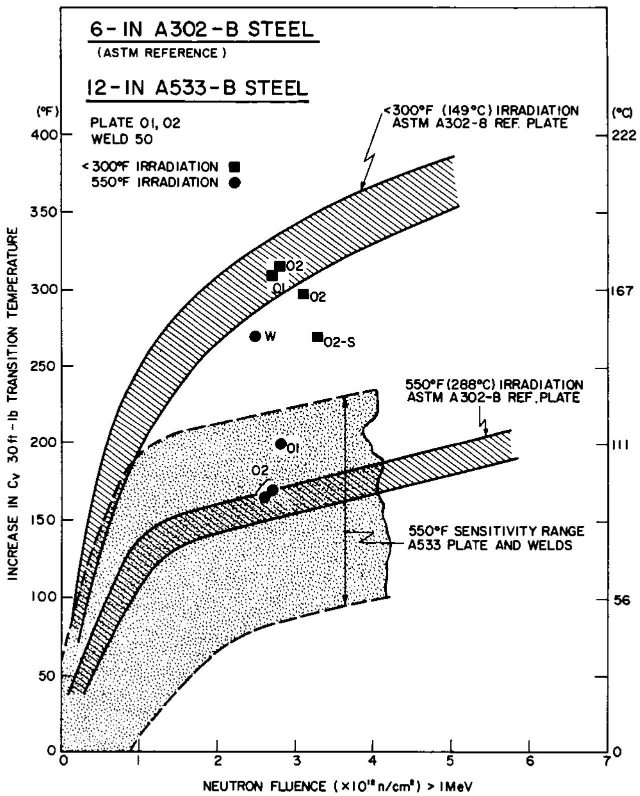

FIG. 38–*Increase in Charpy V-notch* (C_V) *30-ft·lb (5.2 kgm/cm²) transition temperature with increasing fluence at <300°F (149°C) and at 550°F (288°C). Data for the thick section A533-B Class 1 plates (01 and 02) and the weld deposit are shown relative to trends for the A302-B ASTM reference plate and for other A533 plates and welds* [11].

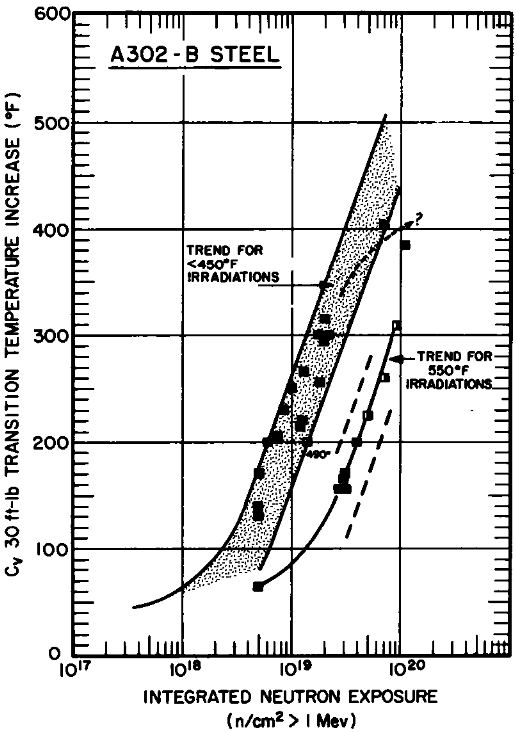

FIG. 39—*Irradiation embrittlement for ASTM 6-in. A302-B reference steel. The half-filled points represent data obtained from the Yankee Atomic Power Plant accelerated exposure surveillance capsule* [19]. *Trend band for <450°F irradiations summarize observations for several different low-alloy steels.*

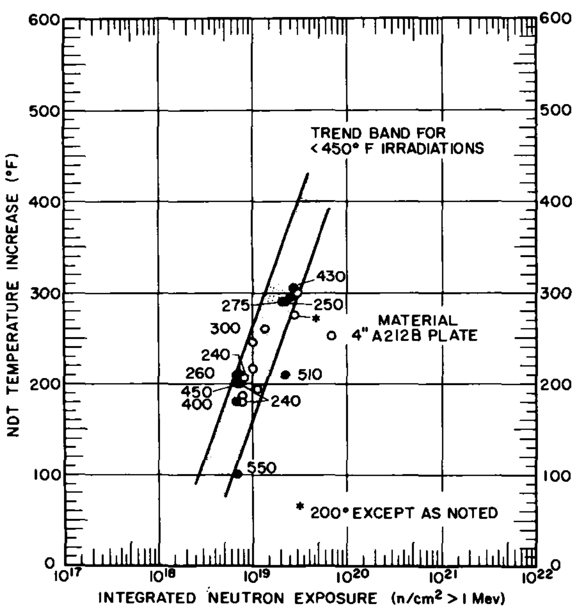

FIG. 40–*Increase in the NDT temperature of A212-B steel resulting from neutron irradiation at various temperatures* [10]. *Numbers adjacent to data points refer to irradiation temperatures (°F). (NDT increase based on* C_V *30-ft·lb transition temperature increase.)*

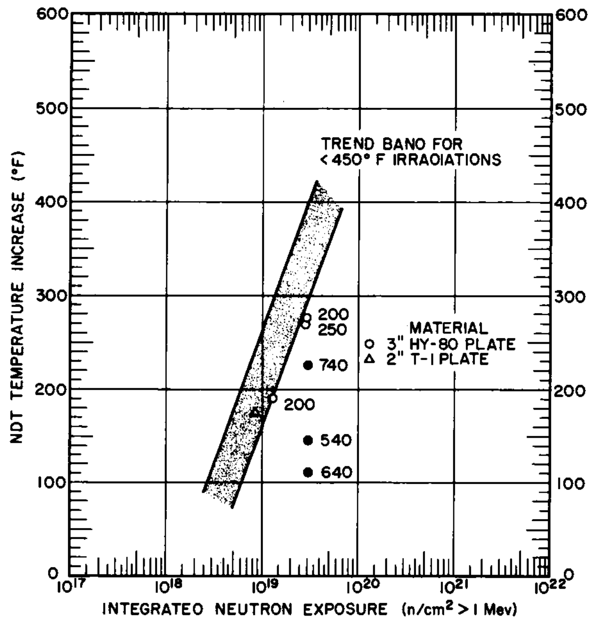

FIG. 41–*Increase in the NDT temperatures of quenched and tempered (HY-80, T-1) steels resulting from neutron irradiation at various temperatures* [10].

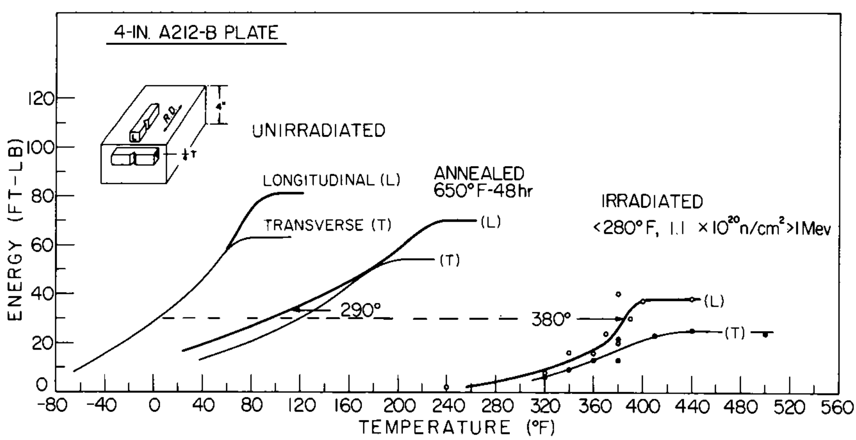

FIG. 42–*Charpy-V notch ductility characteristics of A212-B steel in the unirradiated, irradiated, and postirradiation annealed conditions showing the radiation response in the longitudinal and transverse directions* [19].

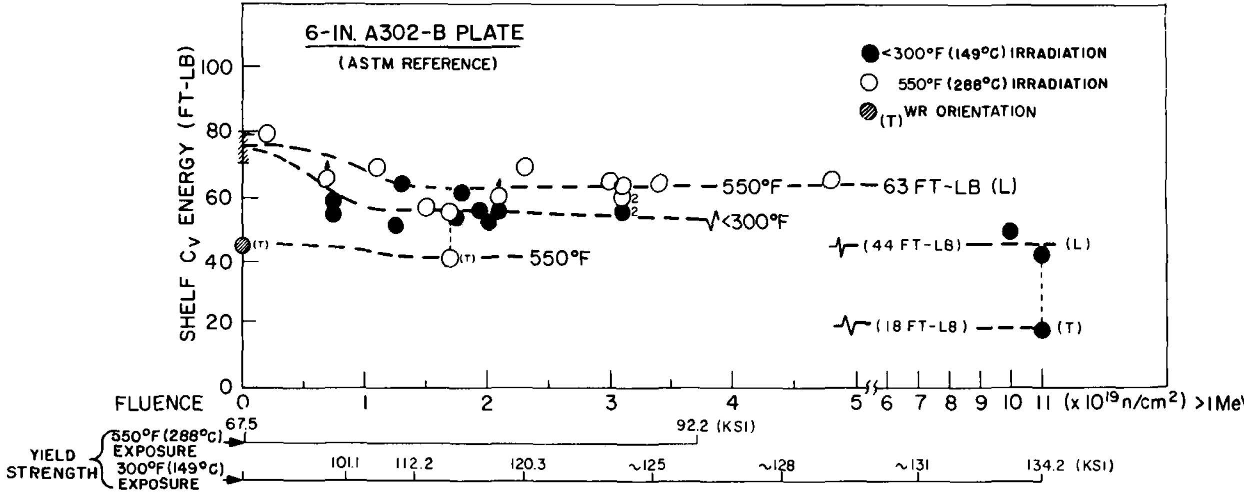

FIG. 43—*Decrease in the Charpy-V shelf energy level of the ASTM A302-B reference plate with increasing fluence at <300°F (149°C) and at 550°F (288°C). Concomitant yield strength increases (0.2 percent offset) for various fluence conditions are also shown*[8].

