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CONTENTS

ABSTRACT

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PROBLEM STATUS

This is an interim report on one phase of the problem; work on other phases is continuing.

AUTHORIZATION

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CHARPY-V NOTCH DUCTILITY CHARACTERISTICS OF NEUTRON-IRRADIATED A537-B AND A350-LF2 STEEL WELDMENTS

INTRODUCTION

The majority of research conducted on steels for nuclear service has emphasized thick (3-inch and greater) plate exposed at elevated temperatures (450°F (232°C) to 750°F (399°C)) and to high fluences (1 to 5×10^{19} neutrons/cm^2 of energies greater than 1 MeV). A meager quantity of data is available on the effects of neutron irradiation of thin (less than 1-inch) plate at low temperatures and to low fluences. The compilation becomes even more minute when plain carbon or low-carbon steel is specified. Thin-plate steel will be used in certain reactor components; hence, understanding how such materials would respond to a nuclear environment is important. To provide such information, a study was undertaken using the steels which serve as the liner for the prestressed concrete vessel of the High-Temperature Gas-Cooled Reactor (HTGR), a typical low temperature-low fluence application. The plates are of type A537-B steel, and the penetration nozzles welded into the liner are of forged-type A350-LF2 steel. The liner will function at less than 150°F (66°C) and may be exposed to a fluence of 2.5×10^{18} neutrons/cm^2 (n/cm^2) during its projected lifetime.

MATERIALS

Five heats of A537-B steel fabricated as 3/4-inch-thick plate were included in the program. The plates were examined in both ASTM WR (weak) and RW (strong) orientations. The A537-B-to-A537-B weld deposit and its companion heat affected zone (HAZ) were tested jointly with one base plate. Weld deposit and HAZ specimens were also taken from the A350-LF2-forging-to-A537-B-plate weldment along with A350-LF2 specimens. In both cases, weld deposit and HAZ specimens were oriented with their long axes perpendicular to the welding direction and with their notches perpendicular to the weldment surface. The HAZ specimen notches were centered on the weld fusion line. The program also included a limited number of specimens from a well-documented type A212-B reference plate (1) for irradiation performance comparisons. The chemical analyses of all materials are given in Table 1.

IRRADIATIONS

Two irradiations were performed in the Union Carbide Research Reactor (UCRR). Specimens were encapsulated in stainless steel to achieve an average irradiation temperature of 150°F (66°C) as indicated by thermocouples in the assembly.

The neutron fluence level was 2.5×10^{18} n/cm^2 $>$ 1 MeV based on an assumed fission spectrum distribution of neutrons indexed by analyses of iron neutron detector wires included in each irradiation assembly. A fission-averaged cross section of 68 mb was used for the $^{54}Fe(n,p)^{54}Mn$ reaction. Techniques for converting fluence values based on an assumed fission spectrum distribution to values representing calculated spectra have been outlined previously (2).

Table 1
Chemical Composition of A537-B Plate, A350-LF2 Forging, and Companion Weld Metals

Material Type	Chemical Analysis (Wt-%)										
	C	Mn	Si	P	S	Ni	Cr	Mo	Al	Cu	V
A537-B	0.20	1.17	0.23	0.012	0.016	0.11	0.16	0.03	0.02	0.16	0.02
A537-B weld*	0.058	0.90	0.46	0.004	0.016	2.03	0.13	0.03	0.02	0.16	0.02
A350-LF2	0.21	1.18	0.27	0.033	0.023	0.22	0.17	0.03	0.02	0.06	0.03
A350-LF2 weld*	0.075	0.91	0.58	0.015	0.017	2.16	0.09	0.06	0.02	0.09	0.04

*As deposited compositions.

RESULTS

Irradiation data developed for plates and weldments are summarized in Table 2. Figures 1 through 5 depict the behavior of the A537-B plates. For all plates, the RW orientation produced preirradiation shelf values approximately equivalent to those of an A302-B steel plate. Individual Charpy-V 30-ft-lb transition temperatures were at or below -85°F (-65°C), in agreement with the mill nil-ductility transition (NDT) temperature of -90°F (-68°C) as determined by the drop-weight test method. The depression of shelf values by irradiation was not marked. Similarly, the shifts in Charpy-V transition temperatures were all relatively low, ranging from 55 to 95°F (31 to 53°C). The plate results given in Fig. 5 were developed by a preliminary investigation prior to initiation of the current program and are shown for the purpose of projecting behavior at a higher fluence level.

The WR data for all A537-B plates display lower shelf values than the respective RW data, with preirradiation values as low as 40 ft-lb recorded. The 30-ft-lb transition temperatures for the WR orientation were not more than 40°F (22°C) higher than those for the RW orientation. After irradiation, the WR orientation shelf energy values for three of the plates fell between 30 and 40 ft-lb. Due to the characteristics of the WR data curves, the shift in the 20-ft-lb transition temperature was arbitrarily selected as an index of radiation embrittlement sensitivity for this test orientation. Using this criterion, the same degree of radiation embrittlement is seen for WR versus RW orientations.

