GE Nuclear Energy

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LASALLE UNIT 2
RPV SURVEILLANCE MATERIALS
TESTING AND ANALYSIS

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ABSTRACT

The surveillance capsule at the 300° azimuthal location (which had 120° capsule identification and contents) was removed at 6.98 EFPY from the LaSalle Unit 2 reactor in Spring 1995. The capsule contained flux wires for neutron fluence measurement and Charpy and tensile test specimens for material property evaluations. 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.

The irradiated Charpy data for the weld specimens were compared to the unirradiated data to determine the shift in Charpy curves due to irradiation. Unirradiated Charpy base plate data was only available for transverse specimens whereas the surveillance specimens are of longitudinal orientation. Thus, evaluation of shifts was not possible for the plate material. The shift results for the weld material are within the predictions of the Regulatory Guide 1.99 Revision 2.

The irradiated tensile data for the plate and weld specimens were summarized. The room temperature irradiated data was compared with the unirradiated data to determine the effect of irradiation on the stress-strain relationship of the materials; only room temperature baseline data was available.

The flux wire results, combined with the lead factor determined from the first fuel cycle, were used to estimate the 32 EFPY fluence. The resulting estimate was in good agreement with the previous nominal 32 EFPY fluence estimate.

ACKNOWLEDGMENTS

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Charpy testing was completed by G. P. Wozadlo, G. E. Dunning and B. D. Frew. Tensile specimen testing was done by S. B. Wisner and chemical composition analysis was performed by P. Wall. Flux wire testing was performed by L. Kessler, R. Kruger and R. Reager. Project management was conducted by Betty Branlund.

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].

Appendix H of 10CFR50 [3] and ASTM E185-70 establish the methods to be used for surveillance of the LaSalle Unit 2 reactor vessel materials. In addition, compliance with ASTM E185-73 [4] has been addressed in the Final Safety Analysis Report [5]. The first vessel surveillance specimen capsule required by 10CFR50 Appendix H [3] was removed from LaSalle Unit 2 in Spring 1995. 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 the vessel materials within the core beltline region. The impact and tensile specimens were tested to establish properties for the irradiated materials.

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 material toughness for the weld material, through Charpy testing. Irradiated tensile testing results are provided and are compared with room temperature unirradiated data to determine the effect of irradiation on the stress-strain relationship of the materials; only room temperature baseline tensile data was available for the plate.

2. SUMMARY AND CONCLUSIONS

2.1 SUMMARY OF RESULTS

The 300° azimuth position 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:

Section 3: Surveillance Program Background

- RPV Materials and Fabrication
- Material Properties
- Surveillance Specimen Chemical Composition
- Specimen Description

Section 4: Peak RPV Fluence Evaluation

Section 5: Charpy V-Notch Impact Testing

Section 6: Tensile Testing

Section 7: Adjusted Reference Temperature and Upper Shelf Energy

The significant results of the evaluation are below:

a. The 300° azimuth position / 120° capsule was removed from the reactor after 6.98 EFPY of operation. 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, 3 weld and 2 HAZ metal specimens.

b. The chemical composition of copper (Cu) and nickel (Ni) for the irradiated surveillance materials were determined from a chemical composition analysis. The best estimate values for the surveillance material chemistries were calculated as

averages of the available baseline and irradiated data. The best estimate values for the surveillance plate are 0.10% Cu and 0.48% Ni, and are 0.04% Cu and 0.89% Ni for the surveillance weld.

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 1.15×10^{17} n/cm^2 at removal.

d. A neutron transport computation had been performed based on the performance of the first fuel cycle. Relative flux distributions in the azimuthal and axial directions were previously developed in Reference 19. The lead factor was 0.98, relating the surveillance capsule flux to the peak inside surface flux.

e. The surveillance Charpy V-Notch specimens were impact tested at temperatures selected to define the upper shelf energy (USE) and the transition of the Charpy V-Notch curves for 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 and unirradiated Charpy specimens established the 30 ft-lb shifts. The weld material showed an 18.6°F shift and a 3.6 ft-lb increase in USE (4.3% increase). The index temperature irradiation shift and the decrease in USE for the plate material was not determined due to insufficient baseline data.

g. The measured shift of 18.6°F for weld, for a fluence of 1.15×10^{17} n/cm^2, was within the Reg. Guide 1.99 [7] range prediction ($\Delta RT_{NDT} \pm 2\sigma$) of -49.6°F to 62.4°F. The best estimate chemical composition for the surveillance weld material was used for this calculation.

h. The irradiated tensile specimens were tested at room temperature (70°F), at reactor operating temperature (550°F), and at 150°F for the additional base and weld specimens. Only room temperature unirradiated tensile test data were

available for comparison. As expected, the room temperature results show that in comparison to unirradiated data the irradiated data has increased strength and decreased ductility typical for irradiation embrittlement.

i. The 32 EFPY RPV peak fluence prediction is 5.38×10^{17} n/cm^2 at the vessel wall, based on the flux wire test and lead factor. This is about 3% higher than the previously established nominal 32 EFPY fluence prediction (5.2×10^{17} n/cm^2 [19]). The 32 EFPY fluence prediction is 3.7×10^{17} n/cm^2 at 1/4 T.

j. 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, Rev. 2. The ART for the limiting material, plate heat C9404-2, at 32 EFPY is 73.8°F and is lower than the 200°F requirement of 10CFR50 Appendix G [1].

k. An update of the beltline material USE values at 32 EFPY was performed using the Reg. Guide 1.99, Rev. 2 methodology. The irradiated USE for all beltline materials will remain above 50 ft-lbs through 32 EFPY as required in 10CFR50 Appendix G [1].

2.2 CONCLUSIONS

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

a. The 30 ft-lb shifts and changes in USE are consistent with Regulatory Guide 1.99 Revision 2 predictions and associated deviations.

b. The values of ART and USE for the reactor vessel beltline materials are expected to remain within limits of 10CFR50 Appendix G [1] (< 200°F and > 50 ft-lbs, respectively) for at least 32 EFPY of operation.

3. SURVEILLANCE PROGRAM BACKGROUND

3.1 CAPSULE RECOVERY

The reactor pressure vessel (RPV) surveillance program consists of 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 is expected to receive equal irradiation because of core symmetry. During the Spring 1995 outage, a surveillance capsule was removed from the 300° azimuthal location. 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 capsule basket was examined for identification. The identification number stamped on the basket corresponded to basket number 2 and reactor number 51, as specified by GE drawings, 131C7717 (Specimen Holder) and 105D4714G006 (Surveillance Program), for the LaSalle Unit 2 120° surveillance materials. A comparison of capsule identification and actual capsule azimuthal location indicates that the capsule identified as the 120° capsule was actually located in the 300° azimuthal location. LaSalle Unit 2 technical staff verified that the capsule was actually pulled from the 300° location per IVVI and work records for the outage. The discrepancy between capsule locations will in no way affect the results of surveillance testing due to symmetry of irradiation in the vessel and presence of the same type of surveillance specimens in each capsule.

The general condition of the basket as received is shown in Figure 3-1. The basket contained three impact (Charpy) specimen capsules and four tensile specimen capsules. During the removal of the Charpy impact specimens from the specimen holders, the weld specimen holder was found to have leaked. The specimens were visually examined for features that could possibly affect test results. The specimens appeared somewhat darker in appearance than the other specimens. This uniform discoloration was most likely caused by the exposure of the specimen to the high temperature water environment. The surfaces of the discolored specimens were similar to the other specimens, i.e., no defects, pits, or detrimental corrosion was observed. Based on these observations, it is was concluded that the specimens were not affected by the exposure to water, and will give credible surveillance results.

3.2 RPV MATERIALS AND FABRICATION

3.2.1 Fabrication History

The LaSalle Unit 2 RPV is a 251 inch diameter BWR/5 design. Construction was performed by CBI Nuclear Company (CBIN) under the 1968 edition of the ASME Code through the 1970 Winter Addenda. The shell and head plate materials are ASME SA533, Grade B, Class 1 low alloy steel (LAS). The nozzles and closure flanges are ASME SA508 Class 2 LAS, and the closure flange bolting materials are ASME SA540 Grade B24 LAS [23]. Submerged arc or shielded metal arc welding of plates was followed by post-weld heat treatment at 1150°F. The fabrication impact test specimens were given a simulated post weld heat treatment at 1150°F plus 25°F minus 50°F, held 50 hours followed by furnace cooling to below 600°F, then air cooled [11]. The identification of plates and welds in the beltline region is shown in Figure 3-2.

3.2.2 Material Properties of RPV at Fabrication

Material certification records were retrieved from GE Quality Assurance (QA) records to determine chemical and mechanical properties of the vessel materials. The retrieved information is documented in the UFSAR [23] and in GE P-T Curve report [15]. Table 3-1 shows the chemistry data for the beltline materials. Properties of the beltline materials and materials at other locations of interest are presented in Table 3-2.

3.2.3 Surveillance Capsule Specimen Chemical Composition

Samples were taken from the irradiated base and weld specimens after they were tested. Chemical analyses were performed using a Spectraspan III plasma emission spectrometer. Each sample was dissolved in an acid solution to a concentration of 40 mg steel per ml solution. The spectrometer was calibrated for determination of Mn, Ni, Mo, Cr, Si and Cu by diluting National Institute of Standards and Technology (NIST) Spectrometric Standard Solutions. The phosphorus calibration involved analysis of seven reference materials from NIST with known phosphorus levels. Analysis accuracies are $\pm$0.005% (absolute) of reported value for phosphorus and $\pm$5% (relative) of reported value for other elements. The chemical composition results are given in Table 3-3 for both irradiated and baseline surveillance plate and weld materials. The baseline data were taken from CBIN material certification records for the plate and weld surveillance specimens [9].

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 (3), and HAZ (2). 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. Surveillance program design information is discussed in GE report [11].

3.3.1 Charpy Specimens

The fabrication of the Charpy specimens is described in the CBIN drawings [10] of the surveillance test program. All materials used for surveillance were fabricated from material of the same heat as one of the beltline plates [9,10].

The base metal specimens were cut from Heat C9481-1. The test plates received the same heat treatment as the fabrication specimens for Heat C9481-1, including the post-weld heat treatment for 50 hours at 1150°F +25°F/-50°F. The Charpy specimens were removed from Heat C9481-1 and machined as described in Section 2.2 of GE report [11]. 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 Charpy specimens had been stamped on one end with the fabrication codes as listed in GE report [11] for LaSalle Unit 2.

The weld metal and HAZ Charpy specimens were fabricated by welding together two pieces of the surveillance test plates Heat C9481-1 with the same weld procedure used to produce welds in the beltline region. Welding records obtained from CBIN show the surveillance weld to be submerged arc weld with heat 5P7397, Linde 124 Flux, and Lot 0342. The filler heat number of the surveillance weld does not match that of a core region seam, however the filler material used meets the requirements of Reference [10] which indicates that a material representative of the core region longitudinal seams could be used [11]. The welded test plates received stress relief heat treatment at 1150°F +25°F/- 50°F to simulate the RPV fabrication conditions. The weld and HAZ specimens were cut from the material as shown in Figure 2-1 of GE report [11] avoiding the volume near the root of the welds. The base metal orientation in the weld and HAZ specimens was longitudinal.

3.3.2 Tensile Specimens

Fabrication of the surveillance tensile specimens is also described in the CBIN surveillance specimen drawings [10]. The materials, and thus the chemical compositions and heat treatments for the base, weld, and HAZ tensiles are the same as those for the corresponding Charpy specimens. The identifications of the base, weld, and HAZ surveillance specimens and a summary of the fabrication methods can be found in GE report [11].

Table 3-1
CHEMICAL COMPOSITION OF RPV BELTLINE MATERIALS FROM FABRICATION CMTR RECORDS[a]

		Composition by Weight Percent							
Identification	**Heat/Lot No.**	**Cu**	**Ni**	**C**	**Mn**	**P**	**S**	**Si**	**Mo**
PLATES:									
Lower Shell Plates:									
21-1	C9425-2	0.12	0.51	0.21	1.25	0.009	0.020	0.25	0.50
21-2	C9425-1	0.12	0.51	0.21	1.25	0.009	0.020	0.25	0.50
21-3	C9434-2	0.09	0.51	0.21	1.31	0.013	0.015	0.21	0.50
Lower-Intermediate Shell Plates:									
22-1	C9481-1	0.11	0.50	0.21	1.27	0.008	0.018	0.23	0.50
22-2	C9404-2	0.07	0.49	0.22	1.38	0.008	0.020	0.27	0.50
22-3	C9601-2	0.12	0.50	0.21	1.28	0.015	0.019	0.23	0.53
Surveillance Plate:	[b] C9481-1	0.084	0.45	.291	1.28	0.003	0.023	0.19	0.34
WELDS:									
Lower-Inter. Vert. BA, BB, BC	3P4000,Flux 124,Lot 3933	0.02	0.89	0.08	1.30	0.012	0.010	0.39	0.42
Lower Vertical BD, BE, BF	3P4966, Flux 124,Lot 1214	0.03	0.90	0.07	1.39	0.011	0.014	0.38	0.53
Girth Weld:									
Lower to Lower-Inter. AB	5P6771,Flux 124,Lot 0342	0.04	0.95	0.06	1.30	0.013	0.011	0.45	0.57
Surveillance Weld:[b] (Tandem Wire)	5P7397, Flux 124, Lot 0342	0.03	0.87	0.069	1.38	0.014	0.015	0.50	0.44

[a] **Data from GE Report [15]**

[b] **Data from CBIN CMTR values. Contract No. 8-CN203 (1980) [28]**

Table 3-2

Mechanical Properties of Beltline and Other Selected RPV Materials

Location	ID. No.	Heat Number	Initial RT_{NDT} (°F)
Beltline[a]:			
Lower Shell Plates	21-1	C9425-2	30
	21-2	C9425-1	32
	21-3	C9434-2	10
Lower Intermediate Shell Plates	22-1	C9481-1	10
	22-2	C9404-2	52
	22-3	C9601-2	10
Vertical Welds[c]	BA,BB,BC	3P4000	-50
	BD,BE,BF	3P4966	-6
Girth Welds[c]	AB	5P6771	-34
Non-Beltline[a]:			
Upper Shell	24-1	A-8453-1	26
Head Flange	30-1	BWK-446	10
Feedwater Nozzle	52-1-1/6	Q2Q25W	-6
Bottom Head	13-3	C9306-2	44
Closure Bolts[b]	35-1	82552	LST = 70

a Test data information from [15]

b Initial RT_{ndt} = LST = 10°F (the lowest CVN test temp.) + 60°F

c These are conservative bounding values from single and tandem wire qualifications.