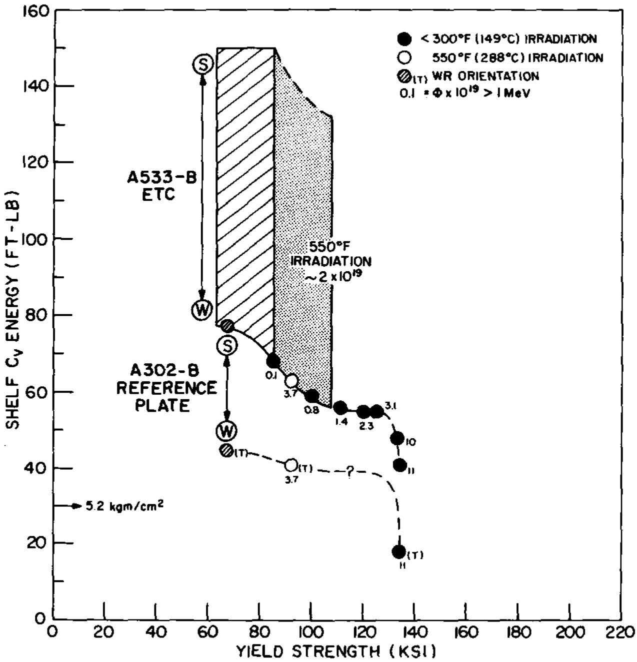

FIG. 44–*Trend in Charpy-V shelf energy reduction versus yield strength increase for the neutron irradiated ASTM A302-B reference plate and various A533 plate and weld metals. Shaded enclosures for the A533 steels represent data for multiple grades and strength classes of thick section materials before and after irradiation at 550°F (288°C). Numbers such as 3.7 adjacent to individual data points indicate measured neutron fluences (in 10^{19} n/cm²)* [8].

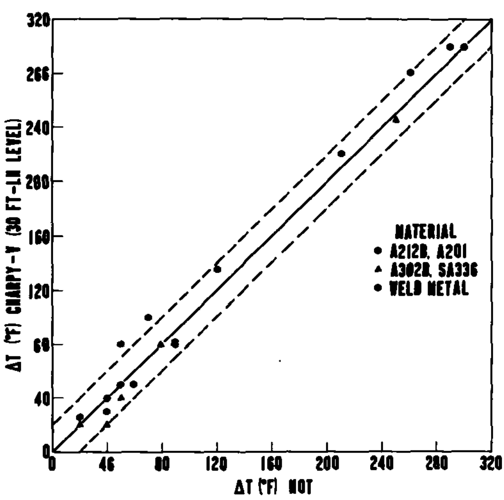

FIG. 45–*Equivalence of the NDT and Charpy-V curve ΔT shifts due to irradiation* [12].

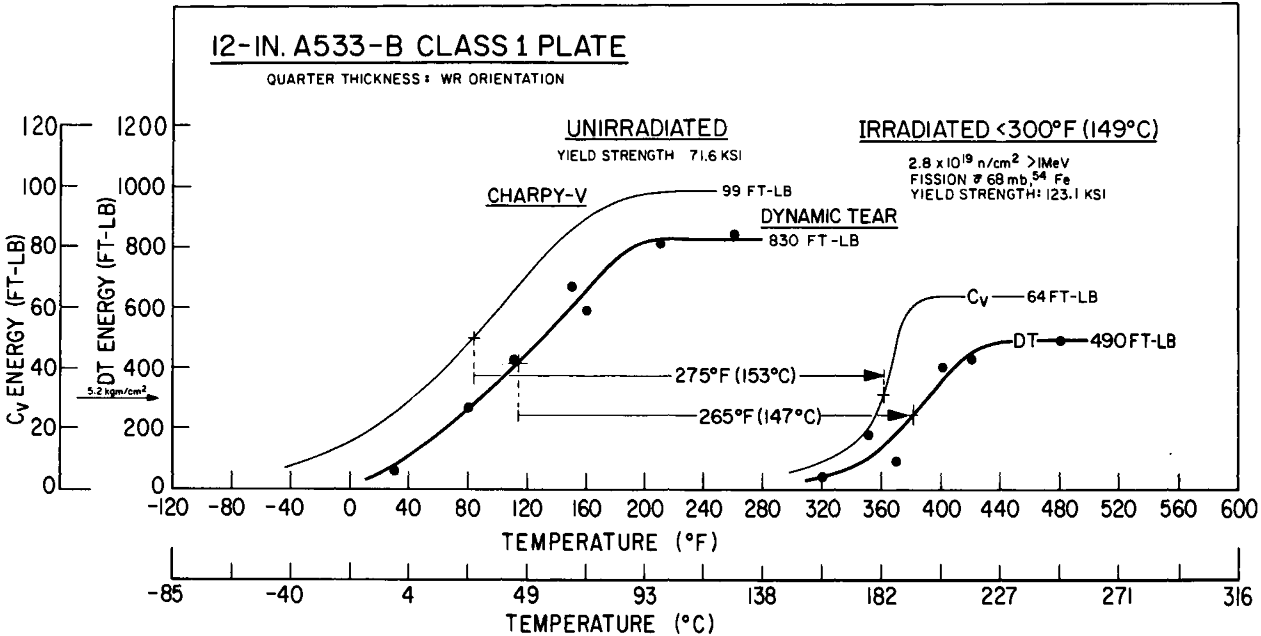

FIG. 46–*Comparison of the Charpy-V* (C_V) *and DT test performance of a thick A533-B Class 1 steel plate (plate 02) before and after <300°F (149°C) irradiation. All specimens were taken from the quarter thickness location and represent the transverse* (WR) *test orientation* [11].

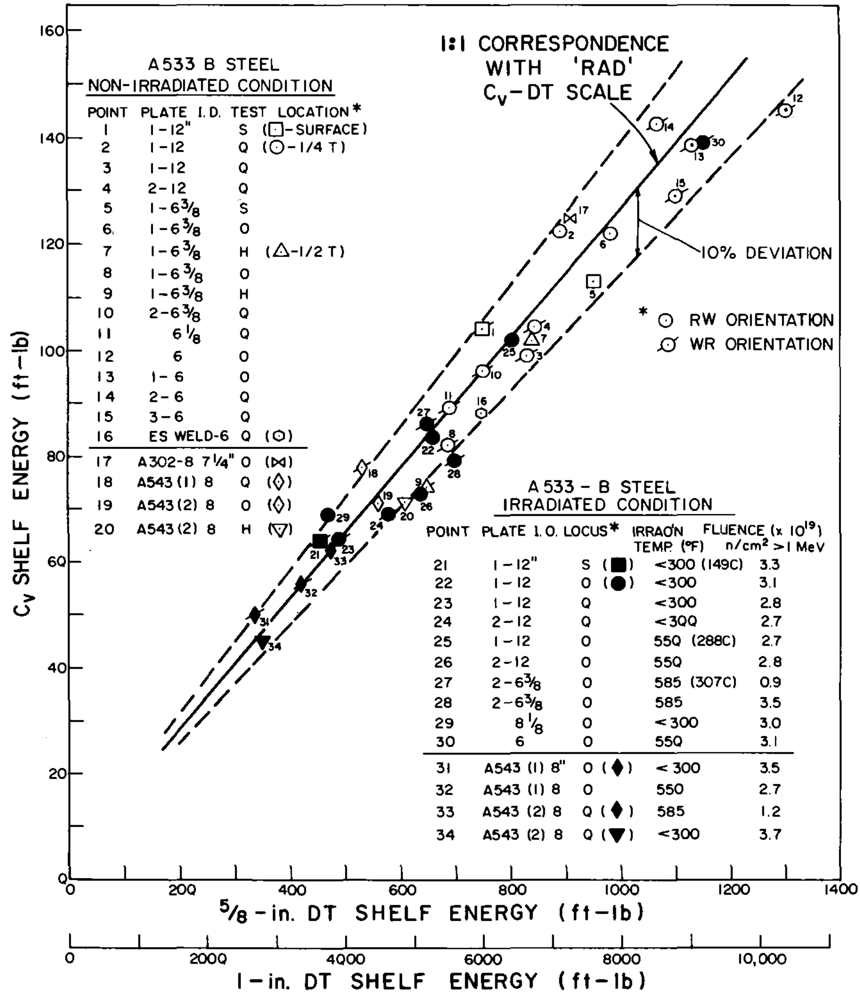

FIG. 47—*Pre- and postirradiation comparisons of C_V and DT shelf energies from numerous plates of A533-B. Comparisons are also illustrated from two plates of A543 steel, an A302-B plate, and an A533 electroslag weld* [13].