The effects of irradiation on the HAZ properties are shown in Fig. 6. The preirradiation curve is rather similar to that for the base plate (Fig. 4). Two curves were drawn through the postirradiation data. The solid curve is an average plot of the results, and the dotted curve is a plot of the greatest apparent embrittlement. As was seen with the RW orientation of individual base plates, neither the drop in the shelf energy nor the shift in transition temperature is very large for this fluence level.

The weld deposit response is shown in Fig. 7. Relative to the parent plate a considerably greater shift in the 30-ft-lb transition temperature from a slightly higher preirradiation value resulted in the weld metal having the highest transition temperature among components of the A537-B weldment.

Table 2
Charpy-V Notch Ductility Characteristics of A537-B and A350-LF2 Steel Weldments
Before and After Irradiation to a Fluence of 2.5×10^{18} n/cm² > 1 MeV at 150°F (66°C)

Material Type	Heat No.	Specimen Orientation*	Charpy-V Transition Temperature (RW at 30-ft-lb and WR at 20-ft-lb)						Full Shear Energy Shelf (ft-lb)	
			Preirradiation		Postirradiation		ΔTT		Preirradiation	Postirradiation
			°F	°C	°F	°C	°F	°C		
A537-B	A2698	RW WR	-120 -80†	-84 -62	-65 -15†	-54 -26	55 65†	30 36	>120 79	105 60
A537-B	C3348	RW WR	-85 -90	-65 -68	-15 -15	-26 -26	70 75	39 42	81 40	68 34
A537-B	C3296	RW WR	-100 -105	-73 -76	-10 -10	-23 -23	90 95	50 53	79 44	67 31
A537-B	B7247	RW WR	-110 -85	-79 -65	-15 -25	-26 -32	95 60	53 33	>120 54	>120 39
A537-B	B3658	RW	-120	-84	+20‡	-7	140‡	78	>120	95
A537-B heat affected zone	B7247	—	-85	-65	-45/+5	-43/-15	40/90	22/50	>120	120
A537-B weld	—	—	-75	-59	+50	+10	125	69	112	100
A350-LF2	—	RW	-45	-43	+50	+10	95	53	>120	86
A350-LF2 heat affected zone	—	—	-40	-40	+25/+65	-4/+18	65/105	36/58	109	73
A350-LF2 weld	—	—	-80	-62	0	-18	80	44	>120	98
A212-B	73N573	RW	+45	+7	+130	+54	85	47	72	67

*RW — longitudinal specimen (strong-direction properties).
WR — transverse specimen (weak-direction properties).
†Evaluated at 30-ft-lb level.
‡5.1×10^{18} n/cm² > 1 MeV at < 250°F (< 121°C).
Average value/extreme value.

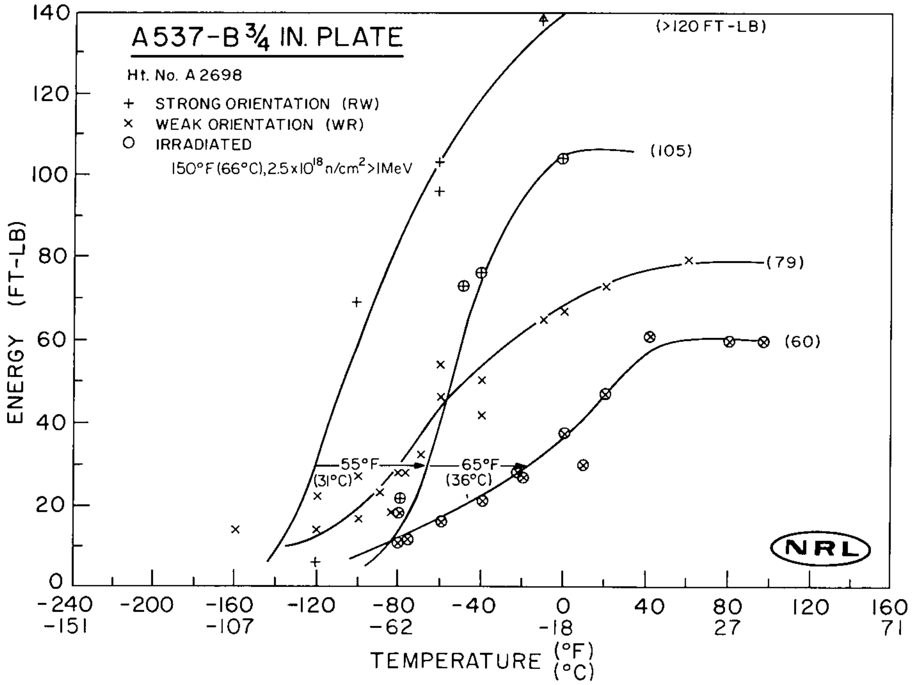

Fig. 1 - Charpy-V notch ductility behavior of A537-B steel plate (heat number A2698) before and after irradiation at 150°F (66°C)