Table 3-3
Chemical Composition of LaSalle 2 Surveillance Materials From Surveillance Specimen Chemical Tests

Metal Sample ID	Metal Sample Type	Cu (wt%)	Ni (wt%)	Mn (wt%)	Mo (wt%)	Si (wt%)	Cr (wt%)	P (wt%)
28832	Base	0.11	0.49	1.24	0.52	0.20	0.13	0.011
28833	Base	0.11	0.51	1.22	0.55	0.23	0.14	0.014
28834	Base	0.10	0.47	1.17	0.50	0.17	0.13	0.011
Baseline A[a]	Base	0.08	0.45	1.28	0.34	0.19	0.09	0.003
Baseline B[b]	Base	0.11[c]	0.50	1.27	0.50	0.23	-	0.008
	Data Avg.	0.10	0.48	1.24	0.48	0.20	0.12	0.01
	Std. Dev.	0.01	0.03	0.04	0.08	0.03	0.02	0.00
28835	Weld	0.04	0.93	1.57	0.50	0.40	0.08	-
28836	Weld	0.04	0.96	1.62	0.51	0.37	0.08	-
28837	Weld	0.05	0.86	1.52	0.48	0.33	0.08	-
28838	Weld	0.05	0.88	1.52	0.49	0.38	0.08	-
28839	Weld	0.04	0.92	1.55	0.51	0.38	0.09	-
28840	Weld	0.04	0.85	1.46	0.47	0.33	0.08	-
28841	Weld	0.03	0.86	1.42	0.45	0.32	0.08	-
28842	Weld	0.03	0.87	1.41	0.45	0.34	0.08	-
28843	Weld	0.03	0.91	1.45	0.48	0.33	0.08	-
28844	Weld	0.04	0.73	1.23	0.35	0.37	0.07	0.015
28845	Weld	0.04	0.96	1.45	0.49	0.32	0.09	0.011
28846	Weld	0.04	0.99	1.47	0.49	0.37	0.09	0.010
Baseline A[a]	Weld	0.03	0.87	1.38	0.44	0.50	0.04	0.014
	Data Avg.	0.04	0.89	1.47	0.47	0.37	0.08	0.01
	Std. Dev.	0.01	0.07	0.10	0.04	0.05	0.01	0.00

[a] See Table 3-1
[b] Baseline data from CB&I CMTR values (1971)
[c] Value per Lukens Steel

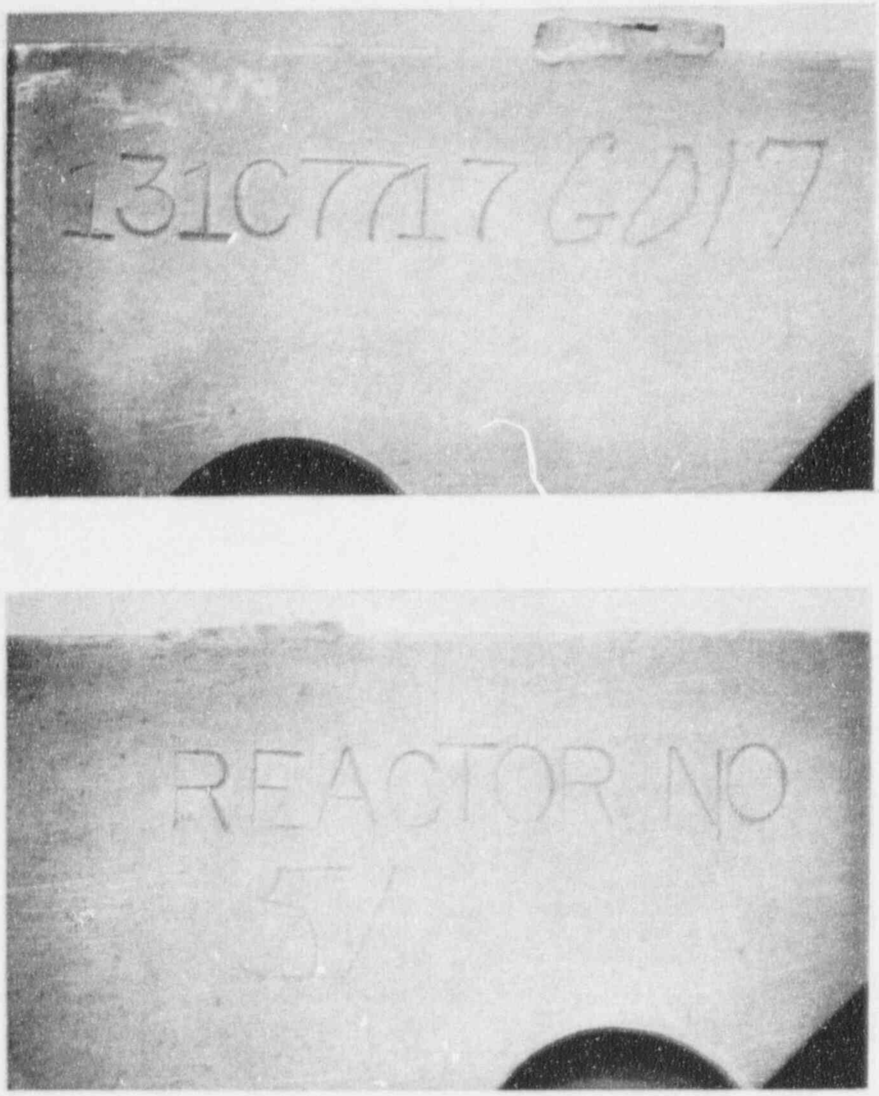


Figure 3-1: Surveillance Capsule Holder Recovered From LaSalle Unit 2
(300° Azimuthal Location)

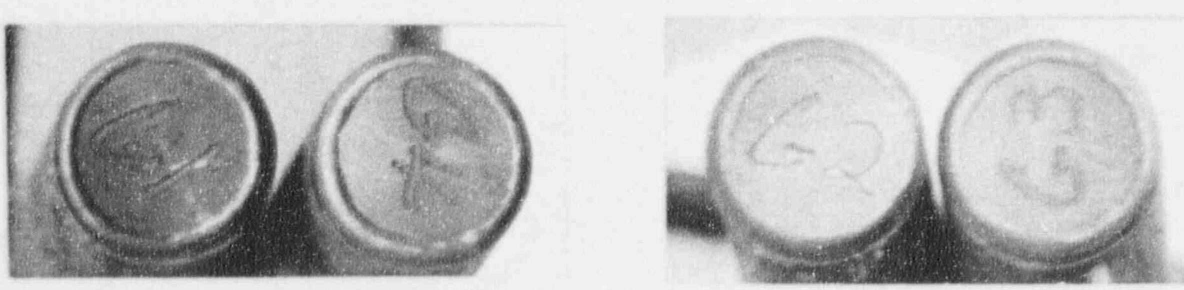


Figure 3-1(a): Tensile Specimen Capsule Identification
(300° Azimuthal Location)

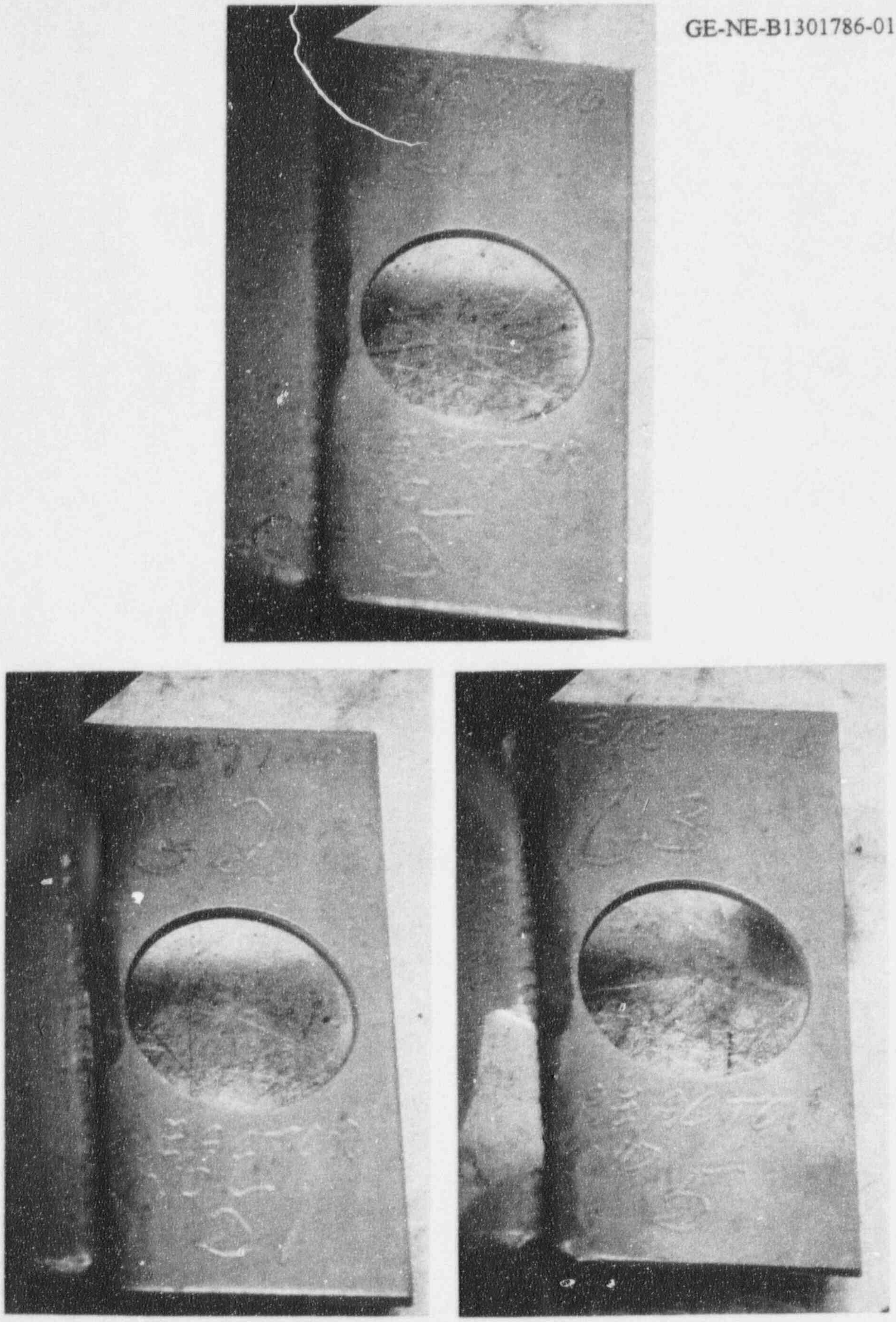
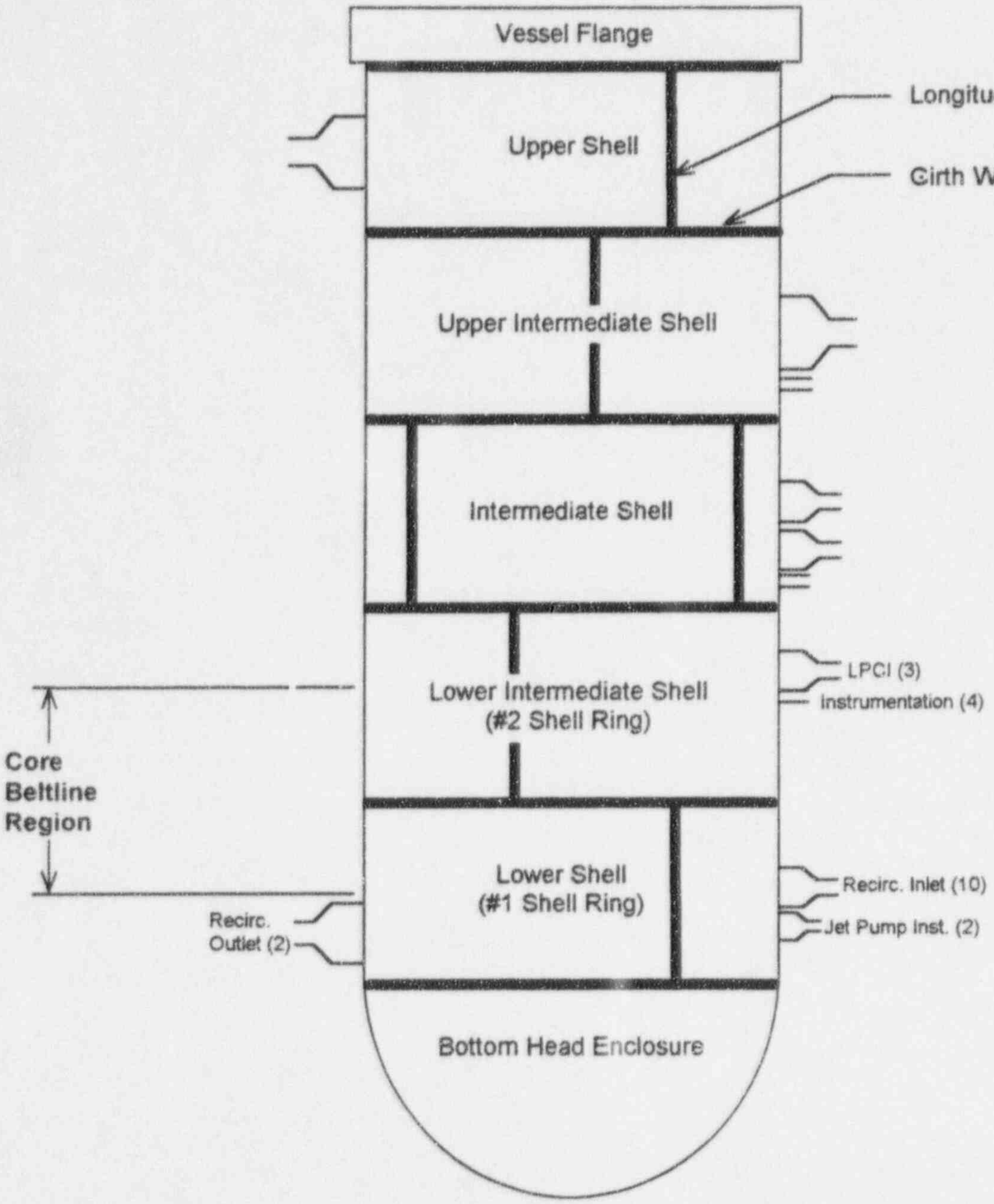


Figure 3-1(b): Charpy Specimen Capsule Identification
(300° Azimuthal Location)



#2 Shell Ring	
Plate:	Heat:
22-1	C9481-1
22-2	C9404-2
22-3	C9601-2

#1 Shell Ring	
Plate:	Heat:
21-1	C9425-2
21-2	C9425-1
21-3	C9434-2

Figure 3-2. Schematic of RPV Showing Identification of Vessel Beltline Plates and Welds

4. PEAK RPV FLUENCE EVALUATION

Flux wires removed from the 300° location / 120° 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 170-cc Ge and 100-cc Ge(Li) gamma spectrometers.

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 were derived from records provided by Commonwealth Edison and are shown in Tables 4-1 and 4-2 respectively.

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 [29] which is 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 spectrum 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 > 0.1 MeV flux were determined from the measured 0.1 to 1 MeV cross section ratio of 1.6 [29].

4.1.2 Results

The measured activity, reaction rate and full-power flux results for the 300° location / 120° surveillance capsule are given in Table 4-3. 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, 1.15×10^{17} n/cm^2 (E > 1 MeV), was obtained by using the following equation:

$$\Phi_{Cu} = \Phi_{fp} \sum_i t_i p_i \qquad (4\text{-}1)$$

where, Φ_{Cu} = fluence measured by the Cu dosimeters
Φ_{fp} = full power flux value for Cu
t_i = operating time
p_i = full power fraction

as shown in Tables 4-1 and 4-2. The fluence was calculated using the Cu flux wire because it has a longer half life and provides a more conservative result. The accuracies of the values in Tables 4-3 for a 2σ deviation are influenced by the following sources of error:

± 10.2%	relative error
± 1%	counting rates
± 15%	power history
± 10%	cross sections

The overall 2σ error is estimated to be about 20%.

4.2 DETERMINATION OF LEAD FACTOR

The flux wires detect flux at a single location and thus reflect power fluctuations associated with the operation of the plant. However, the flux wires are not necessarily 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 inside surface location. The lead factor is a function of the core and vessel geometry and of the distribution of bundles in the core. The lead factor that will be used is discussed in GE report [19] for the LaSalle 2 vessel geometry and was generated by using a first cycle dosimetry analysis

from a reactor having the same configuration as LaSalle 2. The methods used to calculate the lead factor are briefly summarized below but discussed in detail in GE report [19].

4.2.1 Procedure

Determination of the lead factor in [19] for the RPV inside wall was made using a combination of a two-dimensional and a one-dimensional finite element computer analysis. The two-dimensional analysis established the relative azimuthal variation of fluence at the vessel surface and 1/4 T depth. The one-dimensional 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 procedure is discussed in more detail in [19].

4.2.2 Results

The lead factor for the peak location inside surface was determined in [19] to be 0.98.

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 at a particular EFPY and lead factor according to

$$f_{surf} = (f_{cap} * 32\ EFPY)/(LF * CEFPY) \qquad (4\text{-}2)$$

where, f_{surf} = 32 EFPY fluence at the peak vessel inside surface
f_{cap} = capsule fluence measured at the CEFPY
32 EFPY = end of life EFPY based on a 40-year operation at an 80% capacity factor
CEFPY = the current EFPY for the capsule
LF = lead factor

The surveillance capsule was removed from LaSalle 2 at 6.98 EFPY as calculated in Table 4-2, the fluence at 6.98 EFPY was determined to be 1.15×10^{17} n/cm^2 using Equation 4-1,

and the iead factor was determined to be 0.98 as discussed in Section 4.2. Using this information with Equation 4-2, the resulting 32 EFPY fluence value at the peak vessel inside surface is:

$$f_{surf} = (1.15x10^{17} * 32)/(0.98 * 6.98) = 5.38x10^{17}\ n/cm^2 \qquad \text{at the peak location.}$$

The peak surface fluence at 32 EFPY is about 3% higher than the nominal value ($5.2x10^{17}$ n/cm^2) that was calculated from the first cycle dosimetry as reported in GE report [19]. This is well within the 20% accuracy expected as reported in section 4.1.2.