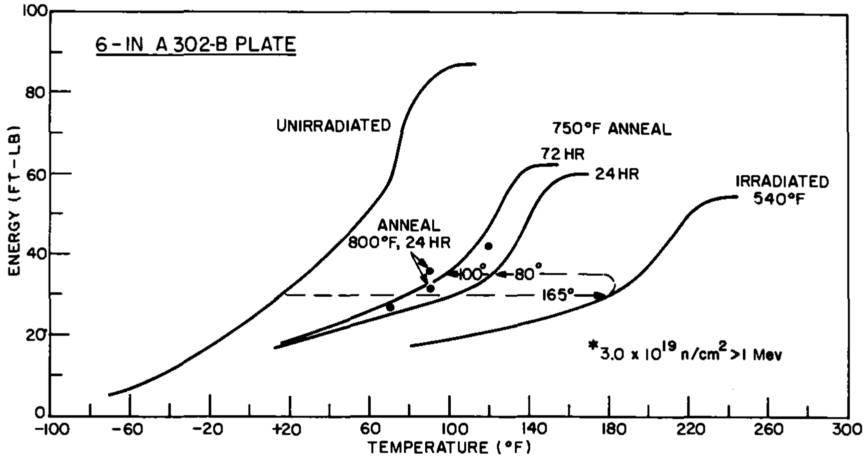

FIG. 48–*Response of the ASTM A302-B reference plate to various low temperature heat treatments after 540°F (282°C) irradiation (Naval Research Laboratory).*

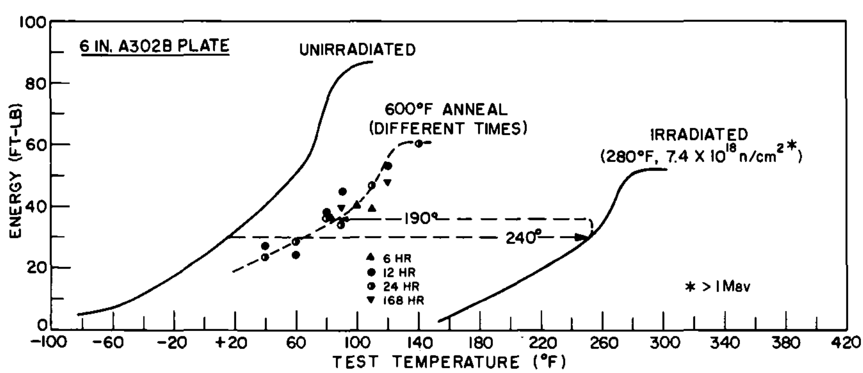

FIG. 49–*Response of the ASTM A302-B reference plate to 600°F (316°C) heat treatment after low temperature (280°F, 138°C) irradiation in the Brookhaven graphite reactor (BGR) (Naval Research Laboratory).*

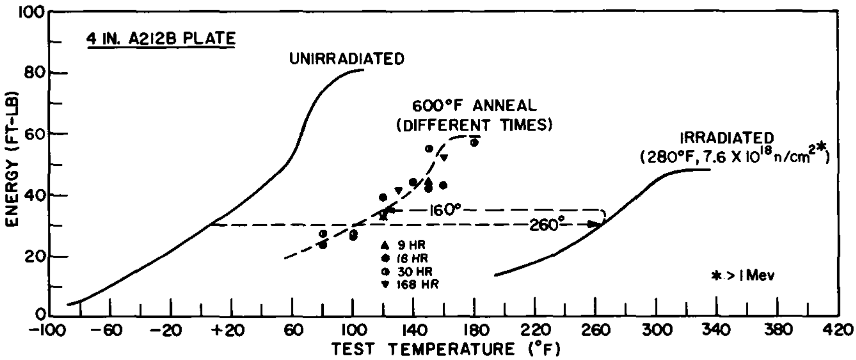

FIG. 50–*Response of the ASTM A212-B reference plate to 600°F (316°C) heat treatment after low temperature (280°F, 138°C) irradiation in the Brookhaven graphite reactor (BGR) (Naval Research Laboratory).*

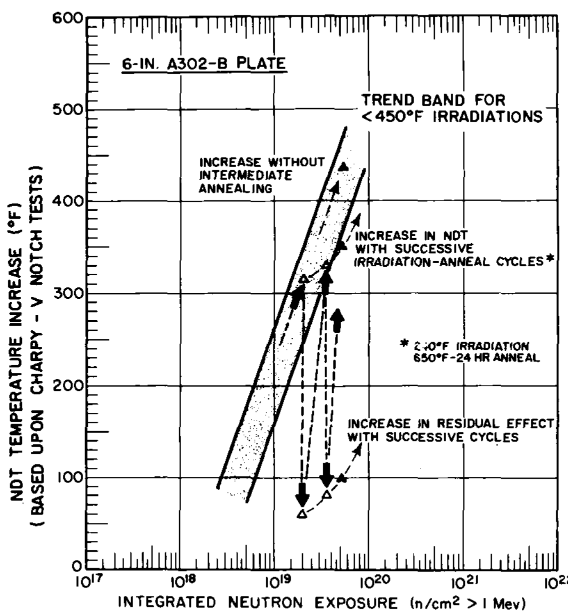

FIG. 51–*NDT temperature behavior exhibited by A302-B steel (ASTM reference plate) at various stages of cyclic irradiation-annealing treatments*[20]. *The experiment involved two half capsules. Capsule 1 established first cycle performance. Capsule 2, irradiated simultaneously with Capsule 1, was annealed subsequently (out of reactor) and reirradiated to determine second cycle performance.*

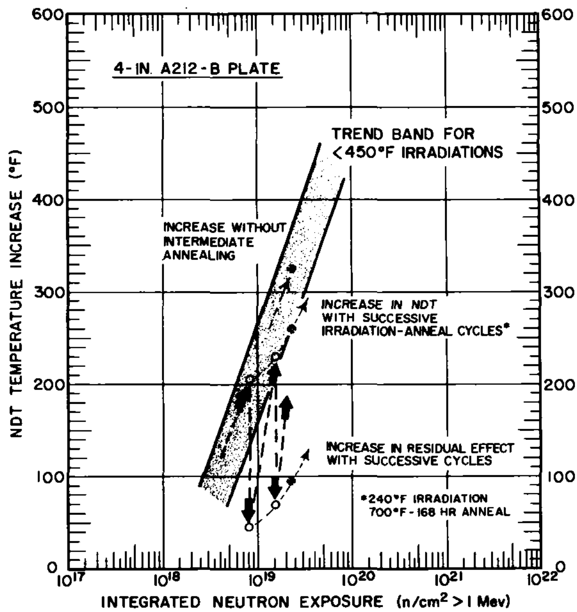

FIG. 52–*NDT temperature behavior exhibited by A212-B steel (ASTM reference plate) at various stages of cyclic irradiation-annealing treatments (Naval Research Laboratory).*

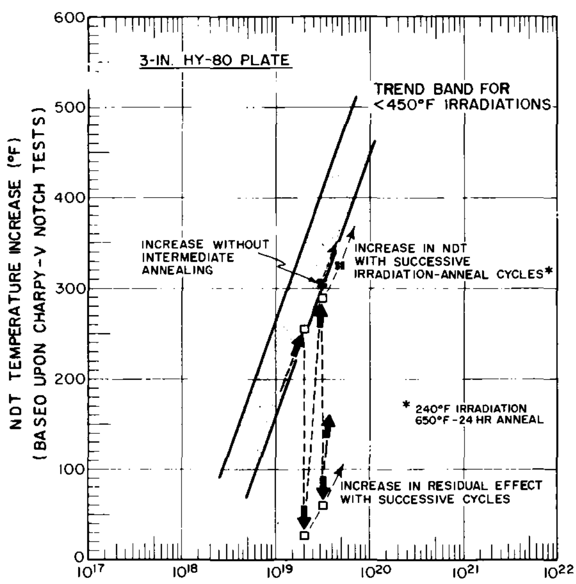

FIG. 53–*NDT temperature behavior exhibited by HY-80 steel at various stages of cyclic irradiation-annealing treatments* [20].

Under elevated temperature (>450°F, 232°C) exposure conditions, radiation-induced property changes tend to be less as a result of dynamic recovery behavior. Dynamic recovery of tensile properties can be appreciable as indicated in Fig. 34 for A302-B steel and in Fig. 35 for the A212-B steel.

Postirradiation biaxial stress performance has also been investigated using the A302-B plate [6]. Uniform strains recorded for internally pressurized tube-type specimens were much less than for uniaxially loaded tension specimens for all exposure conditions studied. Nonetheless, radiation-induced changes in ductility were generally independent of the principal stress ratio (Table 6).

Charpy-V Notch Ductility

Figures 36 and 37 illustrate the Charpy-V (C_V) notch ductility behavior of the A302-B reference plate with low temperature (<300°F, 149°C) and elevated temperature exposure conditions. For this steel, dynamic recovery increases with

TABLE 6—*Biaxial and uniaxial test results for 6-in. A302-B reference steel plate*[a] *(stresses are true stress in thousands of psi) (Courtesy Gulf General Atomic-P. W. Flynn).*

Test Temperature	Fluence $\times 10^{18}$ $E > 1$ MeV	Yield Point	Stress, max	Strain, max
0°C	0 (uniaxial)	70	100	0.100
	0	70	92	0.062
	8.5 (uniaxial)	99	106	0.032
	5.0	88	94	0.016
	7.1	91	94	0.010
	9.5	96	98	0.010
	12.0	98	101	0.009
66°C	0 (uniaxial)	63	91	0.072
	0	63	80	0.023
	7.2 (uniaxial)	87	97	0.027
	5.0	83	84	0.007
	7.9	83	87	0.009
	9.4	82	88	0.012
149°C	0 (uniaxial)	67	94	0.077
	0	57	76	0.032
	8.5 (uniaxial)	78	88	0.031
	5.0	72	77	0.010
	7.1	70	77	0.009
	9.5	80	87	0.019
	12.0	82	83	0.009

[a]Single test results. Values for effective stress, $\bar{\sigma}$, include the effect of pressure, since compressive stresses as high as 10 percent of the axial (or circumferential) stresses were present owing to the small specimen size and high internal pressure.

[b]Effective strain values, $\bar{\epsilon}$, were calculated on the basis of measured values for $\bar{\epsilon}_{zz}$, and $\bar{\epsilon}_{\theta\theta}$. Poisson's ratio was assumed to be 0.5 in the plastic range.

irradiation temperature in the range of about 450°F (232°C) to 750°F (389°C) (normal case). Comparable radiation effects on longitudinal (strong-*RW* orientation) and transverse (weak-*WR* orientation) properties are also noted in Fig. 36. Postirradiation C_V 30 ft·lb transition temperatures increases[8] of *RW* and *WR* test orientations, in general, have been found to compare well for A302-B and A533-B steels[7].

