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BROWNS FERRY STEAM ELECTRIC STATION UNIT 2 VESSEL SURVEILLANCE MATERIALS TESTING AND FRACTURE TOUGHNESS ANALYSIS

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ABSTRACT

The surveillance capsule at 30° azimuth location was removed from the Browns Ferry Unit 2 reactor in Fall 1994. The capsule contained flux wires for neutron fluence measurement and Charpy and tensile test specimens for material property evaluation. The flux wires were evaluated to determine the fluence experienced by the test specimens. Charpy V-Notch impact testing and uniaxial tensile testing were performed to establish the properties of the irradiated surveillance materials. Unirradiated Charpy and tensile specimens were tested as well to obtain the appropriate baseline data.

The irradiated Charpy data for the plate and weld specimens were compared to the unirradiated data to determine the shift in Charpy curves due to irradiation. The results are within the predictions of the Regulatory Guide 1.99 Revision 2.

The irradiated tensile data for the plate and weld specimens were compared to the unirradiated data to determine the effect of irradiation on the stress-strain relationship of the materials. The changes shown in the materials were consistent with the irradiation embrittlement effects shown by the Charpy specimens.

The flux wire results, combined with the lead factor determined from the last fuel cycle, were used to estimate the 32 EFPY fluence. The resulting estimate was about 43% lower than the previous estimate used to develop pressure-temperature curves. Therefore, new pressure-temperature curves were generated.

ACKNOWLEDGMENTS

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1. INTRODUCTION

Part of the effort to assure reactor vessel integrity involves evaluation of the fracture toughness of the vessel ferritic materials. The key values which characterize a material's fracture toughness are the reference temperature of nil-ductility transition (RT_{NDT}) and the upper shelf energy (USE). These are defined in 10CFR50 Appendix G [1] and in Appendix G of the ASME Boiler and Pressure Vessel Code, Section XI [2]. These documents contain requirements used to establish the pressure- temperature operating limits which must be met to avoid brittle fracture.

Appendix H of 10CFR50 [3] and ASTM E185-66 [4] establish the methods to be used for surveillance of the Browns Ferry Unit 2 reactor vessel materials. Capsule removal and testing were done per the requirements of ASTM E185-82 [6] to the extent practical. The first vessel surveillance specimen capsule required by 10CFR50 Appendix H [3] was removed from Unit 2 in Fall 1994. The irradiated capsule was sent to the GE Vallecitos Nuclear Center (VNC) for testing. The surveillance capsule contained flux wires for neutron flux monitoring and Charpy V-Notch impact test specimens and uniaxial tensile test specimens fabricated using materials from or representative of the vessel materials nearest the core (beltline). The impact and tensile specimens were tested to establish properties for the irradiated materials. Unirradiated Charpy and tensile specimens were sent from site to GE Vallecitos Nuclear Center (VNC) and tested using the same testing methods.

The results of the surveillance specimen testing are presented in this report, as required per 10CFR50 Appendices G and H [1 & 3]. The irradiated material properties are compared to the unirradiated properties to determine the effect of irradiation on the tensile properties, through tensile testing, and on material toughness, through Charpy testing. Flux wire results and updated lead factor analyses are used to determine the need for changes to the pressure-temperature (P-T) curves.

2. SUMMARY AND CONCLUSIONS

2.1 SUMMARY OF RESULTS

The 30° azimuth surveillance capsule was removed and shipped to VNC. The flux wires, Charpy V-Notch and tensile test specimens removed from the capsule were tested according to ASTM E185-82 [6]. The methods and results of the testing are presented in this report as follows:

a. Section 3: Surveillance Program Background

b. Section 4: Peak RPV Fluence Evaluation

c. Section 5: Charpy V-Notch Impact Testing

d. Section 6: Tensile Testing

e. Section 7: Development of Operating Limits Curves

The significant results of the evaluation are below:

a. The 30° azimuth position capsule was removed from the reactor. The capsule contained 9 flux wires: 3 copper (Cu), 3 iron (Fe), and 3 nickel (Ni). There were 36 Charpy V-Notch specimens in the capsule: 12 each of plate material, weld material and heat affected zone (HAZ) material. The 8 tensile specimens removed consisted of 3 plate, 2 weld, and 3 HAZ metal specimens.

b. The chemical compositions of the beltline materials were determined from data obtained from GE QA records. The copper (Cu) and nickel (Ni) contents were determined for all beltline heats of plate material. The values for the limiting beltline plate are 0.16% Cu and 0.52% Ni. The limiting beltline weld values are 0.28% Cu and 0.35% Ni.

c. The purpose of the flux wire testing was to determine the neutron flux at the surveillance capsule location. The flux wire results show that the fluence (from E >1 MeV flux) received by the surveillance specimens was 1.52×10^{17} n/cm^2 at removal.

d. A neutron transport computation was performed, based on the performance of the last fuel cycle. Relative flux distributions in the azimuthal and axial directions were developed. The lead factor, relating the surveillance capsule flux to the peak inside surface flux, was 0.98.

e. The surveillance Charpy V-Notch specimens were impact tested at temperatures selected to define the transition of the fracture toughness curves of the plate, weld, and HAZ materials. Measurements were taken of absorbed energy, lateral expansion and percentage shear. From absorbed energy and lateral expansion curve-fit results (for plate and weld metal only), the values of USE and of index temperature for 30 ft-lb, 50 ft-lb and 35 mils lateral expansion (MLE) were obtained (see Table 5-4). Fracture surface photographs of each specimen are presented in Appendix A.

f. The curves of irradiated Charpy specimens and unirradiated Charpy specimens established the 30 ft-lb index temperature irradiation shift and the decrease in USE. The surveillance plate material showed a measured 38°F shift and a 6 ft-lb decrease (4% decrease) in USE. The weld material showed a 1°F shift and essentially no decrease in USE.

g. The measured shifts of 38°F for plate and 1°F for weld, for a fluence of 1.52×10^{17} n/cm^2, were within their respective Reg. Guide 1.99 [7] range predictions ($\Delta RT_{NDT} \pm 2\sigma$) of -20°F to 48°F, and -39°F to 73°F.

h. The irradiated tensile specimens were tested at room temperature (70°F), reactor operating temperature (550°F). The results in comparison to unirradiated data were tabulated (see Tables 6-3 and 6-4) for each specimen including yield and ultimate tensile strength, uniform and total elongation, and reduction of area. The results generally showed increasing strength and decreasing ductility, consistent with expectations for irradiation embrittlement.

i. The 32 EFPY fluence prediction of 6.05×10^{17} n/cm^2, based on the flux wire test and lead factor results presented here, was about 43% lower than that previously established (1.1×10^{18} n/cm^2) for development of P-T curves.

j. As a part of the development of the pressure-temperature (P-T) operating limits curves, the adjusted reference temperature (ART = initial RT_{NDT} + ΔRT_{NDT} + Margin) was predicted for each beltline material, based on the methods of Reg. Guide 1.99. The ARTs for the limiting material, weld ESW, at 32 EFPY is 92.1°F.

k. The beltline material USE values at 32 EFPY were predicted using the methods of Reg. Guide 1.99, with initial beltline USE values based generic USE values (see Table 7-3). It is expected that the actual 32 EFPY USE will be in excess of 50 ft-lbs for all beltline plated and welds. In addition, the results of the USE testing for the surveillance materials show that the BWROG equivalent margin analysis is applicable.

l. P-T curves were developed for three reactor conditions: pressure test (Curve A), non-nuclear heatup and cooldown (Curve B), and core critical operation (Curve C). The curves are valid for 32 EFPY of operation. The beltline curve is more limiting for curve A. For curve B and curve C, the non-beltline curves are limiting for pressures less than approximately 1100 psig. The P-T curves are shown in Figures 7-1 through 7-3. Figure 7-4 shows the combined Curves A, B, and C P-T curves.

2.2 CONCLUSIONS

The requirements of 10CFR50 Appendix G [1] deal basically with vessel design life conditions and with limits of operation designed to prevent brittle fracture. However, based on the evaluation of surveillance testing results, and the associated analyses, the following conclusions are made:

a. The 30 ft-lb shifts and decreases in USE measured were within Regulatory Guide 1.99 Revision 2 predictions.

b. The values of ART and USE for the reactor vessel beltline materials are expected to remain within limits in 10CFR50 Appendix G [1] for at least 32 EFPY of operation.

3. SURVEILLANCE PROGRAM BACKGROUND

3.1 CAPSULE RECOVERY

The reactor pressure vessel (RPV) originally contained three surveillance capsules at 30°, 120°, and 300° azimuths at the core midplane. The specimen capsules are held against the RPV inside surface by a spring loaded specimen holder. Each capsule receives equal irradiation because of core symmetry. During the Fall 1994 outage, the 30° positioned capsule was removed. The capsule was cut from its holder assembly and shipped by cask to the GE Vallecitos Nuclear Center (VNC), where testing was performed.

Upon arrival at VNC, the capsules were examined for identification. The drawing number 117C4060G001 Part #6 is stamped on the Browns Ferry Unit 2 30° surveillance capsule basket. The general condition of the basket as received is shown in Figure 3-1. The capsule contained three impact (Charpy) specimen capsules and four tensile specimen capsules. Each tensile specimen capsule contained two tensile specimens. Each Charpy specimen capsule contained 12 plate, weld or HAZ Charpy specimens and 3 flux wires (one iron, one copper, and one nickel) in a sealed helium environment.

3.2 RPV MATERIALS AND FABRICATION BACKGROUND

3.2.1 Fabrication History

The Browns Ferry 2 RPV is a 251 inch diameter BWR/4 design. Construction was performed by Ishikawajima-Harima Heavy Industries Co. (IHI) to the Summer 1965 Addenda of the 1965 edition of the ASME Code. The shell and head plate materials are ASME SA 302, Grade B, MOD. 1339 Class 1 low alloy steel (LAS). The nozzles and closure flanges are ASME SA 508 Class 2. The vessel plates were heat treated as follows:

Run No.	Max Temp.	Min Temp.	Temp. Range	Time	Quench	Run ID
1	1725°F	1675°F	50°F	6 1/2 hrs	BQ	Austenitizing
2	1650°F	1600°F	50°F	6 1/2 hrs	BQ	Austenitizing
3	1225°F	1175°F	50°F	6 1/2 hrs	BQ	Tempering
4-a Surveillance Plate	1150°F	1100°F	50°F	30 hrs	FC	Stress Relief
4-b Lower Shell Course	1150°F	1100°F	50°F	29 hrs 52 min	FC	Stress Relief
4-c Intermediate Shell Course	1150°F	1100°F	50°F	34 hrs 37 min	FC	Stress Relief

BQ - Brine Quenching
FC - Furnace Cooled

3.2.2 Material Properties of RPV at Fabrication

The chemical and mechanical properties of the vessel materials were retrieved from the information documented in the response to 92-01 [9] and the Browns Ferry letter [11]. Table 3-1 shows the chemistry data for the beltline materials. Properties of the beltline materials and other locations of interest are presented in Table 3-2.

3.3 SPECIMEN DESCRIPTION

The surveillance capsule holder contained 36 Charpy specimens: base metal (12), weld metal (12), and HAZ (12). There were 8 tensile specimens: base metal (3), weld metal (2), and HAZ (3). The holder contained 9 flux wires: 3 iron, 3 nickel and 3 copper. The chemistry and fabrication history for the Charpy and tensile specimens are described in this section.

3.3.1 Charpy Specimens

The fabrication of the Charpy specimens is described in the GE purchase specification [8]. All materials used for surveillance were beltline materials.

The base metal specimens were cut from Heat A0981-1. The test plate received the same heat treatment beltline plates, see Section 3.2.1. The Charpy specimens were removed from the test plate and machined as shown in Figure 3-3. Specimens were machined from the 1/4 T and 3/4 T positions in the plate, in the longitudinal orientation (long axis parallel to the rolling direction). The base metal Charpy specimens from the surveillance capsule were stamped as shown in Figure 3-3; the stamp code is taken from GE Drawing Number 921D277.

The weld metal and HAZ Charpy specimens were fabricated by welding together two piece of the surveillance test plate Heat C-2884 and C-2868. The two plates were electroslag-welded (B&W Weld Procedure WR-12-4) and heat treated the same as the core region plates. The weld specimens and HAZ specimens were fabricated as shown in Figures 3-4 and 3-5, respectively. The base metal orientation in the weld and HAZ specimens was longitudinal. The specimens were stamped on one end as shown in Figure 3-3; the stamp code is taken from GE Drawing Number 921D277.

3.3.2 Tensile Specimens

Fabrication of the surveillance tensile specimens is also described in the GE purchase specification [8]. The materials, and thus the compositions and heat treatments for the base, weld and HAZ tensiles are the same as those for the corresponding Charpy specimens. The specimens were stamped on one end as shown in Figure 3-6; the stamp code is taken from GE Drawing Number 921D276.

The base metal specimens were machined from material at the 1/4 T and 3/4 T depth. The specimens, oriented along the plate rolling direction, were machined to the dimensions shown in Figure 3-6. The gage section was tapered to a minimum diameter of 0.250 inch at the center. The weld metal tensile specimen materials were cut from the welded test plates, as shown in Figure 3-7. The specimens were machined entirely from weld metal, scrapping material that might include base metal. The fabrication method for the HAZ tensile specimens is illustrated in Figure 3-8. The specimen blanks were cut from the welded test plates such that the gage section minimum diameters were machined at the weld fusion line. The finished HAZ specimens are approximately half weld metal and half base metal oriented along the plate rolling direction.

TABLE 3-1 CHEMICAL COMPOSITION OF RPV BELTLINE MATERIALS

Identification	Heat/Lot No.	Composition by Weight Percent[a] C	Mn	P	S	Si	Ni	Mo	Cu
Lower Shell Plates:									
6-127-14	C2467-2	0.20	1.36	0.008	0.013	0.20	0.52	0.47	0.16
6-127-15	C2463-1	0.21	1.33	0.008	0.015	0.16	0.48	0.47	0.17
6-127-17	C2460-2	0.21	1.29	0.012	0.014	0.17	0.51	0.45	0.13
Lower-Intermediate Shell Plates:									
6-127-6	A0981-1	0.20	1.35	0.007	0.011	0.19	0.55	0.49	0.14
6-127-16	C2467-1	0.20	1.36	0.008	0.013	0.20	0.52	0.47	0.16
6-127-20	C2849-1	0.21	1.30	0.010	0.015	0.23	0.50	0.46	0.11
Surveillance Plate:	A0981-1	see above for the plate with the same heat number							
Welds:									
Axial[b]	ES Weld	--	--	0.016	--	--	0.35	--	0.28
Circumferential	D55733	0.08	1.70	0.014	0.005	0.40	0.65	0.45	0.09
Surveillance Weld		0.15	1.49	0.010	0.011	0.09	0.33	0.49	0.20

[a] Data from the 92-01 response [9] except where noted.

[b] Letter from J.Valente to T.R.Mcintyre [11]

TABLE 3-2 MECHANICAL PROPERTIES OF BELTLINE AND OTHER SELECTED RPV MATERIALS

Location	ID. No.	Heat Number	Initial RT_{NDT} (°F)
Beltline[a & b]:			
Lower Shell Plates	6-127-14	C2467-2	-20°F
	6-127-15	C2463-1	-20°F
	6-127-17	C2460-2	0°F
Lower Intermediate Shell Plates	6-127-6	A0981-1	-10°F
	6-127-16	C2467-1	-10°F
	6-127-20	C2849-1	-10°F
Welds:			
Longitudinal	ESW	--	10°F
Circumferential	D55733		-40°F
Non-Beltline[a & b]:			
Head Dome		B5524-2	+10
Top Head Flange		AKU75	+10
Closure Head Segment		C2426-2	+10
		C2426-3	+10
		C1717-3	+10
		C1722-3	+10
Bottom Head Dome		C-2669-2	+42
Bottom Head Upper Torus		B-6747-1	+40
		B-6776-2	+40
		C-2369-1	+40
Jet Pump Nozzle		214484	+54

[a] Test data information from GE-NE-523-A65-0594 [15]