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

$$f = f_{surf}(e^{-0.24x}), \qquad (4\text{-}3)$$

where x = distance, in inches, to the 1/4 T depth. The vessel beltline lower-intermediate shell is 6.44 inches thick ordered, 6.19 inches minimum requirement. The corresponding depth x taken from the minimum required thickness is 1.55 inches. Equation 4-3 evaluated for this value of x gives the 1/4 T value of 32 EFPY fluence, $f = 3.7x10^{17}$ n/cm^2 for the lower intermediate shell ring.

Table 4-1

Summary of Daily Power History

cycle	date on	date off	days on (t_i)	Mwd(t)	cycle	date on	date off	days on (t_i)	Mwd(t)
1	3/10/84	12/31/86	1027	1643179	6	12/28/93	12/31/93	4	7293
2	7/16/87	10/15/88	458	1348380		1/1/94	1/31/94	31	57409
3	2/8/89	3/16/90	402	1081304		2/1/94	2/28/94	28	92[illegible]03
4	6/10/90	6/30/90	21	21988		3/1/94	3/31/94	31	101032
	7/1/90	7/31/90	31	88855		4/1/94	4/30/94	30	92006
	8/1/90	8/31/90	31	100301		5/1/94	5/31/94	31	100675
	9/1/90	9/24/90	24	61928		6/1/94	6/30/94	30	81575
	10/1/90	10/31/90	31	105602		7/1/94	7/31/94	31	102505
	11/1/90	11/30/90	30	100934		8/1/94	8/31/94	31	83343
	12/1/90	12/31/90	31	78916		9/1/94	9/30/94	30	93463
	1/1/91	1/31/91	31	104443		10/1/94	10/31/94	31	67105
	2/1/91	2/28/91	28	92242		11/1/94	11/30/94	30	96659
	3/1/91	3/31/91	31	102206		12/1/94	12/31/94	31	100713
	4/1/91	4/30/91	30	97515		1/1/95	1/31/95	31	101050
	5/1/91	5/31/91	31	101982		2/1/95	2/18/95	18	54409
	6/1/91	6/30/91	30	97922					
	7/1/91	7/31/91	31	102157				total_days	sum
	8/1/91	8/31/91	31	98657				3.35E+03	8.48E+06
	9/1/91	9/24/91	24	48248					
	10/1/91	10/31/91	31	82369					
	11/1/91	11/30/91	30	94903					
	12/1/91	12/31/91	31	96676					
	1/1/92	1/4/92	4	7541					
5	4/20/92	4/30/92	11	27832					
	5/1/92	5/31/92	31	98989					
	6/1/92	6/30/92	30	94439					
	7/1/92	7/31/92	31	94912					
	8/1/92	8/27/92	27	80906					
	9/11/92	9/30/92	20	54361					
	10/1/92	10/31/92	31	98440					
	11/1/92	11/30/92	30	84777					
	12/1/92	12/31/92	31	99758					
	1/1/93	1/31/93	31	100100					
	2/1/93	2/28/93	28	89053					
	3/1/93	3/31/93	31	100762					
	4/1/93	4/30/93	30	96212					
	5/1/93	5/29/93	29	92457					
	6/7/93	6/30/93	24	73391					
	7/1/93	7/31/93	31	102641					
	8/1/93	8/31/93	31	89013					
	9/1/93	9/3/93	3	8119					

Table 4-2

Summary of LaSalle 2 Irradiation Periods

cycle	on	off	days on	MWd	full power days	fpf
1	3/10/84	12/31/86	1027	1643179	494.5	0.481
2	7/16/87	10/15/88	458	1348380	405.8	0.886
3	2/8/89	3/16/90	402	1081304	325.4	0.809
4	6/10/90	1/4/92	574	1685386	507.2	0.884
5	4/20/92	9/3/93	502	1486163	447.2	0.891
6	12/26/93	2/18/95	420	1231540	370.6	0.882

TOTAL (EFPD) = 2550.7
TOTAL (EFPY) = 6.98

Table 4-3

Surveillance Capsule Flux and Fluence For Irradiation From Start-up to 2/18/95 (6.98 EFPY)

Wire (Element)	Average[a] dps/g Element (at end of irradiation)	Average Reaction Rate [dps/nucleus (saturated)]	Full Power Flux[b] (n/cm^2-s) E>1 MeV	Full Power Flux[c] (n/cm^2-s) E>0.1 MeV	Fluence (n/cm^2) E>1 MeV	Fluence[c] (n/cm^2) E>0.1 MeV
Copper	6.68E03	1.95E-18	5.22E08	8.35E08	1.15E17	1.84E17
Iron	5.10E04	1.03E-16	4.86E08	7.78E08	1.07E17	1.71E17
Nickel	8.29E05	1.30E-16	4.77E08	7.52E08	1.05E17	1.67E17
		Value used for fluence[d]:			1.15E17	1.84E17

a Obtained by R.D Reager and L.K. Kessler
b Full power flux, based on thermal power of 3323 Mw_t
c 1.6 times the E >1 MeV result
d Only copper flux wires are used to determine the fluence

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. Testing was conducted in accordance with ASTM E23-88 [12].

5.1 IMPACT TEST PROCEDURE

The Vallecitos testing machine used for irradiated specimens was a Riehle Model P1-2 impact machine, serial number R-89916. The maximum energy capacity of the machine is 240 ft-lb, which produces a test velocity at impact of 15.44 ft/sec. .

The test apparatus and operator were qualified using NIST standard reference material specimens. The Standard Reference Materials (SRMs) consist of three sets of specimens which cover the energy range of the apparatus. Each set has a designated failure energy and a standard test temperature. According to ASTM E23-88 [12], the test apparatus averaged results must reproduce the NIST standard values within an accuracy of $\pm$5% or $\pm$1.0 ft-lb, whichever is greater. The qualification of the Riehle machine and operator is summarized in Table 5-1.

Charpy V-Notch tests were conducted at temperatures between -100°F and 300°F. The cooling fluid used for irradiated specimens tested at temperatures at or below 50°F was ethyl alcohol. At temperatures between 50°F and 200°F, water was used as the temperature conditioning fluid. The specimens were heated in silicon oil for test temperatures 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. After equilibration at the test temperature for at least 5 minutes, the specimens were manually transferred with centering tongs to the Charpy test machine and impacted in less than 5 seconds.

For each Charpy V-Notch specimen the test temperature, energy absorbed, lateral expansion, and percent shear were determined. 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 involved measuring the length and width of the cleavage surface in inches 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 (-100°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 and lateral expansion for base, weld, and HAZ materials are presented in Figures 5-1 through 5-8. The irradiated weld metal curve is plotted along with the corresponding unirradiated curve in Figure 5-9. Due to insufficient baseline data for the unirradiated plate material, a baseline curve was not generated. The fracture surface photographs and a summary of the test results for each specimen are contained in Appendix A.

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

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

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.

5.3 IRRADIATED VERSUS UNIRRADIATED CHARPY V-NOTCH PROPERTIES

Ideally, a shift in RT_{NDT} would be established by comparing the irradiated Charpy specimen data to baseline unirradiated Charpy data. This is possible for the LaSalle 2 surveillance weld material (Heat 5P7397, Linde 124 Flux, Lot 0342), where enough fabrication Charpy data exists to develop a full Charpy curve. This unirradiated weld data was fit to a TANH function as described in the previous section.

The fabrication data for the LaSalle 2 surveillance plate (Heat C9481-1) consists of only 6 Charpy data points at +40°F. This does not allow for development of a full Charpy curve for the

unirradiated plate material by standard procedures. As a result, shifts in Charpy curves could only be determined for the weld material as discussed in the following section.

5.4 COMPARISON TO PREDICTED IRRADIATION EFFECTS

5.4.1 Irradiation Shift

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

Weld:	Copper =	0.04%
	Nickel =	0.89%
	CF =	54
	fluence =	1.15×10^{17} n/cm^2
	Reg. Guide 1.99 ΔRT_{NDT} =	6.5°F
	Reg. Guide 1.99 $\Delta RT_{NDT} \pm 2\sigma_{\Delta}$(56°F) =	62.5°F max, -49.5°F min
	Measured 30 ft-lb shift =	18.6°F

The weight percents of Cu and Ni are best estimates based on averaging (see Table 3-3). The CF shown above is the chemistry factor for the weld material obtained from Table 1 of Reg. Guide 1.99. The fluence factor for the Reg. Guide calculation of 30 ft-lb shift may either be calculated according to the Reg. Guide definition

$$\text{fluence factor} = f^{(0.28 - 0.10 \log f)} \tag{5-1}$$

or it may be obtained from the Reg. Guide Figure 1 [7]. Using equation 5-1, the fluence factor was calculated to be 0.12. These values are used to calculate the Reg. Guide 1.99 prediction for 30 ft-lb shift and USE decrease for comparison to the measured shift and USE decrease for the irradiated surveillance materials. The predicted 30 ft-lb temperature shift (ΔRT_{ndt}) was also calculated according to the Reg. Guide using the equation

$$\Delta RT_{ndt} = (CF)\, f^{(0.28 - 0.10 \log f)}. \tag{5-2}$$

The measured 30 ft-lb temperature shift of 18.6°F (Table 5-4) for the weld is within the bounds of the Reg. Guide prediction with the uncertainty of $\pm 2\sigma$.

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 approximately 6.5% are predicted for the weld material. The actual impact energy curves for the weld show an increase in the USE value of 4.3%. Given the typical scatter in charpy data and the low fluence of the irradiated specimens, an increase in USE is not unexpected. As discussed in Section 5.3, a measured decrease in USE for the plate material could not be directly determined.

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 8/95)	HH-46 1	Ethyl Alcohol	-40	74	
	HH-46 2	Ethyl Alcohol	-40	72.5	
	HH-46 3	Ethyl Alcohol	-40	75.5	
	HH-46 4	Ethyl Alcohol	-40	73	
	HH-46 5	Ethyl Alcohol	-40	77	
			Average	74.4	74.3 ± 3.7 pass
	LL-45 1	Ethyl Alcohol	-40	13	
	LL-45 2	Ethyl Alcohol	-40	13	
	LL-45 3	Ethyl Alcohol	-40	13	
	LL-45 4	Ethyl Alcohol	-40	13	
	LL-45 5	Ethyl Alcohol	-40	13	
			Average	13	12.8 ± 0.64 pass
	SH-5 1	Ethyl Alcohol	70	170	
	SH-5 2	Ethyl Alcohol	70	170	
	SH-5 3	Ethyl Alcohol	70	162.5	
	SH-5 4	Ethyl Alcohol	70	161.5	
	SH-5 5	Ethyl Alcohol	70	156	
			Average	164.0	164.1± 8.2 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 C9481-1, Longitudinal,	28823	-60	7	5	0
	28824	-20	7.5	6	17.6
	28825	0	23	21	49.4
	28826	20	58	41.5	53.8
	28827	30	32	30	44.3
	28828	40	47.5	31.5	43.7
	28829	50	44	36.5	40.2
	28830	65	99.5	74	67.7
	28831	80	101.5	59	70.3
	28832	120	88.5	66	82.4
	28833	200	126	84.5	100
	28834	300	123.5	87.5	100
Weld: Heat 5P7397, Lot 0342, Linde 124 Flux	28835	-100	13.5	7	11.1
	28836	-60	15	10	21.9
	28837	-40	32	30.5	49
	28838	-20	45	34.5	58.4
	28839	0	55	45.5	67.4
	28840	20	67	43.5	80.3
	28841	30	43	37	50.6
	28842	50	61.5	50.5	65.5
	28843	80	78	50.5	91
	28844	120	94	74.5	100
	28845	200	82	73	100
	28846	300	85	85	100
HAZ:	28847	-60	22	21.5	30.1
	28848	-20	27	25	47.2
	28849	-10	45	42	54.5
	28850	0	47	38.5	68.1
	28851	20	106	66	91.5
	28852	30	59	40.5	82.2
	28853	50	71	54.5	87.3
	28854	80	64	41.5	91.9
	28855	100	86	64	100
	28856	120	88	69	100
	28857	200	81	68	100
	28858	300	84.5	78.5	100

Table 5-3

UNIRRADIATED CHARPY V-NOTCH IMPACT TEST RESULTS

	Specimen [a] Identification	Test Temperature (°F)	Fracture Energy (ft-lb)	Lateral Expansion (mils)	Percent Shear (%)
Weld: [b]	1	-70	22	22	5
1NMM	2	-70	16	18	5
Heat 5P7397	3	-70	36	28	5
Tandem Wire	4	-10	58	54	25
(Longitudinal)	5	-10	68	50	20
	6	-10	61	47	20
	7	10	76	60	30
	8	10	73	65	45
	9	10	75	60	50
	10	10	75	58	35
	11	10	69	56	35
	12	40	91	75	80
	13	40	84	63	85
	14	70	79	73	90
	15	70	75	63	95
	16	70	77	74	95
	17	212	84	69	100
	18	212	81	67	100
	19	212	87	75	100
Plate[b]:	1	40	74	61	50
Heat C9481-1	2	40	74	53	50
(Longitudinal)	3	40	81	60	50
	4	40	103	48	40
	5	40	61	66	50
	6	40	85	72	60
Base:	12	-40	17.0	15.0	5
Heat C9481-1,	10	10	23.5	21.0	10
(Transverse)	11	10	22.0	20.5	10
	14	25	36.0	31.0	20-25
	8	40	45.0	42.0	30-35
	9	40	35.0	34.2	30
	13	40	42.0	38.0	30-35
	15	51	40.5	35.0	30
	1	70	51.0	44.5	40
	2	70	50.0	42.5	40
	7	93	71.0	58.5	70
	3	120	93.0	69.5	90-95
	4	200	93.5	74.0	95
	5	200	100.0	72.0	95
	6	200	93.0	69.0	95

[a] I.D.'s are listed for numbering only, i.e. I.D.'s were not preassigned
[b] Fabrication Charpy specimen data from Materials Certification Reports in [28]

Table 5-3

UNIRRADIATED CHARPY V-NOTCH IMPACT TEST RESULTS

	Specimen [a] Identification	Test Temperature (°F)	Fracture Energy (ft-lb)	Lateral Expansion (mils)	Percent Shear (%)
Weld: [b]	1	-70	22	22	5
1NMM	2	-70	16	18	5
Heat 5P7397	3	-70	36	28	5
Tandem Wire	4	-10	58	54	25
(Longitudinal)	5	-10	68	50	20
	6	-10	61	47	20
	7	10	76	60	30
	8	10	73	65	45
	9	10	75	60	50
	10	10	75	58	35
	11	10	69	56	35
	12	40	91	75	80
	13	40	84	63	85
	14	70	79	73	90
	15	70	75	63	95
	16	70	77	74	95
	17	212	84	69	100
	18	212	81	67	100
	19	212	87	75	100
Plate[b]:	1	40	74	61	50
Heat C9481-1	2	40	74	53	50
(Longitudinal)	3	40	81	60	50
	4	40	103	48	40
	5	40	61	66	50
	6	40	85	72	60
Base:	12	-40	17.0	15.0	5
Heat C9481-1,	10	10	23.5	21.0	10
(Transverse)	11	10	22.0	20.5	10
	14	25	36.0	31.0	20-25
	8	40	45.0	42.0	30-35
	9	40	35.0	34.2	30
	13	40	42.0	38.0	30-35
	15	51	40.5	35.0	30
	1	70	51.0	44.5	40
	2	70	50.0	42.5	40
	7	93	71.0	58.5	70
	3	120	93.0	69.5	90-95
	4	200	93.5	74.0	95
	5	200	100.0	72.0	95
	6	200	93.0	69.0	95