Trend data for the A212-B plate suggest irradiation responses similar to those of the A302-B plate. On the other hand, data for the Ni-Cr-Mo steel indicate parallel notch ductility behavior for exposures between 250°F (121°C) and 650°F (361°C), but not for exposure temperatures above 650°F (361°C). The reason for the deviation is the temper embrittlement susceptibility of the Ni-Cr-Mo composition. Studies of another heat of Ni-Cr-Mo have demonstrated clearly that temper embrittlement and radiation embrittlement can be additive effects[*8*]. Postirradiation data for the T-1 plate are not well developed, but, on the basis of alloying composition, its behavior under elevated temperature radiation exposure probably would be comparable to that of the Ni-Cr-Mo plate.

Figure 38 relates C_V 30 ft·lb transition temperature increase to fluence at temperatures <300°F (149°C) and at 550°F (288°C). The data, though acquired from experiments in several difference irradiation facilities, are found quite consistent. Embrittlement develops quite rapidly up to a fluence of about 1×10^{19} n/cm^2; above 1×10^{19} n/cm^2, embrittlement buildup is less rapid, and some indication of embrittlement saturation appears. New data by NRL[*9*] show that the embrittlement process continues with 550°F (288°C) irradiation beyond 5×10^{19} n/cm^2, however; a transition temperature increase of 400°F (222°C) has been recorded for the A302-B plate for a fluence of $\sim 1.5 \times 10^{20}$ n/cm^2 >1 MeV.

Figure 39 depicts an alternate method which has been used to compare the results of different exposure temperature-fluence conditions. A single trend band represents all <450°F (232°C) irradiation data and illustrates the finding[*10*] that many steels have similar irradiation responses at low temperatures and that little if any dynamic recovery occurs in the irradiation temperature range of ambient to 450°F (232°C). Data for the A212-B, Ni-Cr-Mo, and T-1 plates are plotted using semilog coordinates in Figs. 40 and 41. Figure 42 provides documentation of the comparable radiation embrittlement tendencies of the A212-B plate in strong and weak test directions.

The trend of C_V shelf energy decrease with increasing fluence is shown in Fig. 43. Open data points refer to <300°F (149°C) exposure conditions; filled data points refer to 550°F (288°C) exposures. Paralleling the trend of transition

[8]The Charpy V-notch 30-ft·lb (5.2 kgm/cm^2) temperature is often used as a convenient, arbitrary index of brittle/ductile transition for pre-postirradiation comparisons of steel performance.

temperature increase given in Fig. 38, shelf values for the strong orientation decrease markedly during the first 1 x 10^{19} n/cm^2>1 MeV fluence interval after which a strong tendency toward saturation of irradiation effect is evident. Data for the 550°F (288°C) exposure condition define a plateau in the fluence interval 1 to 5 x 10^{19} n/cm^2. Limited data for the weak plate orientation (transverse-*WR*) would suggest a similar trend to that described by the strong orientation (longitudinal-*RW*) data.

Figure 44 compares the relative decrease in C_V shelf energy and increase in yield strength[9] of the A302-B reference plate with progressive exposure. Again, filled points refer to the <300°F (149°C) exposure condition, and the open points refer to the 550°F (288°C) exposure condition. Comparable (3-stage) trend patterns have been indicated individually by thick A533-B plate and welds (including HSST plates 01 and 02)[*11*] and by thick A543 (Ni-Cr-Mo) plates[*8*].

Drop Weight Nil-Ductility Transition (NDT) Temperature

Studies by NRL have demonstrated good (1:1) correspondence between radiation-induced C_V 30 ft·lb transition temperature increase and drop weight NDT temperature increase. Figure 45[*12*] shows results for several low-alloy steel plates and weld metals. Each data point represents a simultaneous exposure of C_V and drop weight (Type P-3) specimens. Data for C_V versus drop weight test comparisons for the A302-B and A212-B reference plates are given in Table 7. Note that the independent determinations of transition temperature increase agree within 10°F (6°C). Postirradiation C_V transition curves for both materials feature a rapid rise in fracture energy over a narrow temperature interval; thus, the difference in C_V index for pre- and postirradiation NDT temperatures is of little real importance.

The conclusion from data given in Fig. 45, Table 7, and elsewhere[*13*] is that the increase in C_V 30-ft·lb transition temperature can be taken as a fair approximation of NDT temperature increase for low- and medium-strength steels such as the A302-B, A212-B, and Ni-Cr-Mo reference steels. One proviso is that C_V shelf energy levels cannot be too greatly reduced by the radiation exposure. Postirradiation shelf values for both examples in Table 7 exceeded 45 ft·lb.

Dynamic Tear (DT) Performance

Postirradiation dynamic tear (DT) test characteristics of the four reference plates have not been established. However, general correlations between C_V and DT test behavior have been observed for the pre- and postirradiation conditions with other similar low-to-medium strength steels[*11,13*]. As a result of two correlations, C_V data for three of the four reference steels[10] have been provided

[9] Ambient temperature tests.
[10] The T-1 steel may not obey the transition and shelf level correlations.

TABLE 7–*Comparison of Charpy V-notch 30-ft·lb transition temperature increase and drop weight nil-ductility transition (NDT) temperature increase by irradiation at <300°F (149°C).*

Reference Plate	Fluence[a] n/cm^2 >1 MeV	Charpy V-notch 30-ft·lb Temperature						NDT Temperature						C_v Energy at NDT	
		Initial		Irradiated		Increase		Initial		Irradiated		Increase		Initial, ft·lb	Irradiated, ft·lb
		°F	°C	°F	°C	ΔT°F	ΔT°C	°F	°C	°F	°C	ΔT°F	ΔT°C		
A302-B	1.8×10^{19}	15	-9	315	157	300	167	10	-12	300	149	290	161	27	15
A212-B	1.1×10^{19}	5	-15	255	124	250	139	-30	-34	230	110	260	144	19	15

[a]Fission spectrum assumption.

both engineering significance and a means of critical interpretation. For example, the postirradiation increase in 50 percent C_V energy transition temperature was shown comparable to the increase in 50 percent DT energy transition temperature for a number of A533-B [*11*] and A543 steel plates [*13*]. For the thin section ($\leqq$3 in.) case, the 50 percent DT energy transition temperature, in turn, is a relatively good approximation of the fracture transition elastic (FTE) temperature, an important parameter for fracture safe design. An illustration of the correspondence observed between C_V and DT transition behavior is given in Fig. 46.

Studies of relative C_V and DT upper shelf energy values before and after irradiation resulted in the second correlation [*13*]. As noted in Fig. 47 the ratio of C_V shelf energy and DT shelf energy is 8.0:1, over a broad range of pre- and postirradiation toughness conditions. The C_V shelf level toughness condition thus can be described and interpreted with Ratio Analysis Diagram (RAD) procedures with the aid of yield strength information [*13*]. Procedures for RAD evaluation of the shelf level toughness condition are given in detail elsewhere [*14,15*].

Postirradiation Annealing Response

Three of the reference plates (A302-B, A212-B, and Ni-Cr-Mo) have been examined for postirradiation annealing response. Significant recovery of pre-irradiation properties has been demonstrated for each steel under certain neutron exposure-heat treatment conditions. Illustrations of annealing response are offered in Figs. 48-53. Figures 51-53 denote performance under cyclic irradiation-annealing conditions. Substantial control over total embrittlement, as measured in terms of transition temperature increase, can be achieved by this technique in some instances. The technique has been applied to an actual reactor vessel (Army SM-1A) for embrittlement relief [*16*]. For the case of Ni-Cr-Mo steel and most high-alloy steels, annealing heat treatment conditions must be selected with care to avoid temper embrittlement formation or other undesirable time-temperature dependent phenomenon.

No effort shall be made here to fully document or qualify annealing responses because material composition, exposure history, and heat treatment jointly have such pronounced influences on recovery behavior and because data taken at face value can be very misleading. One general observation, however, can be stated: higher irradiation temperatures, fluence accumulations, and embrittlement accrual normally lead to higher residual embrittlement for any given set of heat treatment conditions for annealing recovery.

Postirradiation Data Survey and Tabulation

Data developed on the postirradiation tensile properties, notch ductility properties, and others are compiled in Tables 8-15 or presented in Figs. 54-59. For simplicity, the data have been grouped according to contributing organization.