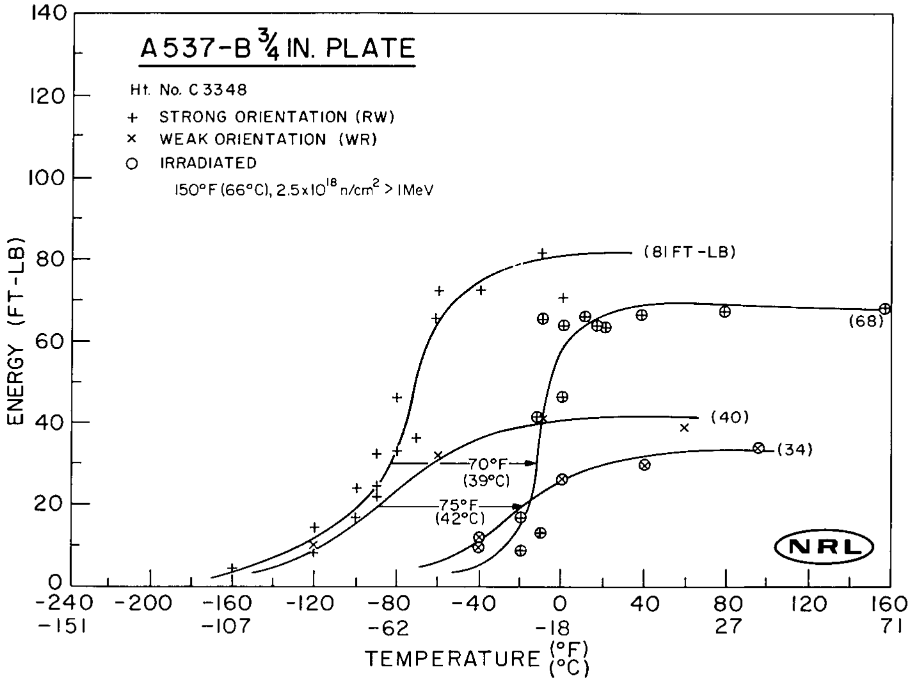

Fig. 2 - Charpy-V notch ductility behavior of A537-B steel plate (heat number C3348) before and after irradiation at 150°F (66°C)

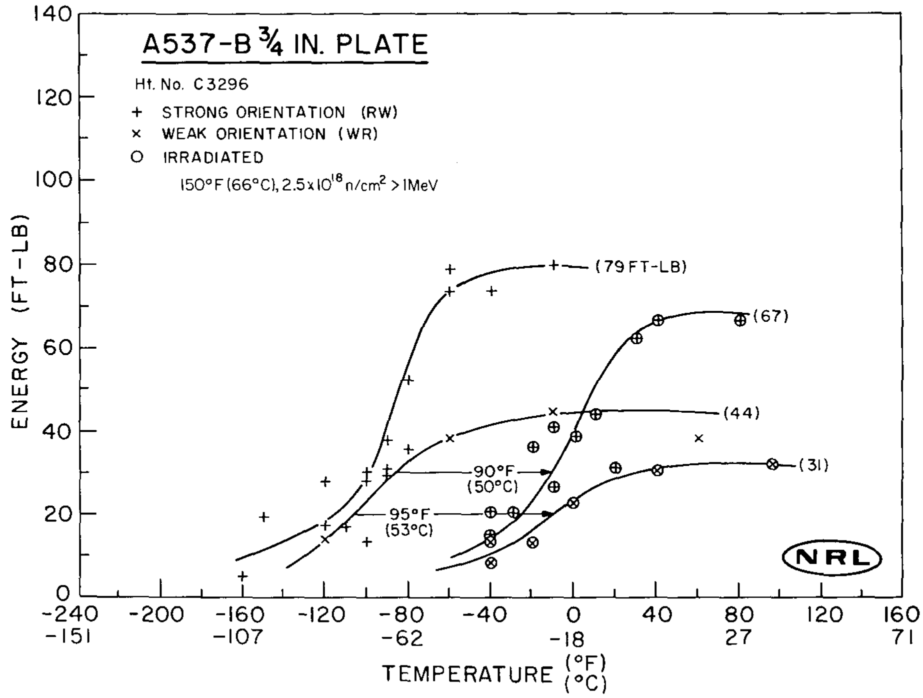

Fig. 3 - Charpy-V notch ductility behavior of A537-B steel plate (heat number C3296) before and after irradiation at 150°F (66°C)

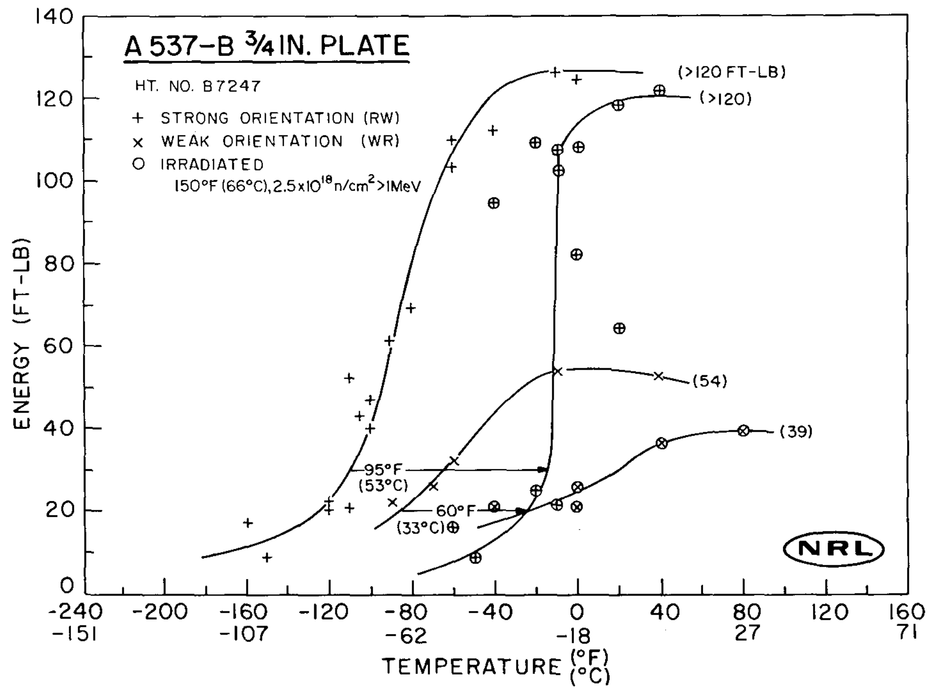

Fig. 4 - Charpy-V notch ductility behavior of A537-B steel plate (heat number B7247) before and after irradiation at 150°F (66°C)

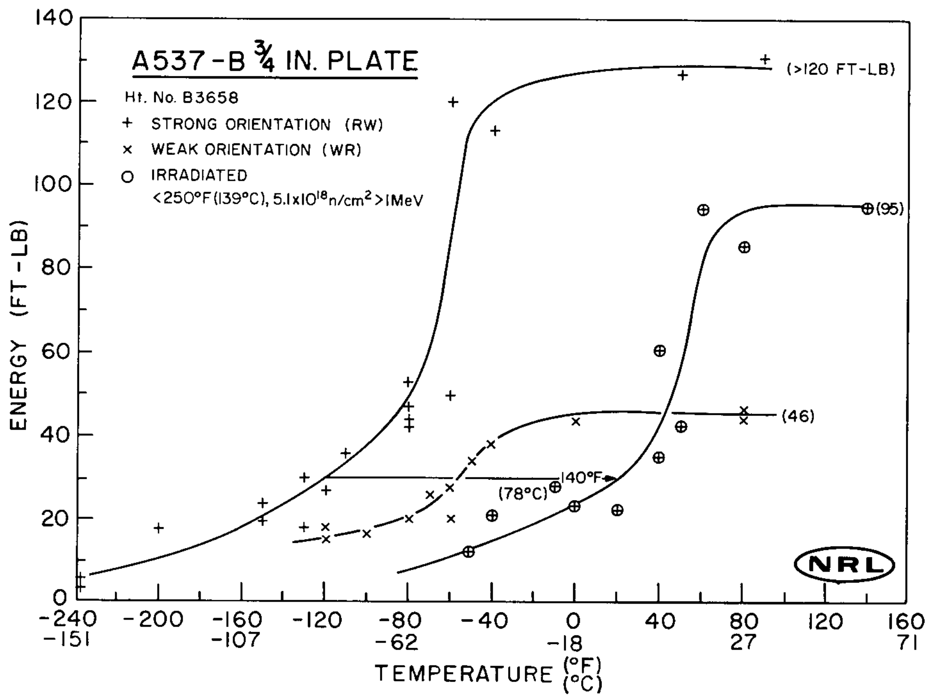

Fig. 5 - Charpy-V notch ductility behavior of A537-B steel plate before and after irradiation at < 250°F (<121°C)

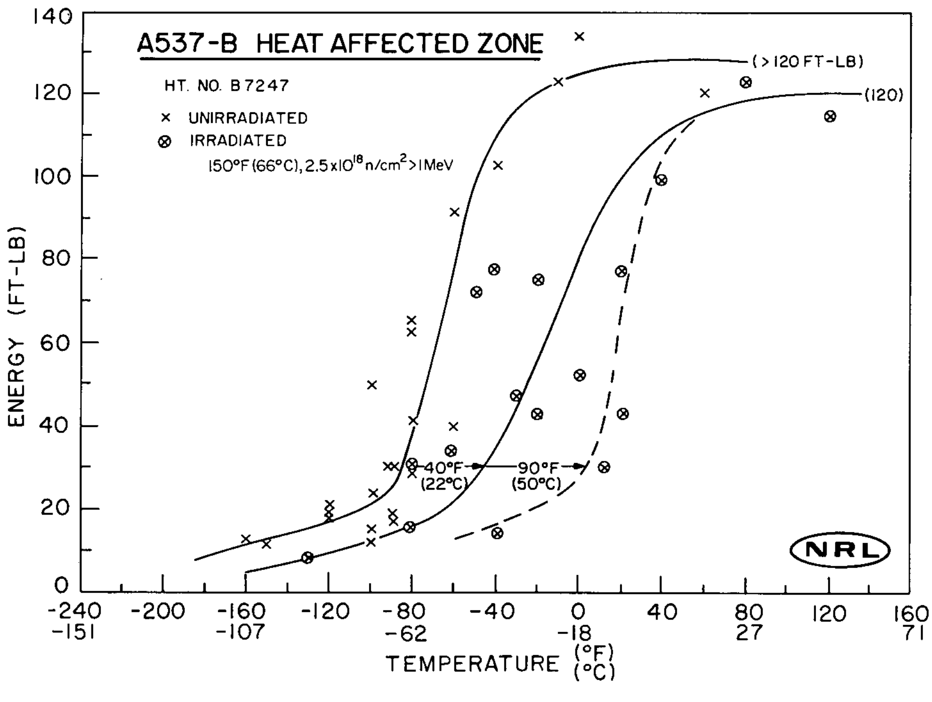

Fig. 6 - Charpy-V notch ductility behavior of A537-B heat affected zone before and after irradiation at 150°F (66°C)

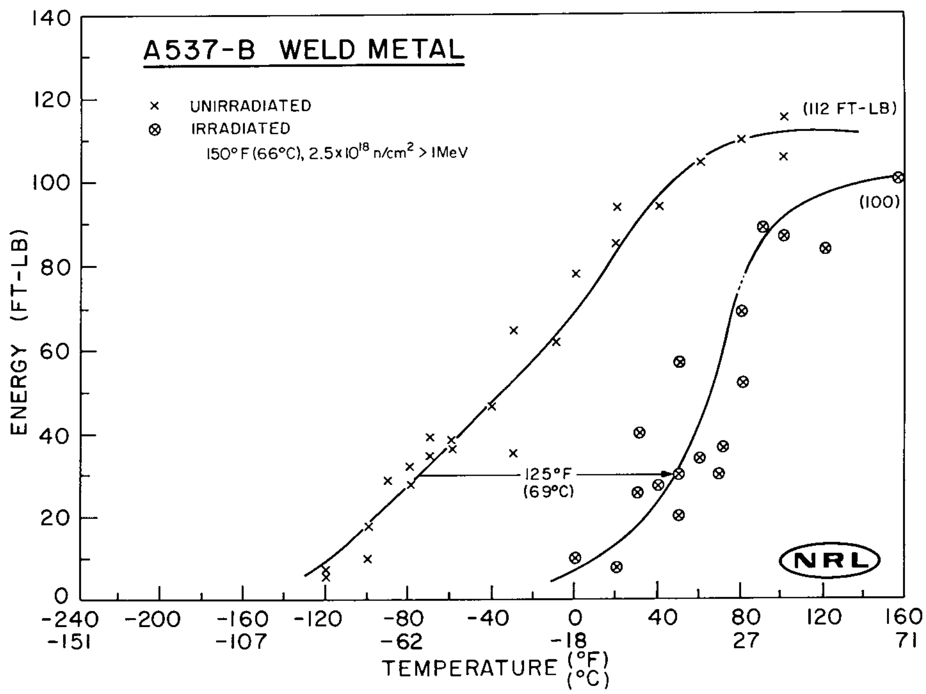

Fig. 7 - Charpy-V notch ductility behavior of A537-B weld deposit before and after irradiation at 150°F (66°C)

The data for the A350-LF2 forging are plotted in Fig. 8. High shelf values are seen for both the unirradiated and the irradiated material conditions. The transition-temperature shift is much the same as that for the A537-B plates; however, the pre-irradiation transition temperature of the forging is not as low. Thus, the notch ductility of the forging after irradiation appears similar to the A537-B weld.

As observed with the A537-B, the A350-LF2 HAZ performance (Fig. 9) is very much like the performance of the forging. The HAZ data show rather high scatter; average and maximum postirradiation transition behavior are indicated by solid and dashed curves, respectively.

The A350-LF2 weld deposit exhibited less sensitivity to irradiation than the parent forging and also retained a higher shelf energy, as illustrated in Fig. 10. Better weld performance is further demonstrated by a lower initiation transition temperature.

The comparison of data in Fig. 11 with results shown in Figs. 1 through 10 indicates that the transition-temperature response of the A537-B and A350-LF2 material on irradiation is analogous to the performance of the A212-B reference plate. While losses in full shear energy absorption are somewhat larger for certain of the liner materials than for the reference plate, absolute shelf level values are equivalent to or exceed corresponding values for the reference plate.

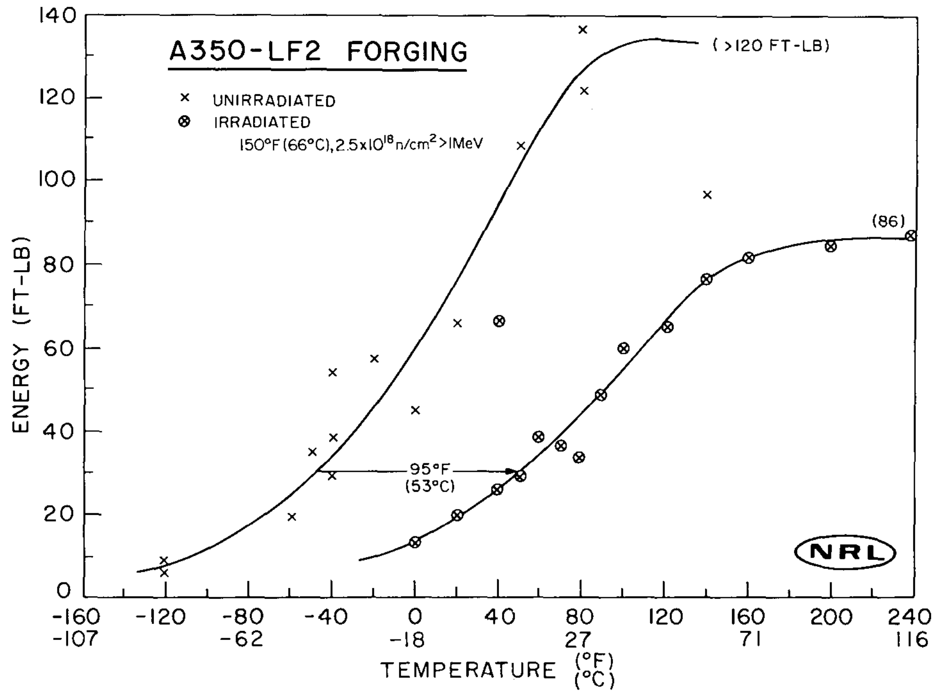

Fig. 8 - Charpy-V notch ductility behavior of A350-LF2 steel forging before and after irradiation at 150°F (66°C)

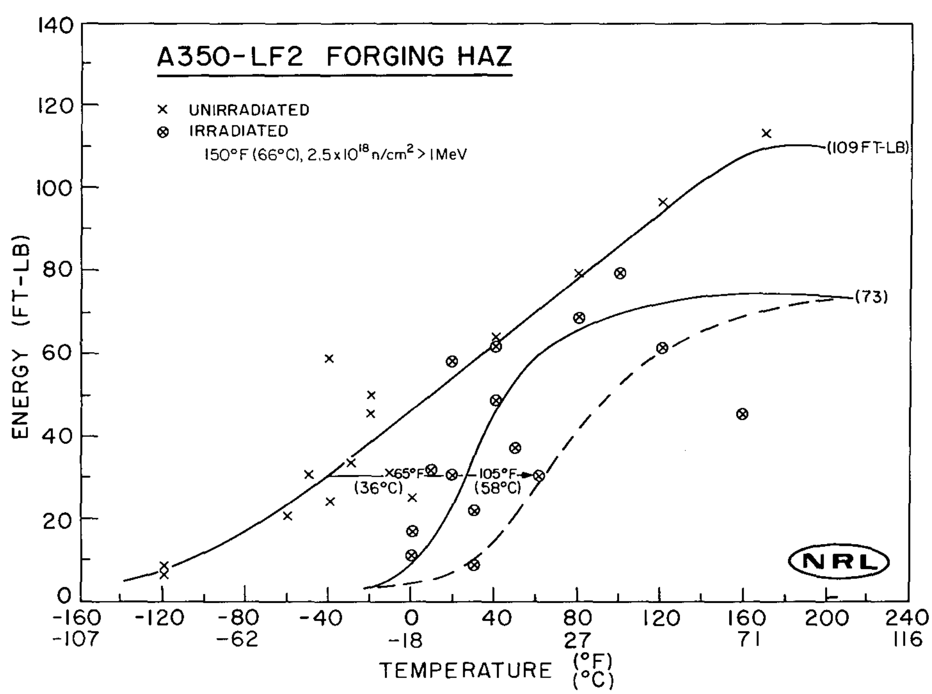

Fig. 9 - Charpy-V notch ductility behavior of A350-LF2 heat affected zone before and after irradiation at 150°F (66°C)

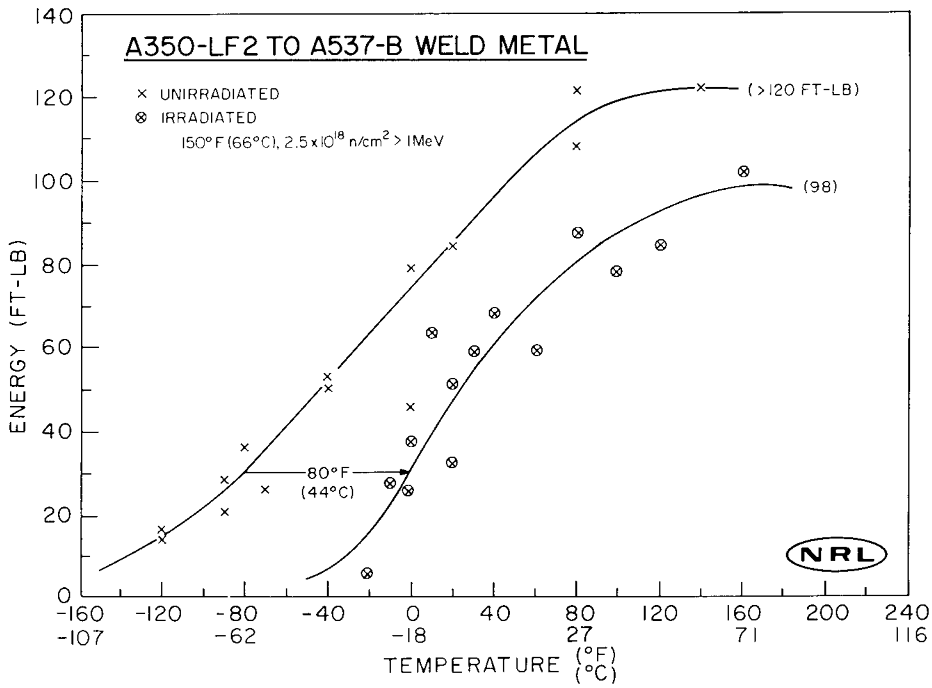

Fig. 10 - Charpy-V notch ductility behavior of A350-LF2 weld deposit before and after irradiation at 150°F (66°C)

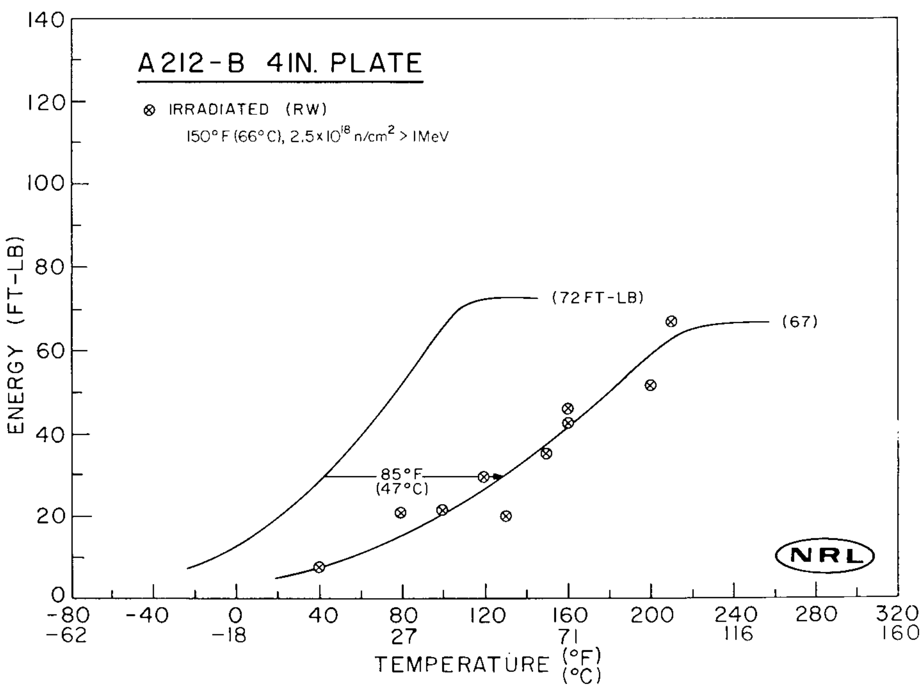

Fig. 11 - Charpy-V notch ductility behavior of A212-B steel plate before and after irradiation at 150°F (66°C)

DISCUSSION

The data presented in the foregoing section demonstrate that significant variability in initial properties as well as in postirradiation properties exists in type A537-B steel as determined from Charpy-V 30-ft-lb transition temperature and ductile shelf energy behavior. To some extent, these variations may be due to the differences in plate fabrication. To produce the desired length and width dimensions from a given ingot size, cross-rolling ratios of 6:1 and 11:1 were employed. In the most radiation-sensitive plate, the transition temperature shift was only 10°F (6°C) greater than that for the A212-B reference plate. The low initial transition temperature of A537-B steel plate, however, would offer a greater tolerance for radiation-induced embrittlement in service.