[b] CMTRs

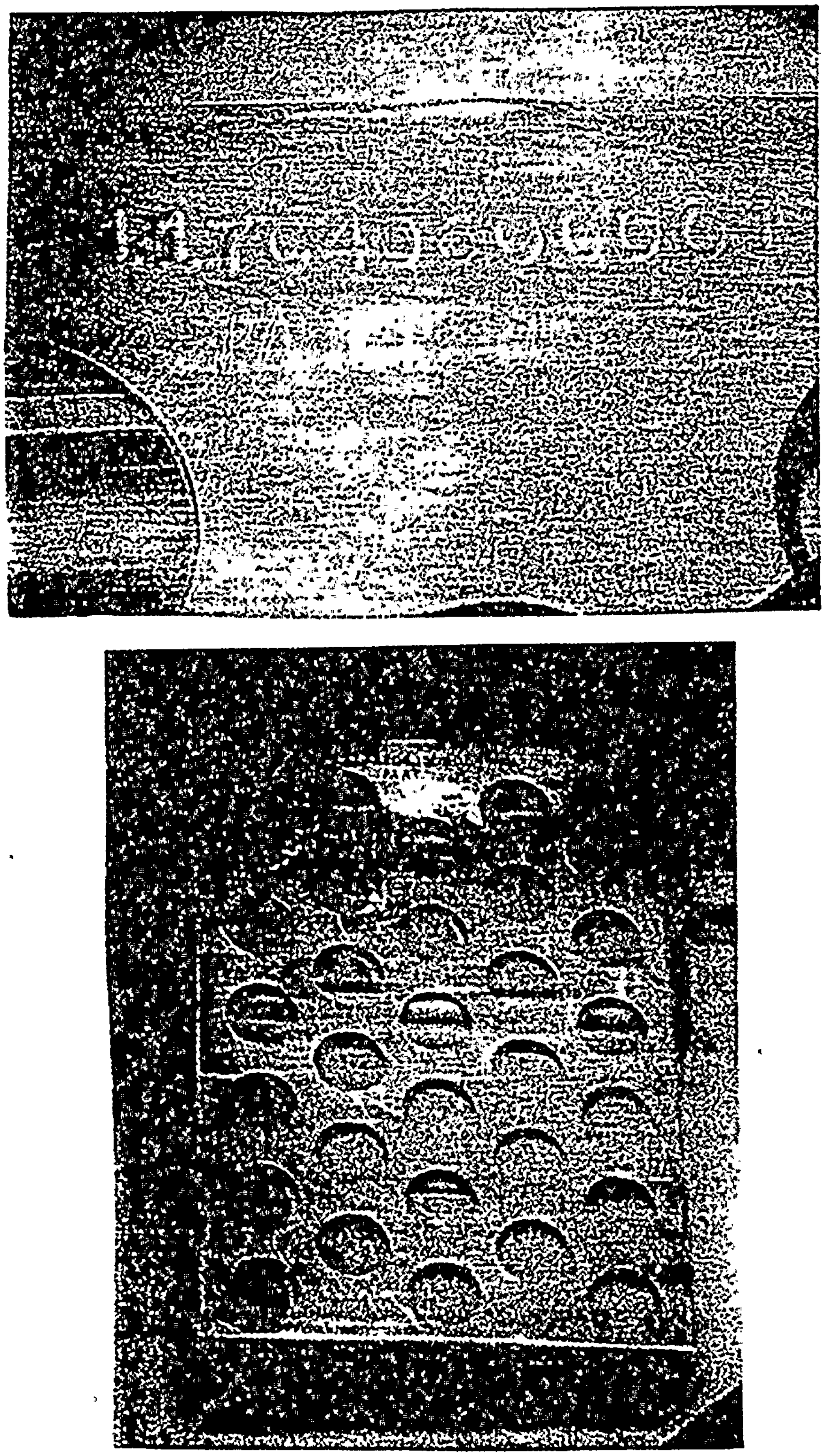


FIGURE 3-1. SURVEILLANCE CAPSULE HOLDER RECOVERED FROM BROWNS FERRY UNIT 2

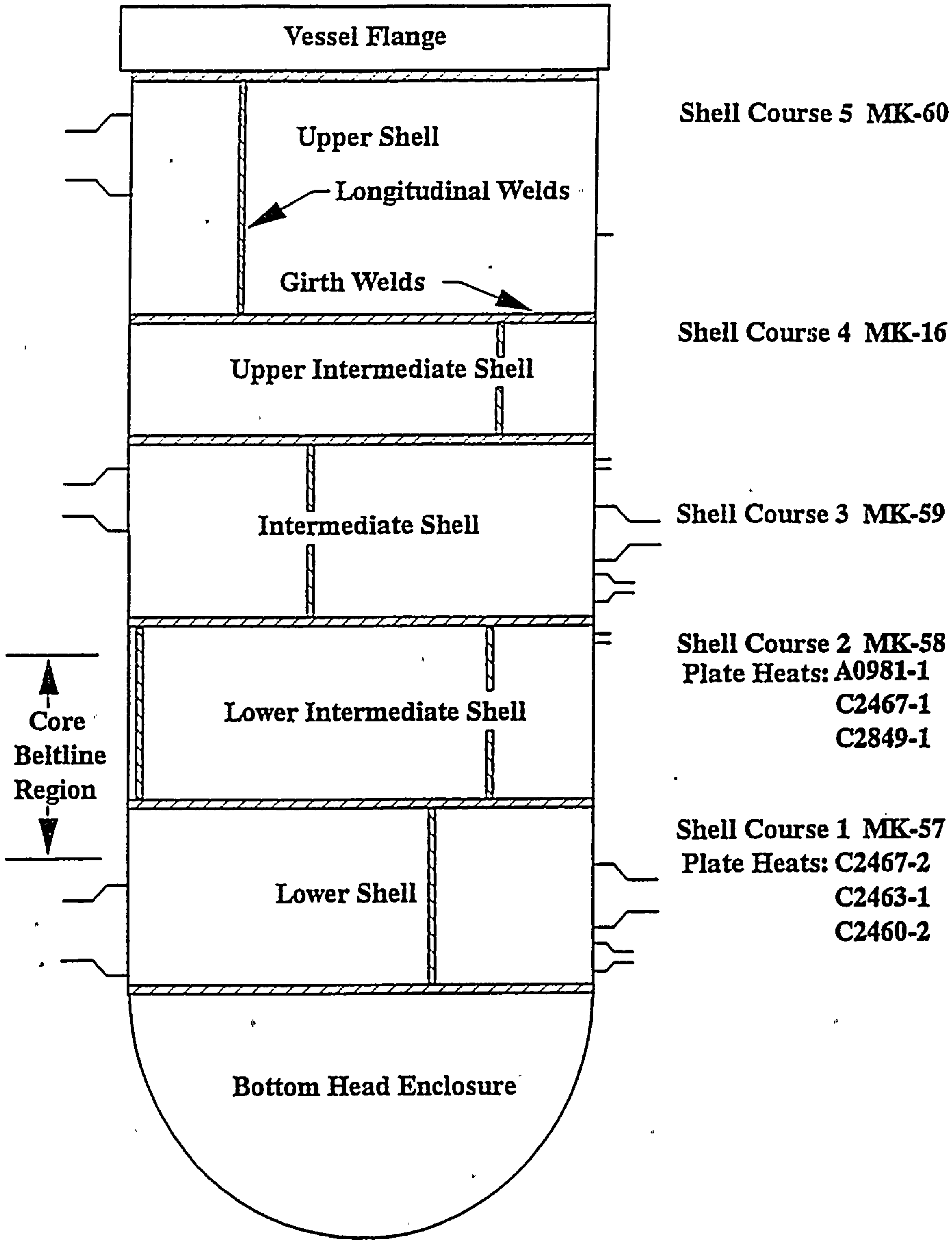


FIGURE 3-2. SCHEMATIC OF THE RPV SHOWING IDENTIFICATION OF VESSEL BELTLINE PLATES AND WELDS

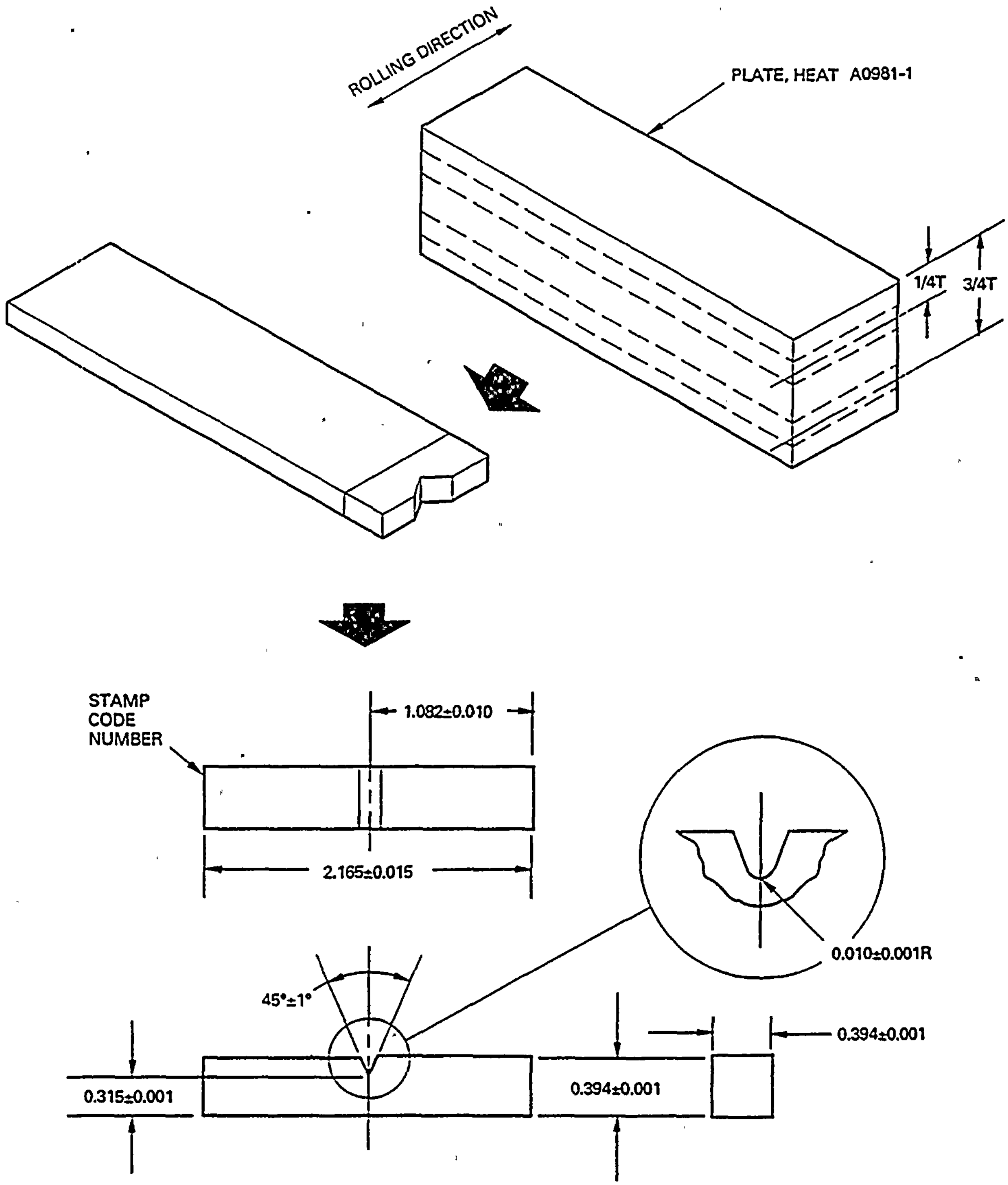


FIGURE 3-3. FABRICATION METHOD FOR BASE METAL CHARPY SPECIMENS

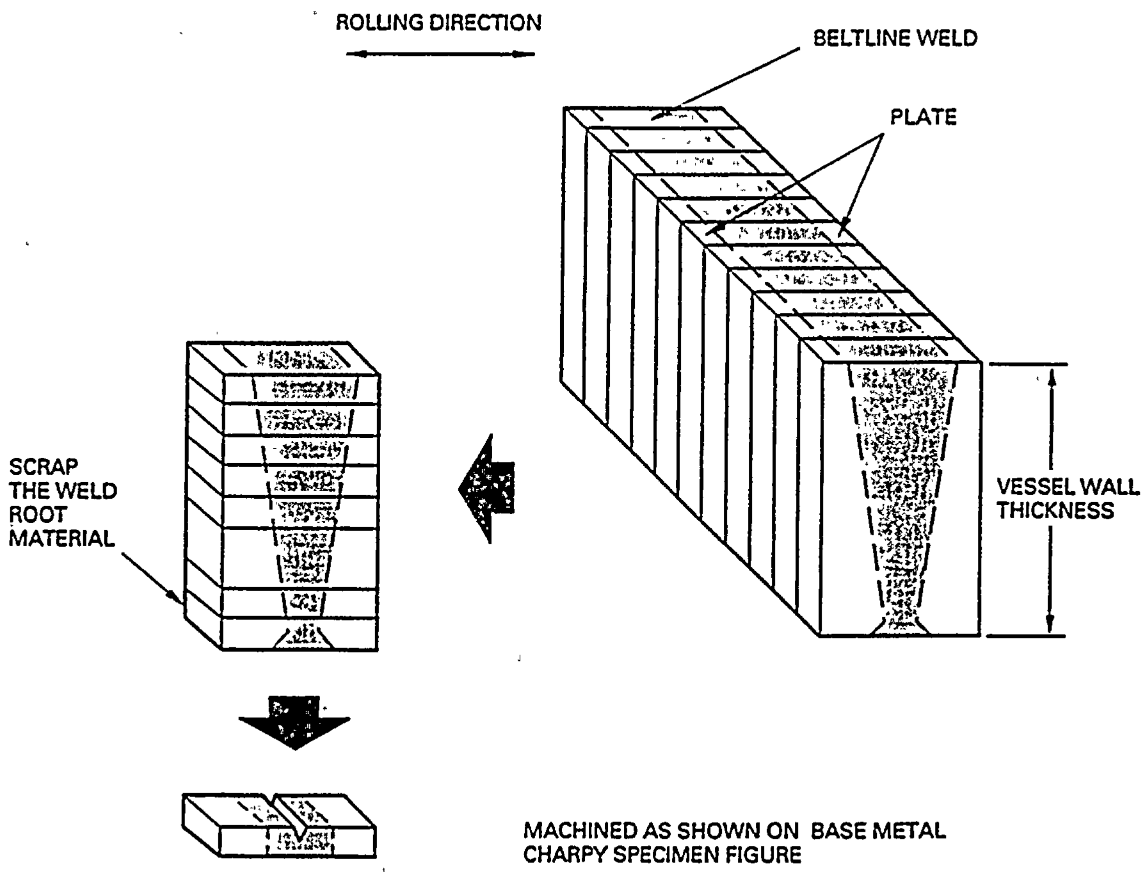


FIGURE 3-4. FABRICATION METHOD FOR WELD METAL CHARPY SPECIMENS

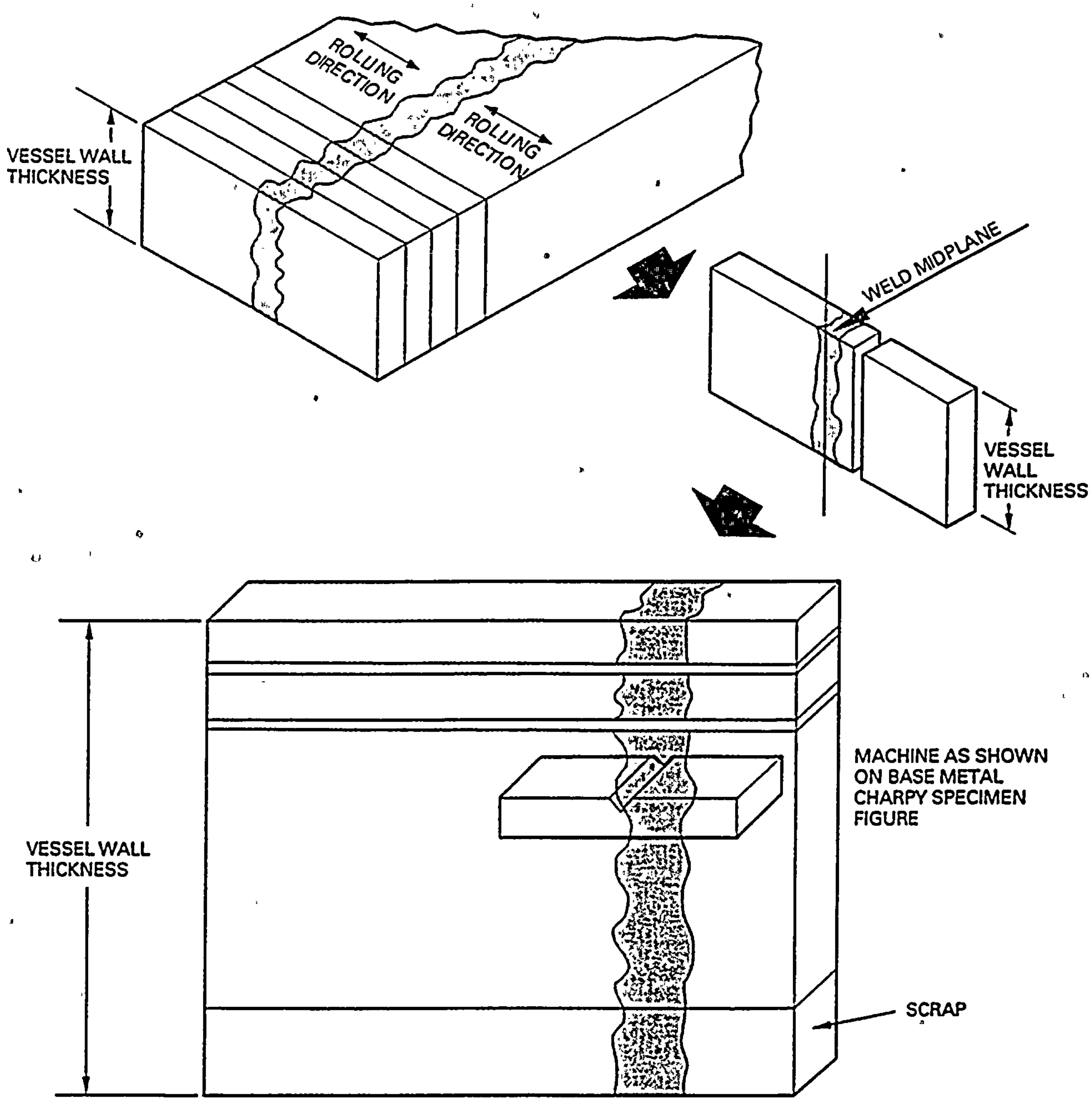


FIGURE 3-5. FABRICATION METHOD FOR HAZ METAL CHARPY SPECIMENS

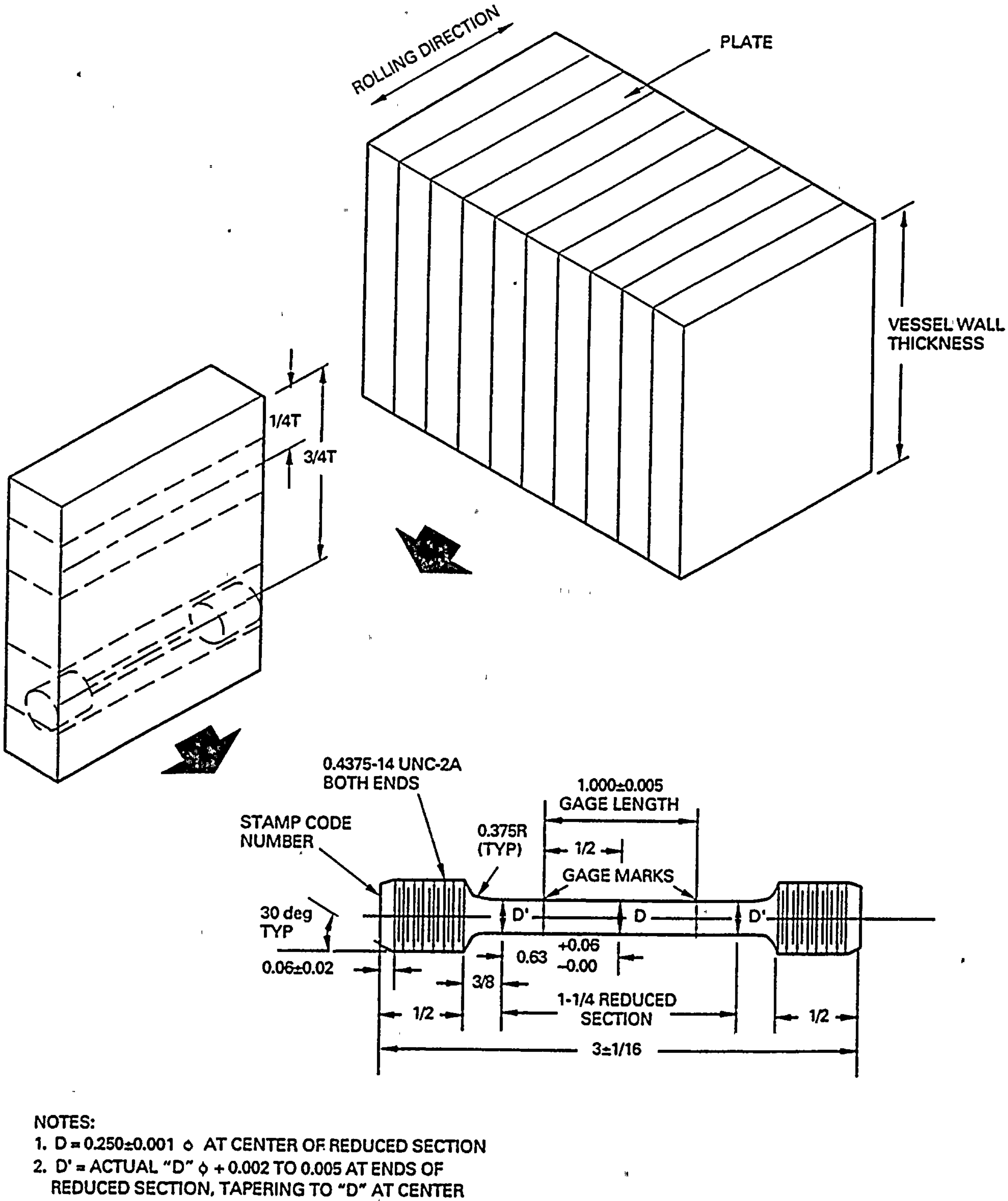


FIGURE 3-6. FABRICATION METHOD FOR BASE METAL TENSILE SPECIMENS

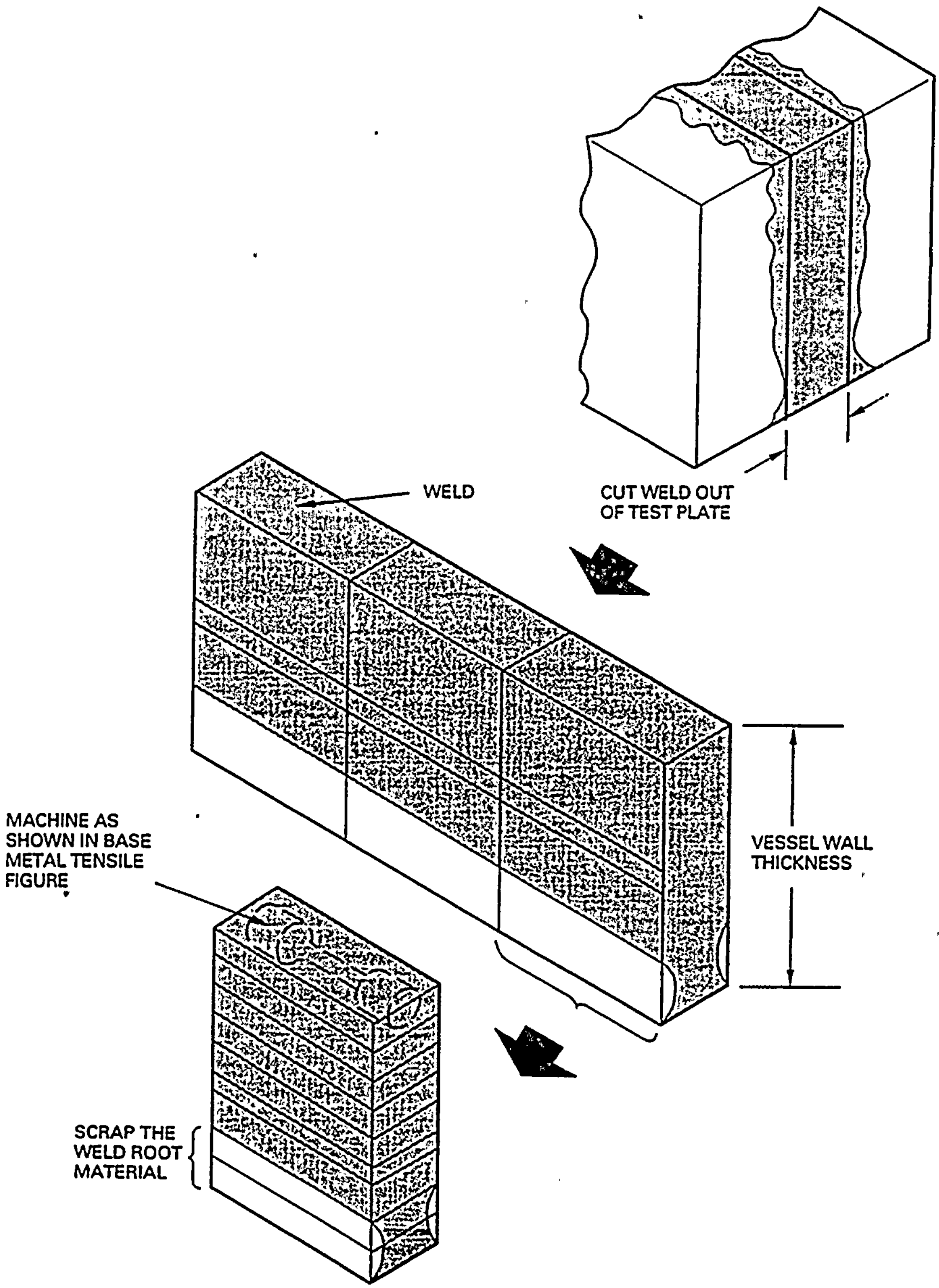


FIGURE 3-7. FABRICATION METHOD FOR WELD METAL TENSILE SPECIMENS

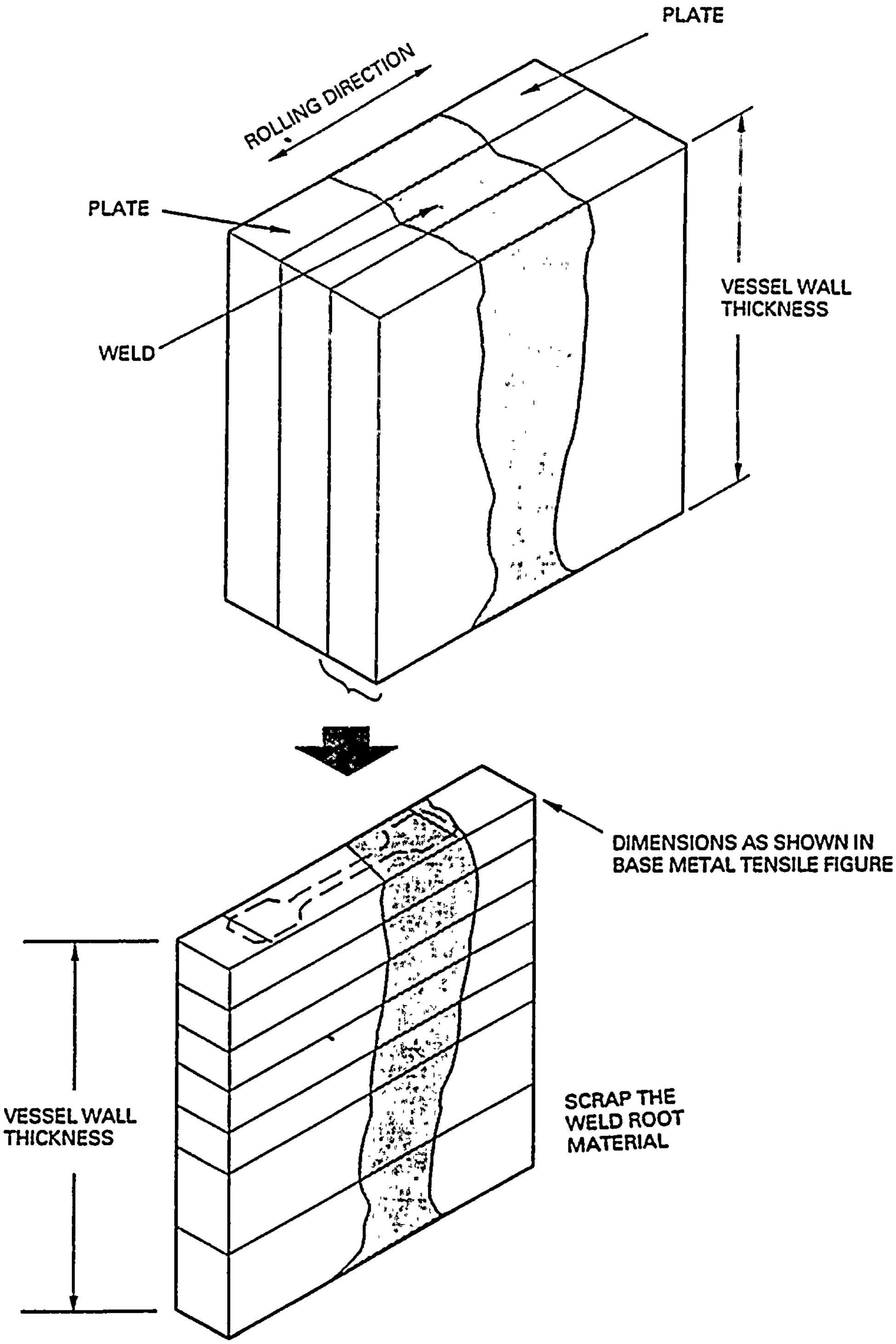


FIGURE 3-8. FABRICATION METHOD FOR HAZ METAL TENSILE SPECIMENS

4. PEAK RPV FLUENCE EVALUATION

Flux wires removed from the 30° capsule were analyzed, as described in Section 4.1, to determine flux and fluence received by the surveillance capsule. The lead factor, determined as described in Section 4.2, was used to establish the peak vessel fluence from the flux wire results. Section 4.3 includes 32 EFPY peak fluence estimates.

4.1 FLUX WIRE ANALYSIS

4.1.1 Procedure

The surveillance capsule contained 9 flux wires: 3 iron, 3 copper, and 3 nickel. Each wire was removed from the capsule, cleaned with dilute acid, weighed, mounted on a counting card, and analyzed for its radioactivity content by gamma spectrometry. Each iron wire was analyzed for Mn-54 content, each nickel wire for Co-58 and each copper wire for Co-60 at a calibrated 4-cm or 10-cm source-to-detector distance with 100-cc Ge(Li) and 170-cc Ge detector systems.

To properly predict the flux and fluence at the surveillance capsule from the activity of the flux wires, the periods of full and partial power irradiation and the zero power decay periods were considered. Operating days for each fuel cycle and the reactor average power fraction are shown in Table 4-1. Zero power days between fuel cycles are listed as well.

From the flux wire activity measurements and power history, reaction rates for Fe-54 (n,p) Mn-54, Cu-63 (n,α) Co-60 and Ni-58 (n,p) Co-58 were calculated. The E >1 MeV fast flux reaction cross sections were determined from past testing at Browns Ferry 3 [10], also a 251 inch, 764 bundle plant, using multiple dosimeter and spectrum unfolding techniques. The cross sections for the iron, copper and nickel wires are 0.213 barn, 0.00374 barn and 0.274 barn, respectively. These values are consistent with other measured cross section functions determined at GE's Vallecitos Nuclear Center from more than 65 spectral determinations for BWRs and for the General Electric Test Reactor using activation monitors and spectral unfolding techniques. These data functions are applied to BWR pressure vessel locations based on water gap (fuel to vessel wall) distances. The cross sections for E >0.1 MeV flux were determined from the measured 1-to-0.1 MeV cross section ratio of 1.6.

4.1.2 Results

The measured activity, reaction rate and full-power flux results for the 30° surveillance capsule are given in Table 4-2. The E >1 MeV flux values were calculated by dividing the wire reaction rate measurements by the corresponding cross sections, factoring in the local power history for each fuel cycle. The fluence result, 1.52×10^{17} n/cm^2 (E >1 MeV) was obtained by multiplying the full-power flux value for copper, iron, and nickel by the operating time and full power fraction, shown in Table 4-1.

The accuracies of the values in Tables 4-2 for a 2σ deviation are estimated to be:

$\pm$ 5% for dps/g (disintegrations per second per gram)
$\pm$ 10% for dps/nucleus (saturated)
$\pm$ 20% for flux and fluence E >1 MeV
$\pm$ 20% for flux and fluence E >0.1 MeV

4.2 DETERMINATION OF LEAD FACTOR

The flux wires detect flux the location of the surveillance capsule. The wires will reflect the power fluctuations associated with the operation of the plant. However, the flux wires are not at the location of peak vessel flux. A lead factor is required to relate the flux at the wires' location to the peak flux. The lead factor is the ratio of the flux at the surveillance capsule to the flux at the peak vessel inside surface location. The lead factor is a function of the core and vessel geometry and of the distribution of power density and voids in the core. The lead factor was generated for the Browns Ferry geometry, using a typical fuel cycle to determine power shape and void distribution. The methods used to calculate the lead factor are discussed below.

4.2.1 Procedure

Determination of the lead factor for the RPV inside wall was made using a combination of two separate two-dimensional neutron transport computer analyses. The first of these established the azimuthal and radial variation of flux in the vessel at the fuel midplane elevational.

established the azimuthal and radial variation of flux in the vessel at the fuel midplane elevational. The second analysis determined the relative variation of flux with elevation. The azimuthal and axial distribution results were combined to provide the ratio of flux, or the lead factor, between the surveillance capsule location and the peak flux locations.

The DORT computer program, which utilizes the discrete ordinates method to solve the Boltzmann transport equation in two dimensions, was used to calculate the spatial flux distribution produced by a fixed source of neutrons in the core region. The azimuthal distribution was obtained with a model specified in (R,θ) geometry, assuming eighth-core symmetry with reflective boundary conditions at 0° and 45°. Calculations were performed using neutron cross-sections from a 26 energy group set, with angular dependence of the scattering cross-sections approximated by a third-order Legendre polynomial expansion.

A schematic of the (R,θ) vessel model is shown in Figure 4-1. A total of 132 radial intervals and 90 azimuthal intervals were used. The model consists of an inner and outer core region, the shroud, water regions inside and outside the shroud, and the vessel wall. The core region material compositions and neutron source densities were representative of conditions at an elevation 75 inches above the bottom of active fuel, which is near the elevation of the wires. Flux as a function of azimuth and radius was calculated in order to establish the azimuth of the peak flux and its magnitude relative to the flux at the wires' location of 30°.

The calculation of the axial flux distribution was performed in (R,Z) geometry, using a simplified cylindrical representation of the core configuration and realistic simulations of the axial variations of power density and coolant mass density. The core description was based on conditions near the azimuth angle of 25° where the edge of the core is closest to the vessel wall. The elevation of the peak flux was determined, as well as its magnitude relative to the flux at the surveillance capsule elevation.

4.2.2 Results

The two-dimensional computations indicate the flux to be a maximum 25.75° past the RPV quadrant references (0°, 90°, etc.), at an elevation about 77 inches above the bottom of active fuel. The peak closest to the 30° location of the surveillance capsule removed is at 25.75°, as shown in Figure 4-2. The relative flux distribution versus elevation is shown in Figure 4-3. The calculated flux at the capsule (R,θ) position along the midplane was modified by an position. The resulting surveillance capsule flux is 8.8×10^8 n/cm^2-s. The peak flux at vessel surface from the transport calculation, incorporating the axial adjustment factor obtained from the (R,Z) calculation is 9.0×10^8 n/cm^2-s. Therefore the lead factor is 8.8/9.0=0.98.

The transport calculation of surveillance capsule flux, 8.8×10^8 n/cm^2-s, is about 49% higher than the dosimetry result of 5.9×10^8 n/cm^2-s. This is attributed to conservatism incorporated in the transport calculation model and may, in part, result from the use of nominal rather than as-built radius. A difference in vessel radius has little, if any, effect on the calculated lead factor. since the difference would affect both capsule radius and vessel radius and would not significantly alter the ratio of fluxes at the two locations.

The fracture toughness analysis is based on a 1/4 T depth flaw in the beltline region, so the attenuation of the flux to that depth is considered. This attenuation is calculated according to Reg. Guide 1.99 requirements, as shown in the next section.

4.3 ESTIMATE OF 32 EFPY FLUENCE

The inside surface fluence (f_{surf}) at 32 EFPY is determined from the flux wire fluence for 8.2 EFPY of 1.52×10^{17} n/cm^2, using the lead factor of 0.98. The time period 32 EFPY is based on 40-year operation at an 80% capacity factor. The resulting 32 EFPY fluence value at the peak vessel inside surface is:

$$f_{surf} = 1.52\times10^{17}*(32/8.2)/0.98$$

$$f_{surf} = 6.05\times10^{17}\ \text{n/cm}^2$$

The peak inside surface fluence of 6.05×10^{17} n/cm^2 is about 43% lower than that used in previous analyses (1.1×10^{18} n/cm^2) [11]. Therefore, the previous numbers were quite conservative.

The 1/4 T fluence (f) is calculated according to the following equation from Reg. Guide 1.99 [7]:

$$f = f_{surf}(e^{-0.24x}) \tag{4-1}$$

where x = distance, in inches, to the 1/4 T depth.

For a vessel beltline lower-intermediate shell and lower shell of 6.13 inches thick, the corresponding depth x is 1.53 inches. Equation 4-1 evaluated for these values of x gives:

$$f = 0.6923\ f_{surf}, \text{ or } f = 4.19 \times 10^{17}\ n/cm^2$$

The impact of these revised fluences on the P-T curves is discussed in Section 7.

TABLE 4-1 SUMMARY OF DAILY POWER HISTORY

Cycle	Cycle Dates	Operating Days	Full Power Fraction	Days Between Cycles
1	7/20/74 - 3/18/78	1338	0.355	
2	4/28/78 - 4/27/79	365	0.723	41
3	6/1/79 - 9/30/80	488	0.759	34
4	11/1/80 - 7/31/82	638	0.784	31
5	3/18/83 - 9/15/84	548	0.759	229
6	7/1/91 - 1/31/93	581	0.849	2478
7	5/31/93 - 10/1/94	489	0.972	121
		4447 (total)	0.743 (average)	

TABLE 4-2 SURVEILLANCE CAPSULE FLUX AND FLUENCE FOR IRRADIATION FROM START-UP TO 10/1/94

Wire (Element)	dps/g Element* (at end of Irradiation)	Reaction Rate [dps/nucleus (saturated)]	Full Power Flux [a] (n/cm^2-s) E >1 MeV	Fluence (n/cm^2) E >1 MeV	Fluence (n/cm^2) E >0.1 MeV
Iron	6.05E+04	1.23E-16	5.80E+08	1.49E+17	2.39E+17
Nickel	1.07E+06	1.67E-16	6.11E+08	1.57E+17	2.52 E+17
Copper	5.62 E+03	2.15 E-18	5.75 E+08	1.48E+17	2.37 E+17
Average				1.52E+17	2.43E+17

[a] Full power flux, based on thermal power of 3293 Mw_t

* Average values of the tests reported.

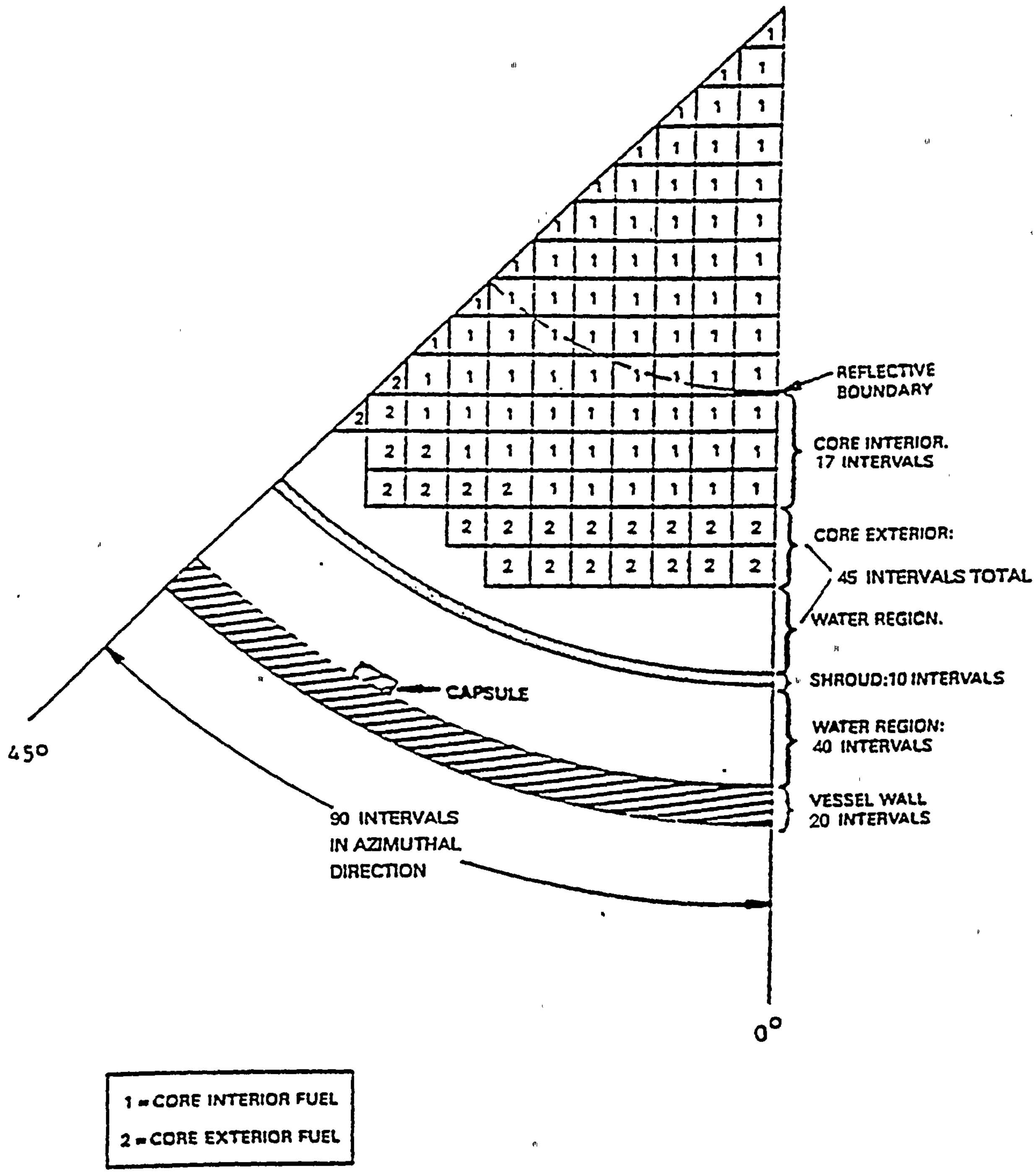


FIGURE 4-1. SCHEMATIC OF MODEL FOR AZIMUTHAL FLUX DISTRIBUTION ANALYSIS

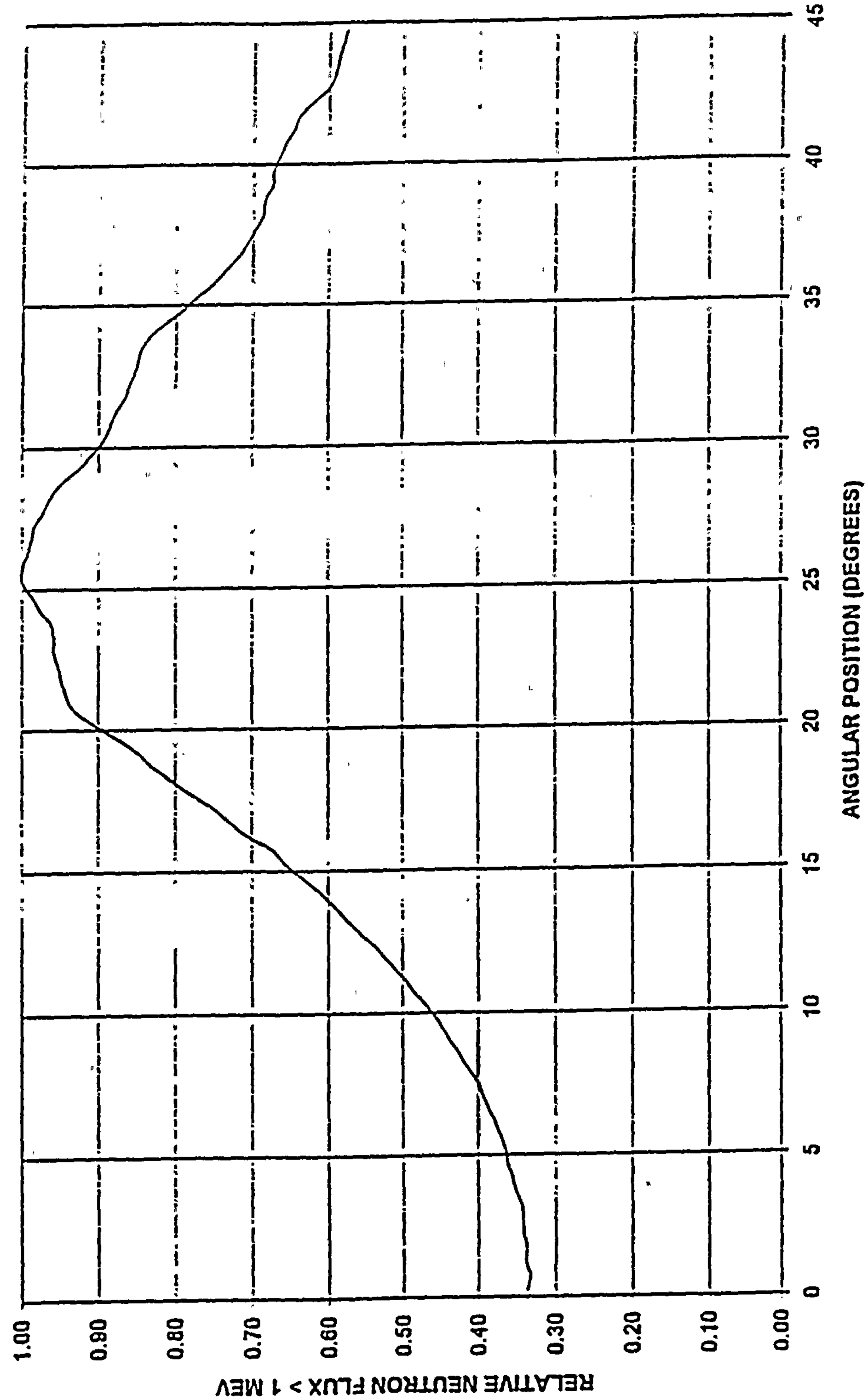


FIGURE 4-2. RELATIVE VESSEL FLUX VARIATION WITH ANGULAR POSITION

FIGURE 4-3
RELATIVE FLUX VS. ELEVATION

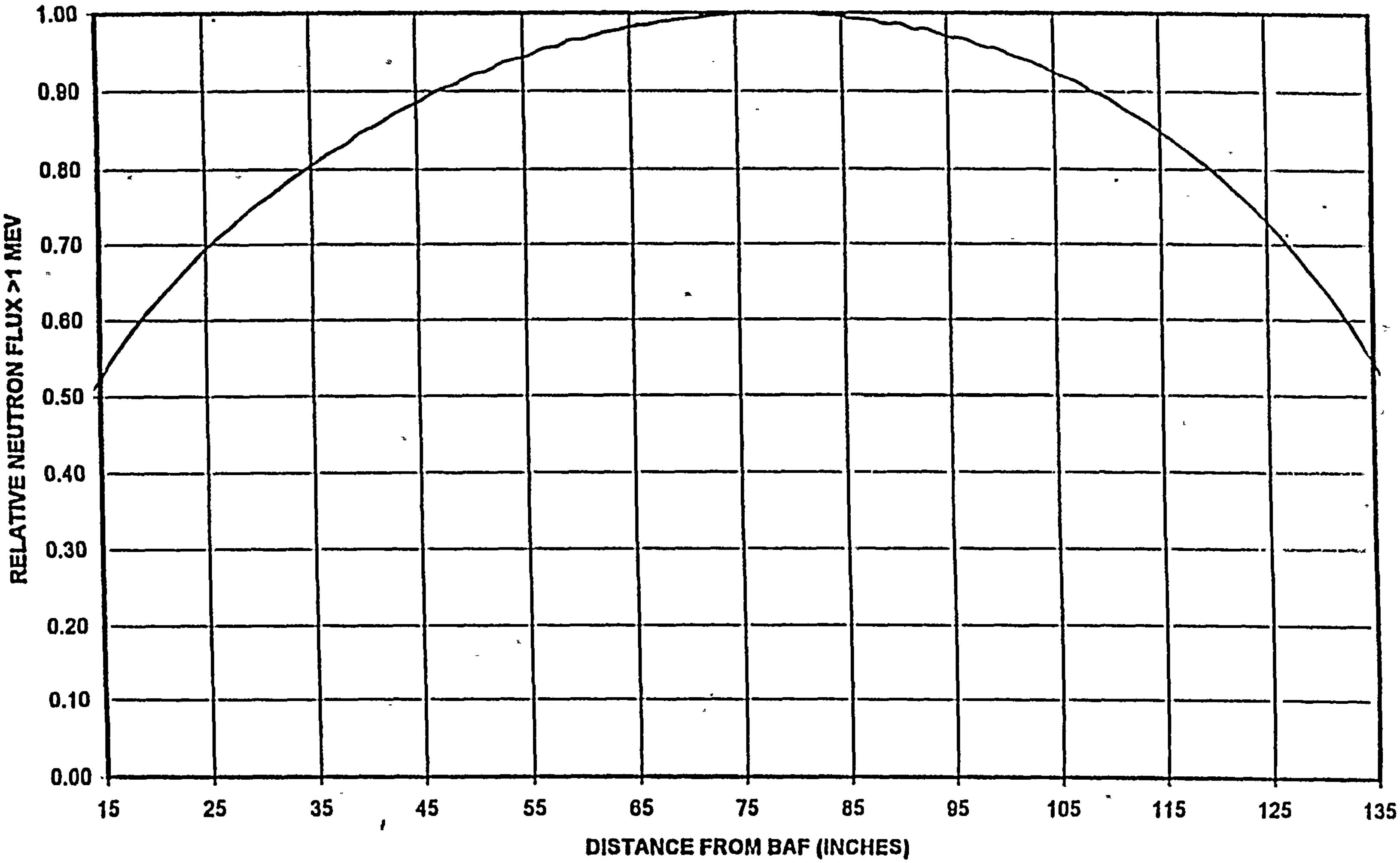


FIGURE 4-3. RELATIVE VESSEL FLUX VARIATION WITH ELEVATION

5. CHARPY V-NOTCH IMPACT TESTING

The 36 Charpy specimens recovered from the surveillance capsule were impact tested at temperatures selected to establish the toughness transition and upper shelf of the irradiated RPV materials. In addition, unirradiated base, weld, and HAZ metal specimens recovered from the Browns Ferry site were tested for baseline data. Testing was conducted in accordance with ASTM E23-88 [12].

5.1 IMPACT TEST PROCEDURE

The Vallecitos testing machine used for irradiated and unirradiated specimens was a Riehle Model PL-2 impact machine, serial number R-89916. The pendulum has a maximum velocity of 15.44 ft/sec and a maximum available hammer energy of 240 ft-lb.

The test apparatus and operator were qualified using NIST standard reference material specimens. The standards consist of sets of high and low energy specimens, each designed to fail at a specified energy at the standard test temperature of -40°F. According to ASTM E23-88 [12], the test apparatus averaged results must reproduce the NIST standard values within an accuracy of ±5% or ±1.0 ft-lb, whichever is greater. The qualification of the Riehle machine and operator is summarized in Table 5-1. The calibration tests are valid for one year.

Charpy V-Notch tests were conducted at temperatures between -80°F and 300°F. The cooling fluid used for both irradiated and unirradiated specimens tested at temperatures below 70°F was ethyl alcohol. At temperatures between 70°F and 200°F, water was used as the temperature conditioning fluid. The specimens were heated in silicon oil above 200°F. Cooling of the conditioning fluids was done by heat exchange with liquid nitrogen; heating was done by an immersion heater. The bath of fluid was mechanically stirred to maintain uniform temperatures. The fluid temperature was measured with a calibrated thermocouple. Once at test temperature, the specimens were manually transferred with centering tongs to the Charpy test machine and impacted within 5 seconds.

For each Charpy V-Notch specimen the test temperature, energy absorbed, lateral expansion, and percent shear were evaluated. In addition, for the irradiated specimens, photographs were taken of fracture surfaces. Lateral expansion and percent shear were measured

according to specified methods [12]. Percent shear was determined using method number 1 of Subsection 11.2.4.3 of ASTM E23-88 [12], which involves measuring the length and width of the fracture surface and determining the percent shear value from Table 2 of ASTM E23-88 [12].

5.2 IMPACT TEST RESULTS

Twelve Charpy V-Notch specimens each of irradiated base, weld, and HAZ material were tested at temperatures (-80°F to 300°F) selected to define the toughness transition and upper shelf portions of the fracture toughness curves. The absorbed energy, lateral expansion, and percent shear data are listed for each material in Table 5-2. Plots of absorbed energy data for base and weld materials are presented in Figures 5-2 and 5-7, respectively. Plots of absorbed energy and lateral expansion data for HAZ material, Figures 5-12 and 5-14, did not fit a hyperbolic curve because of the scatter in the data. Lateral expansion plots for base and weld materials are presented in Figures 5-5 and 5-10, respectively. The irradiated curves are plotted along with their corresponding unirradiated curves in Figures 5-3 and 5-8. The fracture surface photographs and a summary of the test results for each specimen are contained in Appendix A.

Twelve Charpy V-Notch specimens each of unirradiated base, weld and HAZ material were tested at temperatures (-80°F to 300°F) selected to define the toughness transition and upper shelf portion of the fracture toughness curves. The absorbed energy, lateral expansion, and percent shear data are listed in Table 5-3. Plots of absorbed energy data for base and weld metals are presented in Figures 5-1 and 5-6, respectively. Lateral expansion plots for base and weld metals are presented in Figures 5-4 and 5-9, respectively. Plots of absorbed energy and lateral expansion data for HAZ material, Figures 5-11 and 5-13, did not fit a hyperbolic curve because of the scatter in the data.

The plate and weld data sets are fit with the hyperbolic tangent function developed by Oldfield for the EPRI Irradiated Steel Handbook [13]:

$$Y = A + B * \mathrm{TANH}\,[(T - T_0)/C],$$

where Y = impact energy or lateral expansion
T = test temperature, and
A, B, T_0 and C are determined by non-linear regression.

The TANH function is one of the few continuous functions with a shape characteristic of low alloy steel fracture toughness transition curves. Typically the curve fits were generated by setting both shelves free with a default lower shelf energy of 5 ft-lbs or lateral expansion of 4 mils.

5.3 IRRADIATED VERSUS UNIRRADIATED CHARPY V-NOTCH PROPERTIES

As a part of the RPV surveillance test program, extra Charpy V-Notch specimens were fabricated and delivered to the site. Specimens were recovered from storage at the site and forwarded to GE for impact testing. This was done because GE had no records of unirradiated baseline test results for this surveillance program.

The irradiated and unirradiated Charpy V-Notch data curves were used to estimate the values given in Table 5-4: 30 ft-lb, 50 ft-lb and 35 MLE index temperatures, and the USE for the sets of base and weld metal irradiated material data and for the base and weld metal unirradiated material data. Transition temperature shift values are determined as the change in the temperature at which 30 ft-lb impact energy is achieved, as required in ASTM E185-82 [6]. The resulting shifts in Charpy curves are discussed in the next section.

5.4 COMPARISON TO PREDICTED IRRADIATION EFFECTS

5.4.1 Irradiation Shift

The measured transition temperature shifts for the plate and weld materials were compared to the predictions calculated according to Regulatory Guide 1.99, Revision 2 [7]. The inputs and calculated values for irradiated shift are as follows:

Plate:
- Copper = 0.14%
- Nickel = 0.55%
- CF = 98
- fluence = 1.52×10^{17} n/cm^2
- Reg. Guide 1.99 ΔRT_{NDT} = 14°F
- Reg. Guide 1.99 $\Delta RT_{NDT} \pm 2\sigma_\Delta$(34°F) = 48°F max., -20°F min.
- Measured Shift = 37.9 °F

Weld:	Copper =	0.20%
	Nickel =	0.33%
	CF =	120
	fluence =	$1.52\text{x}10^{17}$ n/cm^2
	Reg. Guide 1.99 ΔRT_{NDT} = 17°F	
	Reg. Guide 1.99 $\Delta RT_{NDT} \pm 2\sigma_{\Delta}$(56°F) = 73°F max., -39°F min.	
	Measured Shift = 1.3°F	

The weight percents of Cu and Ni are based on Table 3-1. CF shown above is the chemistry factors from Tables 1 or 2 of Reg. Guide 1.99. The fluence factor is 0.141. The measured shift of 37.9°F for the plate is above the predicted shifts of 14°F and measured shift of 1.3°F for the weld is below the predicted shift of 17°F. The measured shifts for the plate and weld are within the bounds (-20°F to 48°F for the plate material and -39°F to 73°F for the weld material; respectively) of the Reg. Guide 1.99 uncertainty of 2σ.

5.4.2 Change in USE

Using the copper and fluence data above with Figure 2 of Reg. Guide 1.99, decreases in USE of 9% are predicted for the plate and decreases in USE of 13% are expected for the weld. The measured decrease in the USE value of 4% for the plate is below the predicted value. The weld material shows essentially no change in the USE value, which is less than the 13% decrease in USE predicted by the Reg. Guide 1.99.

TABLE 5-1 VALLECITOS QUALIFICATION TEST RESULTS USING NIST STANDARD REFERENCE SPECIMENS

	Specimen Identification	Bath Medium	Test Temperature (°F)	Energy Absorbed (ft-lb)	Acceptable Range (ft-lb)
Vallecitos Riehle Machine (tested 6/28/94)	HH-40 229	Alcohol	-40	75.0	
	HH-40 384	Alcohol	-40	74.5	
	HH-40 980	Alcohol	-40	70.5	
	HH-40 1152	Alcohol	-40	72.5	
	HH-40 1172	Alcohol	-40	75.0	
			Average	73.5	74.9 ± 3.7 pass
	LL-39 080	Alcohol	-40	13.5	
	LL-39 095	Alcohol	-40	13.0	
	LL-39 631	Alcohol	-40	13.5	
	LL-39 775	Alcohol	-40	13.5	
	LL-39 930	Alcohol	-40	13.0	
			Average	13.3	13.2 ± 1.0 pass

TABLE 5-2 IRRADIATED CHARPY V-NOTCH IMPACT TEST RESULTS

	Specimen Identification	Test Temperature (°F)	Fracture Energy (ft-lb)	Lateral Expansion (mils)	Percent Shear (Method 1) (%)
Base: Heat A0981-1, Longitudinal, f=1.52x10^{17} n/cm²	E5C	-80	10.5	10.0	3
	E5Y	-40	17.0	13.5	11
	E7Y	-20	33.0	30.5	13
	E7K	0	38.5	33.0	19
	E71	40	60	50	40
	E7D	60	82.5	61.0	59
	E64	80	94.5	70.0	68
	E5U	100	121.0	91.0	85
	E72	120	120.5	88.0	100
	E51	160	130.0	91.0	100
	E57	200	136.0	94.0	100
	E55	300	131.5	88.0	100
Weld: Heats D55733 f=1.52x10^{17} n/cm²	EB7	-80	2.0	5.0	2
	EB5	-40	13.0	12.5	4
	EBK	-20	37.5	31.0	9
	EAP	0	50.0	42.0	15
	EBD	20	59.5	52.0	22
	EBB	40	59.5	50.0	30
	EB1	80	59.0	52.0	42
	EAM	100	76.5	64.5	50
	EBE	120	87.0	65.0	68
	EB4	160	107.0	87.0	100
	EB2	200	107.5	84.5	100
	EBA	300	113.0	88.5	100
HAZ: f=1.52x10^{17} n/cm²	ED6	-80	3.5	6.0	1
	EJ3	-60	37.0	30.0	12
	EEY	-40	54.0	44.0	24
	EDB	-20	30.0	22.5	7
	EJJ	0	43.5	36.5	19
	EJ5	20	106.0	81.5	65
	EJC	40	93.5	67.0	48
	EJ1	60	107.5	86.0	75
	EDC	80	82.0	73.0	60
	EJB	120	97.5	78.0	100
	EJD	200	107.5	82.0	100
	EEC	300	143.0	92.0	100

TABLE 5-3 UNIRRADIATED CHARPY V-NOTCH IMPACT TEST RESULTS

	Specimen Identification	Test Temperature (°F)	Fracture Energy (ft-lb)	Lateral Expansion (mils)	Percent Shear (Method 1) (%)
Base:	E5J	-80	8.5	5.5	2
Heat A0981-1	E7A	-60	17.5	14	9
Longitudinal	E61	-40	35.5	29	17
	E66	-20	40	37	19
	E7M	0	97	69	47
	E56	20	68	56	37
	E6U	40	73	56	47
	E76	80	104.5	77	86
	E77	100	137	89	100
	E7L	120	134.5	93.5	100
	E5E	200	146.5	90	100
	E6T	300	133	84	100
Weld:	ED6	-80	3.5	6	1
Heats D55733	EJ3	-60	37	30	12
	EEY	-40	54	44	24
	EDB	-20	30	22.5	7
	EJJ	0	43.5	36.5	19
	EJ5	20	106	81.5	67
	EJC	40	93.5	67	48
	EJ1	60	107.5	86	76
	EDC	80	82	73	60
	EJB	120	97.5	78	100
	EJD	200	107.5	82	100
	EEC	300	143	92	100
HAZ:	ED4	-80	13	11.5	3
	EDD	-60	44	34.5	12
	EE1	-40	53	42.5	25
	ED7	-20	25.5	24.5	30
	EE7	0	104.5	79	55
	EDE	40	120.5	84	74
	EJ4	60	121.5	74.5	84
	EEB	80	139.5	88.5	100
	EE5	100	130	88	100
	ED2	120	121	92	100
	EDL	200	126.5	88	100
	EDM	300	110.5	89	100

TABLE 5-4 SIGNIFICANT RESULTS OF IRRADIATED AND UNIRRADIATED CHARPY V-NOTCH DATA

Material	Index Temperature (°F) E=30 ft-lb	Index Temperature (°F) E=50 ft-lb	Index Temperature MLE=35 mil	Upper Shelf[a] Energy (ft-lb)
PLATE: Heat A0981-1, Longitudinal $f=1.52\times10^{17}$ n/cm²				
Unirradiated	-48.4	-14.1	-25.2	141.8/92.1
Irradiated	-10.5	21.8	8.2	135.5/88.1
Difference	37.9	35.9	33.4	6.3/4.0 (4%)

Reg. Guide 1.99, Rev 2 ΔRT_{NDT}[b]: 14 1.99, Rev 2 % Decrease in USE[c]: (9%)
Reg. Guide 1.99, Rev 2 ($\Delta \pm 2\sigma$)[b]: **-20 to 48**

Material	Index Temperature (°F) E=30 ft-lb	Index Temperature (°F) E=50 ft-lb	Index Temperature MLE=35 mil	Upper Shelf[a] Energy (ft-lb)
WELD: Heat D55733 $f=1.52\times10^{17}$ n/cm²				
Unirradiated	-26.9	10.9	-7.7	112.0
Irradiated	-25.6	26.8	2.8	115.3
Difference	1.3	15.9	10.5	-3.3 (-3%)

Reg. Guide 1.99, Rev 2 ΔRT_{NDT}[b]: 17 1.99, Rev 2 % Decrease in USE[c]: (13%)
Reg. Guide 1.99, Rev 2 ($\Delta \pm 2\sigma$)[b]: **-39 to 73**

---

[a] USE values from **Longitudinal/Transverse** oriented Charpies; values are equal for weld metal.
Longitudinal USE from data shown in Figure 5-2.
Transverse plate USE is taken as 65% of the longitudinal USE, per USNRC MTEB 5-2 [16].

[b] Determined in section 5.4.1

[c] See section 5.4.2

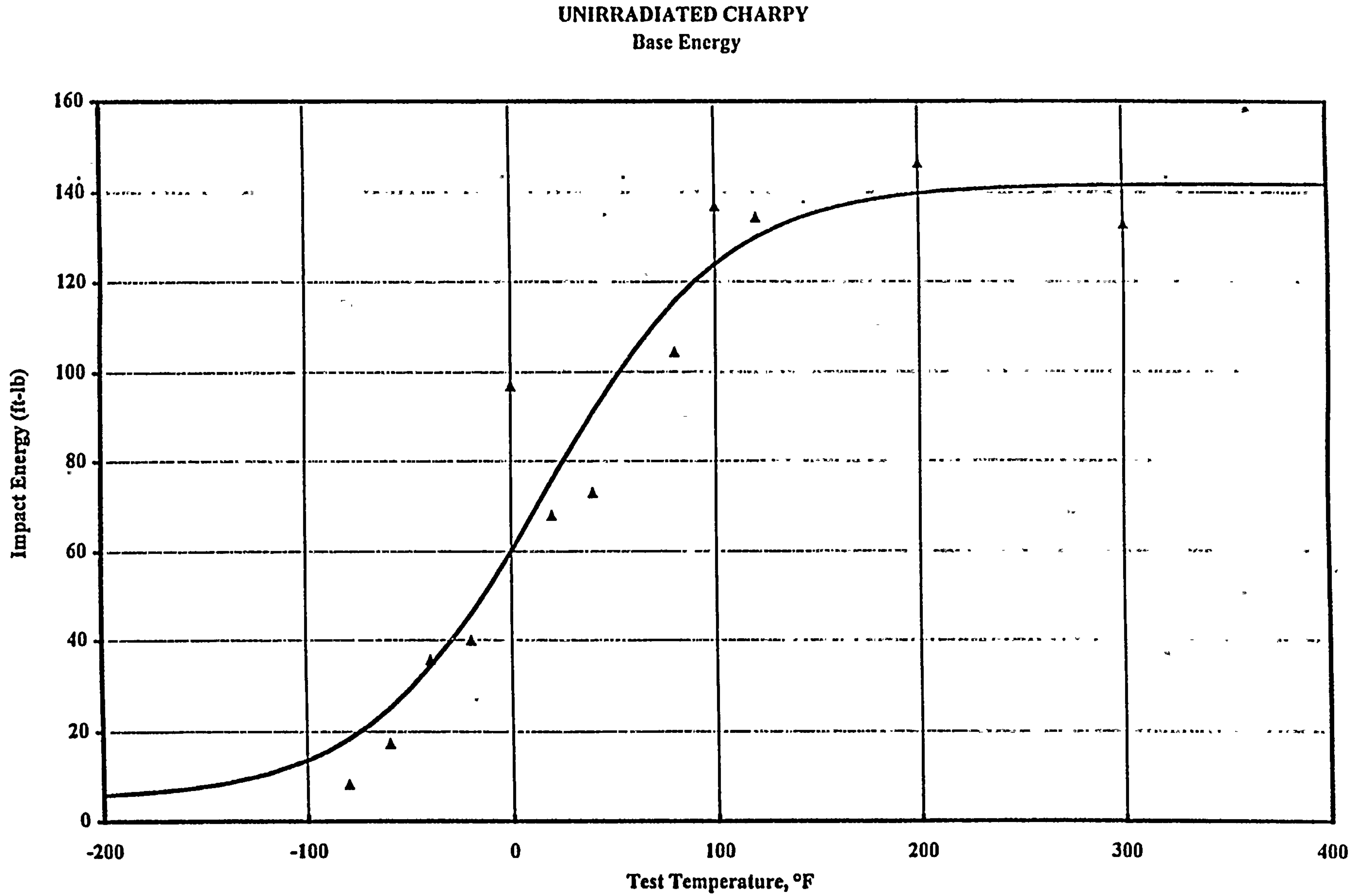


Figure 5-1. Browns Ferry 2 Unirradiated Base Metal Impact Energy

IRRADIATED CHARPY
Base Energy

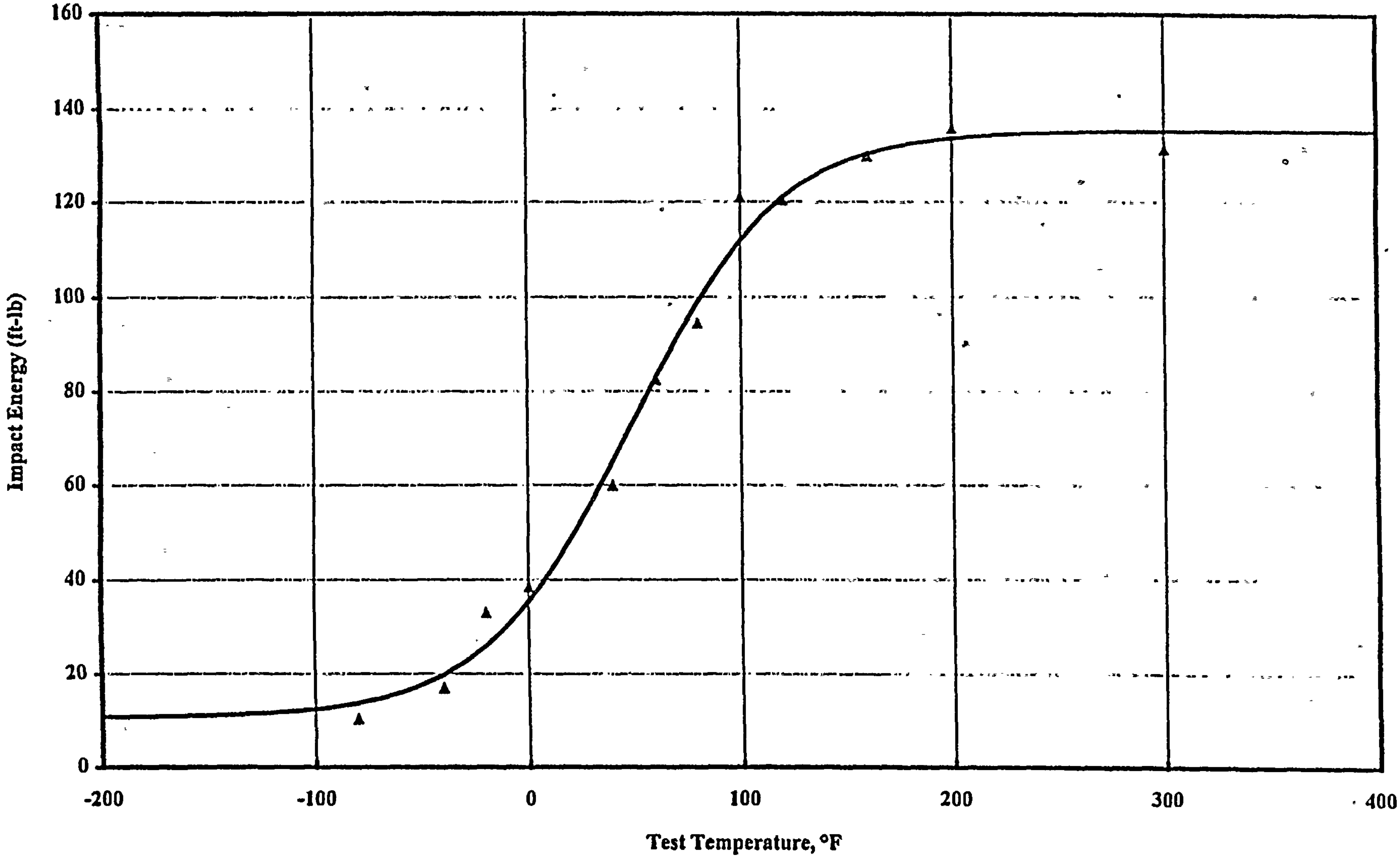


Figure 5-2. Browns Ferry 2 Irradiated Base Metal Impact Energy

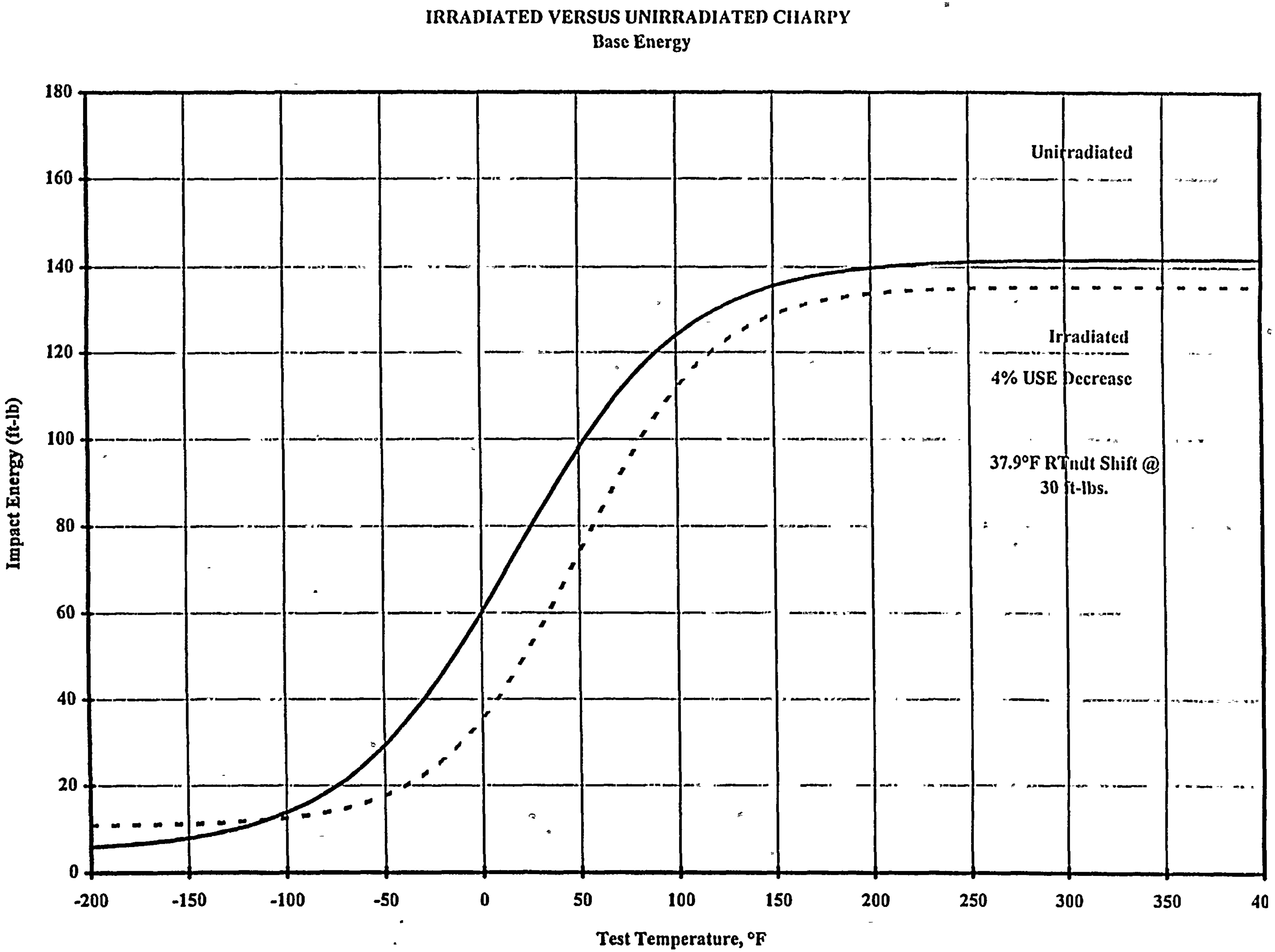


Figure 5-3. Browns Ferry 2 Irradiated and Unirradiated Base Metal Impact Energy

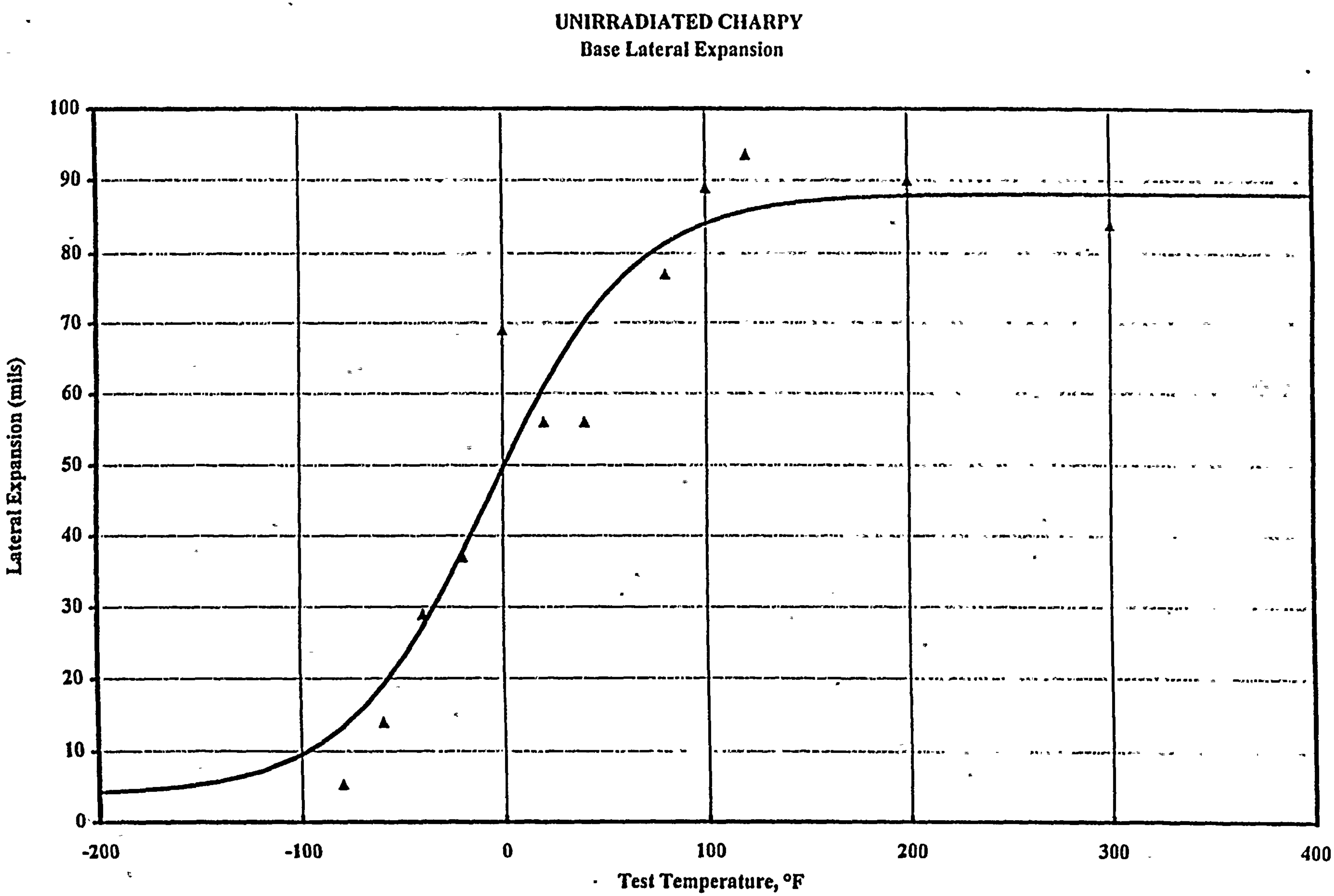


Figure 5-4. Browns Ferry 2 Unirradiated Base Metal Lateral Expansion

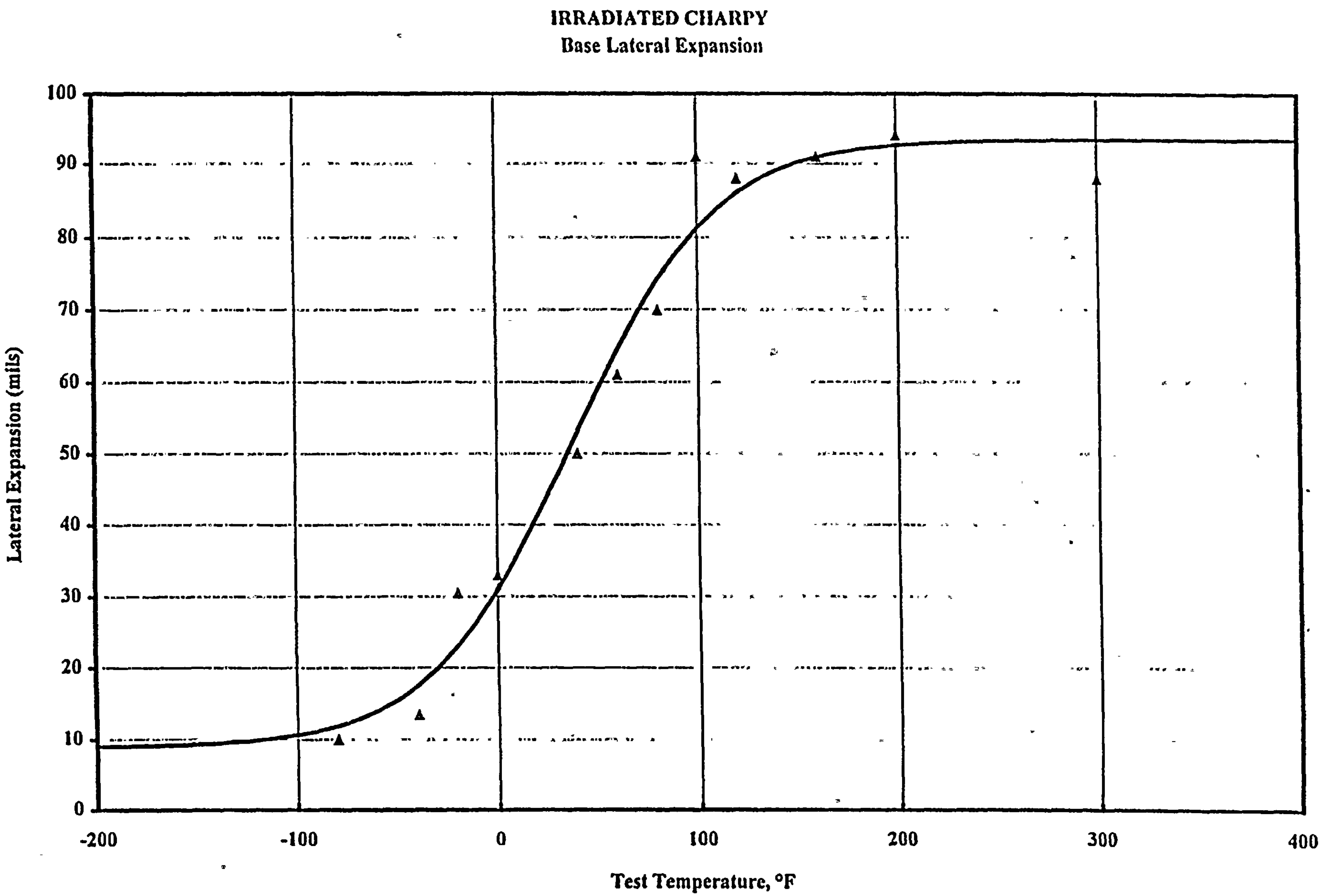


Figure 5-5. Browns Ferry 2 Irradiated Base Metal Lateral Expansion

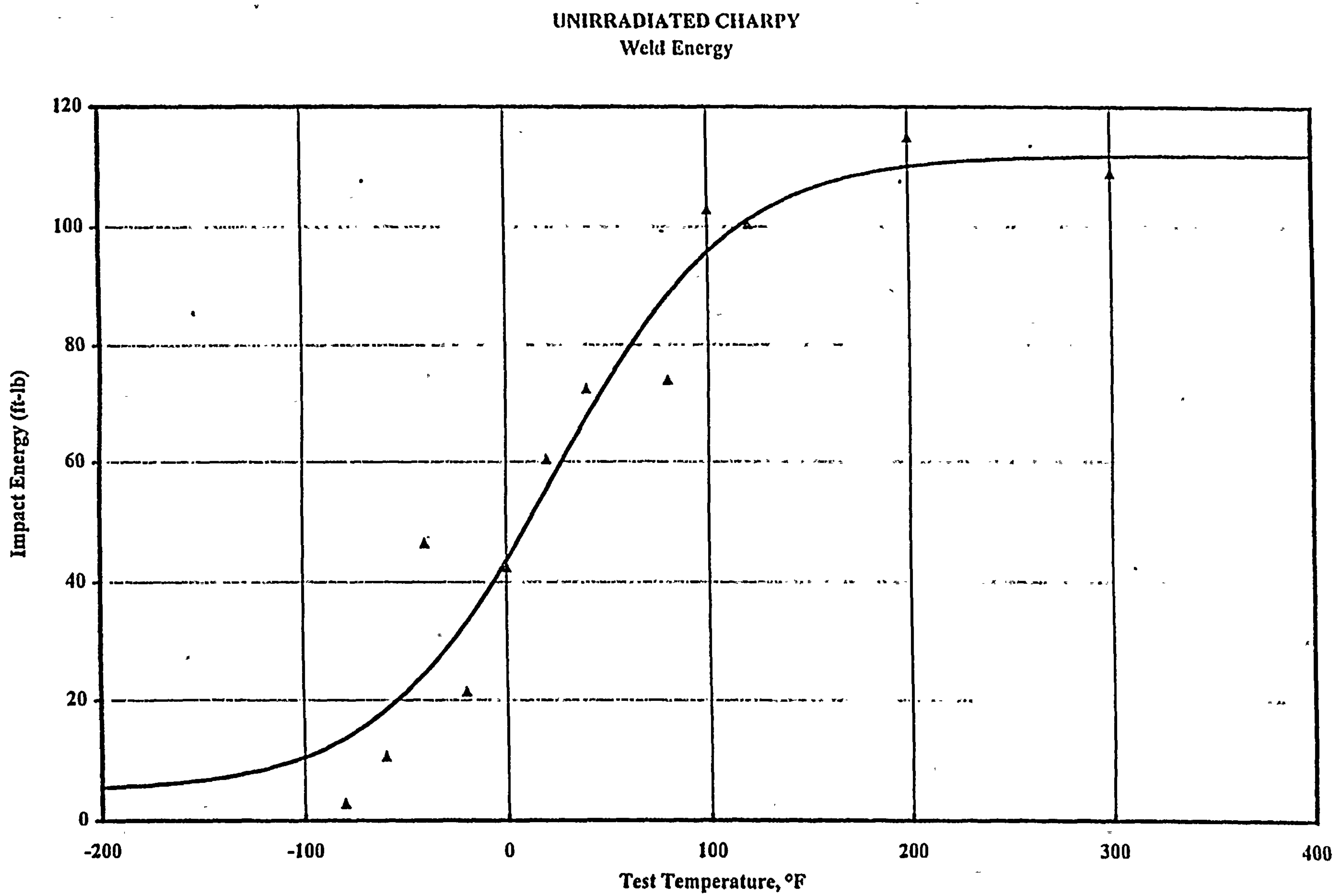


Figure 5-6. Browns Ferry 2 Unirradiated Weld Metal Impact Energy

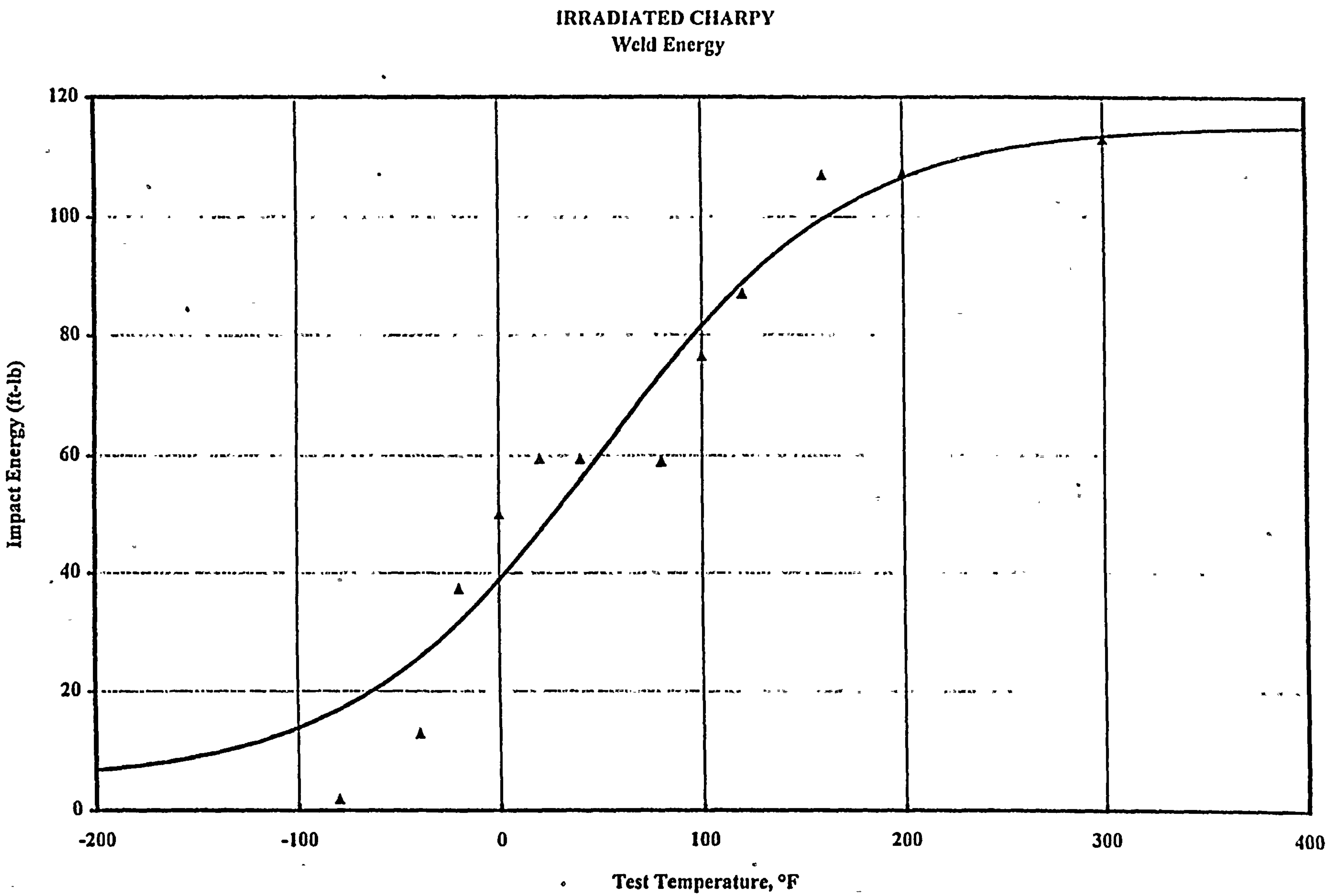


Figure 5-7. Browns Ferry 2 Irradiated Weld Metal Impact Energy

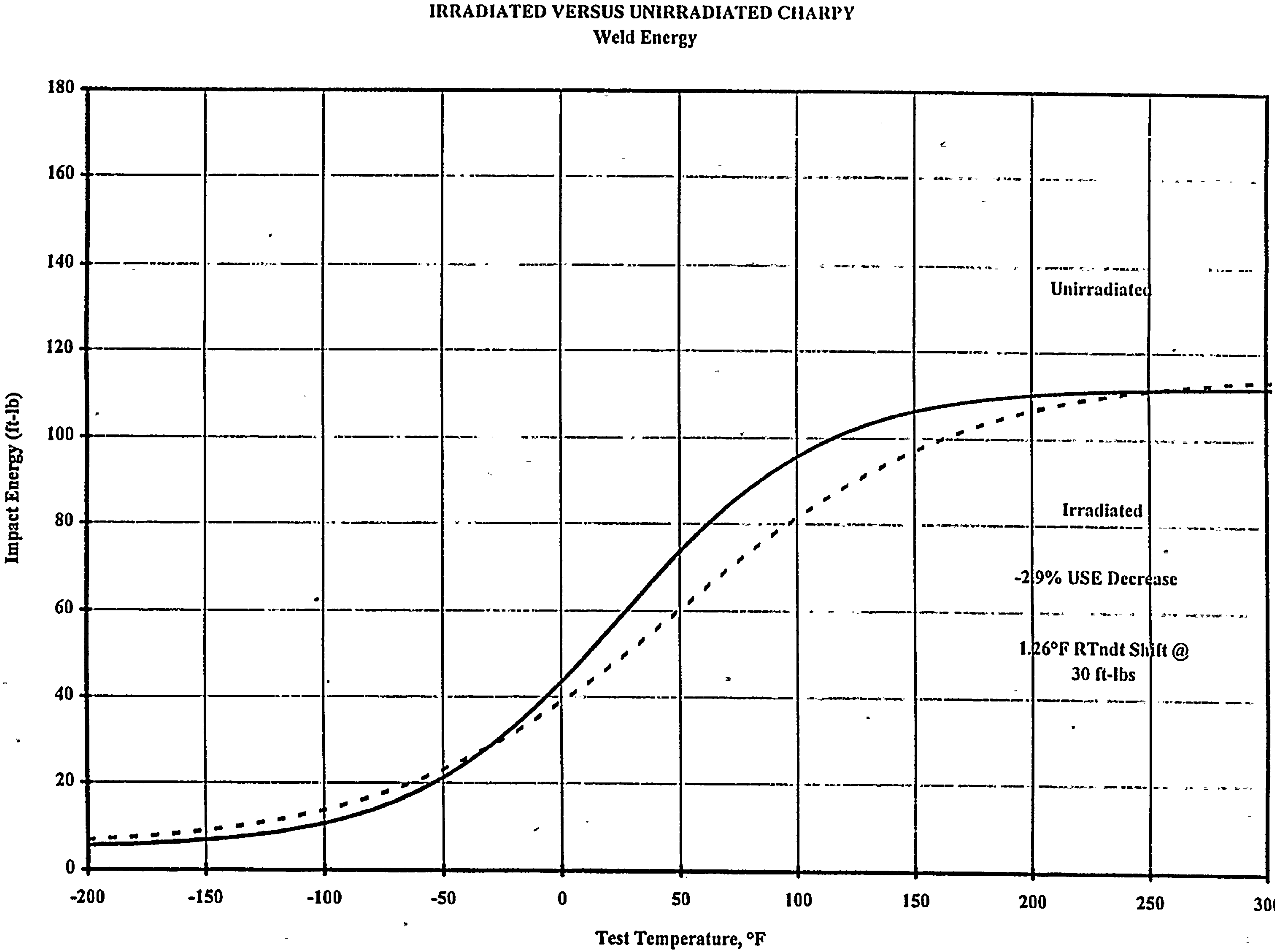


Figure 5-8. Browns Ferry 2 Irradiated and Unirradiated Weld Metal Impact Energy

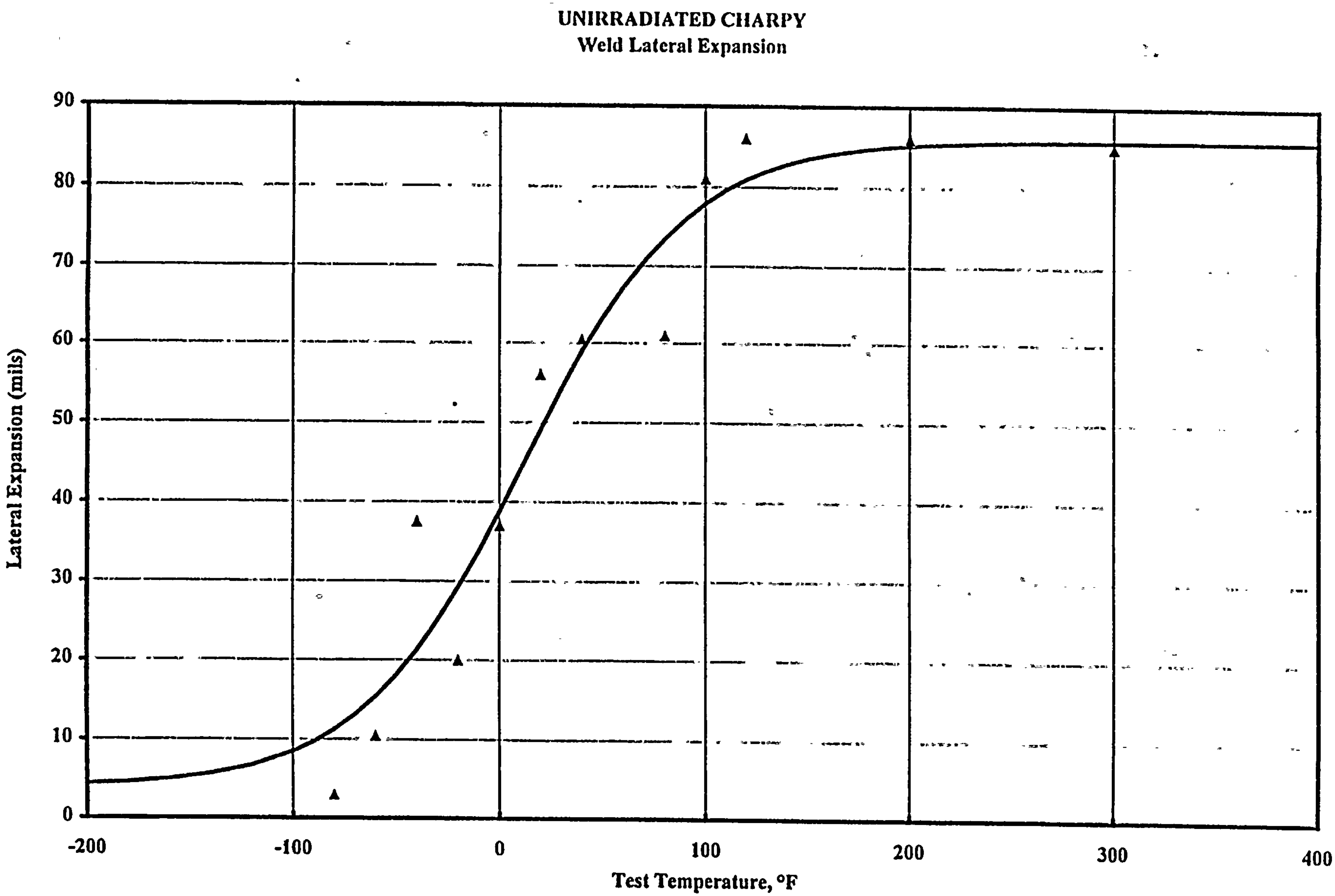


Figure 5-9. Browns Ferry 2 Unirradiated Weld Metal Lateral Expansion

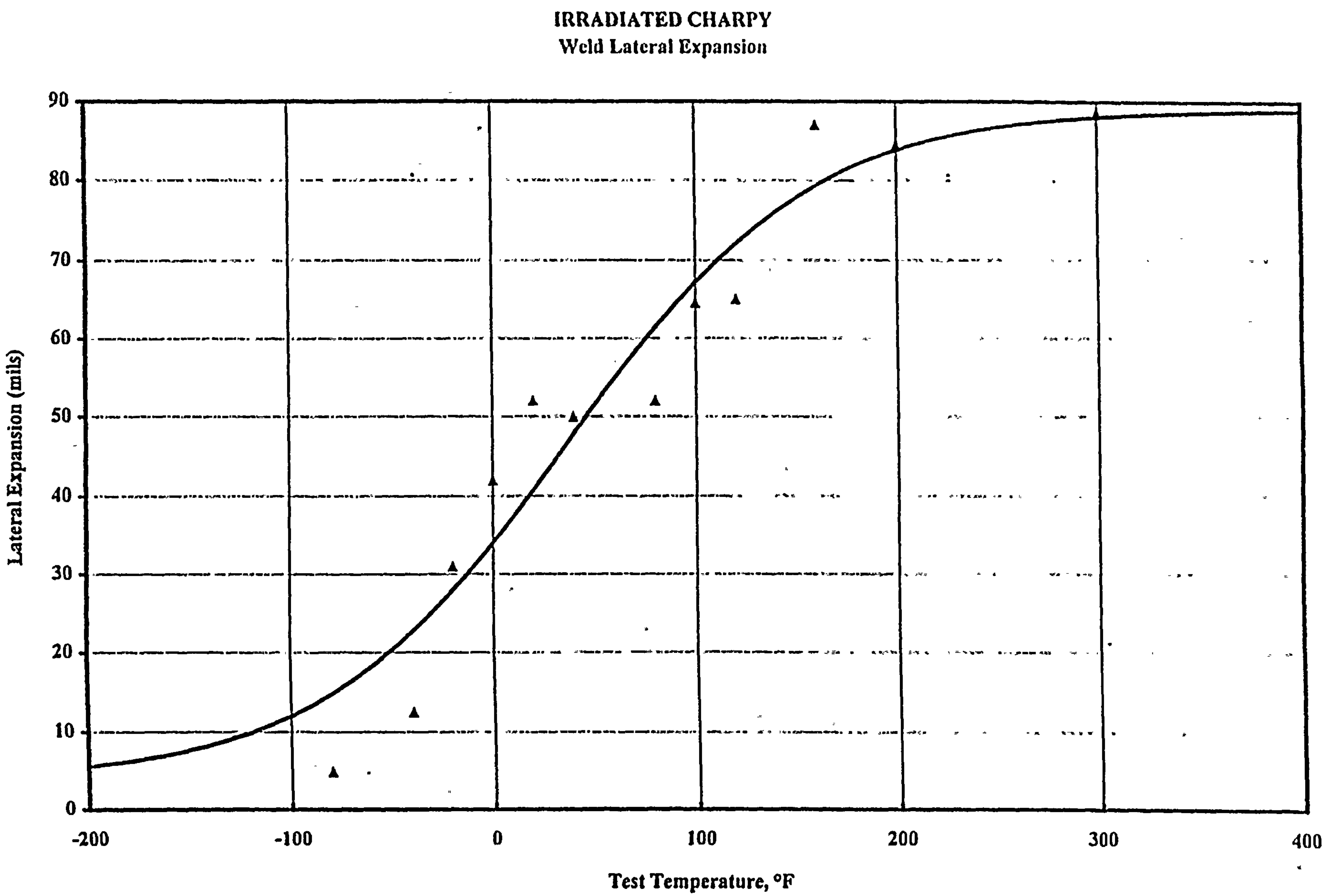


Figure 5-10. Browns Ferry 2 Irradiated Weld Metal Lateral Expansion

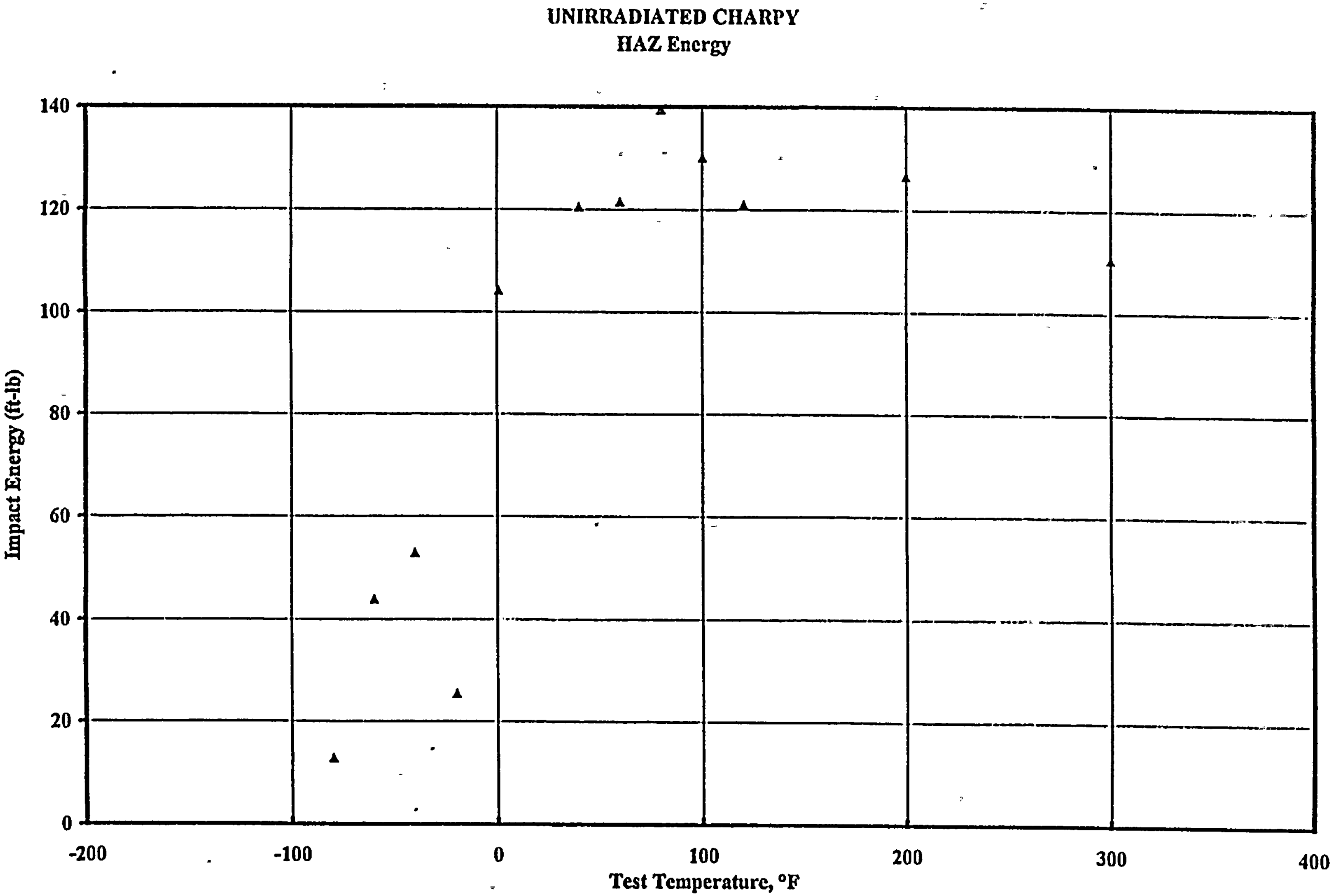


Figure 5-11. Browns Ferry 2 Unirradiated HAZ Metal Impact Energy

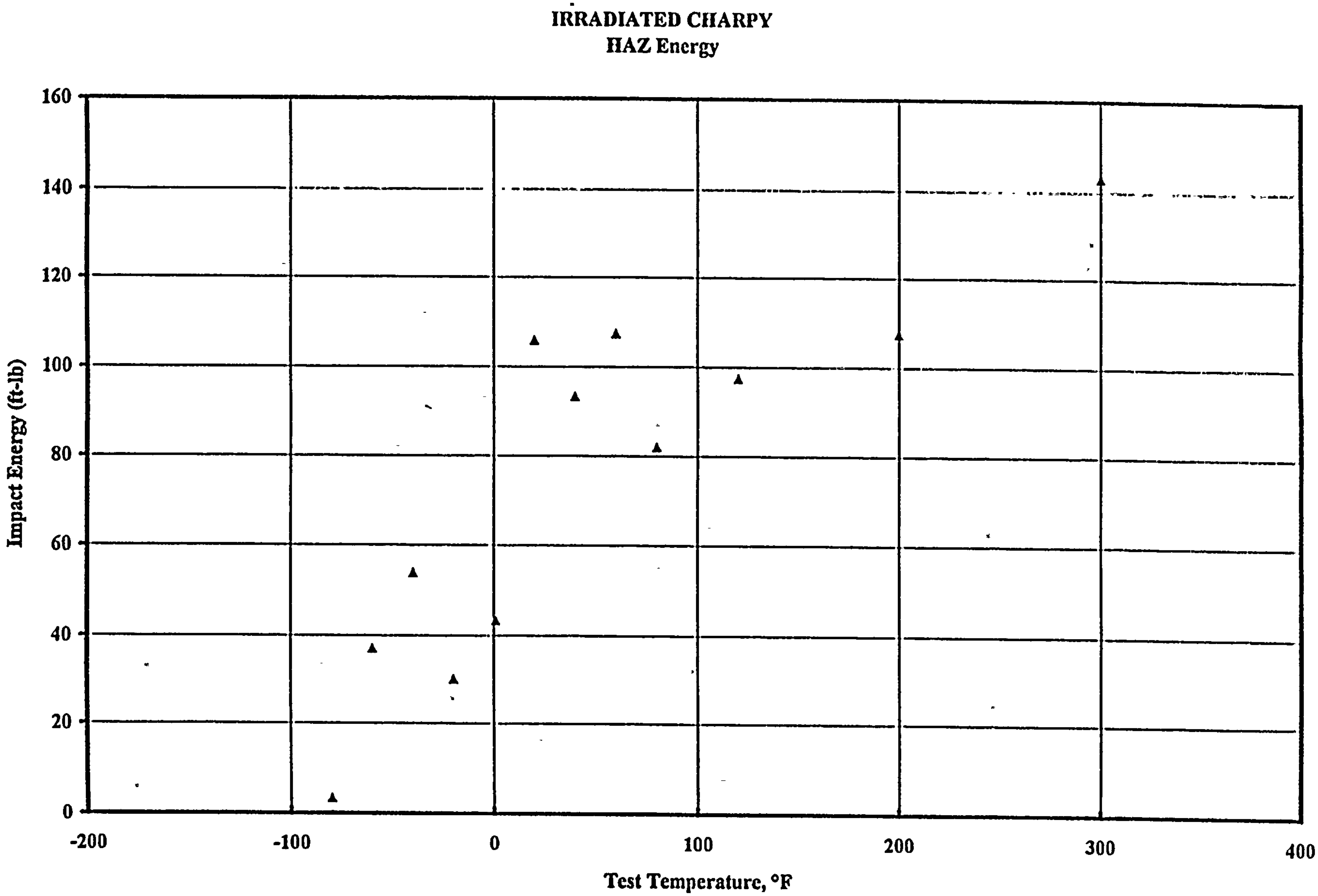


Figure 5-12. Browns Ferry 2 Irradiated HAZ Metal Impact Energy

UNIRRADIATED CHARPY
HAZ Lateral Expansion

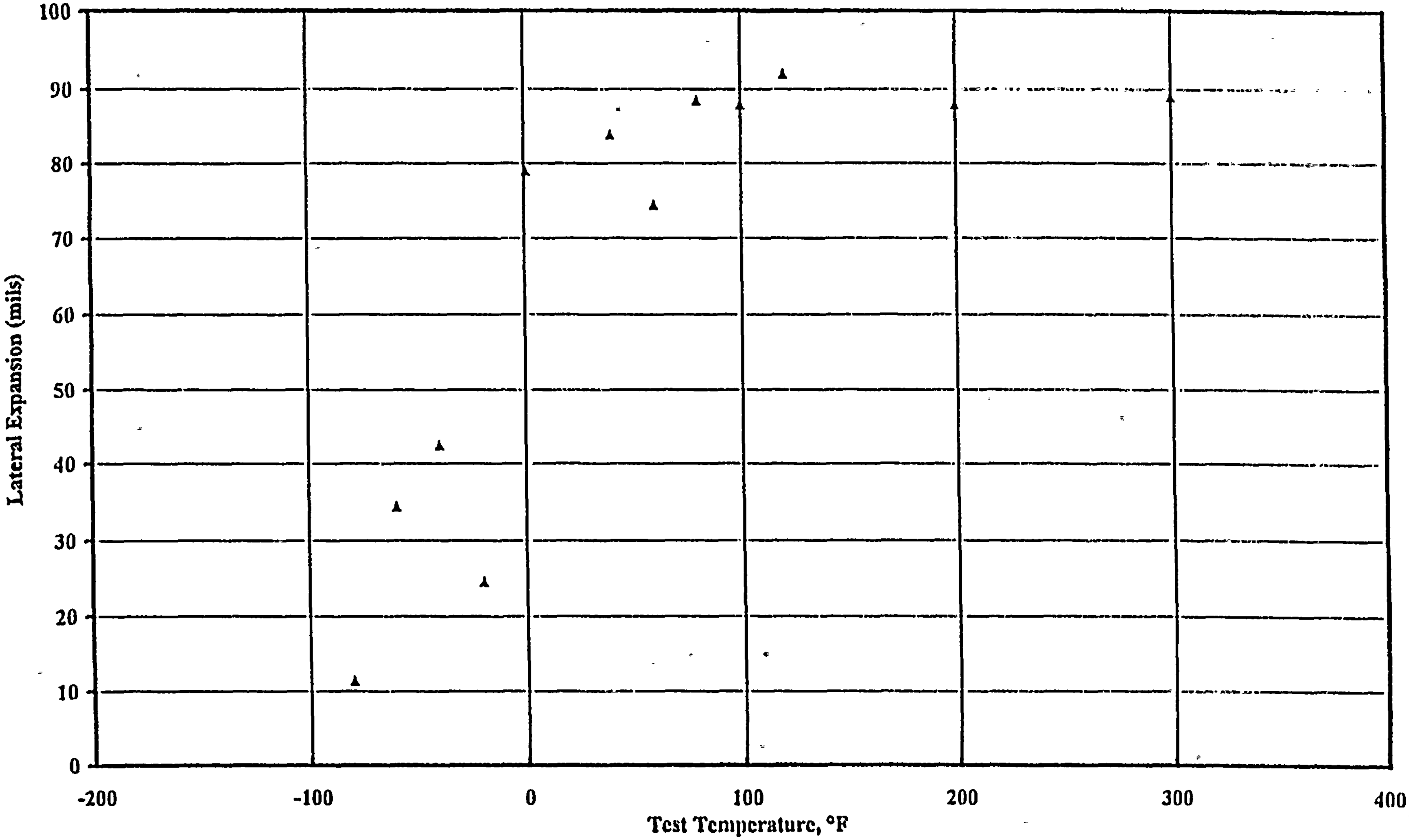


Figure 5-13. Browns Ferry 2 Unirradiated HAZ Metal Lateral Expansion

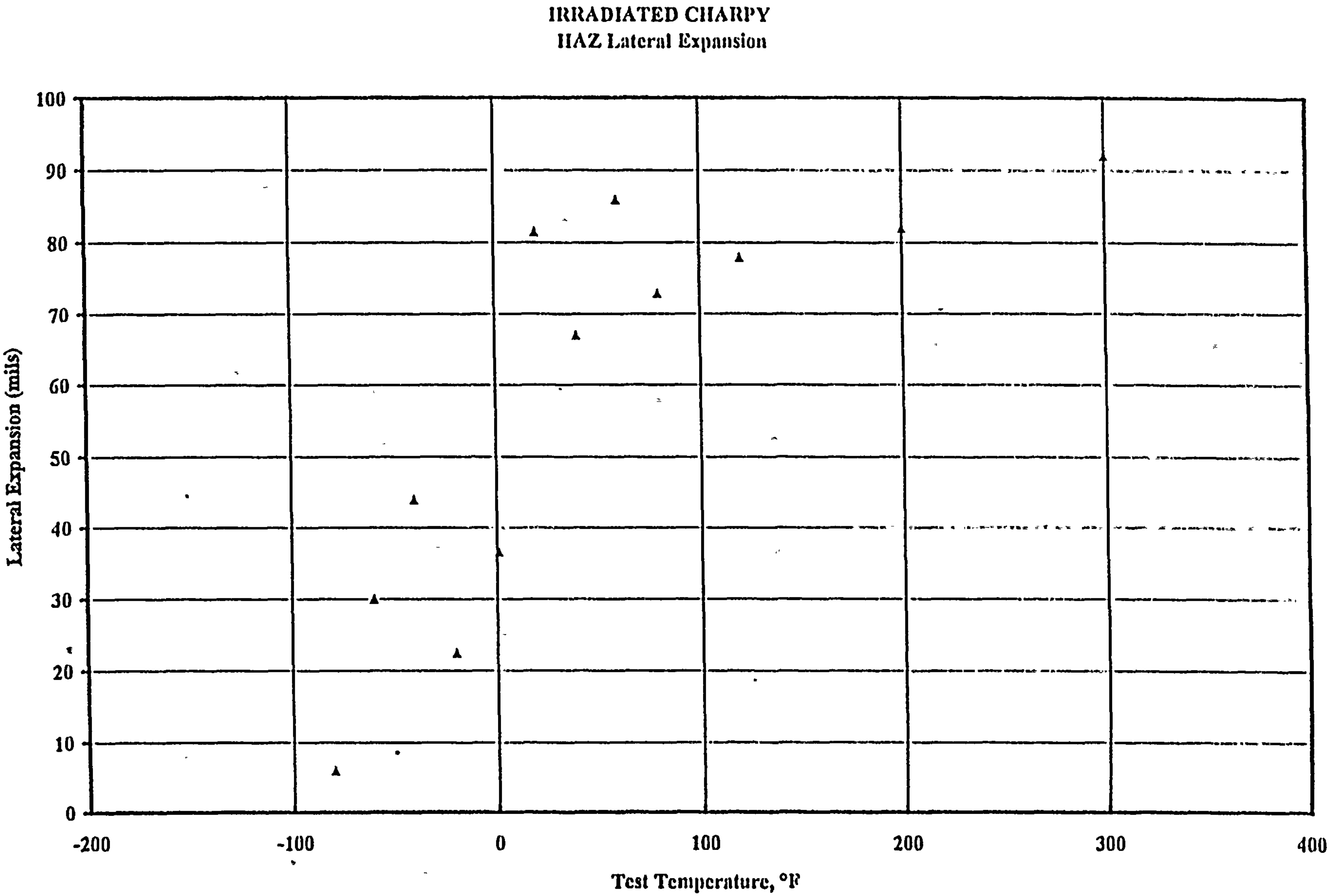


Figure 5-14. Browns Ferry 2 Irradiated HAZ Metal Lateral Expansion

6. TENSILE TESTING

Eight round bar tensile specimens were recovered from the surveillance capsule and six were tested. Uniaxial tensile tests were conducted in air at room temperature (70°F) and RPV operating temperature (550°F). Six unirradiated specimens, sent from the Browns Ferry site to GE-NE San Jose, were tested at the same temperatures. The tests were conducted in accordance with ASTM E8-89 [14].

6.1 PROCEDURE

All tests were conducted using a screw-driven Instron test frame equipped with a 20-kip load cell and special pull bars and grips. Heating was done with a Satec resistance clamshell furnace centered around the specimen load train. The test temperature was monitored and controlled by a chromel-alumel thermocouple spot-welded to an Inconel clip that was friction-clipped to the surface of the specimen at its midline. Before the elevated temperature tests, a profile of the furnace was conducted at the test temperature of interest using an unirradiated steel specimen of the same geometry. Thermocouples were spot-welded to the top, middle, and bottom of a central 1 inch gage of this specimen. In addition, the clip-on thermocouple was attached to the midline of the specimen. When the target temperatures of the three thermocouples were within ±5°F of each other, the temperature of the clip-on thermocouple was noted and subsequently used as the target temperature for the irradiated specimens.

All tests were conducted at a calibrated crosshead speed of 0.005 in/min until well past yield, at which time the speed was increased to 0.05 inch/min until fracture. Crosshead displacement was used to monitor specimen extension during the test.

The test specimens were machined with a minimum nominal diameter of 0.250 inch at the center of the gage length. The yield strength (YS) and ultimate tensile strength (UTS) were calculated by dividing the measured area (0.0491 in^2) into the 0.2% offset load and into the maximum test load, respectively. The values listed for the uniform and total elongations were obtained from plots that recorded load versus specimen extension and are based on a 1.5 inch gage length. Reduction of area (RA) values were determined from post-test measurements of the necked specimen diameters using a calibrated blade micrometer and employing the following formula:

$$RA = 100\% * (A_o - A_f)/A_o$$

After testing, each broken specimen was photographed end-on, showing the fracture surface, and lengthwise, showing the fracture location and local necking behavior.

6.2 RESULTS

Irradiated tensile test properties of Yield Strength (YS), Ultimate Tensile Strength (UTS), Reduction of Area (RA), Uniform Elongation (UE), and Total Elongation (TE) are presented in Table 6-1; all but UE are presented in Table 6-2 for unirradiated specimens. A stress-strain curve for a 550°F base metal irradiated specimen is shown in Figure 6-1. This curve is typical of the stress-strain characteristics of all the tested specimens. The surveillance materials generally follow the trend of decreasing properties with increasing temperature. Photographs of the fracture surfaces and necking behavior are given in Figures 6-2 through 6-4.