TABLE 8–*Radiation induced changes in Charpy-V* (C_V) *notch ductility of 6-in. A302-B reference steel plate.*

Reporting Site	Irradiation Temperature		Fluence,[a] n/cm^2 >1 MeV x 10^{19}	C_v 30-ft-lb Transition Temperature Increase		Postirradiation Shelf Energy, ft·lb	Neutron Experiment Identification[b]
	°F	°C		Δ°F	Δ°C		
Naval Research Laboratory	<300	<149	0.008	0	0	91	IRL-3
			0.014	0	0	87	IRL-3
			0.036	20	11	84	IRL-3
			0.035	35	19	68	IRL-1
			0.059	50	28	68	IRL-1
			0.065	55	31	69	IRL-2
			0.091	50	28	82	IRL-3
			0.099	50	28	67	IRL-1
			0.114	70	39	67	IRL-2
			0.140	80	44	80	IRL-3
			0.160	80	44	66	IRL-1
			0.186	120	67	64	IRL-2
			0.22	85	47	62	Yankee Surveillance
			0.25	125	69	78	IRL-3
			0.26	105	58	59	IRL-1
			0.31	150	83	59	IRL-2
			0.48	205	114	67	KE-1[c]
			0.47	205	114	52	KE-1[d]
			0.50	180	100	51	IRL-2
			0.57	230	128	62	KE-1[e]
			0.50	170	94	≈67	LITR-(18)8H
			0.55	205	114	50	BGR-10
			0.74	240	133	52	BGR-10
			0.78	240	133	58	CVTR
			0.75	205	114	56	LITR-49(47C)
			0.75	170	94	59	UCRR(C3)-1C
			0.85	230	128	≈65	LITR(55)-6
			0.80	200	111	81	LITR(18)-3
			1.0	250	139		LITR(18)-3
			0.89	265	147	79	KE-2[c]
			0.91	265	147	51	KE-2[d]
			1.1	275	153	62	KE-2[e]
			1.2	215	119	49	LITR(53)-50C
			1.25	220	122	51	LITR(28)-49C
			0.63	165		67	IRL-3
			1.3	265	147	64	MTR-19
			1.7	300	167	55	LITR(53)-87C
			1.8	300	167	54	MTR-17

TABLE 8–(*Continued*)

Reporting Site	Irradiation Temperature		Fluence,[a] n/cm² >1 MeV x 10^{19}	C_v 30-ft-lb Transition Temperature Increase		Postirradiation Shelf Energy, ft·lb	Neutron Experiment Identification[b]
	°F	°C		Δ°F	Δ°C		
			1.8	290(DW)	161		MTR-17
			1.8	255	142	61	LITR(18)-62C
			2.0	315	175	57	LITR(53)-25B
			2.0	295	164	52	LITR(53)-25C
			2.1	290	161	55	LITR(55)-84H
			2.2	300	167	57	MTR-20
			2.3	360	200	65	KE-3[c]
			2.5	310	172	69	KE-3[d]
			2.8	360	200	60	KE-3[e]
			3.1	310	172	55	LITR(43)-72C
			3.1	315	175	56	LITR(43)-72C
			7.0	405	225	41	MTR-26
			10.0	385	214	48	MTR-33
			11.0	385	214	40	MTR-30
			11.0	. . .		18(T)	MTR-30
	400	204	0.5	130	72	61	LITR(18)-8
	450	232	0.5	140	78	≈63	LITR(18)-8
	464	241	0.73	191	106	51	LITR(18)-8
	490	254	1.4	200	111	51	LITR(55)-31
	550	288	0.2	50	28	81	UCRR(D3)-14H
	550	288	0.5	65	36	>65	LITR(18)-8
			1.1	140	78	69	LITR(57)-88H
			1.5	155	86	57	LITR(53)-68H
			1.7	140	78	55	LITR(55)-111H
			1.7	. . .	. . .	41T	LITR(55)-111H
			2.1	140	78	>60	LITR(18)-105H
			2.3	160	89	69	LITR(55)-99H
			3.0	155	86	65	LITR(43)-108H
			3.1	155	86	63	LITR(55)-54H
			3.1	130	72	56	LITR(55)-54H(HAZ)
			3.1	165	92	59	LITR(43)-86H
			3.1	160	89	61	LITR(43)-86HSRA
			3.1	170	94	60	LITR(55)-61H
			3.0	165	92	≈55	LITR(18)-13
			3.3	155	86	52	LITR(18)-45H
			3.4	180	100	64	LITR(43)-89H
			3.9	195	108	>48	LITR(18)-20H
			4.8	195	108	64	LITR(55)-85H

			5	225	125	~46	Yankee Surveillance
			7	260	144	~44	Yankee Surveillance
			9	310	172	~42	Yankee Surveillance
	585	307	7.1	165	92	58	BRPR
	600	316	2.6	135	75	≈66	LITR(55)-80H
	650	343	3.0	110	61	>58	LITR(18)-13
			4.1	90	50	>65	LITR(43)-95H
	700	371	1.7	30	17	63	LITR(18)-42H
	750	399	3.0	65	36	≥63	LITR(18)-13
			5.6	65	36	75	LITR(43)-98H
Gulf General	<450	<232	0.27	67	37	72	ETR 1
Atomic [5]			0.45	95	53	63	
			7.6	201	111	49	
Westinghouse [21]	510	266	0.25 to 0.30	87	48	...	TRINO 1
[22]	~525 to	~274 to	0.22	85	47	62	Yankee 1(W)
	450	232	5	~225	~125	~47	Yankee 1(A)
			7	~260	~144	...	Yankee 1(A)
			9	310	172	40	Yankee 1(A)
[21]	~500	~260	~0.3	80	44	74	W Reactor 1
[21]	~550	~288	0.2	85	47	...	W Reactor 2
Bettis Atomic	470 to 520	243 to 271	0.35	65	36	...	EXP A
Power Laboratory [23]			18.0	375	208	...	EXP A

[a]Fission spectrum assumption.
[b]IRL=Industrial Reactor Laboratory, (Plainsboro, N. J.).
Yankee=Yankee Atomic Power Reactor (Rowe, Mass.).
KE=Hanford K Production Reactor East.
LITR=Low Intensity Test Reactor (Oak Ridge National Laboratory).
CVTR=Carolinas Virginia Tube Reactor (Parr, S. C.).
BGR=Brookhaven Graphite Reactor.
MTR=Materials Test Reactor (National Reactor Test Station).
ETR=Engineering Test Reactor.
[c]1.8:1 thermal/fast >0.5 MeV ratio.
[d]5.0:1 thermal/fast >0.5 MeV ratio.
[e]9.0:1 thermal/fast >0.5 MeV ratio.

TABLE 9–*Radiation induced changes in Charpy-V* (C_V) *notch ductility of 4-in. A212-B reference steel plate.*

Reporting Site	Irradiation Temperature		Fluence,[a] n/cm² >1 MeV x10¹⁹	C_V 30-ft-lb Transition Temperature Increase		Postirradiation Shelf Energy, ft·lb	Neutron Experiment Identification[b]
	°F	°C		Δ°F	Δ°C		
Naval Research Laboratory	≤300	≤149	0.44	200	111	60	KE-1[c]
			0.47	215	119	60	KE-1[d]
			0.51	200	111	60	KE-1[e]
			0.55	255	142	52	BGR-10
			0.66	210	117	≈55	LITR(18)-8
			0.70	200	111	≈53	LITR(49)-17
			0.70	210	117	53	LITR(49)-21B
			0.70	205	114	>51	LITR(49)-21C
			0.75	175	97	58	UCRR(C3)-1C
			0.76	260	144	>48	BGR-9
			0.75	180	100	56	LITR(55)-15C
			0.78	185	103	64	LITR(18)-2
			0.78	215	119	48	LITR(49)-47C
			0.78	250	139	58	CVTR
			0.80	205	114	58	LITR(55)-15A
			0.84	235	131	58	KE-2[c]
			0.88	240	133	56	KE-2[d]
			0.92	245	136	54	KE-2[e]
			0.95	245	136	>55	LITR(55)-6
			1.0	215	119	64	LITR(18)-2
			1.1	195	108	60	LITR(41)-14
			1.1	245	136	44	LITR(53)-36C
			1.1	250	139	47	MTR-18
			1.1	260(DW)	144	...	MTR-18
			1.1	195	108	60	LITR(41)-14
			1.2	245	136	48	LITR(53)-50C
			1.3	260	144	~60	MTR-19
			1.3	280	156	~46	LITR(53)-39C
			1.3	245	136	48	LITR(28)-49
			2.1	290	161	≈56	LITR(18)-12
			2.2	290	161	≈50	MTR-20
			2.4	300	167	50	KE-3[c]
			2.5	300	167	50	KE-3[d]
			2.5	300	167	50	KE-3[e]
			2.5	295	164	~54	LITR(18)-11
			2.5	290	161	48	LITR(53)-55C

			2.7	275	153	50	LITR(28)-16
			2.9	300	167	50	LITR(28)-16
			11.0	380	211	38+25(T)	MTR-30
			15.3	≈500	278	32	MTR-27
	400	204	0.66	180	100	~51	LITR(18)-8
	430	221	2.6	305	169	~51	LITR(18)-11
	450	232	0.66	200	111	57	LITR(18)-8
	464	241	0.35	175	97	68	HWCTR
	490	254	1.4	230	128	44	LITR(55)-31
	500	260	2.9	250	139	42	LITR(55)-34
	510	266	2.2	210	117	~58	LITR(18)-12
	550	288	0.66	100	56	61	LITR(18)-8
			3.1	235	131	51	LITR(55)-54H
			3.1	200	111	50	LITR(55)-54H-HAZ
			3.3	215	119	53	LITR(18)-45H
			4.8	220	122	~52	LITR(55)-85H
			15.0	400	222	34	ATR-3
	650	343	4.0	140	78	57	LITR(55)-27
	700	371	1.7	90	50	>55	LITR(18)-42H
Westinghouse Electric Corporation[21]	520	271	0.39 to 0.48	120	67	...	W Reactor 3
Bettis Atomic Power Laboratory[23]	470 to 520	243 to 271	0.11	70	39	...	EXP A
			15.0	360	200	...	EXP A

[a]Fission spectrum assumption.
[b]See footnote[b] Table 8.
[c]1.8:1 thermal/fast >0.5 MeV ratio.
[d]5.0:1 thermal/fast >0.5 MeV ratio.
[e]9.0:1 thermal/fast >0.5 MeV ratio.