[a] I.D.'s are listed for numbering only, i.e. I.D.'s were not preassigned
[b] Fabrication Charpy specimen data from Materials Certification Reports in [28]

Table 5-3

UNIRRADIATED CHARPY V-NOTCH IMPACT TEST RESULTS

	Specimen [a] Identification	Test Temperature (°F)	Fracture Energy (ft-lb)	Lateral Expansion (mils)	Percent Shear (%)
Weld: [b]	1	-70	22	22	5
1NMM	2	-70	16	18	5
Heat 5P7397	3	-70	36	28	5
Tandem Wire	4	-10	58	54	25
(Longitudinal)	5	-10	68	50	20
	6	-10	61	47	20
	7	10	76	60	30
	8	10	73	65	45
	9	10	75	60	50
	10	10	75	58	35
	11	10	69	56	35
	12	40	91	75	80
	13	40	84	63	85
	14	70	79	73	90
	15	70	75	63	95
	16	70	77	74	95
	17	212	84	69	100
	18	212	81	67	100
	19	212	87	75	100
Plate[b]:	1	40	74	61	50
Heat C9481-1	2	40	74	53	50
(Longitudinal)	3	40	81	60	50
	4	40	103	48	40
	5	40	61	66	50
	6	40	85	72	60
Base:	12	-40	17.0	15.0	5
Heat C9481-1,	10	10	23.5	21.0	10
(Transverse)	11	10	22.0	20.5	10
	14	25	36.0	31.0	20-25
	8	40	45.0	42.0	30-35
	9	40	35.0	34.2	30
	13	40	42.0	38.0	30-35
	15	51	40.5	35.0	30
	1	70	51.0	44.5	40
	2	70	50.0	42.5	40
	7	93	71.0	58.5	70
	3	120	93.0	69.5	90-95
	4	200	93.5	74.0	95
	5	200	100.0	72.0	95
	6	200	93.0	69.0	95

[a] I.D.'s are listed for numbering only, i.e. I.D.'s were not preassigned
[b] Fabrication Charpy specimen data from Materials Certification Reports in [28]

Table 5-4

SIGNIFICANT RESULTS OF IRRADIATED AND UNIRRADIATED CHARPY V-NOTCH DATA

Material	Index Temp (°F) E=30 ft-lb	Index Temp (°F) E=50 ft-lb	Index Temp (°F) MLE=35 mil	USE (ft-lb)
PLATE: Heat C9481-1,	Longitudinal			
Irradiated	11.7	37.3	32.1	124.75
HAZ: Heat C9481-1,	Longitudinal			
Irradiated	-31.29	10.24	-5.27	84.6
WELD: Heat 5P7397				
Unirradiated	-59.99	-32.10	-43.23	83.3
Irradiated	-41.40	4.12	-0.83	86.9
Difference	18.59	36.22	42.40	-3.6 (-4.3%)

Reg. Guide 1.99, Rev 2 ΔRT_{NDT} [a]: **6.5**

Reg. Guide 1.99, Rev 2 ($\Delta \pm 2\sigma$) [a]: **-49.6 to 62.4**

1.99, Rev 2. Decrease in USE [b]: **6.5%**

---

a Determined in section 5.4.1

b Determined in section 5.4.2

Figure 5-1

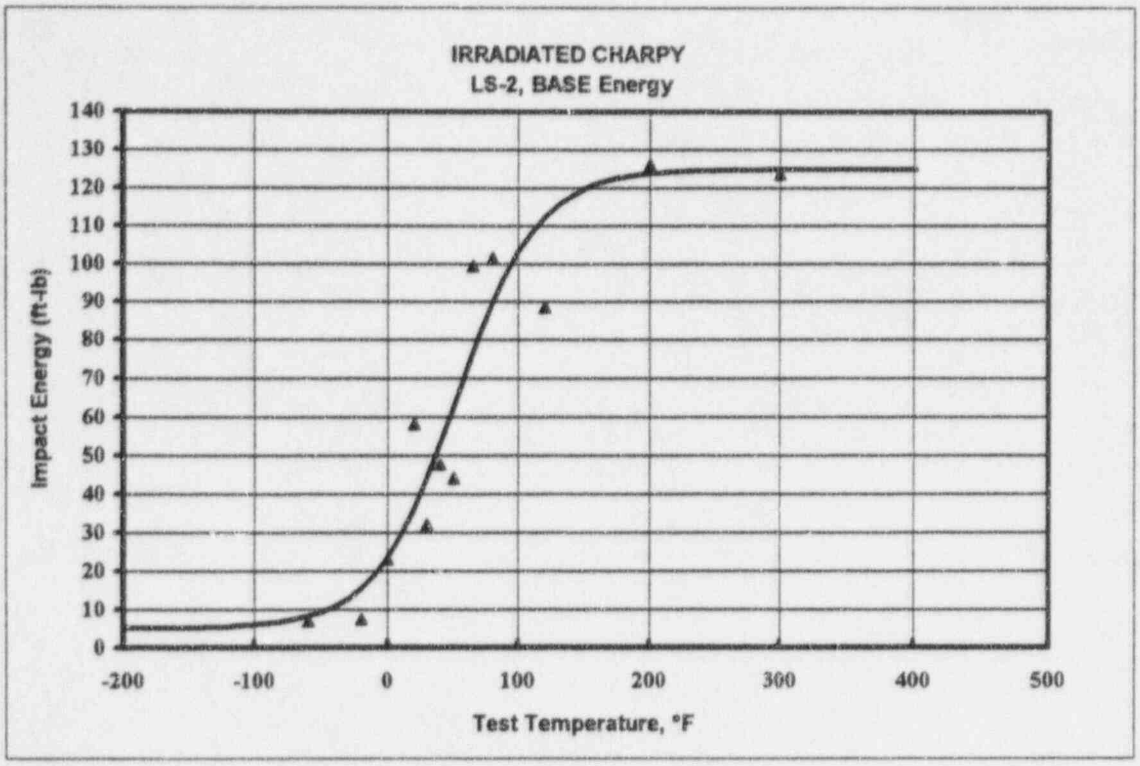


Figure 5-2

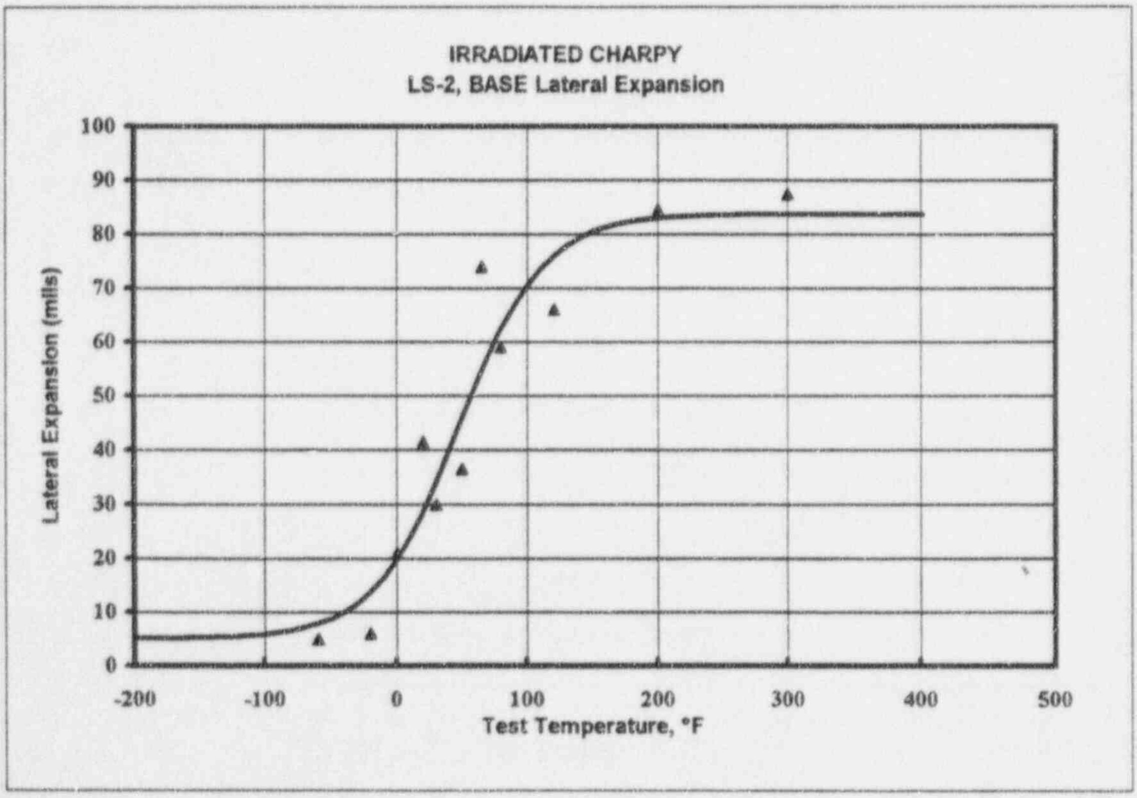


Figure 5-3

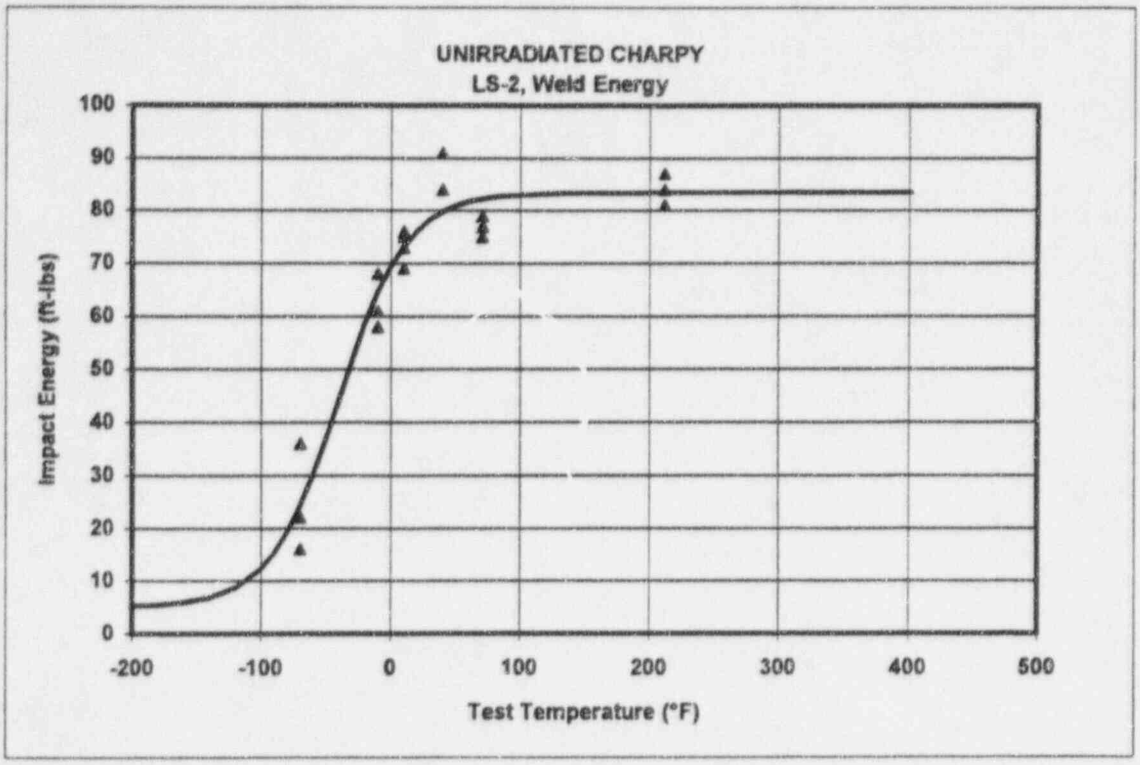


Figure 5-4

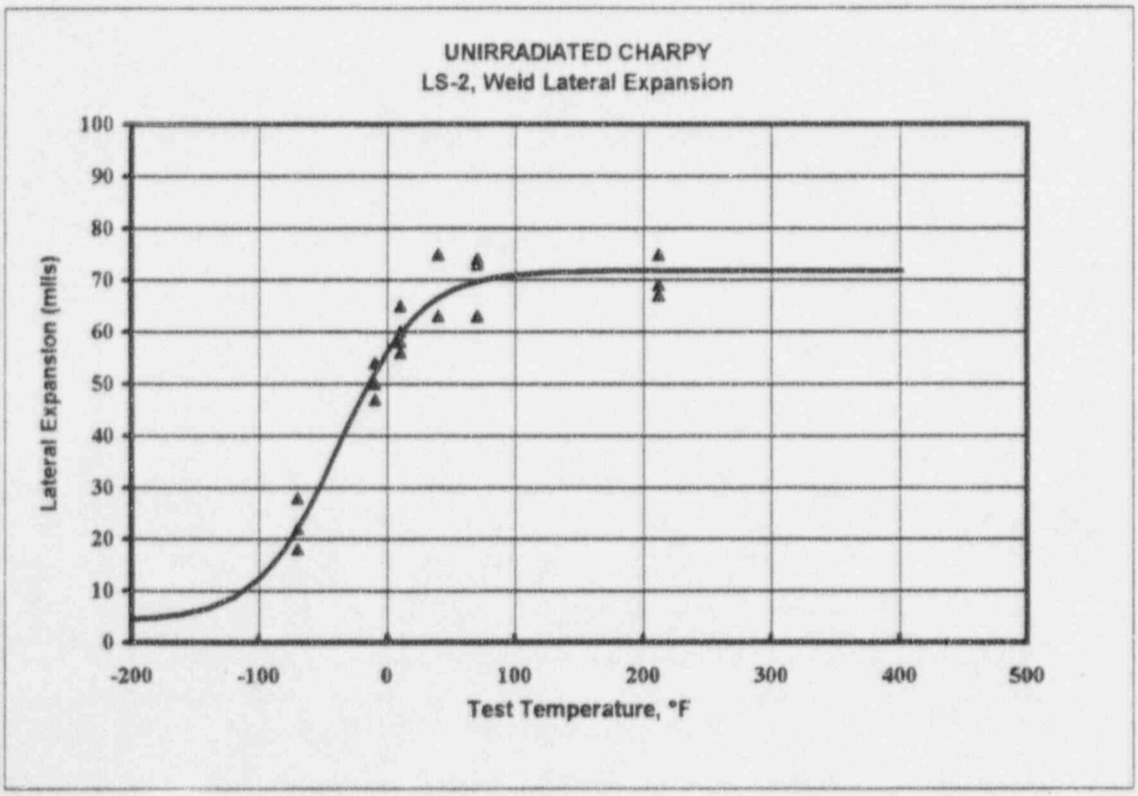


Figure 5-5

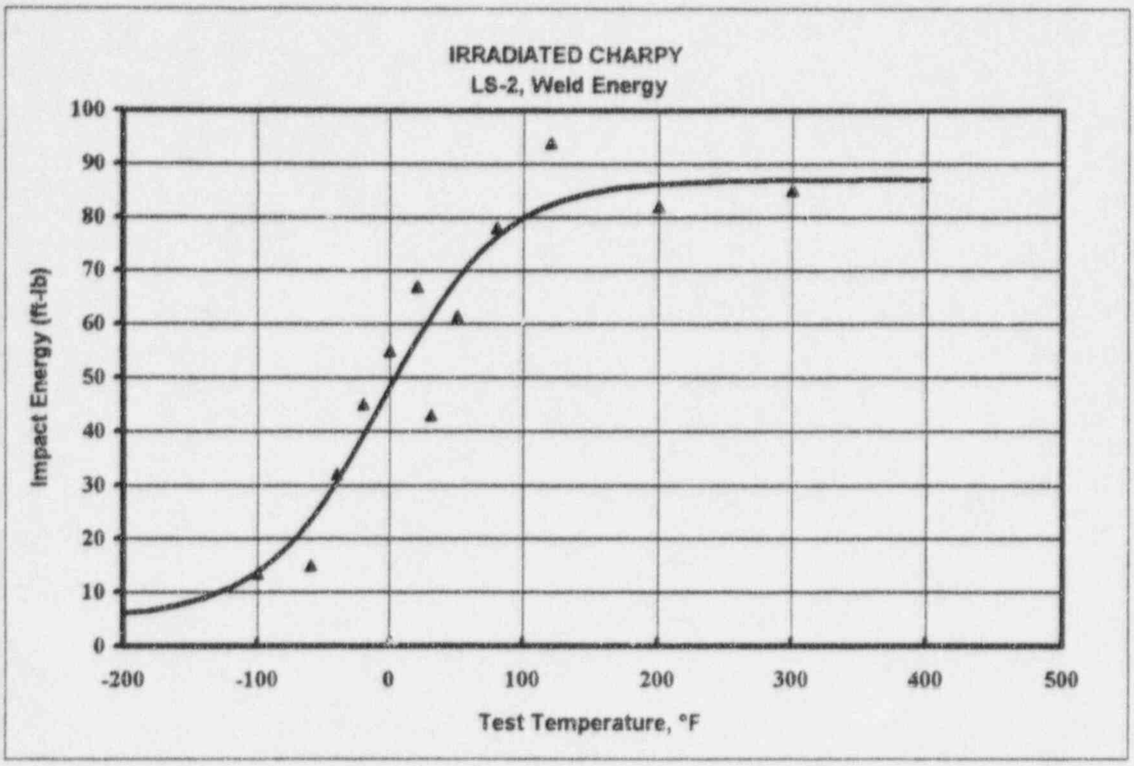


Figure 5-6

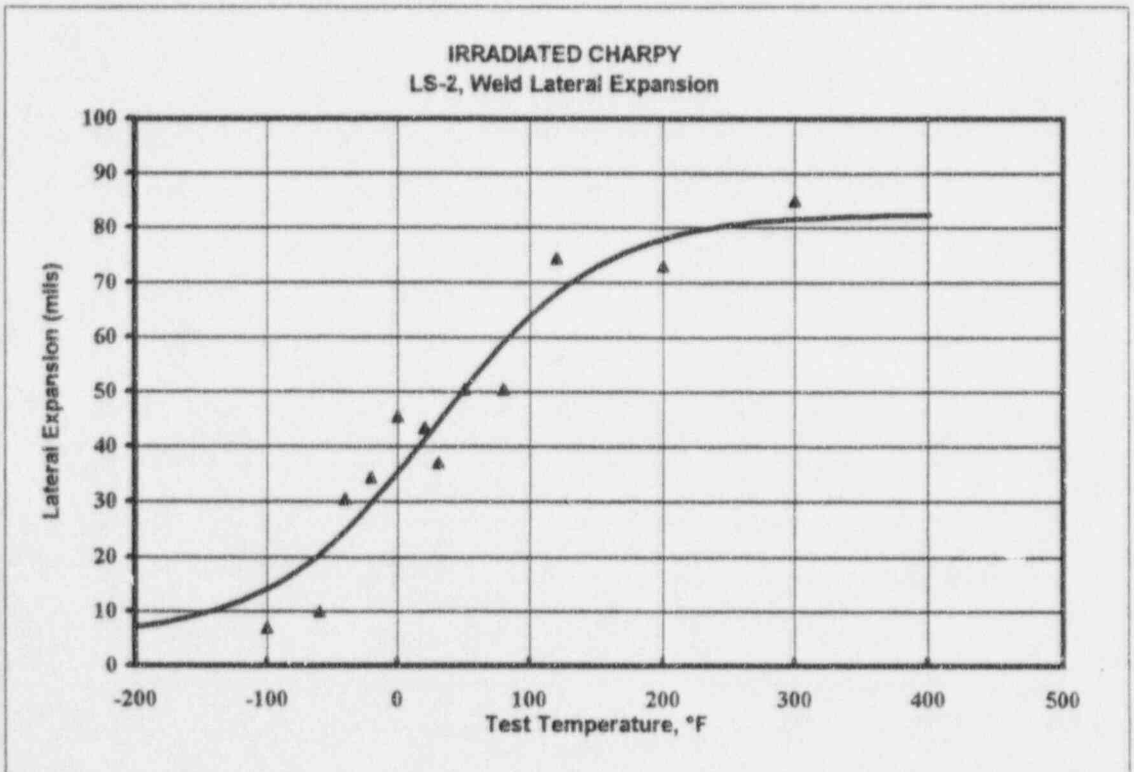


Figure 5-7

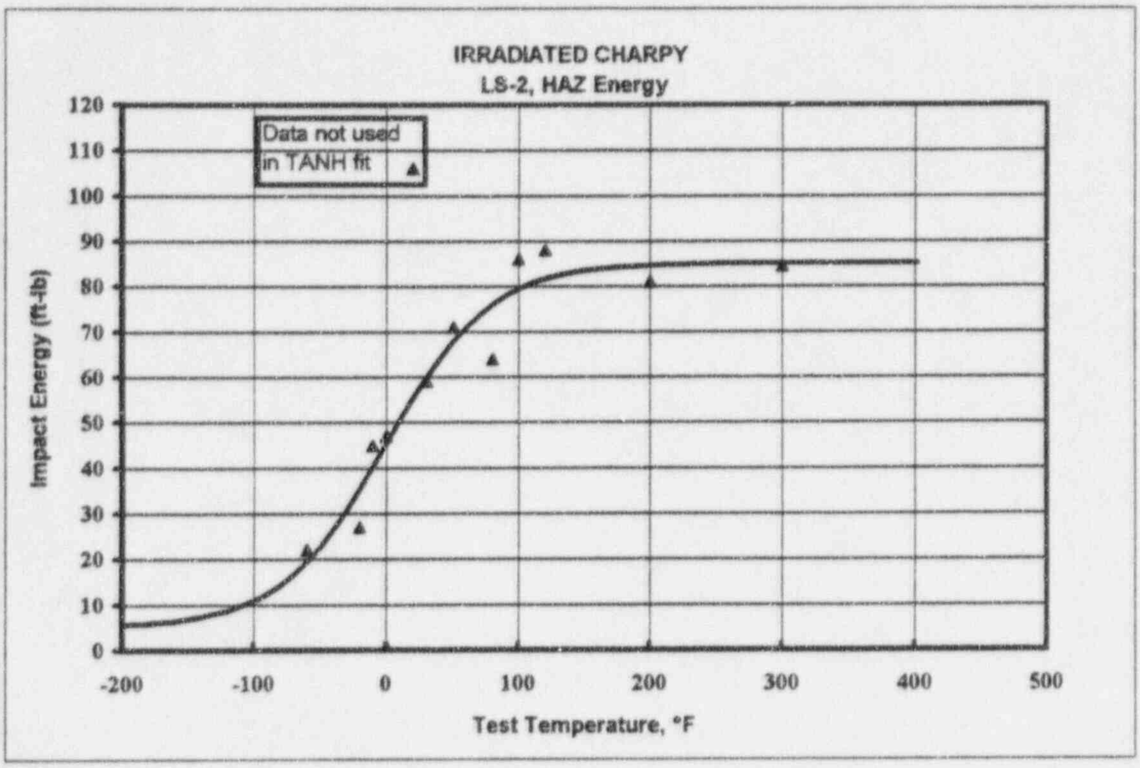


Figure 5-8

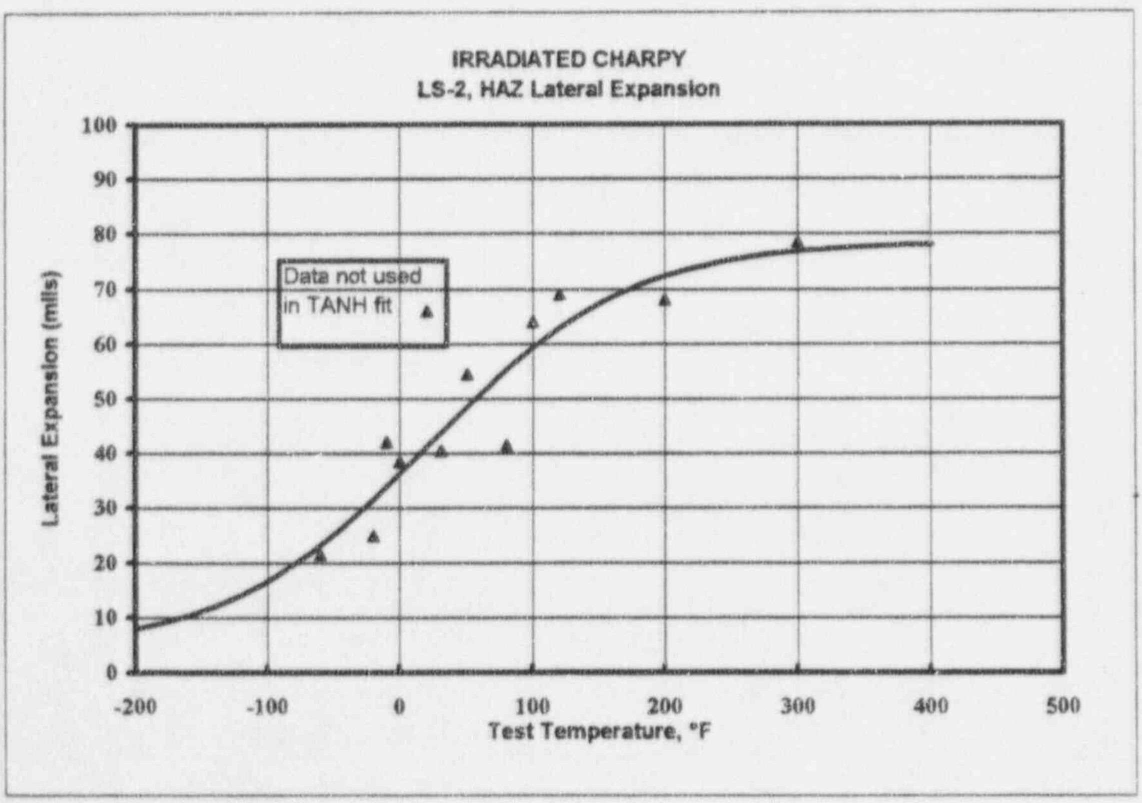


Figure 5-9

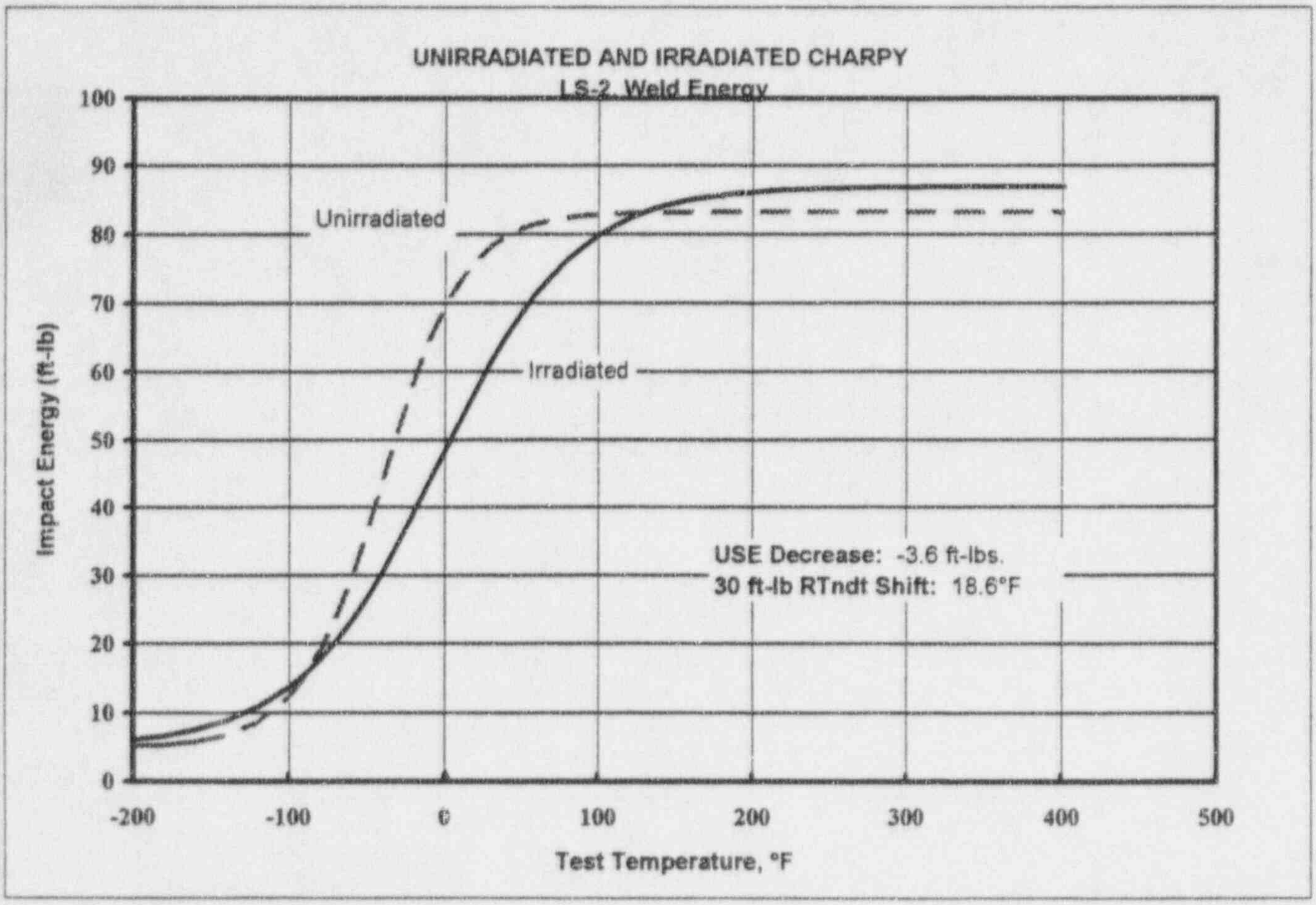
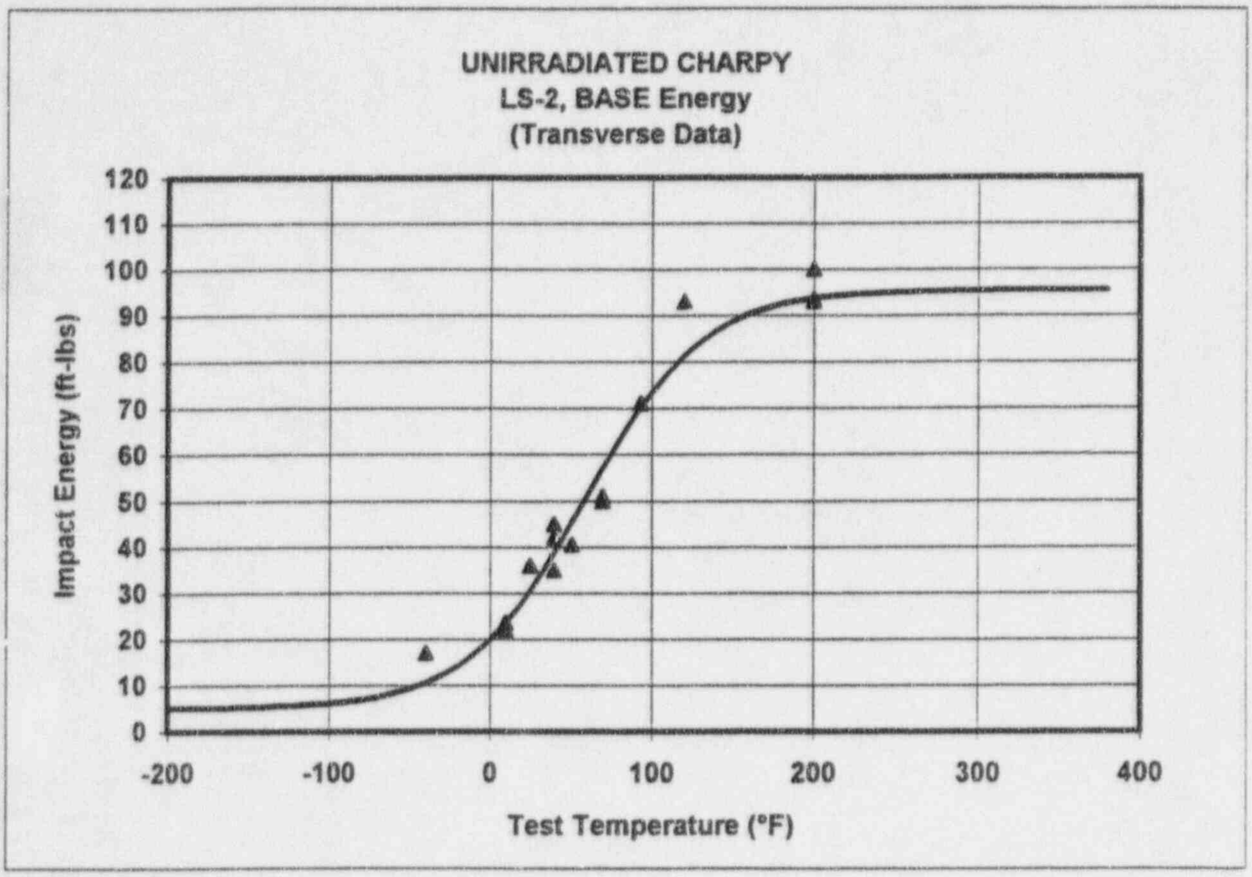

UNIRRADIATED AND IRRADIATED CHARPY
LS-2. Weld Energy
Impact Energy (ft-lb)
100
90
80
70
60
50
40
30
20
10
0
-200
-100
0
100
200
300
400
500
Test Temperature, °F
Unirradiated
Irradiated
USE Decrease: -3.6 ft-lbs.
30 ft-lb RTndt Shift: 18.6°F

Figure 5-10


UNIRRADIATED CHARPY
LS-2, BASE Energy
(Transverse Data)
Impact Energy (ft-lbs)
0
10
20
30
40
50
60
70
80
90
100
110
120
-200
-100
0
100
200
300
400
Test Temperature (°F)

6. TENSILE TESTING

Eight round bar tensile specimens were recovered from the surveillance capsule. Uniaxial tensile tests were conducted in air at room temperature (70°F) at RPV operating temperature (550°F) and at an intermediate temperature of 150°F for the two additional base and weld specimens. 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 by a chromel-alumel thermocouple spot-welded to an Inconel clip that was friction-clipped to the surface of the specimen at its midline.