6.3 IRRADIATED VERSUS UNIRRADIATED TENSILE PROPERTIES

Unirradiated tensile test data was tested to provide direct comparison with the irradiated data at room temperature, shown in Table 6-3. The unirradiated and irradiated plate and weld data at 550° F was compared to determine the irradiation effect, shown in Table 6-4. The trends of increasing YS and UTS and of decreasing TE and for the weld decreasing RA, characteristic of irradiation embrittlement, are seen in the data.

TABLE 6-1: TENSILE TEST RESULTS FOR IRRADIATED RPV MATERIALS

	Specimen Number	Test Temp. (°F)	Yield[a] Strength (ksi)	Ultimate Strength (ksi)	Uniform Elongation (%)	Total Elongation (%)	Reduction of Area (%)
Base:	EKA	70	71.2	92.5	9.3	19.5	71.4
	EKJ	550	68.9	90.1	7.6	16.8	72.2
Weld:	EL1	70	72.4	92.2	9.0	18.7	68.7
	ELC	550	67.5	87.0	7.3	15.0	61.2
HAZ:	EMB	70	70.9	92.6	8.3	17.5	64.5
	EM3	550	65.9	86.8	7.0	14.4	63.9

[a] Yield Strength is determined by 0.2% offset.

TABLE 6-2: TENSILE TEST RESULTS FOR UNIRRADIATED RPV MATERIALS

	Specimen Number	Test Temp.. (°F)	Yield[a] Strength (ksi)	Ultimate Strength (ksi)	Uniform Elongation (%)	Total Elongation (%)	Reduction of Area (%)
Base:	EKC	70	66.9	88.9	---	19.7	70.3
	EKK	550	60.6	83.3	---	17.0	67.9
Weld:	ELB	70	64.2	84.4	---	20.7	70.5
	ELA	550	62.3	81.9	---	15.1	62.5
HAZ:	EM2	70	64.6	84.9	---	16.3	68.3
	EM7	550	63.1	83.9	---	13.9	64.6

[a] Yield Strength is determined by 0.2% offset.

TABLE 6-3 COMPARISON OF UNIRRADIATED AND IRRADIATED TENSILE PROPERTIES AT ROOM TEMPERATURE

		Yield Strength (ksi)	Ultimate Strength (ksi)	Total Elongation (%)	Reduction of Area (%)
Base:	Unirradiated	66.9	88.9	19.7	70.3
	Irradiated	71.2	92.5	19.5	71.4
	Difference [a]	6.4%	4.0%	-1.0%	1.6%
Weld:	Unirradiated	64.2	84.4	20.7	70.5
	Irradiated	72.4	92.2	18.7	68.7
	Difference [a]	12.8%	9.3%	-9.7%	-2.6%

[a] Difference = [(Irrad. - Unirrad.)/Unirrad.] * 100%

TABLE 6-4 COMPARISON OF UNIRRADIATED AND IRRADIATED TENSILE PROPERTIES AT 550°F

		Yield Strength (ksi)	Ultimate Strength (ksi)	Total Elongation (%)	Reduction of Area (%)
Base:	Unirradiated	60.6	83.3	17.0	67.9
	Irradiated	68.9	90.1	16.8	72.2
	Difference [a]	13.7%	8.2%	-1.2%	6.33%
Weld:	Unirradiated	62.3	81.9	15.1	62.5
	Irradiated	67.5	87.0	15.0	61.2
	Difference [a]	8.3%	6.2%	-0.7%	-2.1%

[a] Difference = [(Irrad. - Unirrad.)/Unirrad.] * 100%

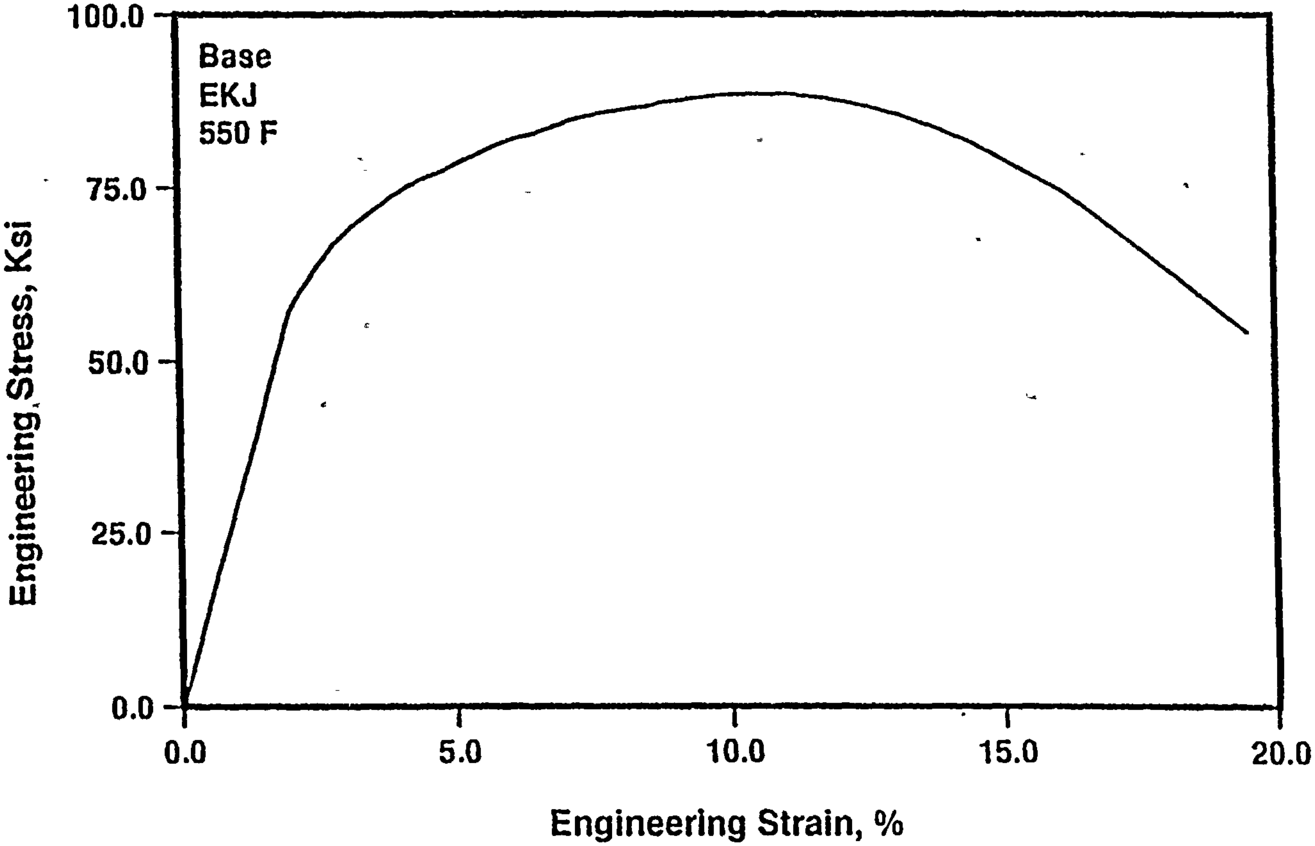
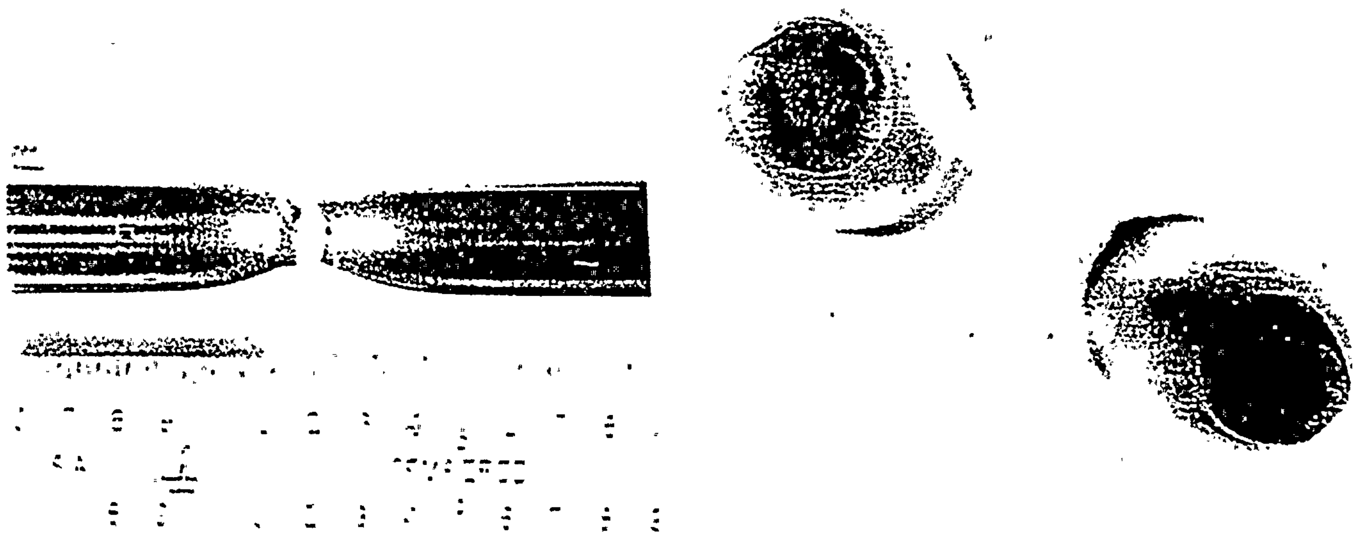


FIGURE 6-1. TYPICAL ENGINEERING STRESS-STRAIN CURVE FOR IRRADIATED RPV MATERIALS

EKA 70°F



EKJ 550°F

FIGURE 6-2. FRACTURE LOCATION, NECKING BEHAVIOR AND FRACTURE APPEARANCE FOR IRRADIATED BASE METAL TENSILE SPECIMENS

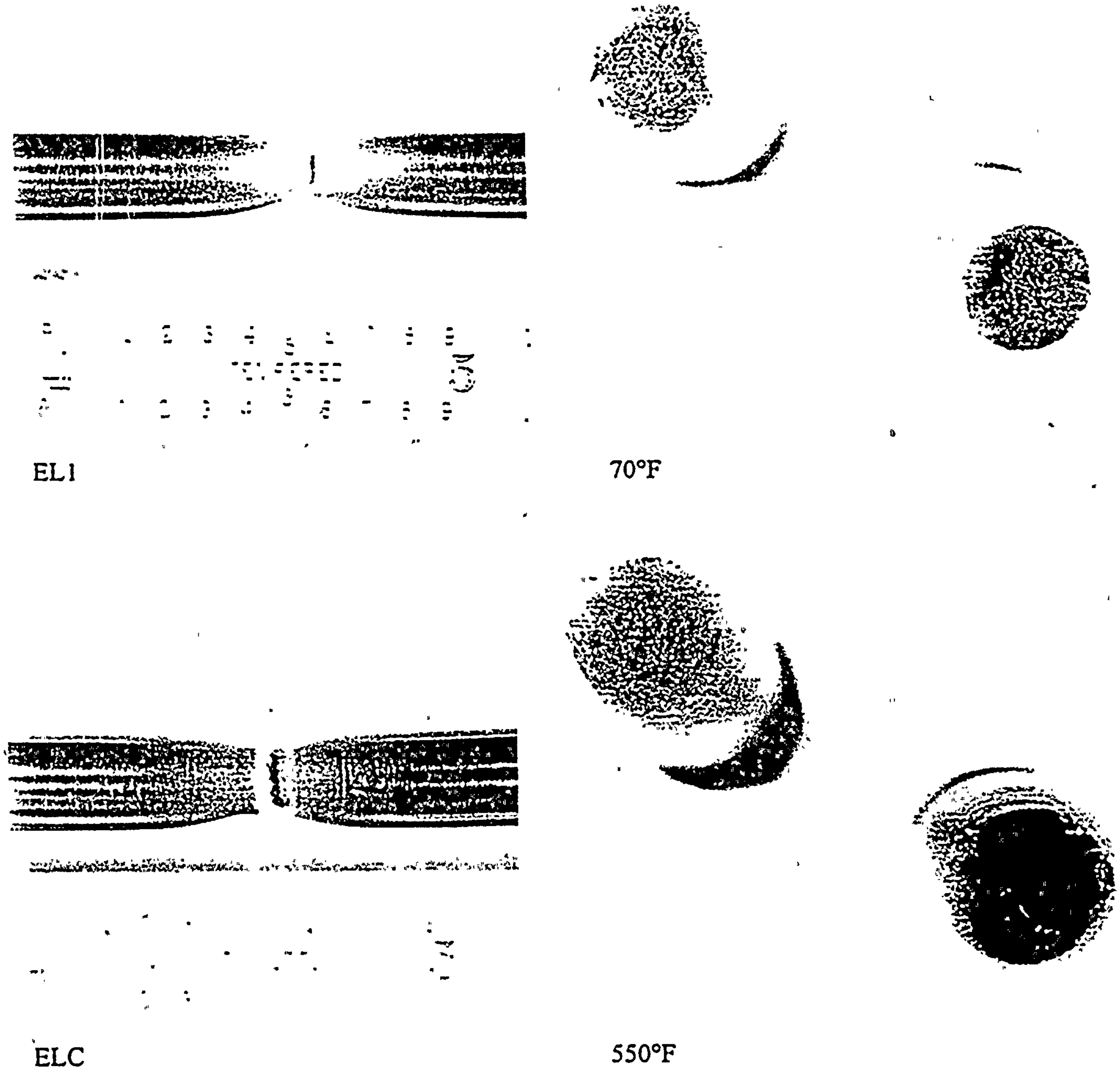
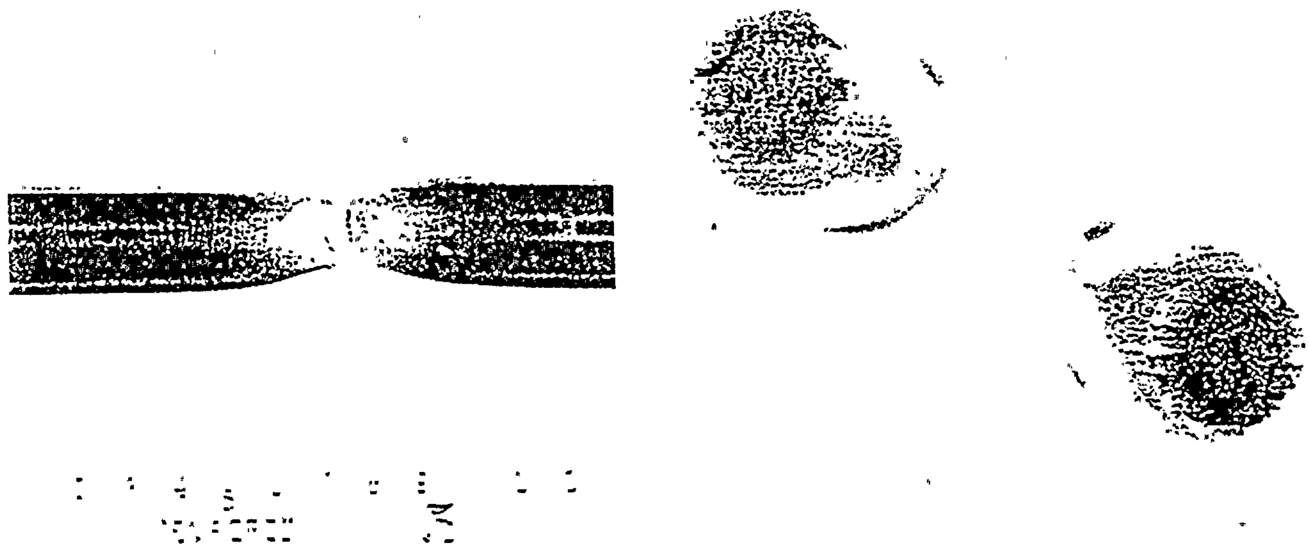
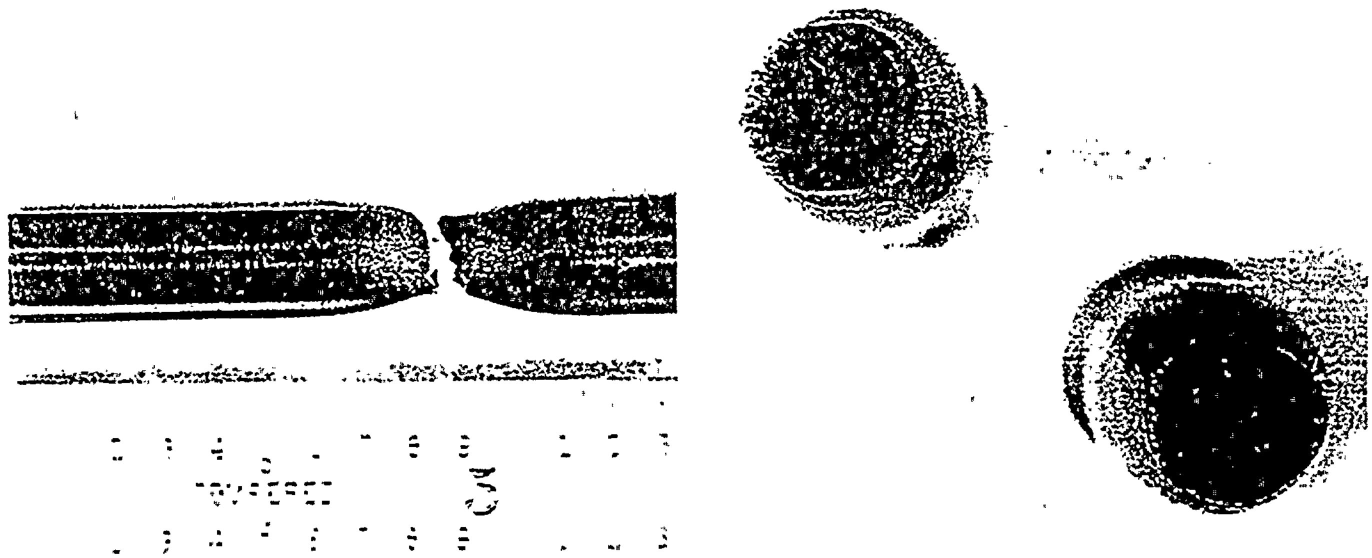


FIGURE 6-3. FRACTURE LOCATION, NECKING BEHAVIOR AND FRACTURE APPEARANCE FOR IRRADIATED WELD METAL TENSILE SPECIMENS



EMB 70°F



EM3 550°F

FIGURE 6-4. FRACTURE LOCATION, NECKING BEHAVIOR AND FRACTURE APPEARANCE FOR IRRADIATED HAZ METAL TENSILE SPECIMENS

7. DEVELOPMENT OF OPERATING LIMITS CURVES

P-T curves for Unit 2 were previously developed in GE report 523-A65-0594 [15]. Therefore, only the aspects of the curves which have changed, as a result of the testing presented here and as a result of ASME Code changes are discussed below.

7.1 BACKGROUND

The revised fluence value in Section 4 (6.05×10^{17} n/cm^2), which is about 43% lower the fluence used in the previous report (1.1×10^{18} n/cm^2), is used in this section to revise the adjusted reference temperatures (ARTs), which are subsequently used to revise the beltline P-T curves.

The P-T curve revision includes consideration of the change to the allowable fracture toughness equation in ASME Code Section XI, Appendix G, which occurred in 1992. The coefficient 1.233 in the K_{IR}/K_{Ia} equation in Figure G-2210-1, became 1.223. The result of the revision is an increase of about 1/2°F to the calculated temperature for a given pressure on the P-T curves (i.e., all curved portions of the P-T curves shift 1/2°F to the right).

7.2 NON-BELTLINE REGIONS

The non-beltline Curve B curves are developed for two regions: the upper vessel region, governed by the jet pump nozzle limits, and the bottom head region, governed by the bottom head dome limits. Table 3-2 has the limiting initial RT_{NDT} values which are: 54°F for the jet pump nozzle and 42°F for the bottom head dome. The 1/2°F adjustment was made to the curved portions of the non-beltline curves, but not to the straight line and step portions, which are based on 10CFR50 Appendix G.

Although bottom head Curve B is not limiting, it is included in Figure 7-2, as there may be transients where the bottom head is cooler than the upper vessel regions.

7.3 CORE BELTLINE REGION

The decreased fluence has an impact on the beltline P-T curves, by decreasing the ARTs of the beltline plates and welds. Figures 7-1 through 7-4 show the beltline curves at 32 EFPY. Table 7-1 shows the beltline curve data points. As with the non-beltline curves, the 1/2°F adjustment was made to the curved portions of the beltline curves.

7.4 EVALUATION OF IRRADIATION EFFECTS

The impact on adjusted reference temperature (ART) due to irradiation in the beltline materials is determined according to the methods in Reg. Guide 1.99 [7], as a function of neutron fluence and the element contents of copper (Cu) and nickel (Ni). The specific relationship from Reg. Guide 1.99 [7] is:

$$ART = \text{Initial } RT_{NDT} + \Delta RT_{NDT} + \text{Margin} \qquad (7\text{-}1)$$

where:

$$\Delta RT_{NDT} = [CF]^* f^{(0.28 - 0.10 \log f)} \qquad (7\text{-}2)$$

$$\text{Margin} = 2^*(\sigma_I{}^2 + \sigma_\Delta{}^2)^{1/2} \qquad (7\text{-}3)$$

CF = chemistry factor from Tables 1 or 2 of Reg. Guide 1.99 [7],
f = 1/4 T fluence (n/cm^2) divided by 10^{19},
σ_I = standard deviation on initial RT_{NDT},
σ_Δ = standard deviation on ΔRT_{NDT}, is 28°F for welds and 17°F for base material, except that σ_Δ need not exceed 0.50 times the ΔRT_{NDT} value.

Once two sets of surveillance capsule data are available, the CF values in Reg. Guide 1.99 [7] can be modified to reflect the results. However, this is only the first set of surveillance data from Unit 2, so only the results of the flux wire tests are factored into beltline ART calculations.

Each beltline plate and weld ΔRT_{NDT} value is determined by multiplying the CF from Reg. Guide 1.99, determined for the Cu-Ni content of the material, by the fluence factor for the EFPY being evaluated. The Margin term and initial RT_{NDT} are added to get the ART of the material. The 32 EFPY ART values are shown in Table 7-2. Results for all of the beltline plates and the electroslag weld are shown.

7.4.1 ART Versus EFPY

The results in Table 7-2 show that the most limiting beltline plate is C2467-1 at 32 EFPY. The resulting ARTs at 32 EFPY are 49.7°F for the plate and 92.1°F for the weld. Figure 7-5 shows the ART as a function of EFPY.

7.4.2 Upper Shelf Energy at 32 EFPY

Paragraph IV.B of 10CFR50 Appendix G [1] sets limits on the upper shelf energy (USE) of the beltline materials. The USE must be above 50 ft-lb at all times during plant operation, assumed here to be up to 32 EFPY. According to the BAW-1845 report the initial USE of the plates was not tested during fabrication, as there was no requirement to do so at that time. Therefore, USE was determined for surveillance material plate and the same USE was applied to corresponding vessel plate material. For the other plates a generic USE value was estimated based on four surveillance plate material USEs. Calculations of 32 EFPY USE, using Reg. Guide 1.99 methods, are summarized in Table 7-3.

The equivalent transverse USE of the plate material is taken as 65% of the longitudinal USE, according to USNRC MTEB 5-2 [16]. Although the plate surveillance data show the decrease in USE to be considerably less than the prediction for the corresponding copper content (see Table 5-4), the USE decrease prediction values from Reg. Guide 1.99 were used for the beltline plates in Table 7-3.

According to the BAW-1845 report the weld metal initial USE values were determined from a generic USE value based on three surveillance weld values. Unlike the plate, the weld metal USE has no transverse/longitudinal correction, because weld metal has no orientation effect. The weld surveillance data also show the decrease in USE to be considerably less than the prediction for the corresponding copper content, however, the USE decrease prediction values from Reg. Guide 1.99 were still used in Table 7-3.

Based on the results in Table 7-3, it is expected that the beltline materials will have USE values above 50 ft-lb at 32 EFPY, as required in 10CFR50 Appendix G [1]. Since USE and ART

requirements are met, irradiation effects are not severe enough to necessitate additional analyses or preparations for RPV annealing before 32 EFPY. Moreover, TVA is a participant in a BWR Owners' Group program to perform analyses to demonstrate equivalent margin [17] in cases as low as 35 ft-lb. Tables B-1 and B-2 in Appendix B show a decrease in surveillance plate and weld USE less than what is predicted in RG 1.99 and that the conclusions of the equivalent margin analysis are fully applicable.

7.5 OPERATING LIMITS CURVES VALID TO 32 EFPY

Figures 7-1 through 7-3 show P-T curves valid to 32 EFPY. The P-T curves are developed by considering the requirements applicable to the non-beltline, beltline and closure flange regions. The beltline curve is more limiting for curve A. For curve B and curve C, the non-beltline curves are limiting for pressures less than approximately 1100 psig. Curve B for the bottom head has been included to provide the appropriate limits for any transients where some bottom head stratification might occur.

TABLE 7-1 BROWNS FERRY 2 P - T CURVE VALUES

*********************************REQUIRED TEMPERATURES*********************************

PRESSURE	32 EFPY BELTLINE CURVE A	NON-BELTLINE CURVE A	BOTTOM HEAD CURVE B	32 EFPY BELTLINE CURVE B	UPPER VESSEL CURVE B	32 EFPY BELTLINE CURVE C	NON-BELTLINE CURVE C
0		82.0			82.0		82.0
10		82.0			82.0		82.0
20		82.0			82.0		82.0
30		82.0			82.0		82.0
40		82.0			82.0		94.6
50		82.0			82.0		107.6
60		82.0			82.0		118.6
70		82.0			88.1		128.1
80		82.0			96.3		136.3
90		82.0			103.3		143.3
100		82.0			109.4		149.4
110		82.0			115.0		155.0
120		82.0			119.9		159.9
130		82.0			124.7		164.7
140		82.0			129.3		169.3
150		82.0			133.6		173.6
160		82.0			137.5		177.5
170		82.0			140.9		180.9
180		82.0			143.9		183.9
190		82.0			146.7		186.7
200		82.0			149.4	81.2	189.4
210		82.0			152.1	91.4	192.1
220		82.0			154.6	100.4	194.6
230		82.0			157.0	108.3	197.0
240		82.0			159.3	115.3	199.3
250		82.0			161.5	121.8	201.5
260		82.0			163.6	127.6	203.6
270		82.0			165.6	133.1	205.6
280		82.0			167.6	138.1	207.6
290		82.0			169.5	142.8	209.5
300		82.0		107.2	171.3	147.2	211.3
310		82.0		114.3	173.1	154.3	213.1
312.5		82.0		115.3	173.5	155.3	213.5
312.5		112.0		115.3	173.5	155.3	213.5
320		112.0		118.2	174.8	158.2	214.8
330		112.0		121.8	176.4	161.8	216.4
340		112.0		125.2	178.0	165.2	218.0
350		112.0		128.5	179.6	168.5	219.6
360		112.0		131.6	181.1	171.6	221.1
370		112.0		134.6	182.6	174.6	222.6

Table 7-1 Browns Ferry 2 P - T Curve Values (Continued)

*********************************REQUIRED TEMPERATURES********************************

PRESSURE	32 EFPY BELTLINE CURVE A	NON-BELTLINE CURVE A	BOTTOM HEAD CURVE B	32 EFPY BELTLINE CURVE B	UPPER VESSEL CURVE B	32 EFPY BELTLINE CURVE C	NON-BELTLINE CURVE C
380		112.0		137.4	184.1	177.4	224.1
390		112.0		140.2	185.6	180.2	225.6
400		112.0	72.6	142.8	187.1	182.8	227.1
410		112.0	81.6	145.4	188.6	185.4	228.6
420		112.0	88.6	147.8	190.0	187.3	230.0
430		112.0	94.6	150.2	191.4	190.2	231.4
440		112.0	99.6	152.5	192.8	192.5	232.8
450		112.0	103.6	154.7	194.1	194.7	234.1
460		112.0	107.1	156.8	195.4	196.8	235.4
470		112.0	110.2	158.9	196.7	198.9	236.7
480		112.0	113.1	160.9	197.9	200.9	237.9
490		112.0	115.9	162.9	199.1	202.9	239.1
500	87.0	112.0	118.6	164.8	200.3	204.8	240.3
510	91.2	112.0	121.3	166.7	201.4	206.7	241.4
520	95.2	112.0	123.9	168.5	202.5	208.5	242.5
530	99.0	112.0	126.5	170.3	203.6	210.3	243.6
540	102.5	112.0	129.0	172.0	204.6	212.0	244.6
550	105.9	112.0	131.4	173.7	205.6	213.7	245.6
560	109.2	112.0	133.7	175.3	206.6	215.3	246.6
570	112.3	112.0	135.9	176.9	207.5	216.9	247.5
580	115.2	112.0	138.0	178.5	208.4	218.5	248.4
590	118.1	112.0	139.8	180.0	209.3	220.0	249.3
600	120.8	112.0	141.6	181.5	210.1	221.5	250.1
610	123.4	112.0	143.3	182.9	210.9	222.9	250.9
620	126.0	114.0	145.1	184.4	211.7	224.4	251.7
630	128.4	116.2	146.7	185.8	212.4	225.8	252.4
640	130.8	118.3	148.4	187.2	213.1	227.2	253.1
650	133.0	120.3	149.9	188.5	213.7	228.5	253.7
660	135.2	122.3	151.4	189.8	214.4	229.8	254.4
670	137.4	124.2	152.9	191.1	215.0	231.1	255.0
680	139.4	126.0	154.4	192.4	215.5	232.4	255.5
690	141.5	127.8	155.8	193.7	216.1	233.7	256.1
700	143.4	129.6	157.2	194.9	216.6	234.9	256.6
710	145.3	131.3	158.6	196.1	217.1	236.1	257.1
720	147.2	132.9	159.9	197.3	217.5	237.3	257.5
730	149.0	134.6	161.2	198.4	218.0	238.4	258.0
740	150.7	136.1	162.4	199.6	218.4	239.6	258.4
750	152.4	137.7	163.6	200.7	218.9	240.7	258.9
760	154.1	139.2	164.7	201.8	219.3	241.8	259.3
770	155.7	140.7	165.8	202.9	219.7	242.9	259.7
780	157.3	142.1	166.9	204.0	220.1	244.0	260.1

Table 7-1 Browns Ferry 2 P - T Curve Values (Continued)

**********************************REQUIRED TEMPERATURES**********************************

PRESSURE	32 EFPY BELTLINE CURVE A	NON-BELTLINE CURVE A	BOTTOM HEAD CURVE B	32 EFPY BELTLINE CURVE B	UPPER VESSEL CURVE B	32 EFPY BELTLINE CURVE C	NON-BELTLINE CURVE C
790	158.9	143.6	168.0	205.1	220.5	245.1	260.5
800	160.4	144.9	169.1	206.1	220.9	246.1	260.9
810	161.9	146.3	170.2	207.1	221.3	247.1	261.3
820	163.4	147.6	171.3	208.1	221.7	248.1	261.7
830	164.8	148.9	172.3	209.1	222.1	249.1	262.1
840	166.2	150.2	173.4	210.1	222.4	250.1	262.4
850	167.6	151.5	174.4	211.1	222.8	251.1	262.8
860	168.9	152.7	175.5	212.0	223.1	252.0	263.1
870	170.2	153.9	176.5	213.0	223.5	253.0	263.5
880	171.5	155.1	177.6	213.9	223.8	253.9	263.8
890	172.8	156.3	178.6	214.8	224.2	254.8	264.2
900	174.0	157.4	179.7	215.7	224.5	255.7	264.5
910	175.3	158.6	180.7	216.6	224.8	256.6	264.8
920	176.5	159.7	181.7	217.5	225.2	257.5	265.2
930	177.6	160.8	182.7	218.4	225.5	258.4	265.5
940	178.8	161.8	183.7	219.3	225.9	259.3	265.9
950	180.0	162.9	184.7	220.1	226.2	260.1	266.2
960	181.1	163.9	185.7	220.9	226.5	260.9	266.5
970	182.2	165.0	186.7	221.8	226.9	261.8	266.9
980	183.3	166.0	187.7	222.6	227.2	262.6	267.2
990	184.3	167.0	188.6	223.4	227.6	263.4	267.6
1000	185.4	167.9	189.6	224.2	227.9	264.2	267.9
1010	186.4	168.9	190.5	225.0	228.2	265.0	268.2
1020	187.5	169.9	191.4	225.8	228.6	265.8	268.6
1030	188.5	170.8	192.2	226.6	228.9	266.6	268.9
1040	189.5	171.7	193.0	227.3	229.2	267.3	269.2
1050	190.5	172.6	193.8	228.1	229.6	268.1	269.6
1060	191.4	173.5	194.6	228.8	229.9	268.8	269.9
1070	192.4	174.4	195.4	229.6	230.2	269.6	270.2
1080	193.3	175.3	196.2	230.3	230.5	270.3	270.5
1090	194.2	176.2	196.9	231.0	230.9	271.0	270.9
1100	195.2	177.0	197.7	231.7	231.2	271.7	271.2
1110	196.1	177.9	198.4	232.5	231.5	272.5	271.5
1120	197.0	178.7	199.1	233.2	231.9	273.2	271.9
1130	197.8	179.5	199.8	233.9	232.2	273.9	272.2
1140	198.7	180.3	200.5	234.5	232.5	274.5	272.5
1150	199.6	181.1	201.2	235.2	232.9	275.2	272.9
1160	200.4	181.9	201.9	235.9	233.2	275.9	273.2
1170	201.3	182.7	202.6	236.6	233.5	276.6	273.5
1180	202.1	183.5	203.2	237.2	233.8	277.2	273.8
1190	202.9	184.2	203.9	237.9	234.1	277.9	274.1

Table 7-1 Browns Ferry 2 P - T Curve Values (Continued)

**********************************REQUIRED TEMPERATURES********************************

PRESSURE	32 EFPY BELTLINE CURVE A	NON-BELTLINE CURVE A	BOTTOM HEAD CURVE B	32 EFPY BELTLINE CURVE B	UPPER VESSEL CURVE B	32 EFPY BELTLINE CURVE C	NON-BELTLINE CURVE C
1200	203.7	185.0	204.6	238.5	234.4	278.5	274.4
1210	204.5	185.7	205.2	239.2	234.8	279.2	274.8
1220	205.3	186.5	205.9	239.8	235.1	279.8	275.1
1230	206.1	187.2	206.5	240.5	235.4	280.5	275.4
1240	206.9	187.9	207.2	241.1	235.7	281.1	275.7
1250	207.6	188.7	207.8	241.7	236.0	281.7	276.0
1260	208.4	189.4	208.5	242.3	236.3	282.3	276.3
1270	209.1	190.1	209.1	242.9	236.6	282.9	276.6
1280	209.9	190.8	209.8	243.5	237.0	283.5	277.0
1290	210.6	191.4	210.4	244.1	237.3	284.1	277.3
1300	211.3	192.1	211.1	244.7	237.6	284.7	277.6
1310	212.0	192.8	211.7	245.3	237.9	285.3	277.9
1320	212.7	193.5	212.4	245.9	238.2	285.9	278.2
1330	213.4	194.1	213.0	246.5	238.5	286.5	278.5
1340	214.1	194.8	213.7	247.0	238.8	287.0	278.8
1350	214.8	195.4	214.3	247.6	239.1	287.6	279.1
1360	215.5	196.1	215.0	248.2	239.4	288.2	279.4
1370	216.2	196.7	215.6	248.7	239.7	288.7	279.7
1380	216.8	197.3	216.3	249.3	240.0	289.3	280.0
1390	217.5	197.9	216.9	249.8	240.3	289.8	280.3
1400	218.2	198.6	217.6	250.4	240.6	290.4	280.6

Table 7-2

BELTLINE ART VALUES FOR BROWNS FERRY 2

Low-Int Shell Thickness =	6.13 inches	Low-Int Shell: 32 EFPY Peak I.D. fluence =	6.05E+17
		32 EFPY Peak 1/4 T fluence =	4.19E+17
Lower Shell Thickness =	6.13 inches	Lower Shell: 32 EFPY Peak I.D. fluence =	6.05E+17
		32 EFPY Peak 1/4 T fluence =	4.19E+17

COMPONENT	I.D.	HEAT	%Cu	%Ni	CF	Initial RTndt	32 EFPY Delta RTndt	Margin	32 EFPY Shift	32 EFPY ART
PLATES:										
Lower Shell	6-127-14	C2467-2	0.16	0.52	112.4	-20	29.9	29.9	59.7	39.7
Lower Shell	6-127-15	C2463-1	0.17	0.48	116.8	-20	31.0	31.0	62.1	42.1
Lower Shell	6-127-17	C2460-2	0.13	0.51	88.3	0	23.5	23.5	46.9	46.9
Low-Int Shell	6-127-6	A0981-1	0.14	0.55	97.8	-10	26.0	26.0	52.0	42.0
Low-Int Shell	6-127-16	C2467-1	0.16	0.52	112.4	-10	29.9	29.9	59.7	49.7
Low-Int Shell	6-127-20	C2849-1	0.11	0.5	73	-10	19.4	19.4	38.8	28.8
WELDS:										
Long.	ESW*		0.28	0.35	154.5	10	41.0	41.0	82.1	92.1
Circumferential	D55733		0.09	0.65	116.7	-40	31.0	31.0	62.0	22.0

* ESW chemistry based on (average + 1 sigma) of several qualification weld chemistries.

TABLE 7-3 UPPER SHELF ENERGY ANALYSIS FOR BELTLINE MATERIALS

Location	Heat	Test Temp.	Initial Longit. USE	Initial Trans. USE	%CU	32 EFPY 1/4T Fluence (x10^17)	32 EFPY %DECR USE	32 EFPY Trans. USE
Lower Shell	C2467-2	USE	120	78	0.16	4.2	12	68.6
	C2463-1	USE	120	78	0.17	4.2	13	67.9
	C2460-2	USE	120	78	0.13	4.2	10	70.2
Int Shell	A0981-1	USE	142	92.3	0.14	4.2	11	82.1
	C2467-1	USE	120	78	0.16	4.2	12	68.6
	C2849-1	USE	120	78	0.11	4.2	9.5	70.6
Welds:								
Axial	All ESW	USE		95	0.28	4.2	19	76.0
Circumferential	ASA weld	USE		145	0.09	4.2	11	129.1

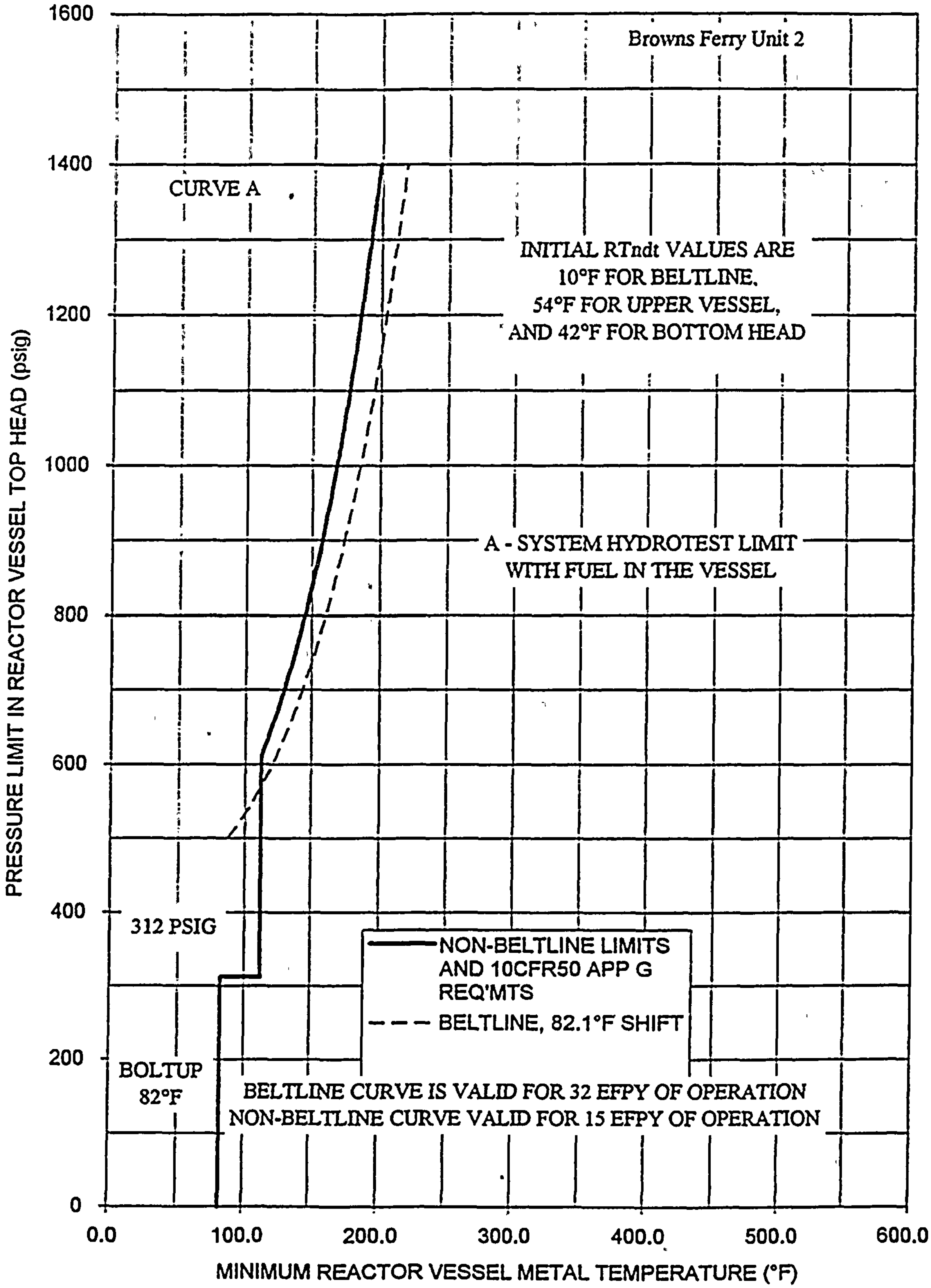


Figure 7-1. Pressure Test P-T Curves for Unit 2

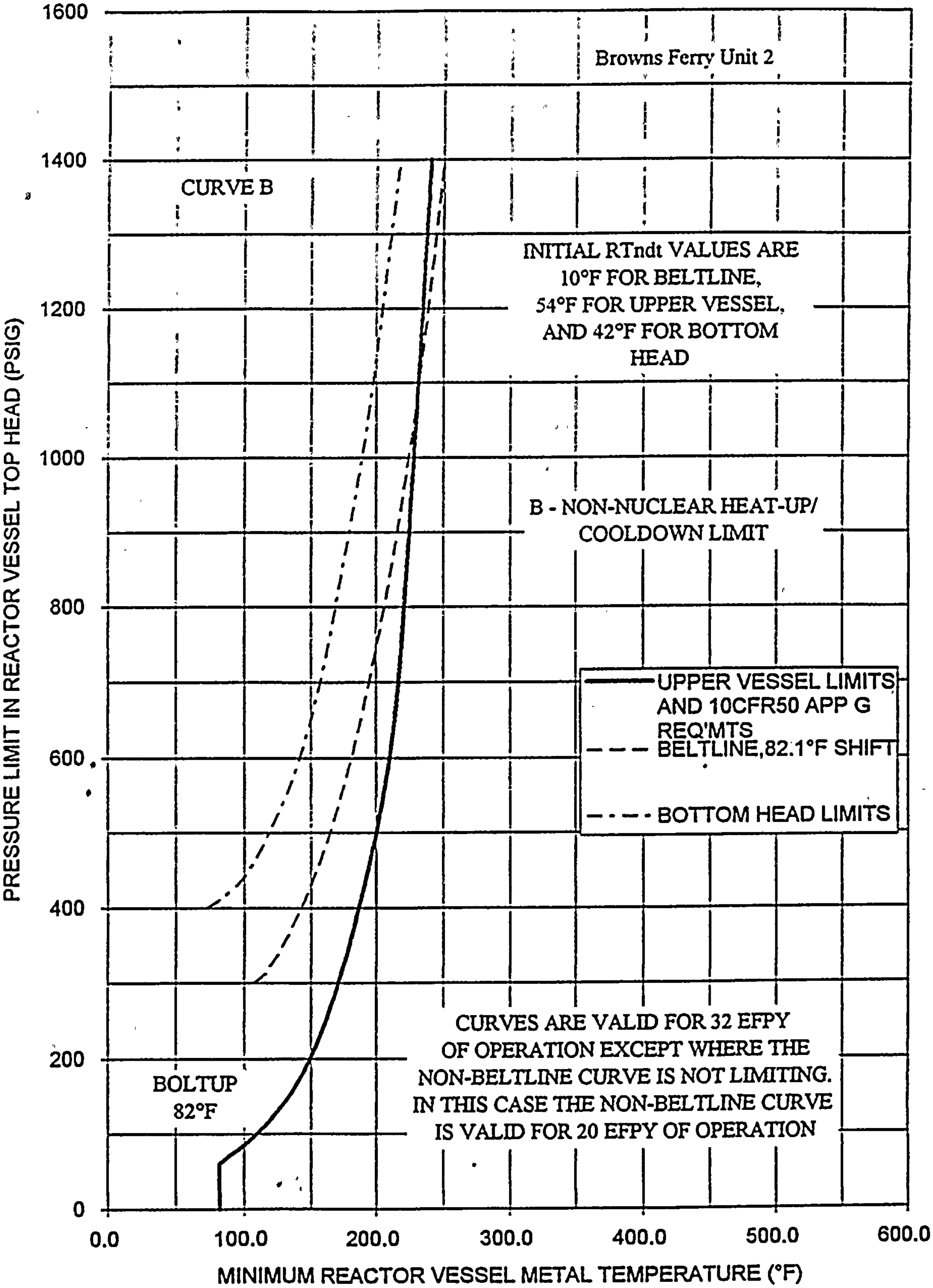


Figure 7-2. Heat-up/Cooldown P-T Curves for Unit 2

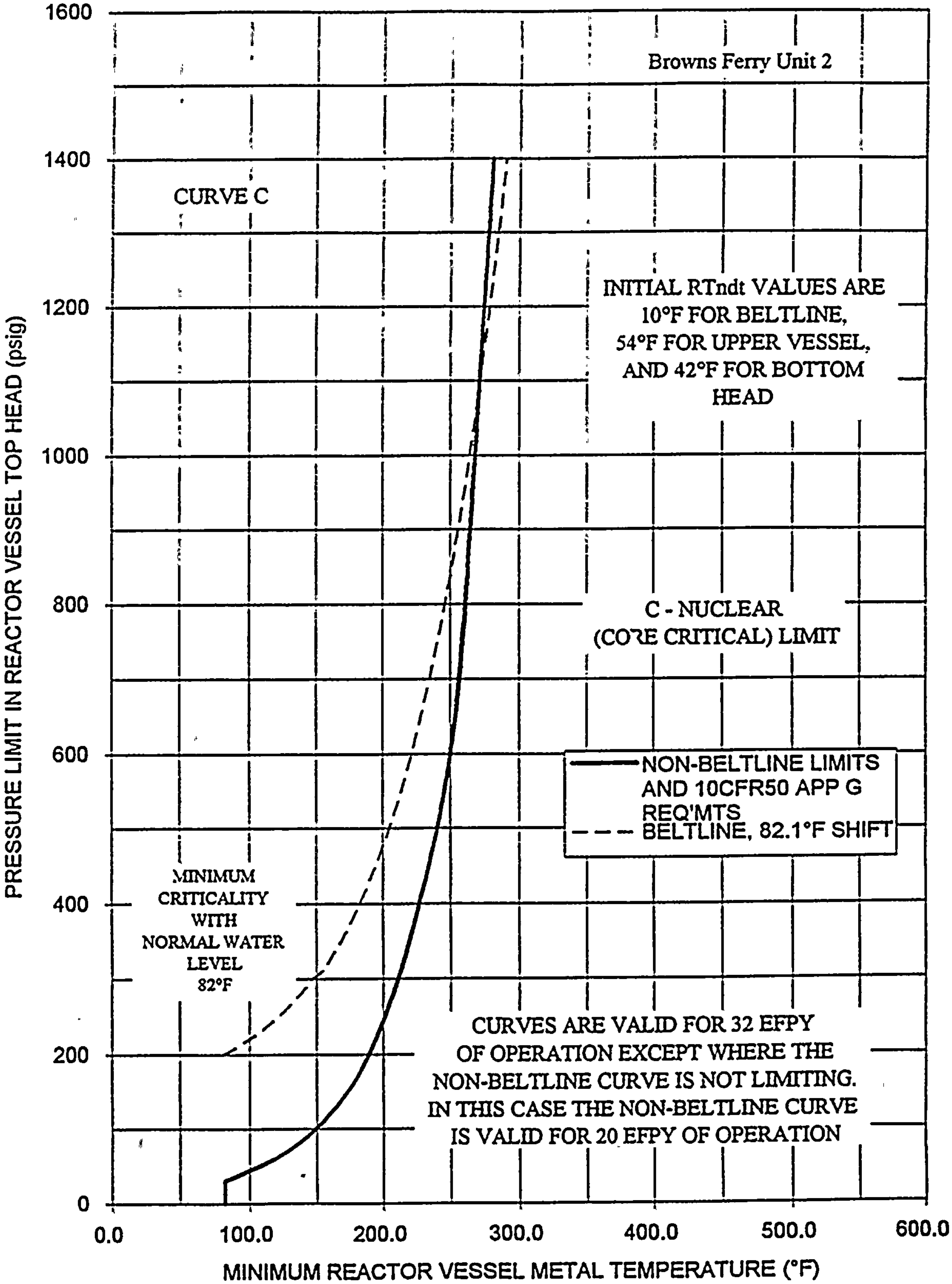


Figure 7-3. Core Critical Operation P-T Curves for Unit 2

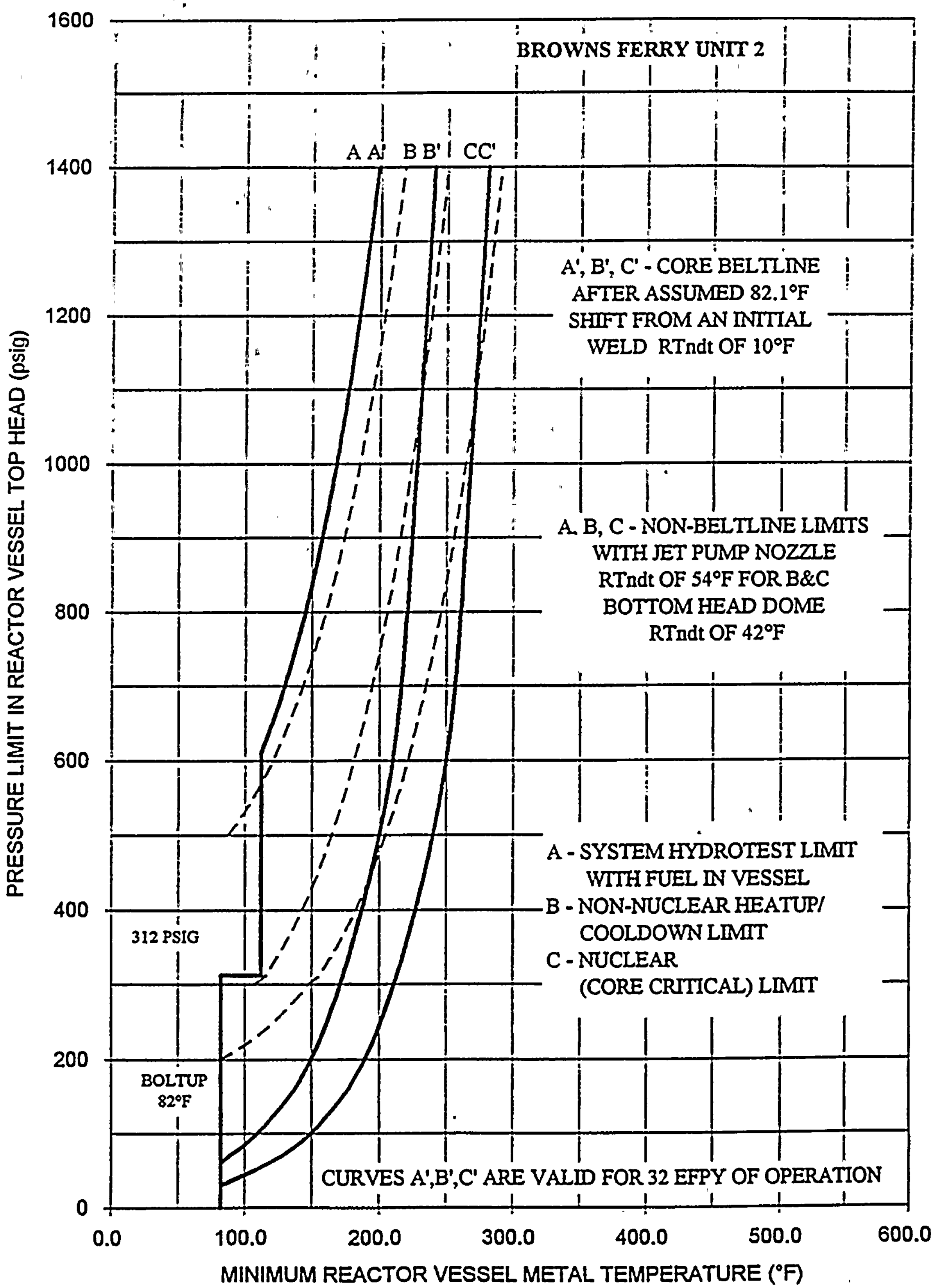
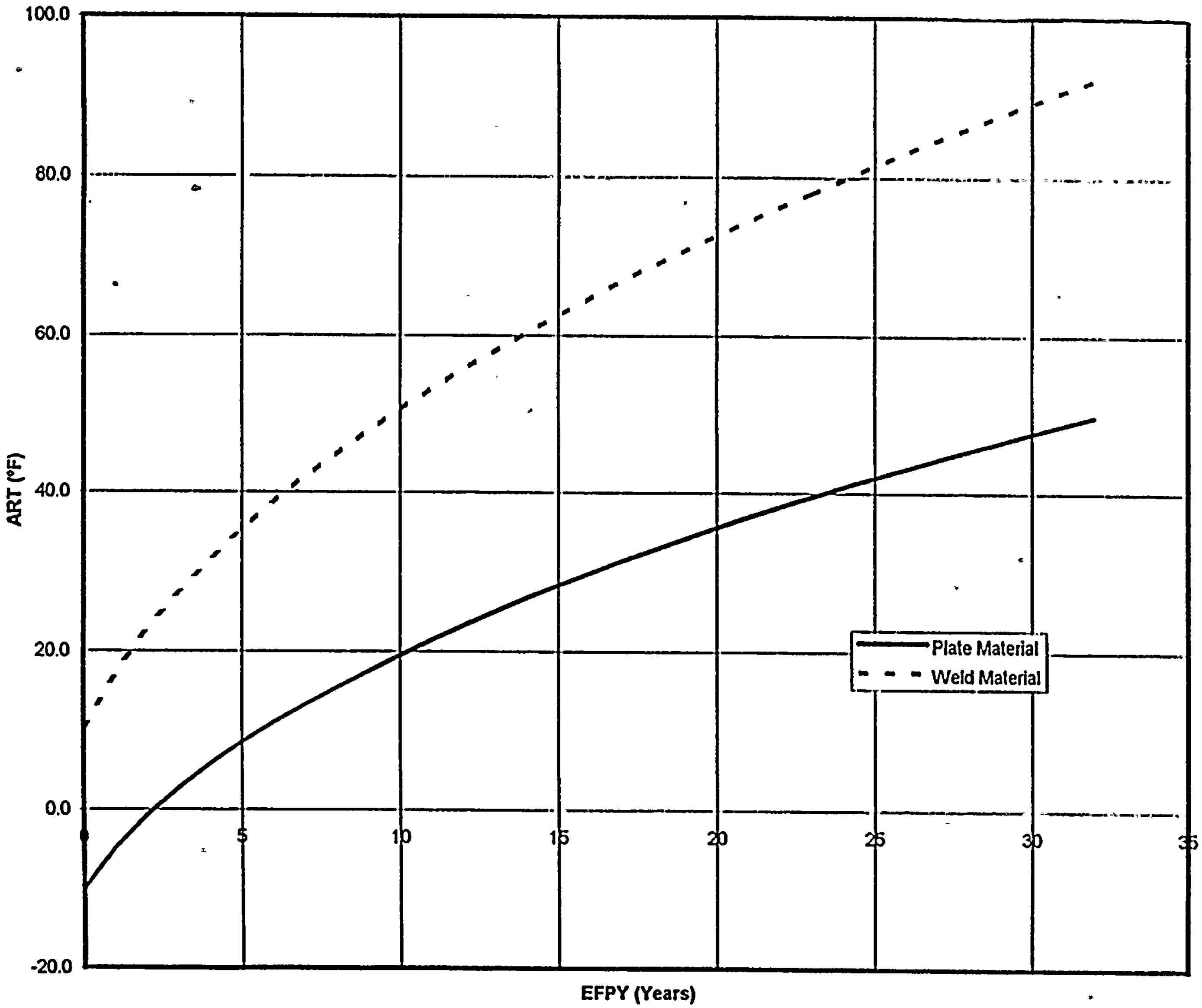


Figure 7-4. Combined P-T Curves for Unit 2



EFPY	ART °F	
	Plate C2467-1	Weld ESW
0	-10.0	10.0
1	-4.8	17.1
2	-0.8	22.6
3	2.6	27.3
4	5.6	31.4
5	8.3	35.2
6	10.9	38.7
7	13.2	41.9
8	15.4	45.0
9	17.5	47.8
10	19.5	50.6
11	21.4	53.2
12	23.2	55.6
13	24.9	58.0
14	26.6	60.3
15	28.2	62.6
16	29.8	64.7
17	31.3	66.8
18	32.8	68.8
19	34.2	70.7
20	35.6	72.6
21	36.9	74.5
22	38.2	76.2
23	39.5	78.0
24	40.7	79.7
25	41.9	81.4
26	43.1	83.0
27	44.3	84.6
28	45.4	86.2
29	46.5	87.7
30	47.6	89.2
31	48.7	90.6
32	49.7	92.1

Figure 7-5. Browns Ferry 2 ART Versus EFPY for Plate and Weld Materials

8. REFERENCES

[1] "Fracture Toughness Requirements," Appendix G to Part 50 of Title 10 of the Code of Federal Regulations, July 1983.

[2] "Protection Against Non-Ductile Failure," Appendix G to Section XI of the 1992 ASME Boiler & Pressure Vessel Code.

[3] "Reactor Vessel Material Surveillance Program Requirements," Appendix H to Part 50 of Title 10 of the Code of Federal Regulations, July 1983.

[4] "Surveillance Test for Nuclear Reactor Vessels," American Society for Testing and Materials, Philadelphia, PA, (ASTM E185-66).

[5] "Browns Ferry Nuclear Plant Updated Final Safety Analysis Report, Section 4.2," Tennessee Valley Authority.

[6] "Conducting Surveillance Tests for Light Water Cooled Nuclear Power Reactor Vessels," Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia, PA, July 1,1982, (ASTM E185-82).

[7] "Radiation Embrittlement of Reactor Vessel Materials," USNRC Regulatory Guide 1.99, Revision 2, May 1988.

[8] "Reactor Pressure Vessel Purchase Specification, Rev. 9," GE-NED, San Jose, CA, (21A1111).

[9] Letter from Ralph H. Shell to U.S. Nuclear Regulatory Commission, "Browns Ferry Nuclear Plant (BFN), Sequoyah Nuclear Plant (SQN), and Watts Bar Nuclear Plant (WBN) - Response to Generic Letter 92-01 (Reactor Vessel Structural Integrity), Tennessee Valley Authority, Chattanooga, Tennessee, July 7, 1992.

[10] G. C. Martin, "Browns Ferry Unit 3 In-Vessel Neutron Spectral Analysis," GENE, Pleasanton, CA, August 1980, (NEDO-24793).

[11] Letter from J. Valente (Restart Engineering Manager - ATH 3A-BFN) to T. R. McIntyre, "Browns Ferry Nuclear Plant - Units 1, 2, and 3 Pressure Temperature Limits Calculation - Attachment 1 and Attachment 2." (Attachment 1 is Branch / Project Identifier ND-Q0999-900054 R0, RIMs Accession Number B22 '90 1227 102, Rev. 0 page 4 of 9).

[12] "Standard Methods for Notched Bar Impact Testing of Metallic Materials," Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia, PA, (ASTM E23-88).

[13] "Nuclear Plant Irradiated Steel Handbook," Electric Power Research Institute, Palo Alto, CA, September 1986, (EPRI Report NP-4797).

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[15] G. W. Contreras, "Tennessee Valley Authority Browns Ferry Nuclear Plant Units 1, 2, and 3 Pressure Temperature Operating Limits," GENE, San Jose, CA, June 1994, (GENE-523-A65-0594).

[16] "Fracture Toughness Requirements," USNRC Branch Technical Position MTEB 5-2, Revision 1, July 1981.

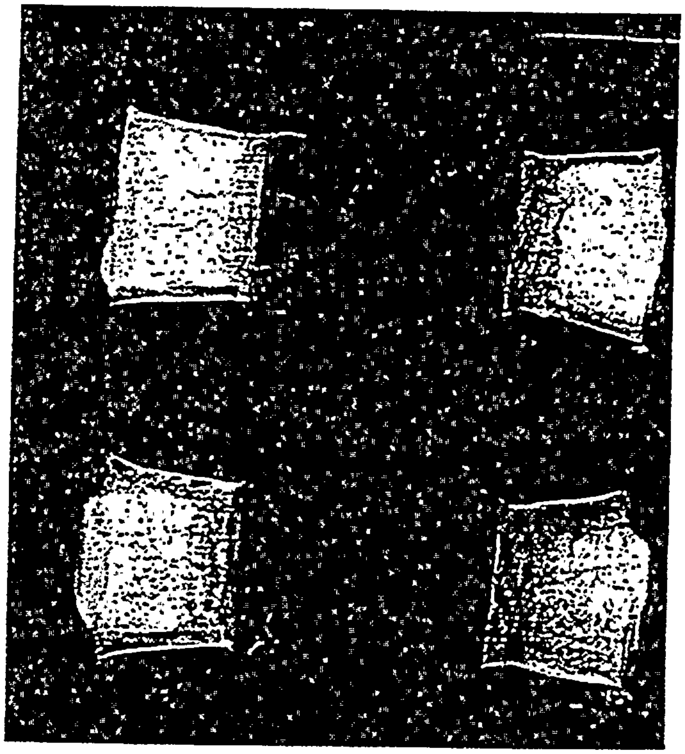
[17] H. S. Mehta, T. A. Caine, and S. E. Plaxton, "10CFR50 Appendix G Equivalent Margin Analysis for Low Upper Shelf Energy in BWR/2 through BWR/6 Vessels," GENE, San Jose, CA, February 1994, (NEDO-32205-A, Revision 1).

APPENDIX A - CHARPY SPECIMEN FRACTURE SURFACE PHOTOGRAPHS

Photographs of each Charpy specimen fracture surface were taken per the requirements of ASTM E185-82. The pages following show the fracture surface photographs along with a summary of the Charpy test results for each irradiated specimen. The pictures are arranged in the order of base, weld, and HAZ materials.

BASE: E71
Temp: 40 °F
Energy: 60.0 ft-lb
MLE: 50.0 mils
Shear: 40 %

BASE: E7D
Temp: 60 °F
Energy: 82.5 ft-lb
MLE: 61.0 mils
Shear: 59 %

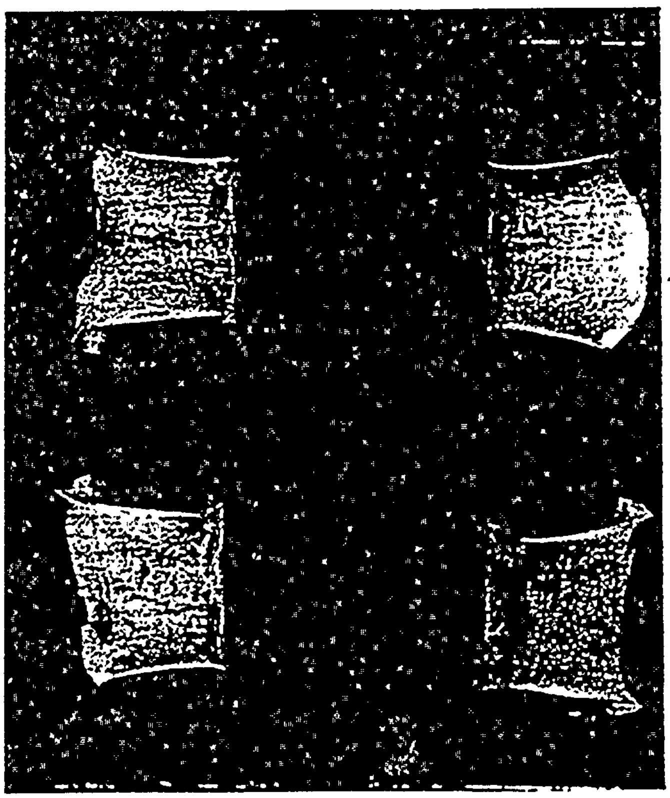


BASE: E64
Temp: 80 °F
Energy: 94.5 ft-lb
MLE: 70.0 mils
Shear: 68 %

BASE: E5U
Temp: 100 °F
Energy: 121.0 ft-lb
MLE: 91.0 mils
Shear: 85 %

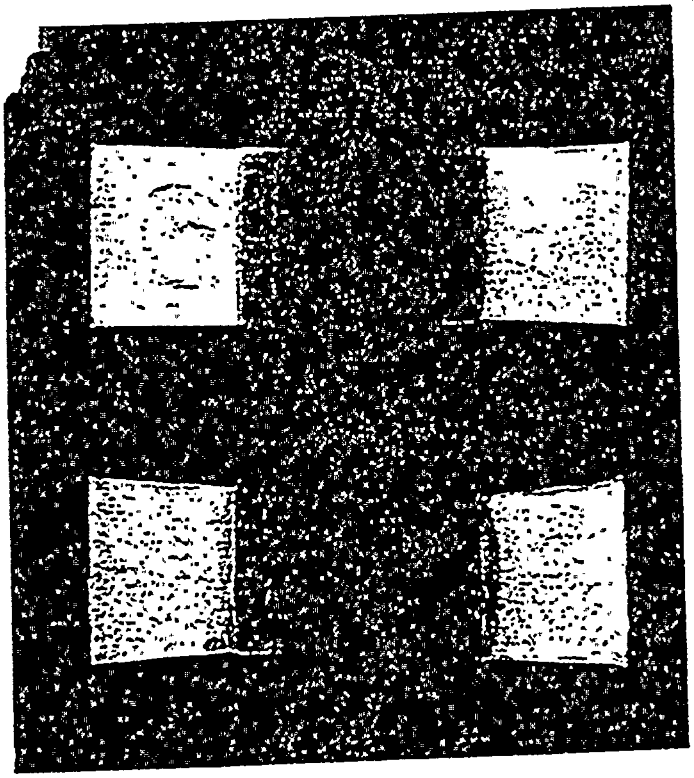
BASE: E72
Temp: 120 °F
Energy: 120.5 ft-lb
MLE: 88.0 mils
Shear: 100 %

BASE: E51
Temp: 160 °F
Energy: 130.0 ft-lb
MLE: 91.0 mils
Shear: 100 %



BASE: E57
Temp: 200 °F
Energy: 136.0 ft-lb
MLE: 94.0 mils
Shear: 100 %

BASE: E55
Temp: 300 °F
Energy: 131.5 ft-lb
MLE: 88.0 mils
Shear: 100 %



BASE: E5C
Temp: -80 °F
Energy: 10.5 ft-lb
MLE: 10.0 mils
Shear: 3 %

BASE: E5Y
Temp: -40 °F
Energy: 17.0 ft-lb
MLE: 13.5 mils
Shear: 11 %

BASE: E7Y
Temp: -20 °F
Energy: 33.0 ft-lb
MLE: 30.5 mils
Shear: 13 %

BASE: E7K
Temp: 0 °F
Energy: 38.5 ft-lb
MLE: 33.0 mils
Shear: 19 %

WELD: EB7
Temp: -80 °F
Energy: 2.0 ft-lb
MLE: 5.0 mils
Shear: 2 %

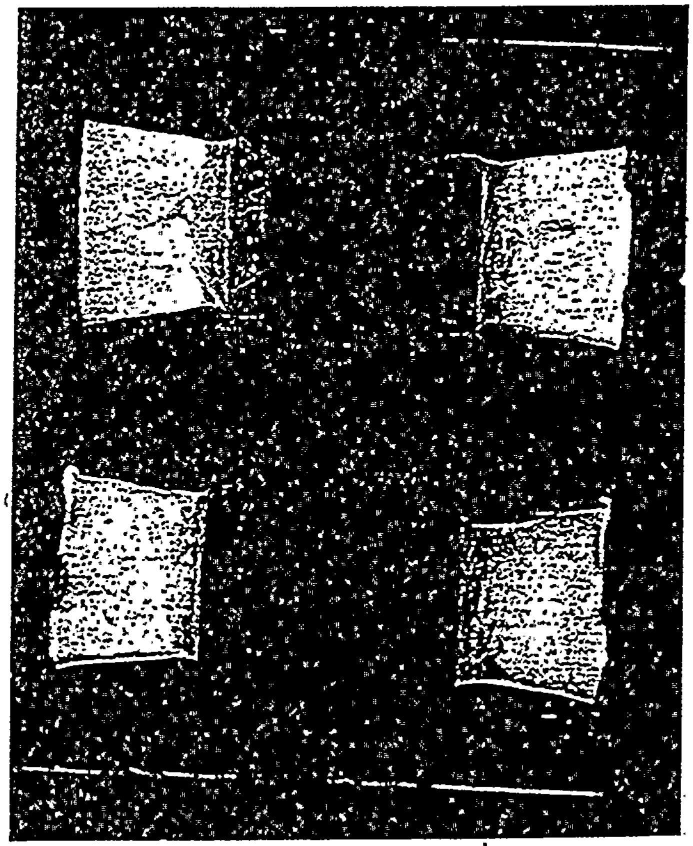
WELD: EB5
Temp: -40 °F
Energy: 13.0 ft-lb
MLE: 12.5 mils
Shear: 4 %

WELD: EBK
Temp: -20 °F
Energy: 37.5 ft-lb
MLE: 31.0 mils
Shear: 9 %

WELD: EAP
Temp: 0 °F
Energy: 50.0 ft-lb
MLE: 42.0 mils
Shear: 15 %

WELD: EBD
Temp: 20 °F
Energy: 59.5 ft-lb
MLE: 52.0 mils
Shear: 22 %

WELD: EB1
Temp: 80 °F
Energy: 59.0 ft-lb
MLE: 52.0 mils
Shear: 42 %

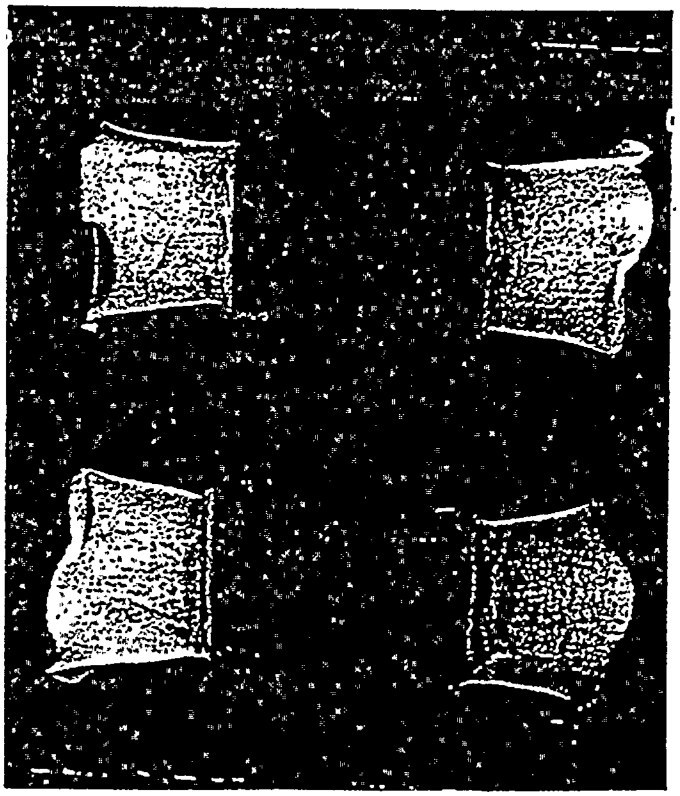


WELD: EBB
Temp: 40 °F
Energy: 59.5 ft-lb
MLE: 50.0 mils
Shear: 30 %

WELD: EAM
Temp: 100 °F
Energy: 76.5 ft-lb
MLE: 64.5 mils
Shear: 50 %

WELD: EBE
Temp: 120 °F
Energy: 87.0 ft-lb
MLE: 65.0 mils
Shear: 68 %

WELD: EB2
Temp: 200 °F
Energy: 107.5 ft-lb
MLE: 84.5 mils
Shear: 100 %

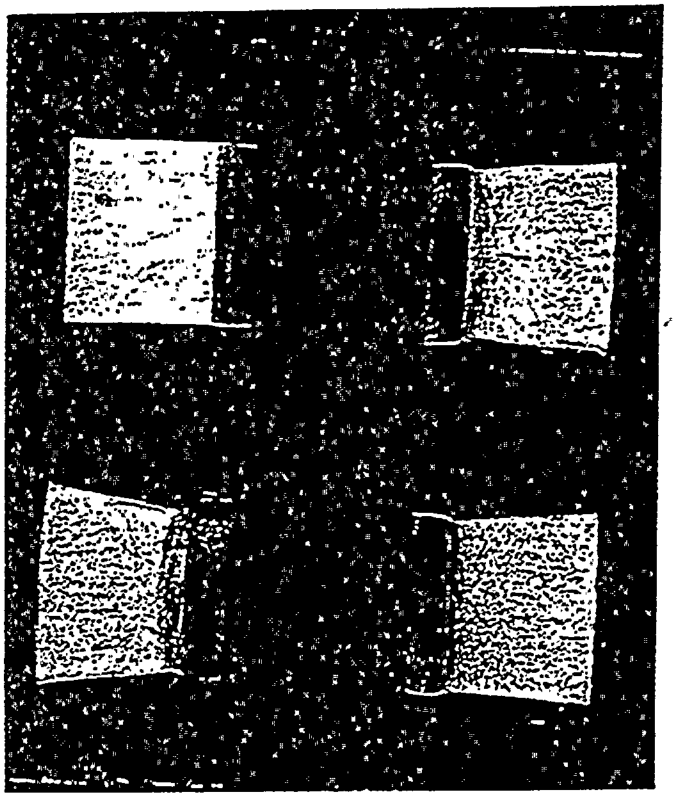


WELD: EB4
Temp: 160 °F
Energy: 107.0 ft-lb
MLE: 87.0 mils
Shear: 100 %

WELD: EBA
Temp: 300 °F
Energy: 113.0 ft-lb
MLE: 88.5 mils
Shear: 100 %

HAZ: ED6
Temp: -80 °F
Energy: 3.5 ft-lb
MLE: 6.0 mils
Shear: 1 %

HAZ: EEY
Temp: -40 °F
Energy: 54.0 ft-lb
MLE: 44.0 mils
Shear: 24 %

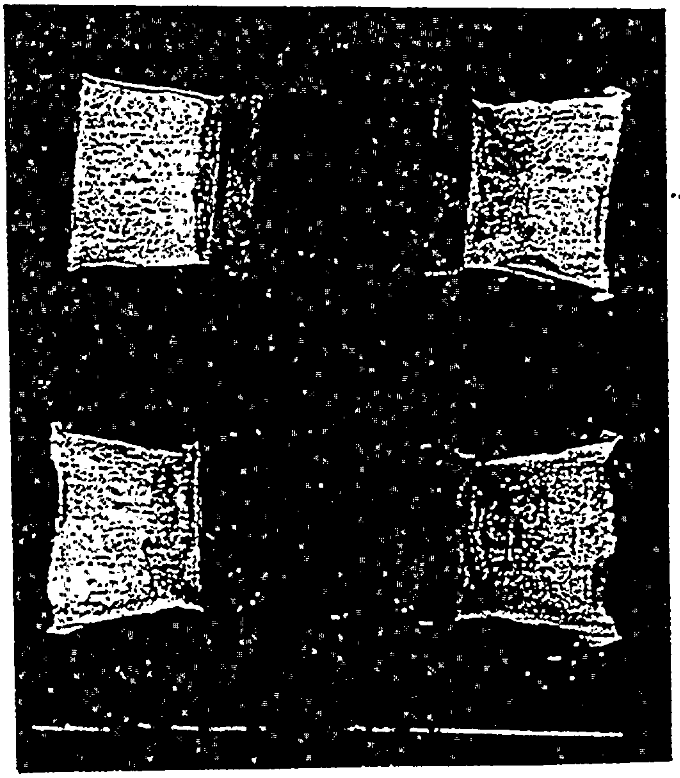


HAZ: EJ3
Temp: -60 °F
Energy: 37.0 ft-lb
MLE: 30.0 mils
Shear: 12 %

HAZ: EDB
Temp: -20 °F
Energy: 30.0 ft-lb
MLE: 22.5 mils
Shear: 7 %

HAZ: EJJ
Temp: 0 °F
Energy: 43.5 ft-lb
MLE: 36.5 mils
Shear: 19 %

HAZ: EJC
Temp: 40 °F
Energy: 93.5 ft-lb
MLE: 67.0 mils
Shear: 48 %

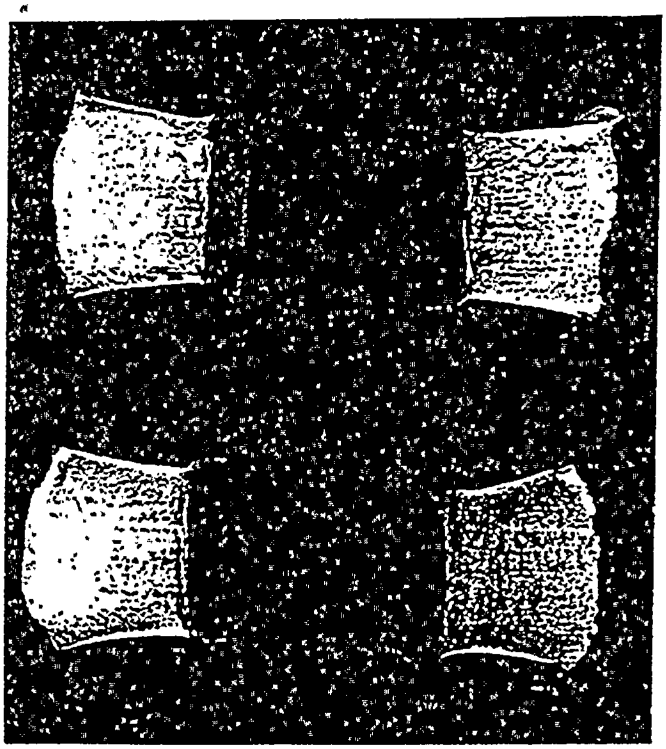


HAZ: EJ5
Temp: 20 °F
Energy: 106.0 ft-lb
MLE: 81.5 mils
Shear: 65 %

HAZ: EJ1
Temp: 60 °F
Energy: 107.5 ft-lb
MLE: 86.0 mils
Shear: 75 %

HAZ: EDC
Temp: 80 °F
Energy: 82.0 ft-lb
MLE: 73.0 mils
Shear: 60 %

HAZ: EJB
Temp: 120 °F
Energy: 97.5 ft-lb
MLE: 78.0 mils
Shear: 100 %



HAZ: EJD
Temp: 200 °F
Energy: 107.5 ft-lb
MLE: 82.0 mils
Shear: 100 %

HAZ: EEC
Temp: 300 °F
Energy: 143.0 ft-lb
MLE: 92.0 mils
Shear: 100 %

3

APPENDIX B EQUIVALENT MARGIN ANALYSIS

TABLE B-1 EQUIVALENT MARGIN ANALYSIS PLANT APPLICABILITY VERIFICATION FORM FOR BROWNS FERRY UNIT 2 - BWR 4/MK I

BWR/3-6 PLATE

Surveillance Plate USE:

%Cu = 0.14

Capsule Fluence = 1.52×10^{17} n/cm^2

Measured % Decrease = 4 (Charpy Curves)

R.G. 1.99 Predicted % Decrease = 9 (R.G. 1.99, Figure 2)

Limiting Beltline Plate USE:

%Cu = 0.17

32 EFPY 1/4T Fluence = 4.2×10^{17} n/cm^2

R.G. 1.99 Predicted % Decrease = 13 (R.G. 1.99, Figure 2)

Adjusted % Decrease = N/A (R.G. 1.99, Position 2.2)

13 % ≤ 21%, so vessel plates are bounded by equivalent margin analysis

TABLE B-2 EQUIVALENT MARGIN ANALYSIS PLANT APPLICABILITY VERIFICATION FORM FOR BROWNS FERRY UNIT 2 - BWR 4/MK I

BWR/2-6 WELD

Surveillance Weld USE:

%Cu = 0.20

Capsule Fluence = 1.52×10^{17} n/cm^2

Measured % Decrease = -3 (Charpy Curves)

R.G. 1.99 Predicted % Decrease = 13 (R.G. 1.99, Figure 2)

Limiting Beltline Weld USE:

%Cu = 0.28

32 EFPY 1/4T Fluence = 4.2×10^{17} n/cm^2

R.G. 1.99 Predicted % Decrease = 21 (R.G. 1.99, Figure 2)

Adjusted % Decrease = N/A (R.G. 1.99, Position 2.2)

21 % ≤ 34%, so vessel welds are bounded by equivalent margin analysis