TABLE 10–*Radiation induced changes in Charpy-V* (C_V) *notch ductility of 3-in. Ni-Cr-Mo reference steel plate.*

Reporting Site	Irradiation Temperature		Fluence,[a]	C_v 30-ft-lb Transition Temperature Increase		Postirradiation Shelf Energy, ft-lb	Neutron Experiment Identification[c]
	°F	°C	n/cm² >1 MeV x 10¹⁹	Δ°F	Δ°C		
Naval Research Laboratory	<300	<149	1.3	190	106	115	LITR(41)-14
			1.1	185	103	~80	LITR(53)-36C
			2.0	265	147	...[b]	LITR(53)-25B
			2.1	245	136	...[b]	LITR(53)-25C
			2.8	270	150	>85	MTR-21
			2.9	275	153	>75	LITR(28)-16
			7.9	490	272	40	MTR-26
	490	254	1.4	100	56	>90	LITR(55)-31
	550	288	3.0	145	81	~90	LITR(18)-13
	650	343	3.0	110	61	>95	LITR(18)-13
	750	399	3.0	225	125	>60	LITR(18)-13

[a]Fission spectrum assumption.
[b]Not determined.
[c]See footnote[b] Table 8.

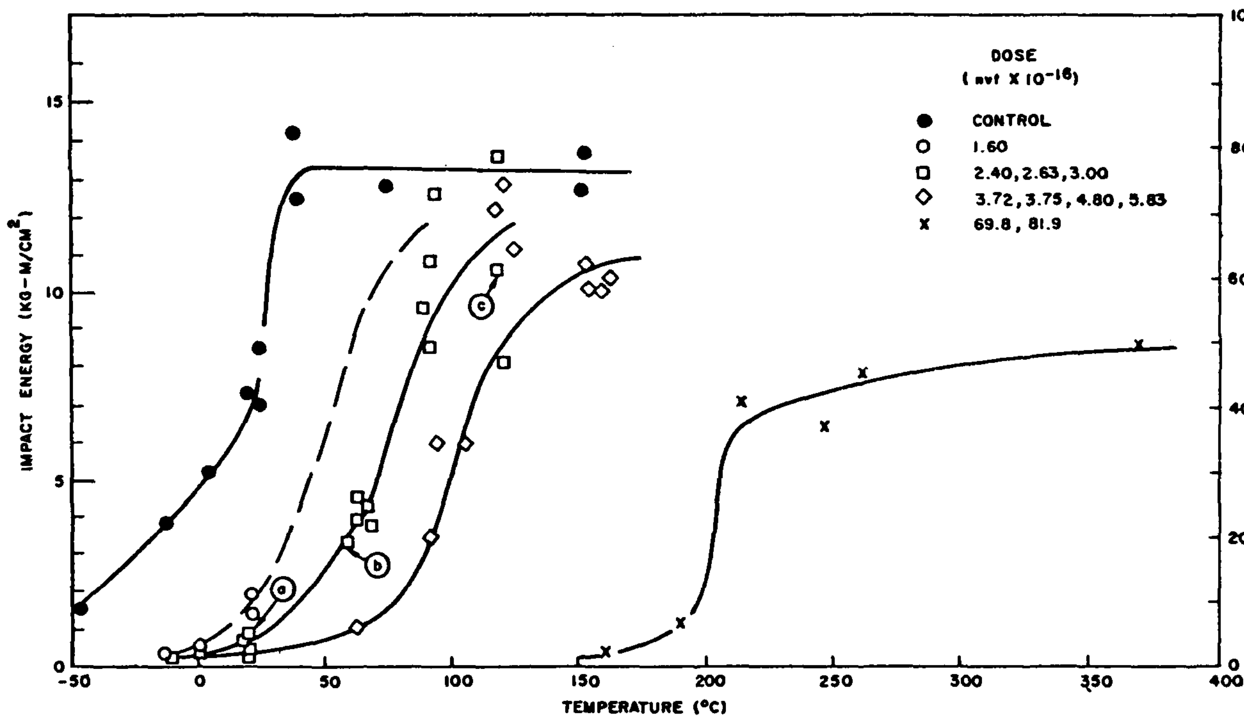

FIG. 54–6-in. *A302-B reference steel plate. Impact energy versus temperature for full size* (C_V) *specimens, first irradiation (threshold value for flux monitor, 4.2 MeV) (after Gulf General Atomic* [6].

TABLE 11 – *Tensile properties of 6-in. A302-B reference steel plate.*[a]

Plate Section	Specimen Orientation[b]	Experiment No.[c]	Irradiation Temperature, °F	Fluence[d] (>1 MeV), x 10^{19} n/cm²	Test Temperature, °F	Yield Strength[e] (0.2% offset), ksi	Tensile Strength, ksi	Reduction of Area, %	Elongation, %
1	L (1/4,1/2, 3/4T)	...	...	0.0	75	69.3(max)	92.0	68.2	32.6
						63.8(min)	84.5	66.0	26.5
						66.1(avg 10 tests)	87.9	67.3	28.4
	L (1/4, 3/4T)	...	...	0.0	250	62.0	82.5	66.9	24.2
					350	61.2(avg 2)	82.8	65.3	23.1
					450	63.0	85.0	63.1	21.8
	T (1/4,3/4T)	...	...	0.0	75	67.3(max)	90.3	54.0	23.8
						64.5(min)	87.0	56.6	26.7
						65.9(avg 2)	88.7	55.4	25.3
	Th (1/4,1/2, 3/4T)	...	...	0.0	75	65.8(max)	84.3	22.4	14.3
						63.3(min)	82.1	14.5	8.6
						64.2(avg 5)	83.3	19.1	12.1
2	L (1/4,3/4T)	...	...	0.0	75	68.3(max)	91.7	67.3	30.5
						65.5(min)	90.0	62.2	26.9
						67.6(avg 6)	90.8	65.1	28.7
	L (3/4T)	LITR(18)-32C	<250	2.4	75	120.4(avg 2)	120.4	53.9	...[i]
					300	101.0	101.0	58.7	...[i]
					450	91.0	94.0	52.3	...[i]
					550	84.8	93.0	52.3	...[i]
	L (1/4T)	MTR-29	<250	9.6	75	134.2	134.4	49.5	...[i]
					300	116.8	116.8	55.0	...[i]
					450	103.0	107.0	46.7	...[i]
					550	99.3	99.5	...[g]	...[i]
					650	88.5	96.0	...[g]	...[i]
3	L (3/4T)	...	...	0.0	75	65.6(avg 2)	87.9	64.1	26.3
	L (1/4T)	(stress relief annealed-SRA)[f]		0.0	75	62.4(avg 2)	83.9	67.3	27.2
	L (3/4T)	MTR-36	<250	5.9	75	131.7(avg 2)	132.1	54.3	12.4
	L(SRA) (1/4T)	MTR-36	<250	5.9	75	128.7	128.7	54.0	13.0
	L (3/4T)	MTR-37	<250	6.2	75	128.5(avg 2)	128.5	43.2[h]	10.8[h]
4	L (1/4,3/4T)	...	...	0.0	75	71.8(max)	94.3	66.9	31.4
						66.0(min)	88.6	60.2	22.3
						70.7(avg 10)	92.3	64.8	27.2
	L (3/4T)	1RL-4	<250	0.07	75	83.2	97.5	...[g]	...[i]
				0.11	75	85.5	98.0	...[g]	...[i]
				0.19	75	88.4	97.6	...[g]	...[i]
				0.31	75	94.2	102.2	...[g]	...[i]

			0.50	75	100.0	104.5	...[g]	...[i]
L	BNL(44)-10	<300	0.75	75	103.6(avg 2)	114.1	52.0	19.4
(1/4,3/4T)								
	HWCTR(G.R.)	<450	0.73	75	96.5	109.6	56.1	21.5
	CVTR(10-L)	<300	0.78	75	110.1	111.2	49.0	15.5
L	LITR(53)-48C	<250	0.85	75	101.1(avg 2)	102.4	62.7	21.5
(1/4T)				300	90.8	92.8	58.7	18.7
				550	84.8	90.5	53.4	20.1
L	LITR(28)-66C	<250	1.3	75	112.2(avg 2)	112.2	50.7	15.4
(1/4T)								
L	LITR(55)-77H	550	3.7	75	92.2	107.4	59.7	...[i]
(1/4,3/4T)				350	86.5	102.0	50.1	...[i]
				450	84.0	105.2	42.0	...[i]
				550	82.5	106.2	41.3	...[i]
L	KE-1[j]	<250	0.51	75	98.6	98.8	63.4	21.4
(1/4T)	1[k]		avg		100.2	100.2	62.7	20.2
	1[l]				101.7	101.7	62.2	19.2
	KE-2[j]	<250	0.97	75	109.0	109.0	61.7	14.5
	2[k]		avg		110.9	110.9	61.5	14.8
	2[l]				110.8	110.8	62.0	14.9
	KE-3[j]	<250	2.5	75	118.5	118.6	52.6	13.2
	3[k]		avg		121.1	121.2	51.6	13.4
	3[l]				121.9	121.9	52.2	13.5

[a]Naval Research Laboratory data; see also Gulf General Atomic data, Table 6 and Siemans-Schuchertwerke data, Table 15.

[b]L=longitudinal (parallel to primary plate rolling direction).
T=transverse (perpendicular to primary plate rolling direction).
Th=thickness (parallel to plate thickness direction).

[c]See footnote[b] Table 8.

[d]Fission $\bar{\sigma}$ = 68 mb, ^{54}Fe.

[e]0.252-in.-diameter specimen.

[f]Stress relief annealed by six cycles at 1125°F for 30 h total.

[g]Not available.

[h]One determination only.

[i]Specimen broke out of 1 in. gage length.

[j]1.8:1 thermal/fast >0.5 MeV ratio.

[k]5.0:1 thermal/fast >0.5 MeV ratio.

[l]9.0:1 thermal/fast >0.5 MeV ratio.