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 into the 0.2% offset load and into the maximum test load, respectively. The values listed for the uniform and total elongation were obtained from plots that recorded load versus specimen extension and are based on a 1.5 inch nominal 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. 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

Only unirradiated room temperature tensile test data was available for comparison. As expected the trends are increasing YS and UTS and decreasing TE (see Table 6-2), characteristic of irradiation embrittlement in most cases.

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:	P1-1	70	64.4	87.7	12.0	21.1	67.3
	P1-3	150	63.1	85.7	11.0	20.0	70.1
	P1-2	550	57.5	83.4	11.7	18.9	63.6
Weld:	P2-1	70	69.4	86.2	12.5	21.9	66.6
	P2-3	150	73.0	86.2	12.4	22.7	72.5
	P2-2	550	66.6	82.7	11.1	18.5	64.6
HAZ:	P3-1	70	61.4	86.0	10.8	19.3	71.4
	P3-2	550	69.1	78.1	8.6	15.4	70.8

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

Table 6-2: Comparison of Unirradiated and Irradiated Tensile Properties at Room Temperature

		Yield Strength (ksi)	Ultimate Strength (ksi)	Total Elongation (%)	Reduction of Area (%)
Base:	Unirradiated[b]	63.8	85.2	26.5	N/A
	1st Capsule	64.4	87.7	21.1	67.3
Weld:	Unirradiated	64.9	82.2	22.0	65.4
	1st Capsule	69.4	86.2	21.9	66.6

[b] Values taken as average of data in the material certification reports.

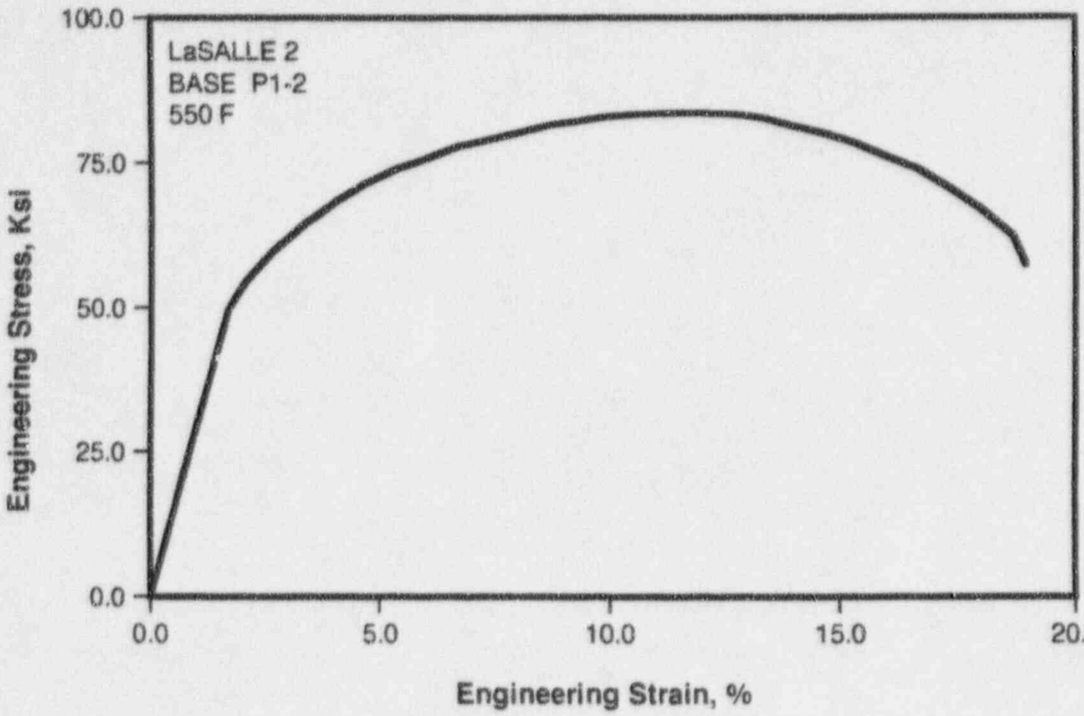


Figure 6-1. Typical Engineering Stress-Strain for Irradiated RPV Materials

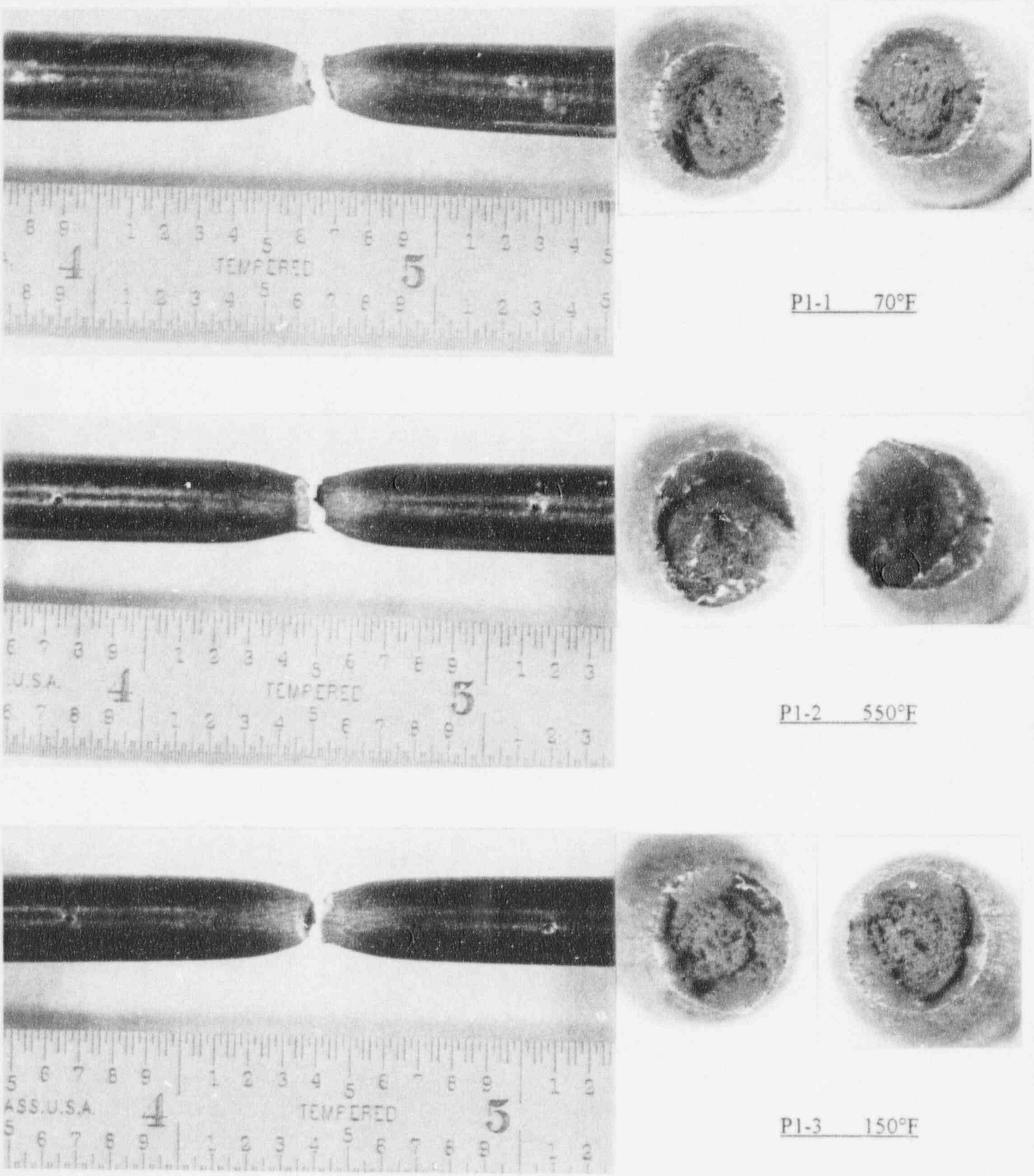
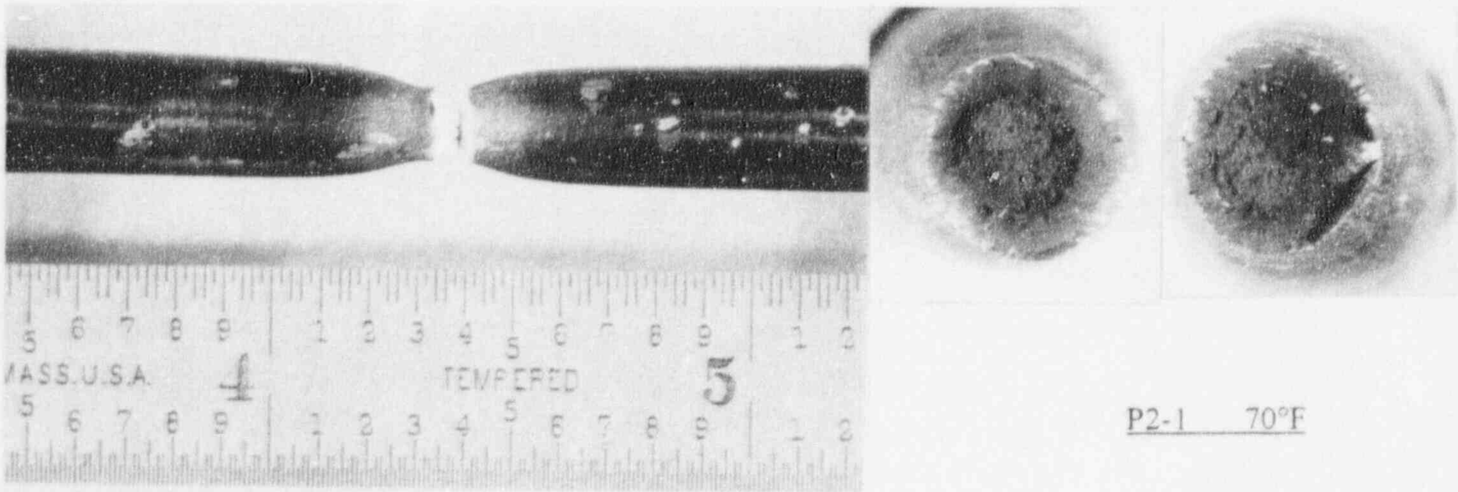
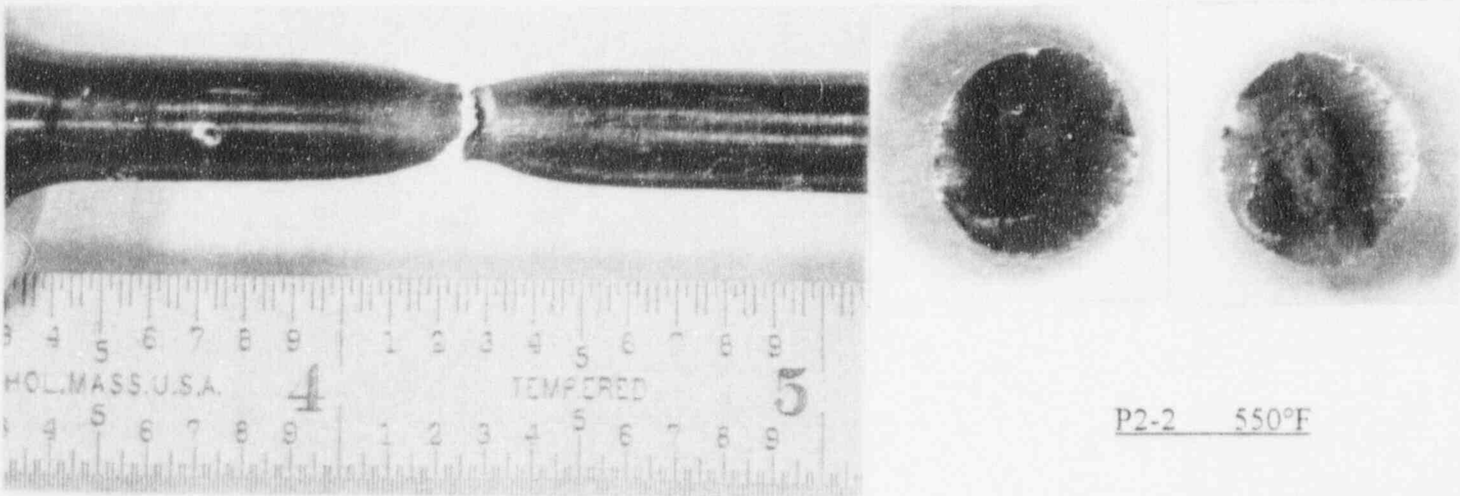


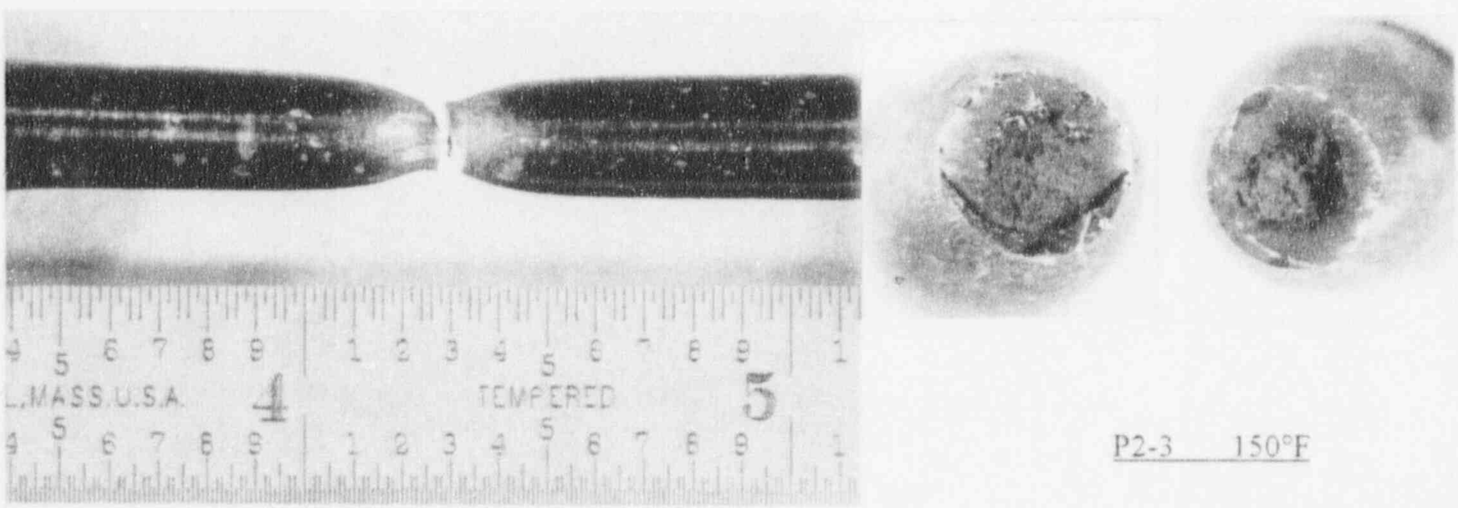
Figure 6-2: Fracture Location, Necking Behavior and Fracture Appearance for Irradiated Base Metal Tensile Specimens.



P2-1 70°F

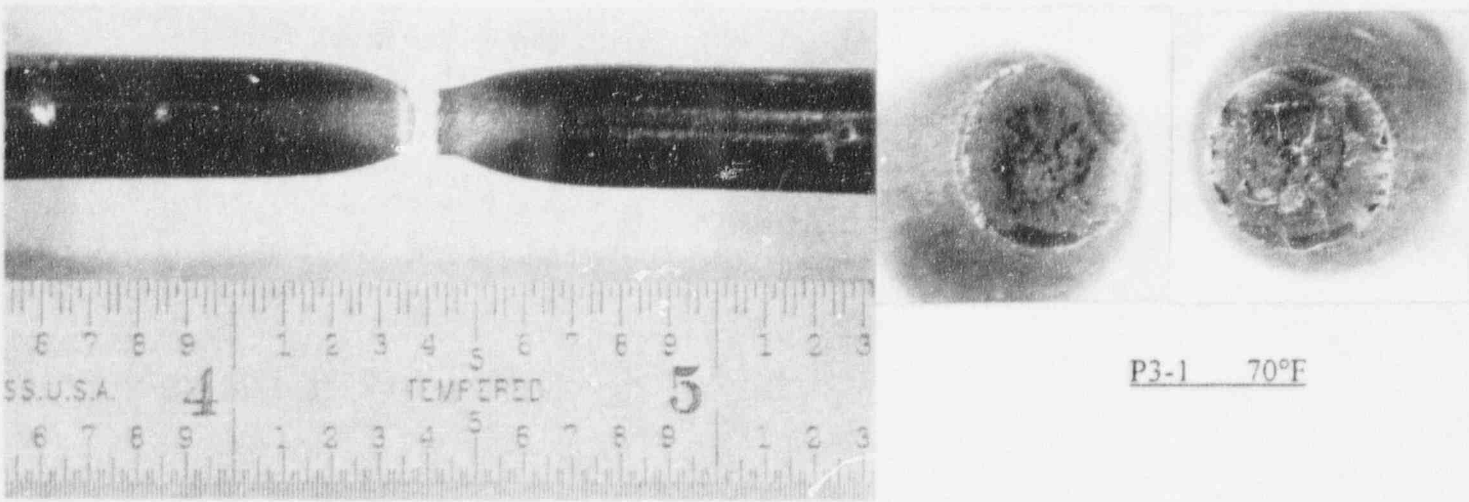


P2-2 550°F



P2-3 150°F

Figure 6-3: Fracture Location, Necking Behavior and Fracture Appearance for Irradiated Weld Metal Tensile Specimens



P3-1 70°F

P3-2 550°F

Figure 6-4: Fracture Location, Necking Behavior and Fracture Appearance for Irradiated HAZ Tensile Specimens

7. ADJUSTED REFERENCE TEMPERATURE AND UPPER SHELF ENERGY

The 32 EFPY peak fluence value of 5.38×10^{17} n/cm^2 in Section 4.3 is used to calculate the 32 EFPY 1/4 T fluence value of 3.7×10^{17} n/cm^2. The 32 EFPY 1/4 T fluence is used in this section to calculate adjusted reference temperatures (ARTs) and upper shelf energy (USE) decrease for the beltline materials.

7.1 ADJUSTED REFERENCE TEMPERATURE AT 32 EFPY

The effect on adjusted reference temperature (ART) due to irradiation in the beltline materials is determined according to the methods in Reg. Guide 1.99, Rev. 2 [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, Rev. 2 [7] is:

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

where:

$$\Delta RT_{ndt} = CF \cdot f^{(0.28-0.10\log f)} \qquad (7\text{-}2)$$

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

CF = chemistry factor from Tables 1 or 2 of Reg. Guide 1.99, Rev. 2 [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.

The ART values are calculated based upon best estimate chemistry data as described in Section 5.4.1. The chemistry for weld 5P7397 is 0.04% Cu and 0.89% Ni, which has a corresponding chemistry factor of 54. The chemistry for plate C9481-1 is 0.10% Cu and 0.48% Ni, which has a chemistry factor of 65.

Each beltline plate and weld ΔRT_{NDT} value is determined by multiplying the CF from Reg. Guide 1.99, Rev. 2 determined for the Cu-Ni content of the material, by the fluence factor for the EFPY being evaluated. The Initial RT_{NDT}, ΔRT_{NDT} and Margin are added to get the

ART of the material. The 32 EFPY ART values for all of the beltline plates and several of the most limiting beltline welds are shown in Table 7-1. The ART for the limiting beltline material, plate heat C9404-2, at 32 EFPY is 73.8°F.

7.2 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. Calculations of 32 EFPY USE, using Reg. Guide 1.99, Rev. 2 methods, are summarized in Table 7-2. The values for initial USE were obtained from [20] for all but the surveillance plate (C9481-1) where baseline transverse USE data was available.

The equivalent transverse USE of the plate material is taken as 65% of the longitudinal USE, according to USNRC MTEB 5-2 [17]. Unlike the plate, the weld metal USE has no transverse/longitudinal correction because weld metal has no orientation effect. The USE decrease prediction values from Reg. Guide 1.99 [7] were used for the beltline plates and welds in Table 7-2. Based on the above results, the beltline materials will have USE values above 50 ft-lb at 32 EFPY, as required in 10CFR50 Appendix G [1]. The lowest USE predicted for 32 EFPY is 52.1 ft-lb (for plate heat C9434-2).

Most of the initial weld upper shelf energy data was based on 10°F measurements. However, enough Unirradiated Charpy data was available for the surveillance weld (5P7397) to generate a hyperbolic tangent curve fit. From this curve fit the Initial USE of 83.3 ft-lb was determined (Figure 5-5).

Since USE and ART requirements are met, irradiation effects are not severe enough to necessitate additional analyses. Because adequate USE data is available and all 32 EFPY USE values are above 50 ft-lb, adoption of the BWROG equivalent margin analysis [18] is not necessary, although that analysis is applicable and bounding for LaSalle 2.

Table 7-1
BELTLINE 1/4 T ART VALUES FOR LASALLE UNIT 2
GE Method for Calculating Initial RTndt

Plate
Thickness = 6.19 inches

Plate
32 EFPY Peak I.D. fluence = 5.36E+17
32 EFPY Peak 1/4 T fluence = 3.70E+17

Weld
Thickness = 6.19 inches

Weld
32 EFPY Peak I.D. fluence = 5.36E+17
32 EFPY Peak 1/4 T fluence = 3.70E+17

COMPONENT	HEAT OR HEAT/LOT	%Cu	%Ni	CF	Initial RTndt °F		32 EFPY Δ RTndt °F	Margin °F	32 EFPY Shift °F	32 EFPY ART °F
PLATES:										
Lower										
21-1	C9425-2	0.12	0.51	81	30.0		20.06	20.06	40.13	70.13
21-2	C9425-1	0.12	0.51	81	32.0		20.06	20.06	40.13	72.13
21-3	C9434-2	0.09	0.51	58	10.0		14.37	14.37	28.73	38.73
Lower-Intmed										
22-1	C9481-1	0.11	0.50	73	10.0		18.08	18.08	36.16	46.16
22-2	C9404-2	0.07	0.49	44	52.0		10.90	10.90	21.80	73.80
22-3	C9601-2	0.12	0.50	81	10.0		20.06	20.06	40.13	50.13
Surveillance Plate (a)	C9481-1	0.084	0.45	54	10.0	*	13.38	13.38	26.75	36.75
VERTICAL WELDS:										
Lower Intermediate										
BA,BB,BC	3P4000	0.02	0.89	27	-50	b	6.7	6.7	13.4	-36.6
Lower										
BD,BE,BF	3P4966	0.03	0.90	41	-6.0	b	10.2	10.2	20.3	14.3
GIRTH WELD:										
Lower to Lower-Int.										
AB	5P6771	0.04	0.95	54	-34.0	b	13.4	13.4	26.8	-7.2
Surveillance Weld (a)	5P7397 (Tandem Wire)	0.03	0.87	41	-70.0		10.2	10.2	20.3	-49.7

a) Data from CBIN CMTR values. Contract No. 8-CN203 (1980) [28] (* Initial RTndt assumed the same as for plate 22-1)
b) These are conservative bounding values from single and tandem wire qualifications.

Table 7-2

Upper Shelf Energy Analysis for LaSalle Unit 2 Beltline Material

LOCATION	HEAT	TEST TEMP.	INITIAL LONGIT. USE	INITIAL[a] TRANS USE	%Cu	%DECR.[b] USE	32 EFPY[c] TRANS. USE
PLATES:							
Lower:							
21-1	C9425-2	*	102	66.3	0.12	11	57.7
21-2	C9425-1	*	94	61.1	0.12	11	53.2
21-3	C9434-2	40	91	59.2	0.09	9	52.1
Low-Int:							
22-1	C9481-1	40	-	95.5[d]	0.10[e]	9.5	86.4
22-2	C9404-2	*	116	75.4	0.07	8	67.5
22-3	C9601-2	40	107	69.6	0.12	11	60.6
WELDS:							
Low-Int. Vertical:							
BA,BB,BC	3P4000	10	-	99	0.02	8	91.1
Lower Vertical:							
BD,BE,BF	3P4966	10	-	84	0.03	8.5	76.9
Girth Welds:							
Lower to Low.-Int.							
AB	5P6771	10	-	61	0.04	9	55.5

* USE values estimated from statistical evaluation in Appendix B of [20]

[a] Values obtained from [20]

[b] Values obtained from Figure 2 of [7] for 32 EFPY fluence = 5.38×10^{17} n/cm^2.

[c] 32 EFPY Trans USE = Initial Trans USE * {1 - (% Decrease USE / 100)}

[d] Value obtained from baseline transverse data set [28]

[e] Value obtained from best estimate surveillance chemistry results (Table 3-3)

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," Annual Book of ASTM Standards, E185-73, March 1973

[5] LaSalle Unit 2 Steam Electric Station Final Safety Analysis Report, Section 5.3

[6] "Conducting Surveillance Tests for Light Water Cooled Nuclear Power Reactor Vessels," Annual Book of ASTM Standards, E185-82, July 1982.

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

[9] CBIN, QA Records for LaSalle 2 Replacement Surveillance Test Specimens, Contract Number 8-CN203, General Electric VPF# 6078-017-1 April 1980.

[10] CBIN, "Surveillance Test Specimen Preparation Plan for Contract: LaSalle 2 RPV", Contract 8-CN203, General Electric VPF# 6078-014-4, November 1979.

[11] R. G. Carey, "LaSalle County Unit 2 Surveillance Program Evaluation," GENE, San Jose, CA, January 1996, (GE Report GE-NE-523-155-1292).

[12] "Standard Methods for Notched Bar Impact Testing of Metallic Materials," Annual Book of ASTM Standards, E23-88

[13] "Nuclear Plant Irradiated Steel Handbook," EPRI Report NP-4797, September 1986.

[14] "Standard Methods of Tension Testing of Metallic Materials," Annual Book of ASTM Standards, E8-89.

[15] T. A. Caine, " LaSalle County Station Units 1 and 2 Fracture Toughness Analysis Per 10CFR50 Appendix G," GENE, San Jose, CA, March 1988,(GE Number SASR 88-10).

[16] intentionally left blank

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

[18] Letter from James T. Wiggins to Mr. Lesley A. England, "Acceptance for Referencing of Topical Report NEDO-32205, Revision 1, '10CFR50 Appendix G Equivalent Margin Analysis for Low Upper Shelf Energy in BWR/2 through BWR/6 Vessels," USNRC, Washington, D.C., December 8, 1993.

[19] T. A. Caine, "Flux Wire Dosimeter Evaluation for LaSalle Nuclear Power Station, Unit 2", GENE, San Jose, CA, October 1987, (GE Report SASR 87-59).

[20] T. A. Caine, "Upper Shelf Energy Evaluation for LaSalle Units 1 and 2," GENE, San Jose, CA, June 1990, (GE Report SASR 90-07).

[21] intentionally left blank

[22] intentionally left blank

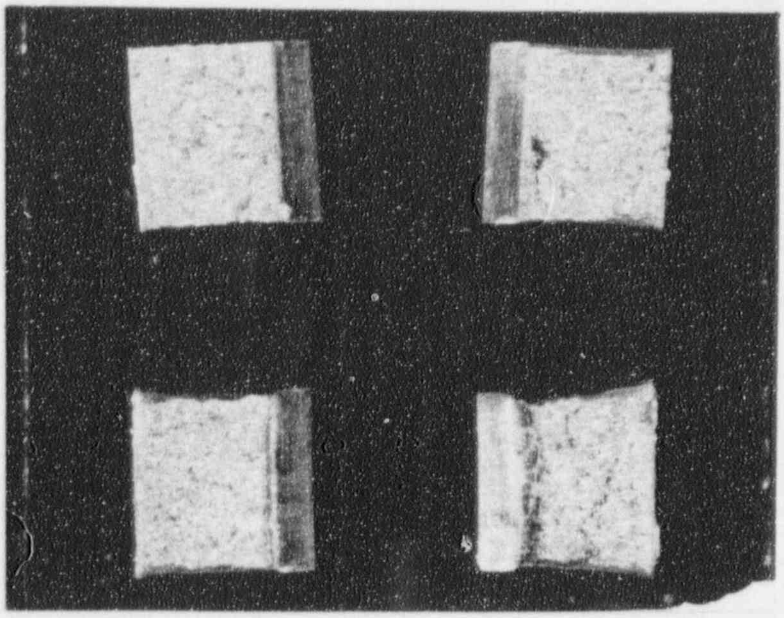
[23] LaSalle Unit 2 Steam Electric Station Updated Final Safety Analysis Report, Section 5.2.

[28] Letter, dated 3/16/94, G.W. Contreras, GE San Jose, to R. Willems, GE Oak Brook, subject LaSalle RPV Archive Material Records Search.

[29] Martin, G.C., "Browns Ferry Unit 3 In-Vessel Neutron Spectral Analysis," GENE, San Jose, CA, August 1980, (GE Report NEDO-24793).

APPENDIX A
IRRADIATED 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.

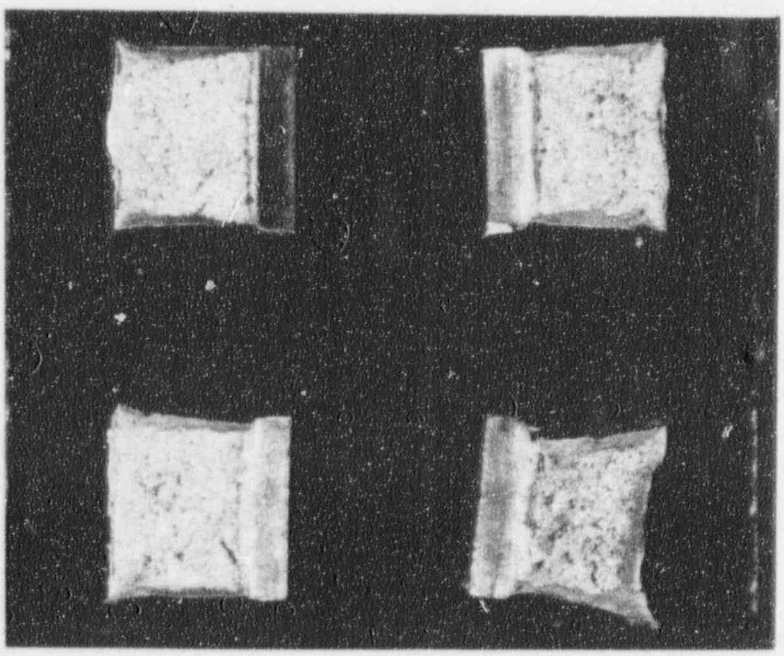


BASE: 28823
Temp: -60 °F
Energy: 7 ft-lb
MLE: 5 mils
Shear: 0 %

BASE: 28824
Temp: -20 °F
Energy: 7.5 ft-lb
MLE: 6 mils
Shear: 17.6 %

BASE: 28825
Temp: 0 °F
Energy: 23 ft-lb
MLE: 21 mils
Shear: 49.4 %

BASE: 28826
Temp: 20 °F
Energy: 58 ft-lb
MLE: 41.5 mils
Shear: 53.8 %

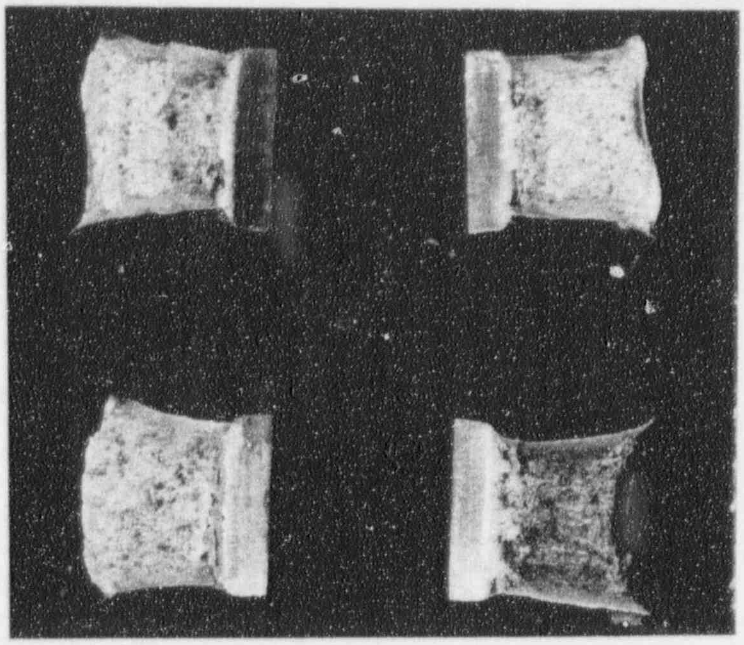


BASE: 28827
Temp: 30°F
Energy: 32 ft-lb
MLE: 30 mils
Shear: 44.3 %

BASE: 28828
Temp: 40°F
Energy: 47.5 ft-lb
MLE: 31.5 mils
Shear: 43.7 %

BASE: 28829
Temp: 50°F
Energy: 44 ft-lb
MLE: 36.5 mils
Shear: 40.2 %

BASE: 28830
Temp: 65 °F
Energy: 99.5 ft-lb
MLE: 74 mils
Shear: 67.7 %

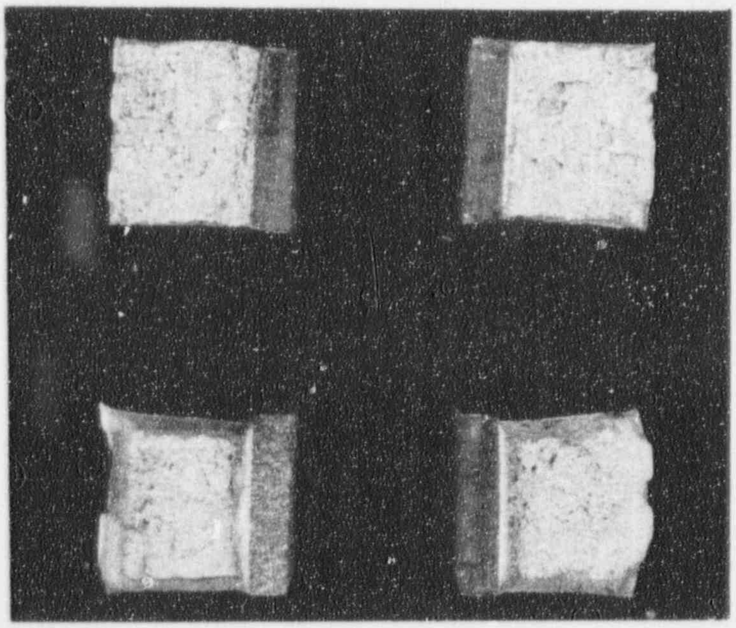


BASE: 28831
Temp: 80 °F
Energy: 101.5 ft-lb
MLE: 59 mils
Shear: 70.3 %

BASE: 28832
Temp: 120 °F
Energy: 88.5 ft-lb
MLE: 66 mils
Shear: 82.4 %

BASE: 28833
Temp: 200 °F
Energy: 126 ft-lb
MLE: 84.5 mils
Shear: 100 %

BASE: 28834
Temp: 300 °F
Energy: 123.5 ft-lb
MLE: 87.5 mils
Shear: 100 %



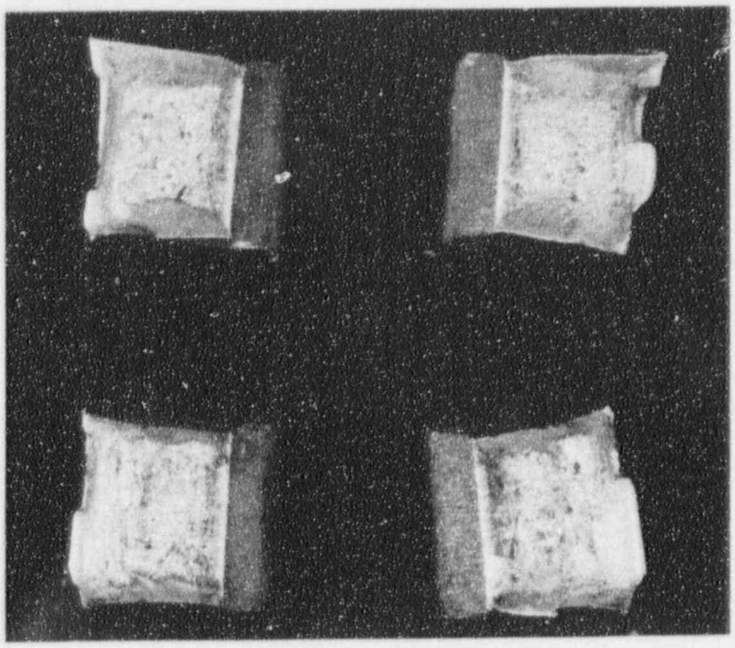
WELD: 28835
Temp: -100 °F
Energy: 13.5 ft-lb
MLE: 7 mils
Shear: 11.1 %

WELD: 28836
Temp: -60 °F
Energy: 15 ft-lb
MLE: 10 mils
Shear: 21.9 %

WELD: 28837
Temp: -40 °F
Energy: 32 ft-lb
MLE: 30.5 mils
Shear: 49 %

WELD: 28838
Temp: -20 °F
Energy: 45 ft-lb
MLE: 34.5 mils
Shear: 58.4 %

WELD: 28839
Temp: 0 °F
Energy: 55 ft-lb
MLE: 45.5 mils
Shear: 67.4 %

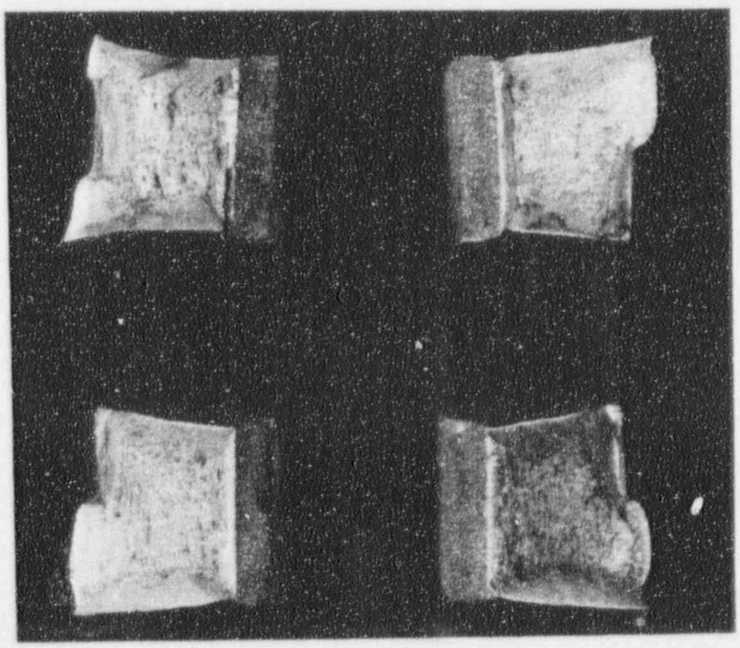


WELD: 28840
Temp: 20 °F
Energy: 67 ft-lb
MLE: 43.5 mils
Shear: 80.3 %

WELD: 28841
Temp: 30 °F
Energy: 43 ft-lb
MLE: 37 mils
Shear: 50.6 %

WELD: 28842
Temp: 50 °F
Energy: 61.5 ft-lb
MLE: 50.5 mils
Shear: 65.5 %

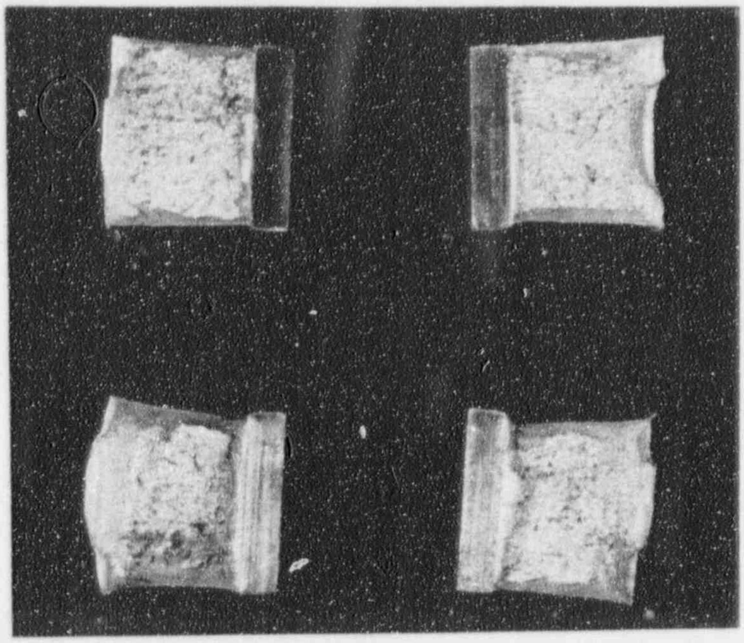
WELD: 28843
Temp: 80 °F
Energy: 78 ft-lb
MLE: 50.5 mils
Shear: 91 %



WELD: 28844
Temp: 120°F
Energy: 94 ft-lb
MLE: 74.5 mils
Shear: 100 %

WELD: 28845
Temp: 200 °F
Energy: 82 ft-lb
MLE: 73 mils
Shear: 100 %

WELD: 28846
Temp: 300 °F
Energy: 85 ft-lb
MLE: 85 mils
Shear: 100 %

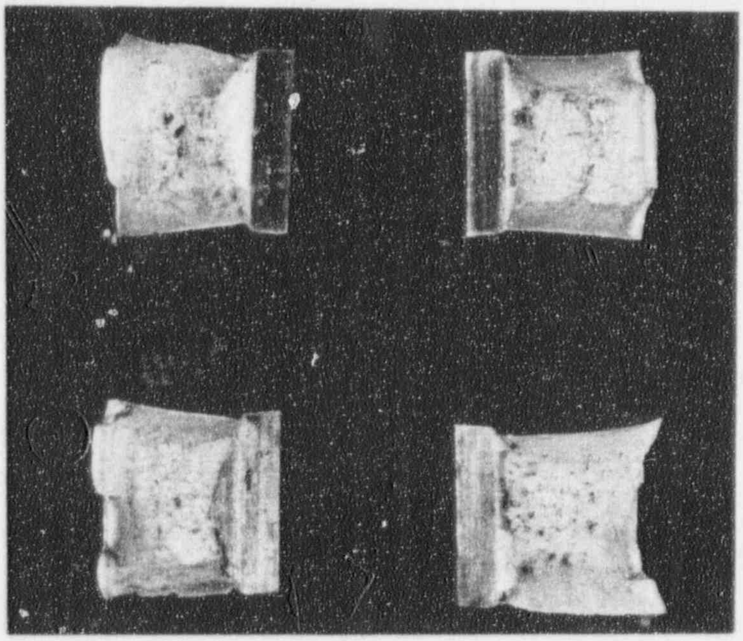


HAZ: 28847
Temp: -60 °F
Energy: 22 ft-lb
MLE: 21.5 mils
Shear: 30.1 %

HAZ: 28848
Temp: -20 °F
Energy: 27 ft-lb
MLE: 25 mils
Shear: 47.2 %

HAZ: 28849
Temp: -10 °F
Energy: 45 ft-lb
MLE: 42 mils
Shear: 54.5 %

HAZ: 28850
Temp: 0 °F
Energy: 47 ft-lb
MLE: 38.5 mils
Shear: 68.1 %



HAZ: 28851
Temp: 20 °F
Energy: 106 ft-lb
MLE: 66 mils
Shear: 91.5 %

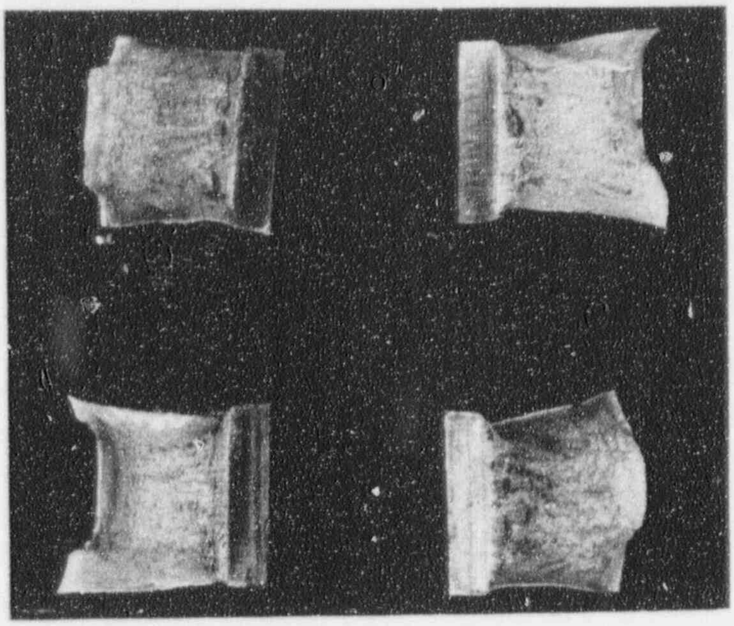
HAZ: 28852
Temp: 30 °F
Energy: 59 ft-lb
MLE: 40.5 mils
Shear: 82.2%

HAZ: 28853
Temp: 50 °F
Energy: 71 ft-lb
MLE: 54.5 mils
Shear: 87.3 %

HAZ: 28854
Temp: 80 °F
Energy: 64 ft-lb
MLE: 41.5 mils
Shear: 91.9 %

HAZ: 28855
Temp: 100 °F
Energy: 86 ft-lb
MLE: 64 mils
Shear: 100 %

HAZ: 28856
Temp: 120 °F
Energy: 88 ft-lb
MLE: 69 mils
Shear: 100 %



HAZ: 28857
Temp: 200 °F
Energy: 81 ft-lb
MLE: 68 mils
Shear: 100 %

HAZ: 28858
Temp: 300 °F
Energy: 84.5 ft-lb
MLE: 78.5 mils
Shear: 100 %

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