The WR orientation shelf values of several A537-B plates were degraded by irradiation to values as low as 31 ft-lb, a level where additional irradiation might lead to the potential for low-energy ductile tear fracture in the WR orientation.

The evaluation of A537-B-to-A537-B and A537-B-to-A350-LF2 weldments indicated that the parent metal or weld deposit selectively determines weldment performance. With the A537-B weldments, the weld deposit having a higher initial transition temperature and a greater shift under irradiation is the most sensitive component. In the A350-LF2 weldment, the properties of the base forging rather than those of the weld deposit were changed the most. This was expected based on available literature showing a high sensitivity to irradiation for type A350-LF1 (modified) and A350-LF3 steels, when exposed at temperatures below 450°F (232°C) (3,4). Although the shift in transition temperature of the A350-LF2 forging was not significantly greater than that observed for the A537-B plate or the weld deposit, the relatively high preirradiation value effectively accentuates any irradiation-induced change in transition temperature.

Comparison of the performance of the weld deposits for the A537-B-to-A537-B weldment versus the A350-LF2-to-A537-B weldment indicated a significant difference in irradiation-induced transition-temperature increases (125°F versus 50°F) (69°C versus 28°C) and absolute postirradiation transition temperatures (50°F versus 0°F) (10°C versus -18°C). This points up the need for evaluating the various types of weld deposits made in structural nuclear components rather than relying on the results of a single weldment.

SUMMARY

The vast amount of research which has been performed on thick-section steel irradiated to high fluences and at high temperatures tends to overshadow the research on thin structural plates, which are employed in the nuclear power industry. Although these thin plates may not be greatly stressed or even subjected to high fluences and temperatures, the responses to their relatively low-service fluences and temperatures may nonetheless be of critical significance. The assessments of the Charpy-V notch ductility characteristics of two such steels, types A537-B and A350-LF2, and companion welds have been completed. Specimens from the 3/4-inch weldments were irradiated to a low fluence of 2.5×10^{18} n/cm^2 > 1 MeV at a temperature of 150°F (66°C). The following primary observations and general conclusions regarding large thin-walled structures exposed to nuclear irradiation are emphasized:

1. The initial transition temperature should minimally be low enough to sustain irradiation-effect increases and still include a margin of safety.

2. Sufficient testing of materials actually used in construction should be conducted to demonstrate plate-to-plate variability, weld metal behavior, and heat affected zone (HAZ) response as well as any anisotropism.

3. To secure desirable notch impact properties in the weak orientation, cross-roll ratios approaching unity should be employed in the plate fabrication where possible.

Specific conclusions relating to the steel studies are:

1. Charpy-V properties of A537-B steel vary significantly from plate to plate, particularly with respect to the WR (weak) orientation. Preirradiation Charpy-V full shear energy absorption values for five heats ranged from 79 to greater than 120 ft-lb for RW (strong) orientation and from 40 to 79 ft-lb for WR (weak) orientation. Postirradiation values ranged from 67 to greater than 120 ft-lb for RW orientation and from 31 to 60 ft-lb for WR orientation.

2. Postirradiation Charpy-V 30-ft-lb transition temperatures of those A537-B plates examined ranged from -65°F to -10°F (-54°C to -23°C) (RW orientation) resulting from transition-temperature increases of 55°F to 96°F (31°C to 53°C). Postirradiation transition temperatures of an A350-LF2 forging and an A212-B reference plate were 50°F and 130°F (10°C and 54°C), respectively, stemming from individual increases of 95°F and 85°F (53°C and 47°C).

3. Weld deposits between A537-B plates and between an A350-LF2 forging and an A537-B plate exhibited equivalent preirradiation transition temperatures (≈75°F or 24°C) but dissimilar irradiation embrittlement sensitivity. Postirradiation transition temperature of the A537-B weld was 50°F versus 0°F (10°C versus -18°C) for the A350-LF2 weld.

4. Composite performance of the A537-B-to-A537-B weldments after irradiation was determined to be limited by weld metal Charpy V-notch properties while that of the A350-LF2-forging-to-A537-B-plate weldment was determined by the properties of the forging. In both cases, a higher preirradiation transition temperature of one component was the major factor determining overall weldment notch ductility properties.

5. The weld HAZ of A537-B weldments appears to be about as sensitive to irradiation embrittlement as the A537-B base plate. Similarly, the HAZ of A350-LF2 weldments behaves in approximately the same manner as the base forging. Maximum transition temperatures of the HAZ of A537-B and A350-LF2 weldments were 5°F and 65°F (-15°C and 18°C), respectively.

6. The irradiation responses of individual components of A537-B and A350-LF2 weldments as determined by increases in the transition temperature are of the same magnitude as that for an A212-B reference plate. Generally, lower preirradiation transition temperatures of the weldment components compared to the reference plate offer a somewhat greater tolerance to radiation-induced embrittlement.

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