TABLE 12–*Tensile properties of 4-in. A212-B reference steel plate.*[a]

Plate Section	Specimen Orientation[b]	Experiment No.[c]	Irradiation Temperature, °F	Fluence[d] (> 1 MeV), x10^{19} n/cm^2	Test Temperature, °F	Yield Strength[e] (0.2% offset), ksi	Tensile Strength, ksi	Reduction of Area, %	Elongation, %
1	L (1/4,1/2,3/4T)	...	...	0.0	75	54.3(max)	85.3	67.0	31.7
						45.3(min)	74.0	63.6	30.6
						49.6(avg 7 tests)	80.4	64.5	31.2
	T (1/4,1/2,3/4T)	...	...	0.0	75	53.8(max)	85.2	59.7	42.5
						47.6(min)	70.9	49.0	26.7
						50.9(avg 7)	79.0	55.0	33.3
	Th (~1/2T)	...	...	0.0	75	45.5(max)	73.0	17.4	13.3
						43.8(min)	52.0	11.6	10.0
						44.4(avg 4)	70.7	15.4	11.6
	L (1/4T)	KE-1[f]	<250	0.47	75	92.6	95.8	62.5	24.5
		1[g]		avg		87.5	88.5	60.2	24.8
		1[h]				95.3	97.2	62.9	24.2
		KE-2[f]	<250	0.88	75	93.6	94.5	61.0	23.1
		2[g]		avg		94.4	95.7	59.9	22.3
		2[h]				94.8	95.4	62.5	22.5
		KE-3[f]	<250	2.5	75	105.4	105.6	55.1	14.0
		3[g]		avg		116.2	116.2	54.6	13.6
		3[h]				115.2	115.2	53.8	14.4
2	L (1/4,3/4T)	...	...	0.0	75	54.0(max)	87.0	67.3	45.0
						43.0(min)	73.5	60.7	36.5
						48.0(avg 8 tests)	78.7	64.2	39.7
					350	39.3	76.4	65.5	...[i]
					450	37.7	67.4	59.2	...[i]
					550	40.5	77.2	46.1	...[i]
					750	...(avg 2)	62.6	71.1	...[i]
	L (1/4T)	LITR(53)-48	<250	0.85	75	83.8(avg 2)	85.7	61.4	24.7
					450	54.1	70.8	55.0	26.7
					550	46.9	71.4	50.1	30.1
					750	40.6	64.8	66.0	[d]
	L (3/4T)	HWCTR (GR)	<450	0.35	75	73.0(avg 2)	89.5	55.0	23.9
		BNL(44)-10	<300	0.75	75	88.7(avg 2)	100.1	55.6	21.7
		CVTR, 10-L	<300	0.78	75	95.5(avg 2)	96.6	47.3	18.5
	L (1/4,3/4T)	LITR(43)-77H	550	3.7	75	88.8	104.5	56.1	...[i]
					350	79.7	101.8	46.7	...[i]
					450	73.6	98.4	44.3	...[i]
					550	73.7	98.2	40.7	...[i]

					650	. . .(avg 2)	45.5	48.7	. . .[i]
3	L (1/4,1/2,3/4T)	. . .	. . .	0.0	75	49.9(max)	80.1	67.3	40.3
						43.8(min)	72.8	60.2	32.6
						45.6(avg 6 tests)	75.2	64.6	35.5
	L (1/4T)	LITR(55)-15C	<300	0.75	75	83.7[k]	88.2	54.1	19.8
	L (1/4T)	MTR-20	<300	2.2	75	99.8(avg 2)[k]	102.5	37.2	. . .
	L (1/4T)	LITR(18)-32	<250	2.35	75	98.9(avg 2)	98.9	58.1	. .[j]
					450	71.1	76.0	56.6	. .[j]
					550	73.0	. . .	48.4	. .[j]
					650	54.0	75.0	58.2	. .[j]
					750	48.5	62.7	65.5	. .[j]
	L (1/4T)	MTR-29	<250	9.6	75	112.2(avg 2)	113.9	46.3	. .[j]
					450	86.0	86.3	44.3	. .[j]
					550	78.2	78.2	. . .	. .[j]
					650	64.5	77.0	51.2	. .[j]
					750	54.0	77.0	58.2	. .[j]
	L (1/4T)	LITR(18)-11	<450	2.5	75	96.2(avg 2)	105.4	46.7	16.9
	L (1/4T)	LITR(18)-12(A)	275	2.1	75	98.5(avg 2)	99.7	57.0	15.9
		LITR(18)-12(B)	510	2.1	75	87.9(avg 2)	104.9	56.3	21.2
	L (1/4T)	LITR(55)-27	650	4.0	75	65.2	88.9	59.0	30.5

[a]Naval Research Laboratory data; see also Brookhaven National Laboratory data, Figs. 56-59.
[b]L=longitudinal (parallel to primary plate rolling direction).
T=transverse (perpendicular to primary plate rolling direction).
Th=thickness (parallel to plate thickness direction).
[c]See footnote[b] Table 8.
[d]Fission $\bar{\sigma}$ = 68 mb, ^{54}Fe.
[e]0.252-in.-diameter specimen except as noted.
[f]1.8:1 thermal/fast >0.5 MeV ratio.
[g]5.0:1 thermal/fast >0.5 MeV ratio.
[h]9.0:1 thermal/fast >0.5 MeV ratio.
[i]Not available.
[j]Specimen broke out of 1-in. gage length.
[k]0.180-in.-diameter specimen.

TABLE 13–*Tensile properties of 3-in. Ni-Cr-Mo reference steel plate.*[a]

Plate Section	Specimen Orientation[b]	Experiment No.[c]	Irradiation Temperature °F	Fluence[d] (> 1 MeV), x10^{19} n/cm^2	Test Temperature, °F	Yield Strength[e] (0.2% offset), ksi	Tensile Strength, ksi	Reduction of Area, %	Elongation, %
1	L (1/4,3/4T)	...	...	0.0	75	93.5(max)	108.5	78.1	31.1
						85.0(min)	101.8	75.4	25.6
						88.3(avg 8 tests)	104.0	77.0	27.8
	L (1/4T)	LITR(53)-48	<250	0.85	75	112.8(avg 2)	112.8	72.1	20.3
					450	88.0	99.3	73.8	21.8
					550	82.8	98.5	73.3	21.6
					750	82.0	93.8	65.5	..[f]
	L (1/4T)	LITR(53)-25B	<250	2.0	75	134.4	136.4	66.0	10.4
	L (1/4T)	LITR(18)-32	<250	2.3	75	141.3(avg 2)	142.0	60.8	..[g]
					450	108.5	109.5	69.1	..[g]
					550	96.5	105.8	70.4	..[g]
					650	84.0	98.0	69.1	..[g]
					750	80.0	94.6	73.0	..[g]
	L (1/4T)	MTR-26	<300	7.0	75	153.8(avg 2)	154.5	16.4	..[f]
	L (1/4T)	MTR-29	<300	9.0	75	163.3(avg 2)	164.3	14.5	..[g]
	L (1/4T)	LITR(43)-77	550	3.7	75	107.0	115.7	72.9	..[f]
					350	93.0	105.0	69.8	..[f]
					450	91.3	104.0	73.3	..[f]
					550	93.5	106.5	70.7	..[f]
	L (1/4T)	LITR(55)-27	650	4.0	75	95.0	110.6	68.7	24.4

[a]Naval Research Laboratory data; see also Brookhaven National Laboratory data, Figs. 56-59.
[b]L = longitudinal (parallel to primary plate rolling direction).
[c]See footnote[b] Table 8.
[d]Fission $\bar{\sigma}$ = 68 mb, ^{54}Fe.
[e]0.252-in.-diameter specimen.
[f]Not available.
[g]Specimen broke out of 1 in. gage length.

TABLE 14—*Tensile properties of 2-in. T-1 reference steel plate.*[a]

Plate Section	Specimen Orientation[b]	Experiment No.[c]	Irradiation Temperature, °F	Fluence[d] (> 1 MeV), $\times 10^{19}$ n/cm^2	Test Temperature, °F	Yield Strength[e] (0.2% offset), ksi	Tensile Strength, ksi	Reduction of Area, %	Elongation, %
1	L	...	...	0.0	75	110.0(max)	120.7	67.0	20.0
	(1/4,3/4T)					106.9(min)	114.3	52.6	17.3
						108.0(avg 4 tests)	118.0	59.9	18.7
	L	LITR(18)-32	<250	2.3	75	148.9(avg 2)	149.5	48.3	..[f]
	(1/4T)								
	L	MTR-29	<300	9.6	75	163.4(avg 2)	164.1	44.0	..[f]
	(1/4T)								

[a]Naval Research Laboratory data.
[b]L=longitudinal (parallel to primary plate rolling direction).
[c]See footnote[b] Table 8.
[d]Fission $\bar{\sigma} = 68$ mb, ^{54}Fe.
[e]0.252-in. diameter specimen.
[f]Specimen broke out of 1 in. gage length.

TABLE 15–*Preirradiation tensile and Charpy V-notch ductility properties of 6-in. A302-B reference steel plate*[a] *(Courtesy Siemens-Schuchertwerke; E. Klausnitzer)* [26].

Tensile Properties			
Yield Strength (0.2% offset),[b] kp/mm²	Tensile Strength, kp/mm²	Reduction in Area, %	Elongation, %
47.4	64.4	68.0	25.0
47.0	64.4	69.5	24.5
46.7	63.3	70.0	27.0

Charpy V-Notch Ductility	
Temperature, °C	Energy, kpm/cm² [c]
-60	1.5
-40	2.4
-20	3.9
-10	6.4
0	8.5
10	11.3
20	18.8
40	18.0
60	18.8

[a]Irradiations underway in M2FR and KW0 reactors at 270 and 300°C, respectively.
[b]Single determination.
[c]Average five determinations.

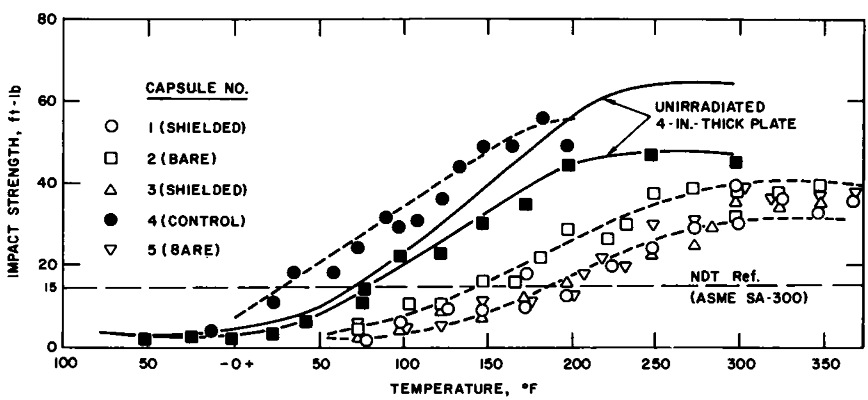

FIG. 55–*Effect of EBWR plutonium core irradiation on impact strength of SA-212-B Charpy V-notch specimens. Also included are data from three impact test machine calibrations with an unirradiated, 4-in.-thick SA-212-B plate (after Argonne National Laboratory* [27]*).*

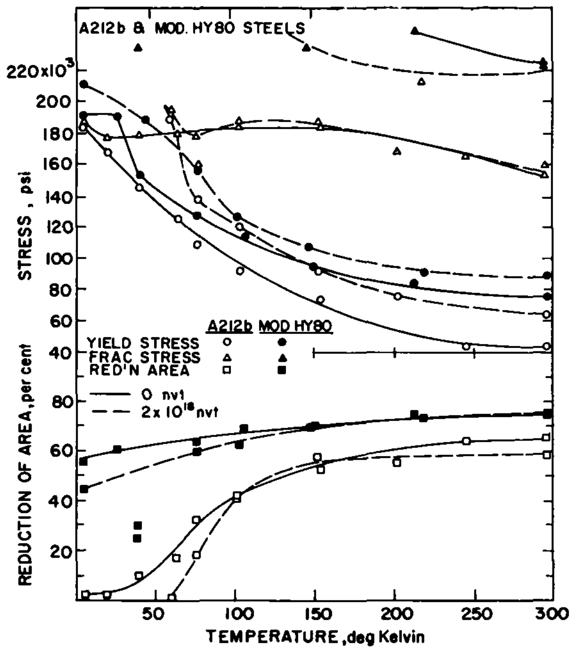

FIG. 56—*The yield stress, fracture stress and reduction of area versus temperature for A212 Grade B and modified HY80 steels before and after irradiation (after Brookhaven National Laboratory* [24]*).*

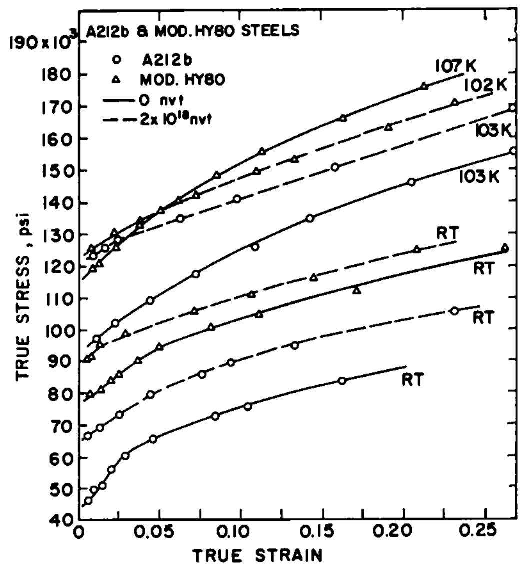

FIG. 57—*The pre- and postirradiation true stress-true strain curves for A212 Grade B and modified HY80 steels (after Brookhaven National Laboratory* [24]*).*

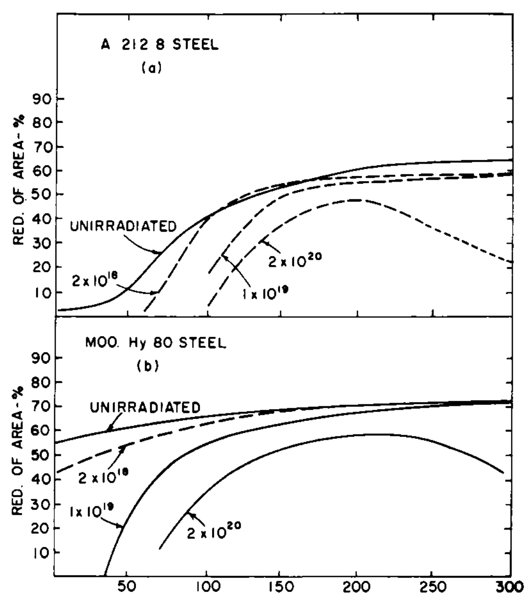

FIG. 58—*Effect of neutron exposure on the embrittlement of* (a) *A212-B steel,* (b) *modified HY80 steel (after Brookhaven National Laboratory* [25]*).*

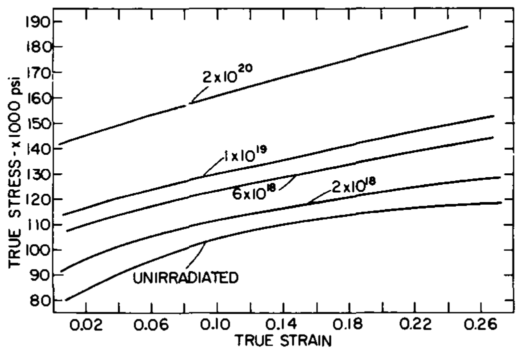

FIG. 59—*Room temperature true stress-true strain curves of modified HY80 steel after various neutron exposures (after Brookhaven National Laboratory* [25]*).*

Summary and Conclusions

A survey of the recipients of the original ASTM correlation monitor materials has been conducted and a summarization made of the experimental data developed by their respective research and reactor surveillance programs. It has been determined that the interest and use of the reference correlation monitor material by both type programs has diminished since 1962. Decreased interest has partially been the result of the current selection of A533-B steel over A302-B or A212-B steel for new reactor vessel construction and the observation of wide heat-to-heat variability in irradiation response level due to minor composition variations, particularly with respect to trace impurities[*7,16-18*]. The use and study of reference materials in a radiation environment, nonetheless, has helped appreciably to advance radiation effects technology and to resolve many important uncertainties concerning the radiation environment and its definition.

The original stock of correlation monitor material has been largely depleted; only a few square feet of archive material remain. A replacement stock of reference plate representing the steel of new reactor vessel construction (A533-B) has been secured by Subcommittee 2 of ASTM Committee E-10 on Radiation Effects.[11] Since wide variability in irradiation response between plates and weld metals can come about as a result of composition dissimilarities, perhaps it is even more important now to include limited numbers of correlation monitor material specimens in new reactor surveillance programs. The reasoning is that the cause of any radiation induced changes to actual vessel materials beyond (or below) projections can be subsequently traced to either the environment or the particular steel with certainty.

Ultimately, it may be possible to eliminate radiation embrittlement as a source of major concern to reactor vessel operations by the development and

[11] Requests for test sections should be directed to Subcommittee 2.

application of highly radiation resistant steels and weld metals.[16,18]. While much progress has been made toward this end, the need continues for surveillance and surveillance reference material.

Acknowledgments

I express my sincere appreciation to the many organizations which responded to the letters of inquiry and which contributed to the summary of radiation effects information contained in this report. I particularly thank the following individuals for their particular contributions and efforts in the preparation of this report: J. V. Alger (U. S. Steel Corporation, Applied Research Laboratory); C. Z. Serpan, Jr. (Naval Research Laboratory); S. Yanichko and T. R. Mager (Westinghouse Electric Corporation, Nuclear Energy Systems); D. J. Semans (Westinghouse Electric Corporation, Bettis Atomic Power Laboratory); P. W. Flynn (Gulf General Atomic); J. G. Y. Chow (Brookhaven National Laboratory); N. Balai (Argonne National Laboratory); and P. Higgins (General Electric-Atomic Products Division).

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APPENDIX I

QUESTIONNAIRE
(Abridged)

Date ________

ASTM Reference Correlation Monitor Materials (Plate)
(6-in. A302-B ______, 4-in. A212-B______),
3-in. HY-80______, 2-in. T-1______)

Primary person to contact for any future correspondence:

Name:

Address:

Telephone:

1. Preirradiation data developed? Yes ( ) No ( )

   If yes, list type:

2. Preirradiation data reported? Yes ( ) No ( )

   Company report ( ) Open Literature ( )

   Preirradiation thermal control data included? Yes ( ) No ( )

3. Primary reference report(s) containing preirradiation and thermal control data (Please list major data sources only):

4. Specimen irradiations: Completed? ( ) Underway? ( )
   Planned ( )

5. Specimen types for irradiation determinations:

6. Postirradiation tests and evaluations:

   Completed? ( ) Underway? ( ) Planned? ( )

   For those irradiation experiments (surveillance and/or research) completed, list specimen types:

   Data reported? Yes ( ) No ( ) If yes,

   Company report ( ) Open Literature ( )

   For those irradiation experiments (surveillance and/or research) underway, list specimen types:

   Approximate time of specimen discharge from reactor:

   Experiments described? Yes ( ) No ( ) If yes,

   Company report ( ) Open Literature ( )

7. Primary reference report(s) containing postirradiation data (Please list major data sources only*)
8. Neutron fluence determinations:

    Foil measurements?

    Spectrum calculations?

    Low power flux extrapolations?

    Reactor operator estimates?

9. Exposure temperature determinations:

    Measured?

    Approximated from coolant temp/gamma heat?

*If list of reports is too extensive (that is, exceeds 8-10) please indicate as such and the company representative designated above will be contacted directly by a Task Group member for possible assistance and further discussion.

Offered to the Task Group by:

Address:

Telephone: