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DUANE ARNOLD ENERGY CENTER REACTOR PRESSURE VESSEL SURVEILLANCE MATERIALS TESTING

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ABSTRACT

A surveillance capsule was removed from the Duane Arnold Energy Center reactor at the end of Fuel Cycle 7. The capsule contained flux wires for neutron fluence measurement and Charpy and tensile test specimens for material property evaluation. A combination of flux wire testing and computer analysis was used to establish the vessel peak flux magnitude and end-of-life predicted fluence. Charpy V-Notch impact testing and uniaxial tensile testing were performed to establish the material properties of the irradiated vessel beltline. Unirradiated data were not available at the time of surveillance testing to establish an irradiation shift, so the irradiation effects were projected to the vessel end-of-life using Regulatory Guide 1.99, Revision 1. The predicted end-of-life conditions of reference temperature and upper shelf energy were found to be less severe than the limits requiring vessel thermal annealing.

During the irradiated specimen testing, archive unirradiated specimens were retrieved. The unirradiated specimen testing is underway at General Electric. The surveillance test report will be revised to include the unirradiated specimen results when testing is completed.

ACKNOWLEDGMENTS

Flux wire testing was performed by G. C. Martin. The Charpy V-Notch testing was done by J. L. Bennett. S. G. Wisner tested the tensile specimens, with the help of G. H. Henderson. C. R. Judd performed the chemical composition testing.

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 (Reference 1) and in Appendix G of the ASME Boiler and Pressure Vessel Code, Section III (Reference 2). These documents contain requirements that establish the pressure-temperature operating limits which must be met to avoid brittle fracture.

Appendix H of 10CFR50 (Reference 3) and ASTM E185-82 (Reference 4) establish the methods to be used for surveillance of the reactor vessel materials. In April, 1985 one of the surveillance specimen capsules required by Reference 3 was removed from the Duane Arnold Energy Center (DAEC) reactor after 7 fuel cycles of irradiation, or 5.9 effective full power years (EFPY) of operation. The surveillance capsule contained flux wires for neutron flux monitoring and Charpy V-Notch impact test specimens and uniaxial tensile test specimens fabricated from the vessel plate and weld materials nearest the core (the beltline). The impact and tensile specimens were tested to establish material properties for the irradiated vessel materials. The results of surveillance specimen testing are presented in this report.

The original plan to compare the surveillance data to unirradiated data had to be modified when General Electric (GE), after searching their archive fabrication records, determined that the fabrication test specimens and the surveillance test specimens had been taken from different plates. Furthermore, review of unirradiated weld data retrieved from Chicago Bridge & Iron showed insufficient Charpy data for a meaningful comparison with the surveillance test results.

When Iowa Electric Light & Power (IEL&P) was informed of this, they retrieved unirradiated Charpy and tensile specimens from inventory and plans were made for GE to perform additional testing. This report will be revised to include comparison with unirradiated data when the additional testing is completed.

Predictions of the RT_{NDT} and USE at end of reactor life (EOL) are made using Regulatory Guide 1.99, Revision 1 (Reference 5) for comparison with allowable values in Reference 1. Operating limits curves, developed using Reference 5, were previously reported in NEDC-30839 (Reference 6).

2. SUMMARY AND CONCLUSIONS

2.1 SUMMARY OF RESULTS

Surveillance capsule 1 was removed from the DAEC reactor at the end of Fuel Cycle 7 and shipped to the General Electric Vallecitos Nuclear Center. The flux wires, Charpy V-Notch and tensile test specimens removed from the capsule were tested according to ASTM E185-82 (Reference 4). The methods and results of the fracture toughness testing are presented in this report as follows:

a. Section 3: Surveillance Program Background

b. Section 4: Flux Wire Test Evaluation

c. Section 5: Charpy V-Notch Testing

d. Section 6: Tensile Testing

e. Section 7: Predicted End-of-Life Conditions

The significant results of the evaluation are summarized as follows:

a. Capsule 1 was removed from the 288° azimuth position of the reactor. The capsule contained 6 flux wires: 2 each of pure copper (Cu), nickel (Ni) and iron (Fe). There were 24 Charpy V-Notch specimens: 8 each of plate material, weld material and heat affected zone (HAZ) material. The 6 tensile specimens removed consisted of 2 plate, 2 weld and 2 HAZ metal specimens. All specimen materials were positively identified as being from the vessel beltline.

b. The chemical compositions of the beltline materials were identified through a combination of literature research and testing. The copper (Cu), phosphorus (P) and nickel (Ni) contents were determined for all heats of plate material and for the seam welds in the beltline. The maximum values for the beltline plates are 0.15% Cu, 0.011% P and 0.64% Ni. For the beltline welds, the maximums are 0.03% Cu, 0.021% P and 0.97% Ni.

c. The flux wires were tested to determine the neutron flux at the surveillance capsule location. The fast flux (>1.0 MeV) measured was 2.6×10^{9} n/cm²-s. Based on the flux wire data, the surveillance specimens had received a fluence of 4.9×10^{17} n/cm² at removal.

d. Lead factors for the DAEC vessel geometry and core power distribution were computed in Reference 6. The lead factors for the surveillance capsule are 0.78 to the peak vessel surface location and 0.99 to the peak 1/4 T depth location. The EOL fluence, based on 32 EFPY, was calculated with the 1/4 T lead factor and the flux wire results, including a 4% power uprate at 6 EFPY. The resulting value of 3.6×10^{18} n/cm² is less than the value calculated in Reference 6.

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 percent shear. Fracture surface photographs of each specimen are presented in Appendix A. From absorbed energy and lateral expansion results for the plate, weld and HAZ materials, the following values were extracted: index temperatures for 30 ft-lb, 50 ft-lb, and 35-mil lateral expansion (MLE) values, and USE.

f. The irradiated tensile specimens were tested at room temperature (76°F) and reactor operating temperature (550°F). The results tabulated for each specimen include yield and ultimate tensile strength (UTS), uniform and total elongation, and reduction of area. The plate, weld, and HAZ specimens behave similarly for most properties, with the weld metal showing more temperature dependency in yield strength.

g. The irradiated plate material tensile test results are compared to unirradiated data from the vessel fabrication test program. The yield strength and UTS increased with irradiation, and the total elongation decreased with irradiation. These trends are characteristic of irradiation embrittlement.

h. The USE values for beltline plates 1-20 and 1-21 and for the beltline weld material are predicted using Reference 5 for the EOL condition. The plate values were corrected to 65% of the longitudinal USE to estimate the transverse USE, according to the recommendation in Branch Technical Position MTEB 5-2 (Reference 7).

2.2 CONCLUSIONS

Surveillance testing is done to support or replace calculated information related to operating conditions and EOL vessel beltline conditions, as outlined in Reference 1. The results obtained from surveillance testing which impact these conditions are the predicted EOL fluence, the shift in RT_{NDT} for the beltline materials and the USE.

The flux wire testing, combined with the lead factors from the Reference 6 analysis, give an EOL fluence prediction which is about 20% lower than the value predicted in Reference 6. Since the fluence directly affects the allowable pressure-temperature limits of operation, the Reference 6 operating limits curves, which have been incorporated into the Technical Specifications, are conservative.

During testing of the irradiated surveillance specimens, it was determined that the unirradiated specimen data available from records were not meaningful for measuring experimental RT_{NDT} shift by comparison with irradiated specimen results. IEL&P personnel retrieved unirradiated specimens from storage and sent them to GE for testing. The testing is currently in progress at GE, and this report will be revised when unirradiated test results are complete. The operating limits curves, which are valid for 12 EFPY, should not be adjusted to reflect the updated fluence until the plate and weld experimental RT_{NDT} shifts are available.

The USE values for beltline plates and welds for the EOL condition were calculated using Reference 5 methods with data from surveillance tests and fabrication tests. The lowest EOL values, 70 ft-lb for plate 1-20 and 95 ft-lb for the weld, are above the minimum allowable of 50 ft-lb from Reference 1.

The USE results established in this report, with the RT_{NDT} shift results reported in Reference 6, show that the DAEC vessel is in compliance with the fracture toughness requirements of 10CFR50 Appendix G.

3. SURVEILLANCE PROGRAM BACKGROUND

3.1 CAPSULE RECOVERY

The DAEC reactor was shut down in February 1985 for refueling and maintenance. The accumulated thermal power output was $3.45x10^6$ MWd or 5.9 EFPY. The reactor pressure vessel (RPV) originally contained three surveillance capsules at 36°, 108°, and 288° azimuths at the core midplane. The specimen capsules are held against the RPV inside surface by a spring loaded specimen holder. Capsule 1 at 288° was removed by DAEC personnel on April 9, 1985. The capsule was cut from the holder assembly and shipped by a 200 Series cask to the General Electric Vallecitos Nuclear Center in Pleasanton, California.

Upon arrival at Vallecitos, the capsule was examined for identification. The reactor code of 35 from Reference 8 and the capsule number were confirmed on the capsule, as shown in Figure 3-1. The capsule contained two Charpy specimen packets and three tensile specimen tubes. Each Charpy packet contained 12 Charpy specimens and 3 flux wires. The three tensile specimen tubes contained a total of six specimens. The tensile specimen gage sections were protected by aluminum sleeves, and during removal of the sleeves, the threaded ends of the specimens were slightly damaged. The threads were later chased with a die-hex re-threading tool. The gage sections of the tensile specimens were not damaged during removal.

3.2 RPV MATERIALS AND FABRICATION BACKGROUND

3.2.1 Fabrication History

The DAEC RPV is a 183-inch diameter BWR/4. It was field fabricated by Chicago Bridge & Iron to the 1965 ASME Code with Addenda up to and including Winter 1967. The shell and head plates are ASME SA-533 Grade B, Class 1 low alloy steel (LAS). The nozzles and closure flanges are ASME SA-508 Class 2 LAS, and the closure flange bolting materials are ASTM A540 Grade B24 LAS. The fabrication process employed quench and temper heat treatment immediately after hot forming, then shielded metal arc welding (SMAW) and post-weld heat treatment in the field. The post-weld heat treatment was typically 10 hours at 1150°± 25°F. The arrangement of plates and welds relative to the core beltline and various nozzles is shown in Figure 3-2.

3.2.2 Material Properties of RPV at Fabrication

A search of General Electric Quality Assurance (QA) records was made to determine the chemical and mechanical properties of the plates and welds in the RPV beltline. The results were reported in Reference 6, and are summarized in Table 3-1, including the initial RT_{NDT} values calculated. The Reference 6 work was supplemented with more specific information from Chicago Bridge & Iron on the weld materials that went into the beltline longitudinal and girth welds. The limiting weld materials used in the beltline welds are shown in Table 3-1.

3.2.3 Specimen Chemical Composition

Samples were taken from base metal tensile specimens ETJ and ETK and from weld metal tensile specimens EU3 and EU6 after they were tested. Samples from the tensile specimens represent the Charpy specimens as well, since both were taken from the same plate and weld, as discussed in Subsection 3.3. A total of four samples were analyzed. Chemical analysis was performed using a plasma emission spectrometer. Each sample was decomposed and dissolved, and a portion prepared for evaluation by the spectrometer. The spectrometer was calibrated with a standard solution containing 700 ppm Fe, 8 ppm Mn, 2 ppm Cu, 5 ppm Ni, 5 ppm Mo, 5 ppm Cr, 1 ppm Si, 1 ppm Co, and levels of perchloric acid and lithium consistent with the test. The phosphorus calibration was done by analyzing a series of seven National Bureau of Standards (NBS) steels with known phosphorus contents. The chemical composition results are given in Table 3-2.

3.3 SPECIMEN DESCRIPTION

The surveillance capsule contained 24 Charpy specimens: base metal (8), weld metal (8), and HAZ (8). There were tensile specimens: base metal (2), weld metal (2), and HAZ (2). The 6 flux wires recovered were iron (2), nickel (2) and copper (2). 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 Surveillance Test Drawings T4 through T12 (Reference 9). All materials used for specimens were beltline materials from the lower intermediate shell course.

The base metal specimens were cut from plate 1-21 (Heat B0673-1). The chemical analysis of this heat of low alloy steel is in Reference 6, as summarized in Table 3-1. The test plate was heat treated for 50 hours at 1150°F plus 25°F or minus 50°F to conservatively simulate the post-weld heat treatment of the vessel. The method used to machine the specimens from the test plate is 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 identification of the base metal Charpy specimens recovered from the surveillance capsule is shown in Table 3-3.

The weld metal and HAZ Charpy specimens were fabricated from pieces of plate 1-21 that were welded together using "the same welding procedures as used to weld the core area shell plates together" (Reference 9). The chemical analysis of the surveillance weld material is shown in Table 3-2. The welded test plate for the weld and HAZ Charpy specimens received a heat treatment of 1150°F plus 25°F or minus 50°F for 50 hours to conservatively represent the heat treatment of the RPV. 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. Contained in Table 3-3 are the identifications of the weld metal and HAZ Charpy specimens from the surveillance capsule.

3.3.2 Tensile Specimens

Fabrication of the surveillance tensile specimens is described in the Reference 9 drawings. The chemical composition and heat treatment 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 tensile specimens recovered from the surveillance capsule are given in Table 3-3. A summary of the fabrication methods is presented below.

The base metal specimens were machined from material at the 1/4 T and 3/4 T depth in plate 1-21. 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 material was cut from the welded test plate, 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 plate such that the gage section minimum diameter was machined at the HAZ centerline. The finished HAZ specimens are approximately half weld metal and half base metal, oriented along the plate rolling direction.

Table 3-1

MATERIAL PROPERTIES OF VESSEL COMPONENTS

Identification	Heat/Lot No.	Chemistry (wt %) Cu	P	Ni	Charpy Test Temp. (°F)	Energy (ft-lb)	Dropweight Temp. (°F)	RT_{NDT}[a] (°F)
Lower Plates:								
(Shell 1) 1-18	C6439-2	0.09	0.012	0.51	40	36,48,43	40	40
1-19	B0402-1	0.13	0.012	0.47	40	83,85,72	40	40
Lower-Intermed. Plates:								
(Shell 2) 1-20	B0436-2	0.15	0.008	0.64	40	57,54,62	-30	10
1-21	B0673-1	0.15	0.011	0.61	40	99,104,121	-30	10
Longitudinal Welds	Ht. 432Z0471 Lot B003A27A	0.03	0.017	0.91	10	100,102,106	-	-50
Girth Weld	Ht. 07L669 Lot K004A27A	0.03	0.014	1.02	10	50,50,54	-	-50
Upper Plates:								
(Shell 4) 1-24	C6794-2				10	37,44,33	10	14
1-25	C7090-1				10	61,67,79	10	10
Standby Liquid Control Nozzle	E20VW				40	38,60,26	40	58

[a] RT_{NDT} values are calculated to be equivalent to transverse RT_{NDT}.

Table 3-2

PLASMA EMISSION SPECTROMETRY CHEMICAL ANALYSIS OF RPV SURVEILLANCE PLATE AND WELD MATERIALS

Element	Base Metal Tensile ETJ	Base Metal Tensile ETK	Weld Metal Tensile EU3	Weld Metal Tensile EU6
Mn	1.4	1.3	1.3	1.2
P	0.006	0.006	0.011	0.010
Cu	0.15	0.15	0.02	0.02
Si [a]	0.07	0.06	0.32	0.33
Ni	0.70	0.69	1.00	0.90
Mo	0.63	0.62	0.49	0.49
Cr	0.14	0.14	0.04	0.03
Co	0.014	0.013	0.013	0.012

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[a] Si results may be low, because of precipitation during dissolution heating.

Table 3-3

IDENTIFICATION OF CHARPY AND TENSILE SPECIMENS
REMOVED FROM SURVEILLANCE CAPSULE

Charpy Specimens

Base	Weld	HAZ
EBJ [a]	EE2	ELK
EBK	EE3	ELL
EBL	EE4	ELM
EBP	EE5	ELP
EBT	EJ1	ELT
EBU	EJ2	ELY
EBY	EJ3	EMT
EC1	EJ4	EMY

Tensile Specimens

Base	Weld	HAZ
ETJ [a]	EU3	EY1
ETK	EU6	EY2

[a] All specimen identifications include a double-dot over the middle symbol.

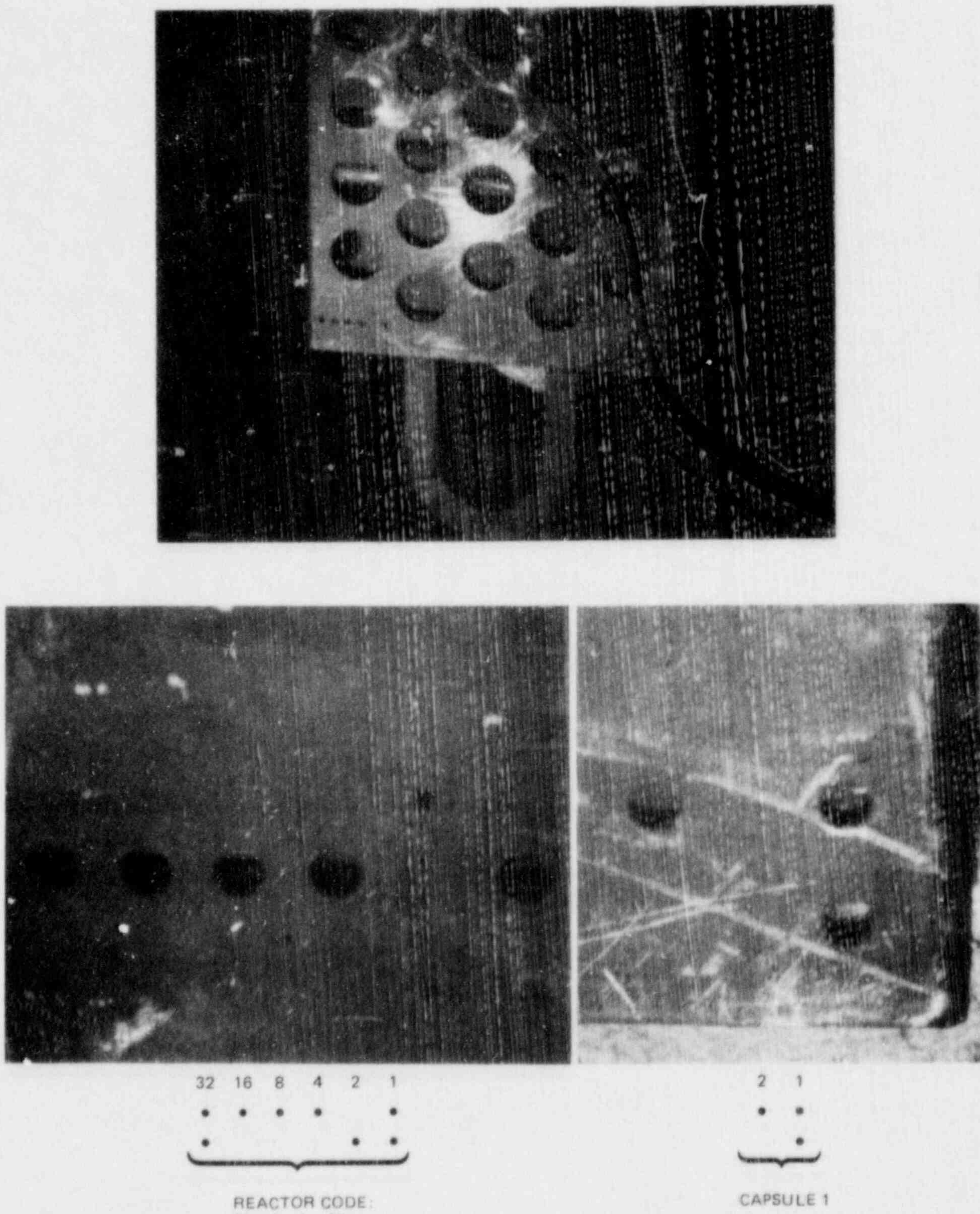


Figure 3-1. Surveillance Capsule Recovered from DAEC Reactor

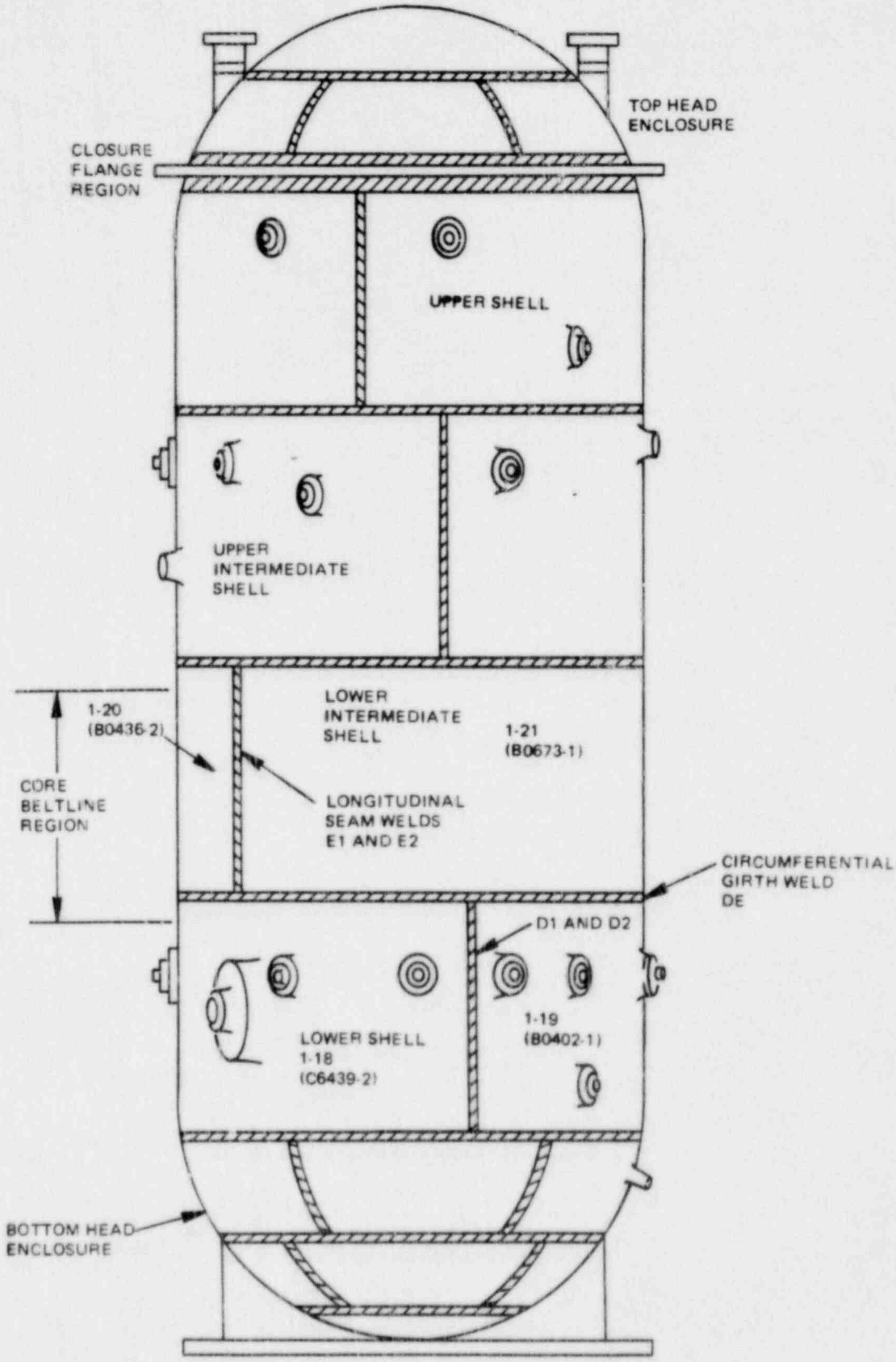


Figure 3-2. Schematic of the RPV Showing Arrangement of Vessel Plates and Welds

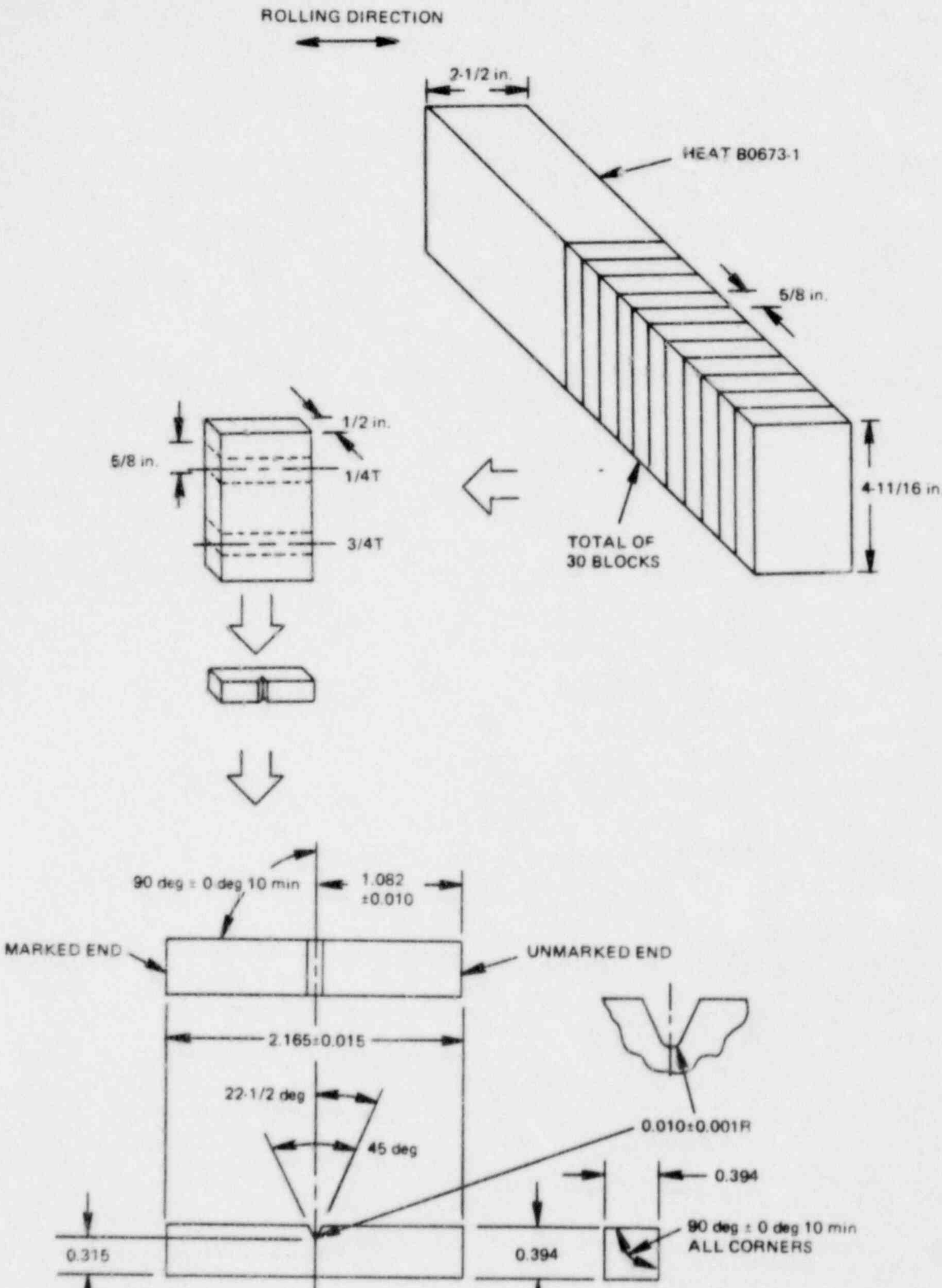


Figure 3-3. Fabrication Method for Base Metal Charpy Specimens

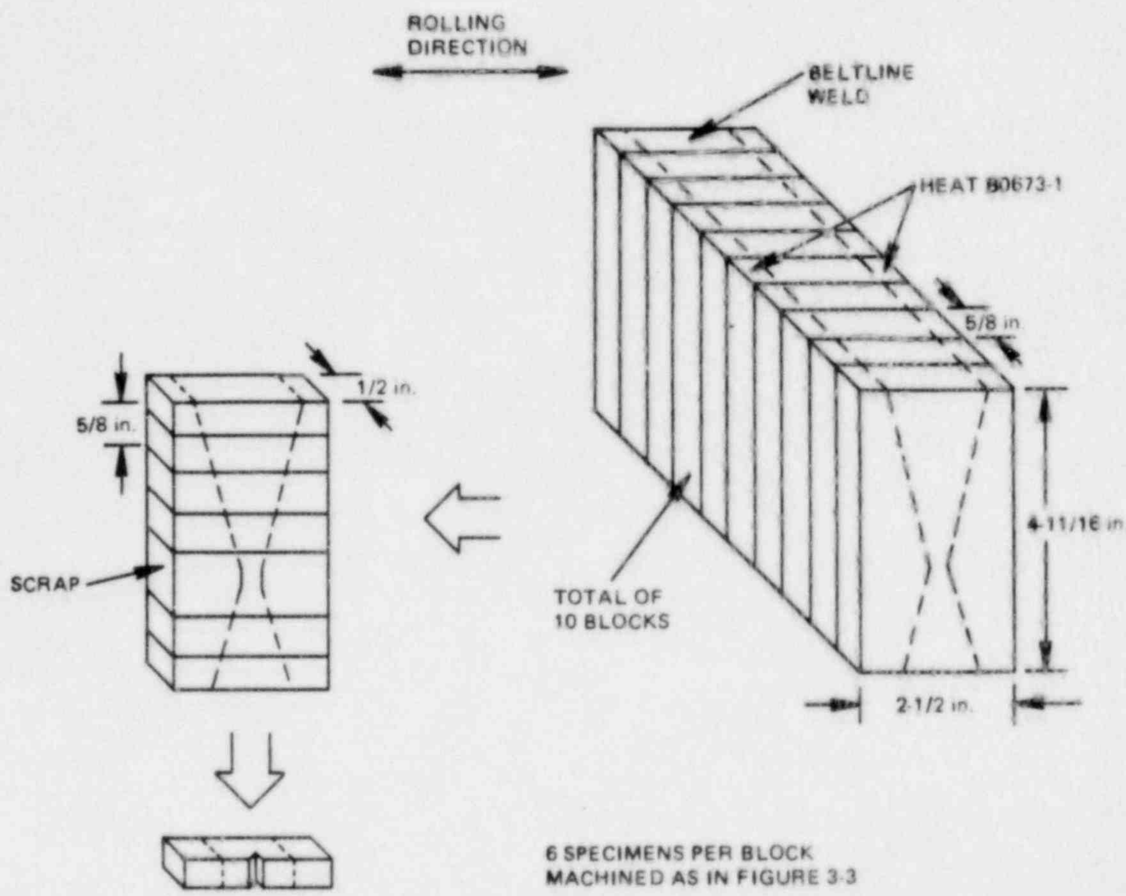


Figure 3-4. Fabrication Method for Weld Metal Charpy Specimens

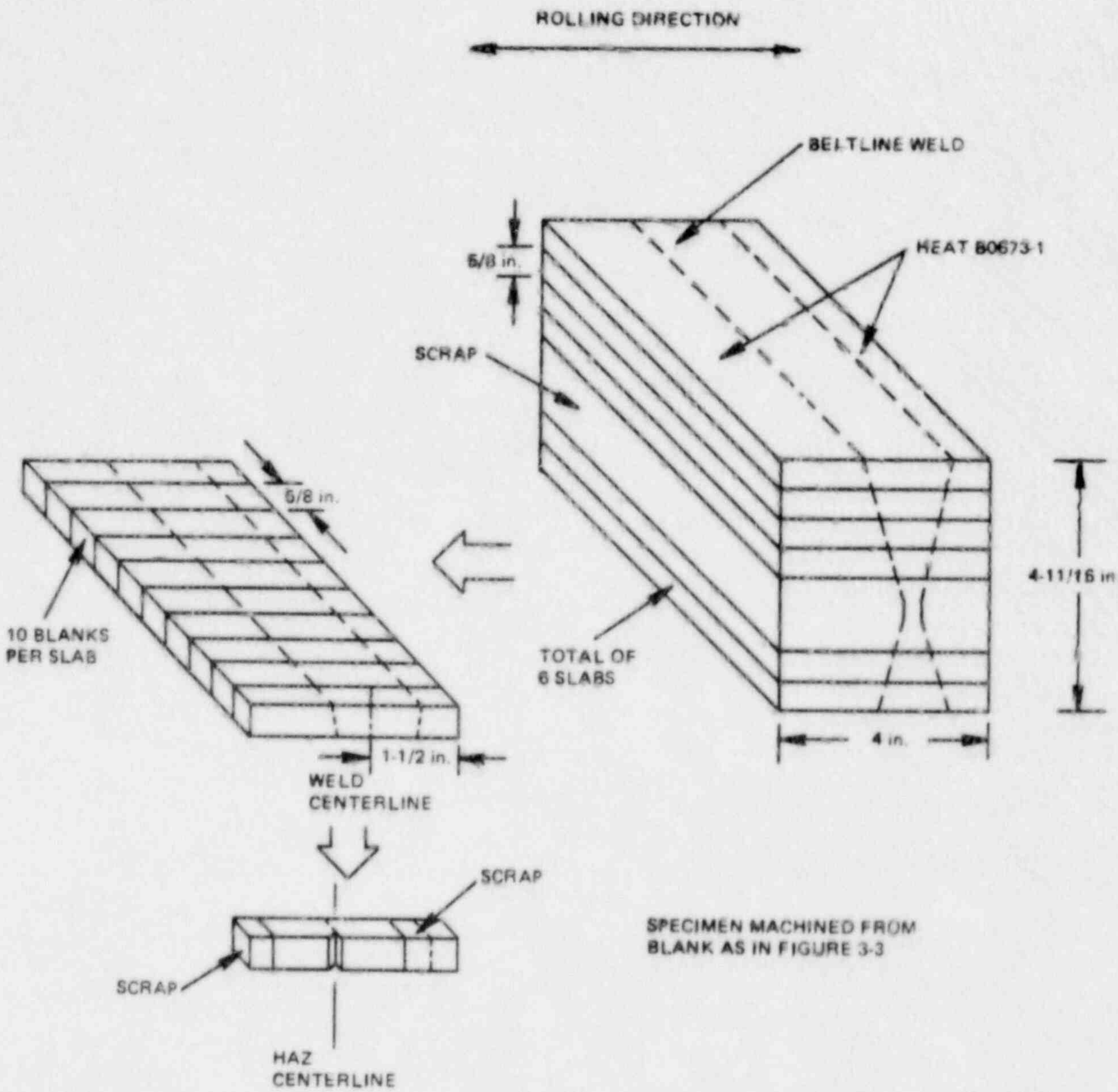


Figure 3-5. Fabrication Method for HAZ Charpy Specimens

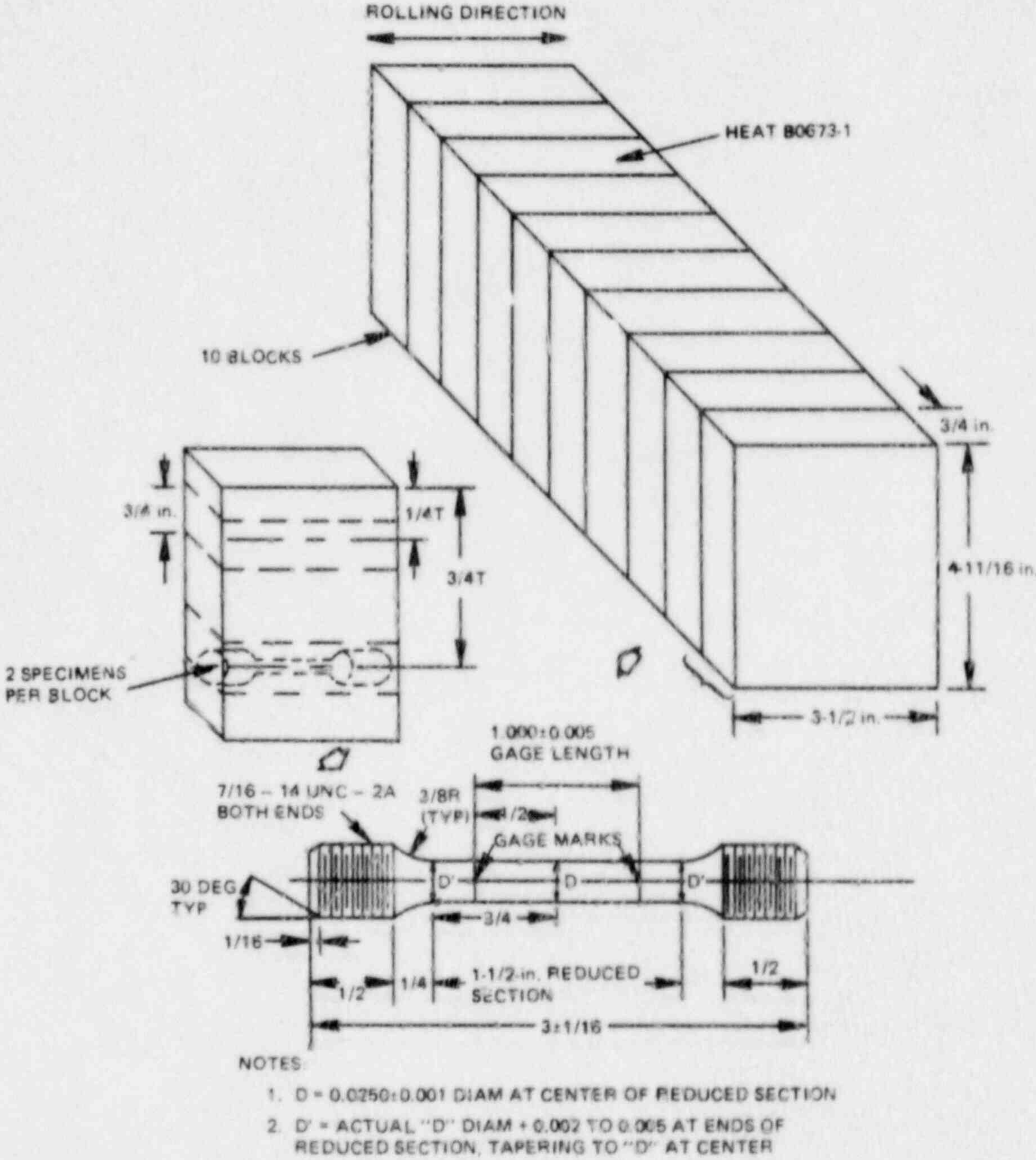


Figure 3-6. Fabrication Method for Base Metal Tensile Specimens

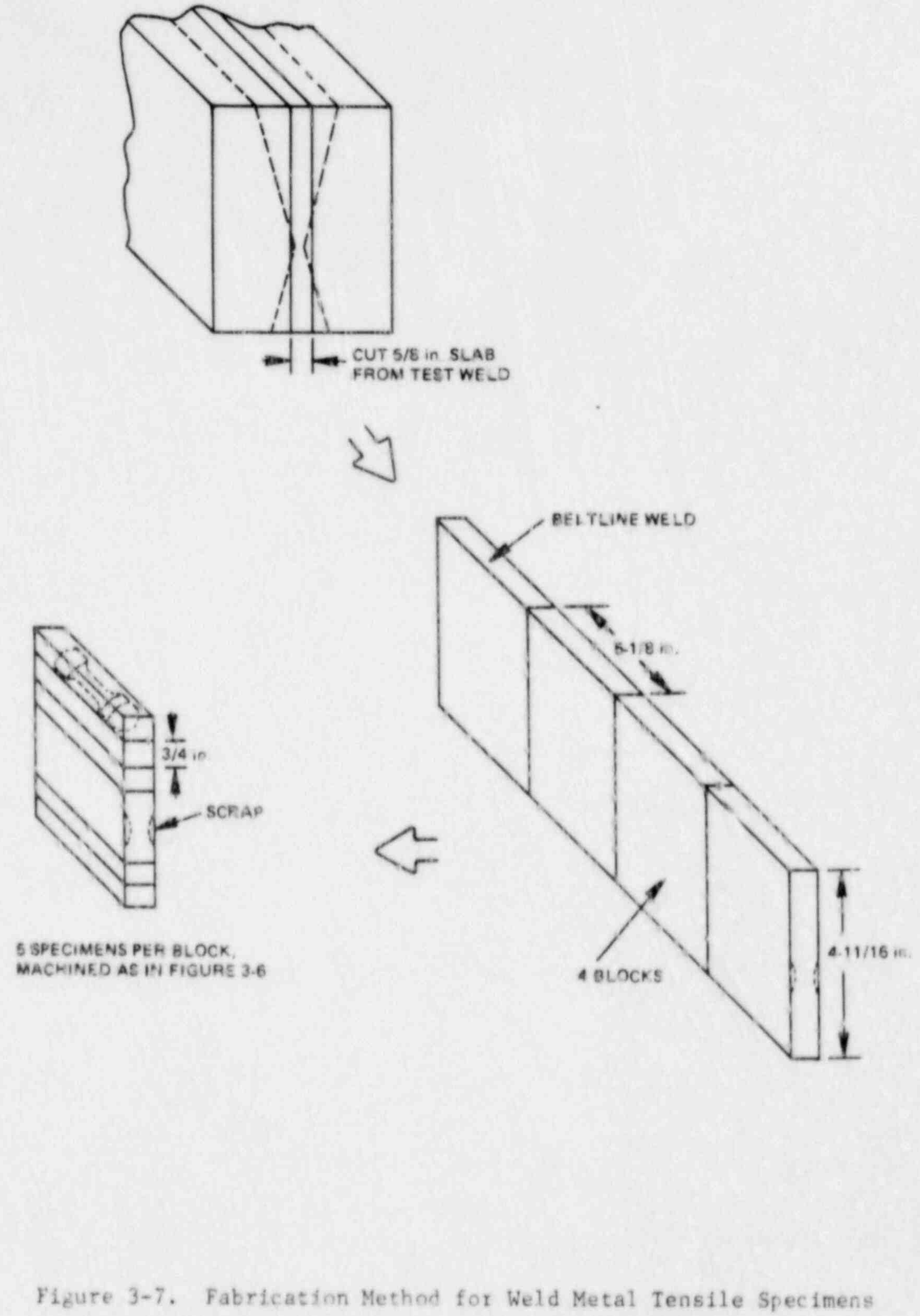


Figure 3-7. Fabrication Method for Weld Metal Tensile Specimens

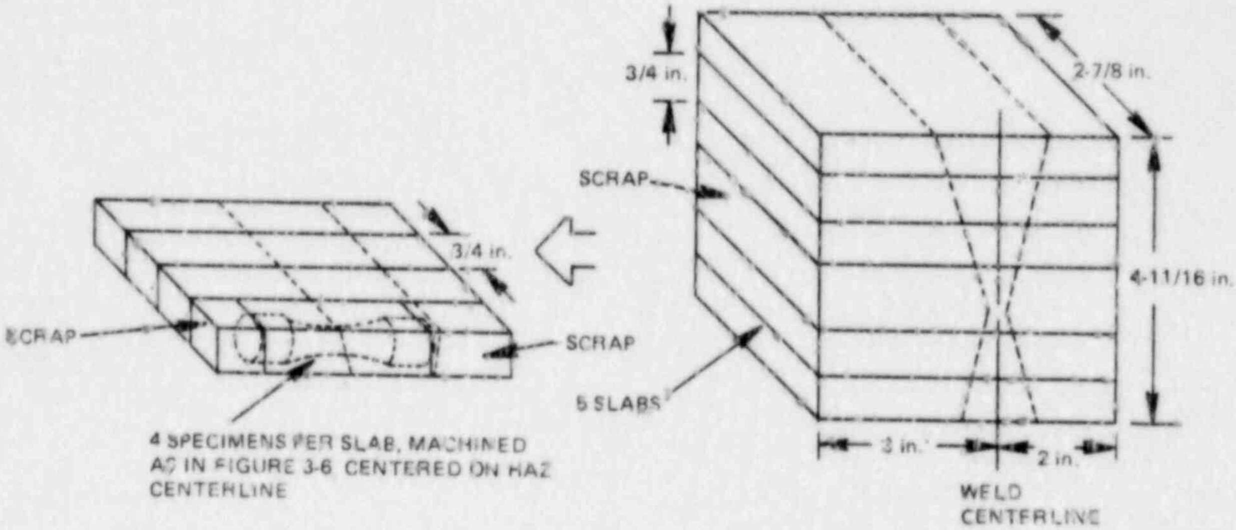


Figure 3-8. Fabrication Method for HAZ Tensile Specimens

4. FLUX WIRE TEST EVALUATION

Reference 6 includes a determination of the peak vessel flux and fluence, based on analytical results and results from a test performed on flux wires removed from the vessel after Fuel Cycle 2. The flux wires removed with the current surveillance capsule give more representative values of flux, as explained later, and provide a measurement of the fluence accumulated by the Charpy and tensile surveillance specimens. Updated values of peak vessel flux and fluence are computed using the latest flux wire results and the lead factors from Reference 6.

4.1 FLUX WIRE ANALYSIS

4.1.1 Procedure

The surveillance capsule contained six flux wires: two each of iron, nickel and copper. 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- or 10-cm source-to-detector distance with an 80-cc Ge(Li) detector system. The gamma spectrometer was calibrated using NBS material.

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 average reactor 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, Ni-58 (n,p) Co-58 and Cu-63 (n,α) Co-60 were calculated. The >1 MeV fast flux reaction cross sections for the iron, copper, and nickel wires were estimated to be 0.157 barn, 0.0027 barn and 0.204 barn, respectively. These values were obtained from measured cross-section functions determined at Vallecitos from more than 65 spectral determinations for BWRs and for the General Electric Test Reactor using activation monitor and spectral unfolding techniques. Similarly, the >0.1 MeV cross sections for the iron, copper, and nickel wires were estimated from the measured 1-to-0.1 cross-section ratio of 1.6.

4.1.2 Results

The measured activity, reaction rate and determined full-power flux results for the surveillance capsule are given in Table 4-2. The >1 MeV and >0.1 MeV flux values of 2.6×10^9 and 4.2×10^9 n/cm²-sec from the flux monitors were calculated by dividing the reaction rate measurement data by the appropriate cross sections. The corresponding fluence results, 4.9×10^{17} and 7.8×10^{17} n/cm² for >1 MeV and >0.1 MeV, respectively, were obtained by multiplying the full-power flux density values by the product of the total seconds irradiated (2.79×10^8 sec) and the full-power fraction (0.671).

Generally, for long-term irradiations, dosimetry results from copper flux wires are considered most accurate because of the length of the half-life of Co-60 (5.27 years) compared to those of iron's Mn-54 (312.5 days) and nickel's Co-58 (70.8 days). The iron and nickel flux wires, which are more sensitive to fluctuations in reactor power levels and to peripheral bundle power variations, showed reasonable agreement with the copper wires, varying by 10% and 20%, respectively. Given this, and the fact that the copper wire results were the most conservative, the copper flux wire results were used to predict capsule fluence and EOL vessel fluence.

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

± 5% for dps/g (disintegrations per second per gram)

± 12% for dps/nucleus (saturated)

± 30% for flux and fluence >1 MeV

± 40% for flux and fluence >0.1 MeV

A set of flux wires from DAEC was evaluated by General Electric in 1977. The >1 MeV flux was 3.1×10^9 n/cm^2-sec. The result from this study of 2.6×10^9 n/cm^2-sec is about 15% lower. The Reference 6 analysis of flux as a function of position indicates that the current flux wire test results, from the 288° location, should be slightly higher than the first test results from 36°. As a result, the current flux is effectively 23% lower than the first flux wire test result. This difference is probably due to the variations in operation typical in the first fuel cycle. The most recent flux wires, which have been exposed to years of steady-state operation, provide a more reliable reading of the vessel steady-state flux. Therefore, the latest measured flux is used in Subsection 4.3 to predict EOL fluence.

4.2 FLUX DISTRIBUTION LEAD FACTORS

A lead factor is a calculated ratio between the flux at the surveillance capsule location and the flux at the location of peak flux in the beltline region (at the inside surface or at 1/4 T depth). The computer analyses required to establish the lead factors for the DAEC vessel were performed for Reference 6, and the results are discussed therein. The lead factors for the 288° capsule are 0.78 to the peak inside surface location and 0.99 to the peak 1/4 T location.

4.3 ESTIMATE OF END-OF-LIFE FLUENCE

The EOL fluence (f) is estimated using the upper bound (130%) of the measured flux from Table 4-2 with the lead factor to the 1/4 T location. As discussed in Reference 6, a power uprate from 1593 MW to 1658 MW is assumed at 6 EFPY. Flux is proportional to thermal power for a given core radial power shape, so the two fluxes are:

2.6×10^9 n/cm^2-s * 1.30/0.99 = $\underline{3.41\times10^9 \text{ n/cm}^2\text{-s}}$ for 6 EFPY, and

3.41×10^9 * (1658/1593) = $\underline{3.55\times10^9 \text{ n/cm}^2\text{-s}}$ for 7 through 32 EFPY.

The EOL condition of 32 EFPY represents 1.01×10^9 seconds of full power irradiation, or 3.16×10^7 seconds per EFPY. The EOL fluence is:

f = 3.16×10^7 sec/EFPY(3.41×10^9 * 6 EFPY + 3.55×10^9 * 26 EFPY), or

f = 3.6×10^{18} n/cm^2.

This EOL fluence is significantly lower than the value used in the Reference 6 analysis of 4.4×10^{18} n/cm^2. The impact of the lower fluence value is discussed in Section 7.

Table 4-1

SUMMARY OF DAILY POWER HISTORY

Cycle	Cycle Dates	Operating Days	Percent of Full Power	Days Between Cycles
1a	5/13/74 - 6/6/75	389	0.525	
				42
1b	7/18/75 - 2/13/76	210	0.686	
				61
2	4/14/76 - 3/12/77	332	0.695	
				62
3	5/13/77 - 3/17/78	308	0.823	
				40
4a	4/26/78 - 6/17/78	52	0.700	
				265
4b	3/9/79 - 2/9/80	337	0.808	
				68
5	4/17/80 - 3/20/81	337	0.806	
				72
6	5/31/81 - 2/12/83	622	0.540	
				82
7	5/5/83 - 2/2/85	639	0.651	
		3226	0.671 (average)	

Table 4-2

SURVEILLANCE CAPSULE LOCATION FLUX AND FLUENCE
FOR IRRADIATION FROM 5/13/74 TO 2/2/85

Wire (Element)	Wire Weight (g)	dps/g Element (at end of Irradiation	Reaction Rate [dps/nucleus (saturated)]	Full Power Flux [a] (n/cm²-s) >1 MeV	Full Power Flux [a] (n/cm²-s) >0.1 MeV	Fluence (n/cm²) >1 MeV	Fluence (n/cm²) >0.1 MeV
Copper 64713	0.3611	1.99×10^{4}	7.15×10^{-18}				
Copper 64741	0.3588	1.87×10^{4}	6.75×10^{-18}				
		Average =	6.95×10^{-18}	2.6×10^{9}	4.2×10^{9}	4.9×10^{17}	7.8×10^{17}
Iron 64713	0.0694	1.39×10^{5}	3.67×10^{-16}				
Iron 64741	0.1663	1.37×10^{5}	3.62×10^{-16}				
		Average =	3.65×10^{-16}	2.3×10^{9}			
Nickel 64713	0.3234	1.84×10^{6}	4.04×10^{-16}				
Nickel 64741	0.3211	1.93×10^{6}	4.24×10^{-16}				
		Average =	4.14×10^{-16}	2.0×10^{9}			

[a] Full power of 1593 MW_t.

5. CHARPY V-NOTCH IMPACT TESTING

The 24 Charpy specimens recovered from the surveillance capsule were tested at temperatures selected to establish the toughness transition and USE of the irradiated RPV materials. Testing was conducted in accordance with ASTM E23-82 (Reference 10).

5.1 PROCEDURE

The testing machine used 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 U.S. Army Watertown standard specimens. The standards are designed to fail at 74.1 ft-lb and 13.9 ft-lb at a test temperature of -40°F. According to Reference 10, the averaged test apparatus results must reproduce the Watertown standard values within an accuracy of ±5% or ±1.0 ft-lb, whichever is greater. The successful 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 400°F. For tests between 32°F and 212°F, the temperature conditioning fluid was water. Dichloromethane was used at temperatures below 32°F. Above 212°F, a silicone oil was used. Cooling of the conditioning fluids was done with liquid nitrogen, and heating by an immersion heater. The fluids were mechanically stirred to maintain uniform temperatures. The fluid temperature was measured by a chromel-alumel thermocouple and a copper-constantan thermocouple. These were calibrated with boiling water (212°F), and ice water (32°F). Once at test temperature, the specimens were manually transferred with centering tongs to the Riehle machine and impacted within 5 seconds.

For each Charpy V-Notch specimen tested, test temperature, energy absorbed, lateral expansion, and percent shear were evaluated. Lateral expansion and percent shear were measured according to Reference 10 methods. Percent shear was determined with Method 2 of Subsection 11.2.4.3 of Reference 10, which involves a comparison of the fracture surface appearance with the reference fracture surfaces in Figure 15 of Reference 10.

5.2 RESULTS

Eight Charpy V-Notch specimens each of base metal, weld metal and HAZ were tested at temperatures selected to define the toughness transition and USE portions of the fracture toughness curve. Absorbed energy, lateral expansion and percent shear data are listed in Table 5-2 for each material. Plots of absorbed energy data for base, weld, and HAZ metal are presented in Figures 5-1, 5-2 and 5-3, respectively. Lateral expansion plots for base, weld and HAZ metal are given in Figures 5-4, 5-5 and 5-6, respectively.

The data sets were freehand-fit with best-estimate S-shaped curves, characteristic of fracture toughness transition curves. The curve fits were done without the help of a baseline curve, because unirradiated data are currently unavailable, as discussed in Subsection 5.3. Therefore, the curves will probably be redrawn when unirradiated data are curve-fit for comparison. The curves of impact energy and lateral expansion were used to determine the index temperatures shown in Table 5-3. Longitudinal USE values were taken from the curves, and then corrected to equivalent transverse USE with the methods in Reference 7.

The HAZ data typically show the greatest scatter, because the HAZ has in effect been uniquely heat treated by the welding process, and because of the uncertainty of the specimen notch location relative to the weld fusion line. The HAZ results in this case are very consistent, probably because there is little difference in the Charpy curves for the base and weld metals.

Photographs were taken of the Charpy specimen fracture surfaces. The fracture surface photographs were used to evaluate percent shear. The photographs and a summary of test results for each specimen are contained in Appendix A.

5.3 IRRADIATED VERSUS UNIRRADIATED CHARPY V-NOTCH PROPERTIES

As a part of the RPV fabrication test program, Charpy V-Notch testing was done at various temperatures using one of the unirradiated RPV plate materials. However, the fabrication test specimens were made from plate 1-20, whereas the surveillance specimens were made from plate 1-21. Since these are different heats of low alloy steel, comparison between the unirradiated and irradiated data is not meaningful. Table 3-1 contains three Charpy impact energies at a single test temperature for plate 1-21. These results are not enough data for a comparison.

There is no current basis for establishing unirradiated weld metal properties, because Chicago Bridge & Iron records do not show the specific weld wire heat used in the surveillance weld. At best, there are currently available three Charpy data at one temperature, which are inadequate for comparison.

During testing of the irradiated specimens, IEL&P informed GE that there were unirradiated archive Charpy specimens in IEL&P storage. Plans were made to test up to 18 each of base, weld and HAZ Charpy specimens, as recommended in Reference 4. This unirradiated specimen testing is in progress, and this report will be revised to include the unirradiated data as soon as testing is complete.

Table 5-1

QUALIFICATION TEST RESULTS USING
U.S. ARMY WATERTOWN SPECIMENS
(TESTED IN FEBRUARY 1986)

Qualification Test Specimen Identification	Test Temperature (°F)	Energy Absorbed Mechanical Gage (ft-lb)
EE3-0427	-40	72.0
EE3-0075	"	74.5
EE3-0233	"	80.0
EE3-0956	"	75.8
EE3-0365	"	74.2
Average		75.3
Allowable	-40	74.1 ± 3.7 Acceptable
DD5-0442	-40	15.0
DD5-0905	"	13.8
DD5-0486	"	14.0
DD5-0977	"	14.0
DD5-0831	"	14.0
Average		14.2
Allowable	-40	13.9 ± 1.0 Acceptable

Table 5-2

CHARPY V-NOTCH IMPACT TEST RESULTS
FOR IRRADIATED RPV MATERIALS

Specimen Identification	Test Temperature (°F)	Fracture Energy (ft-lb)	Lateral Expansion (mils)	Percent Shear (Method 2) (%)
Base:				
EBU	-60	4.0	4	0
EBP	-20	15.0	19	0
EBT	10	15.5	26	40
EC1	20	49.5	45	40
EBK	40	60.0	49	40
EBJ	120	101.5	70	70
EBL	200	144.5	95	90
EBY	400	160.0	98	90
Weld:				
EJ1	-100	6.5	11	0
EJ2	-60	15.3	24	10
EJ4	-40	22.0	26	10
EE5	-20	63.5	54	40
EE2	40	75.2	69	60
EE3	120	97.2	86	80
EE4	200	109.0	90	70
EJ3	400	101.0	91	100
HAZ:				
ELY	-60	8.0	15	0
ELP	-20	13.5	18	20
EMY	0	15.0	16	30
ELT	10	51.7	43	40
ELK	40	65.0	50	50
ELL	120	90.1	66	70
ELM	200	126.5	84	90
EMT	400	124.5	75	100

Table 5-3

SIGNIFICANT RESULTS OF IRRADIATED
CHARPY V-NOTCH DATA

Material	Index Temperature (°F)			Upper[a] Shelf Energy (ft-lb)
	E=30 ft-lb	E=50 ft-lb	MLE=35 mil	L/T
Base	14°F	47°F	20°F	160/104
Weld	-26°F	6°F	-35°F	101/101
HAZ	19°F	47°F	40°F	126/82

a Longitudinal (L) USE is read directly from Figures 5-1, 5-2 and 5-3. Transverse (T) USE is taken as 65% of the longitudinal USE, according to Reference 7. L/T USE values are equal for weld metal, which has no orientation effect.

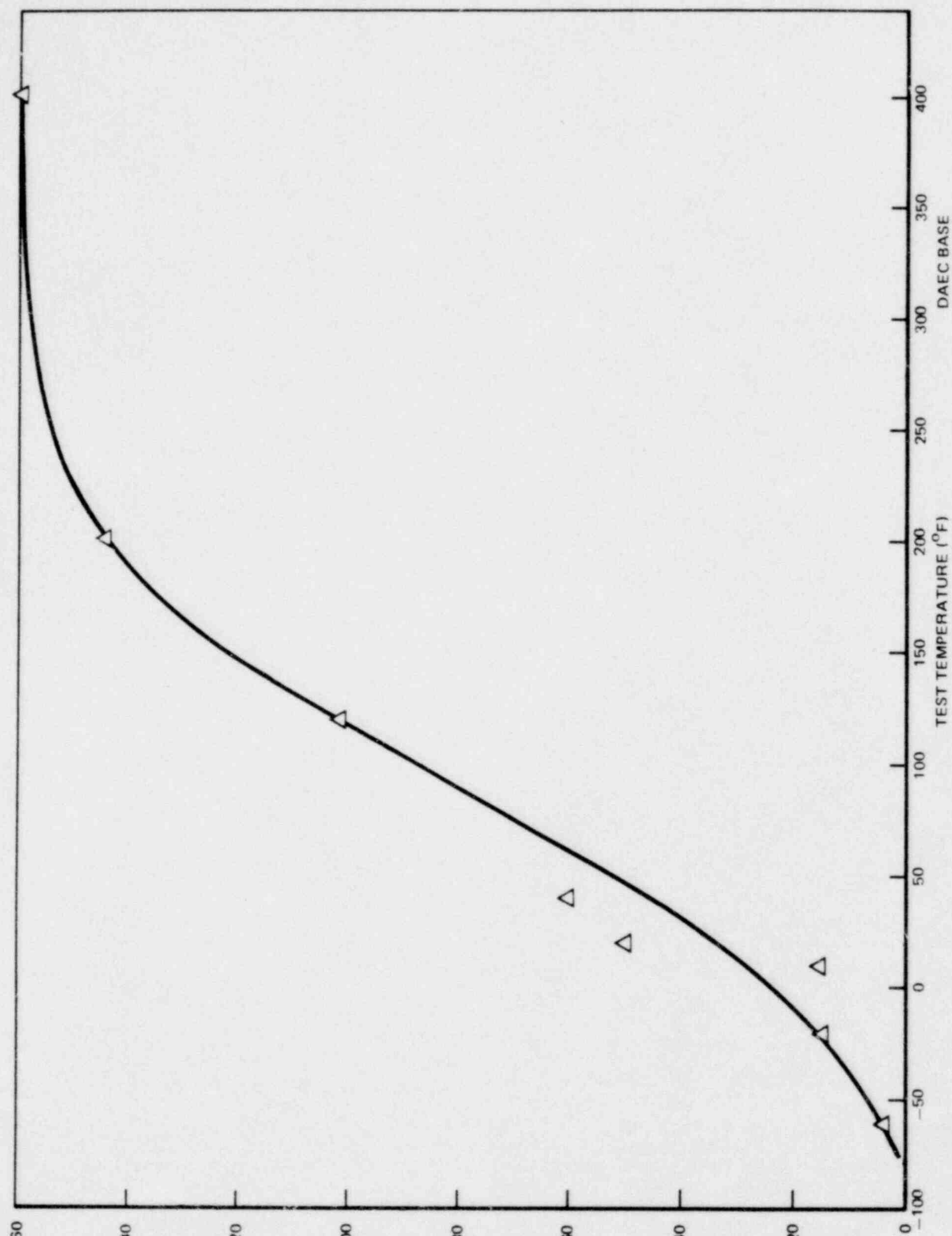


Figure 5-1. DAEC Irradiated Base Metal Impact Energy

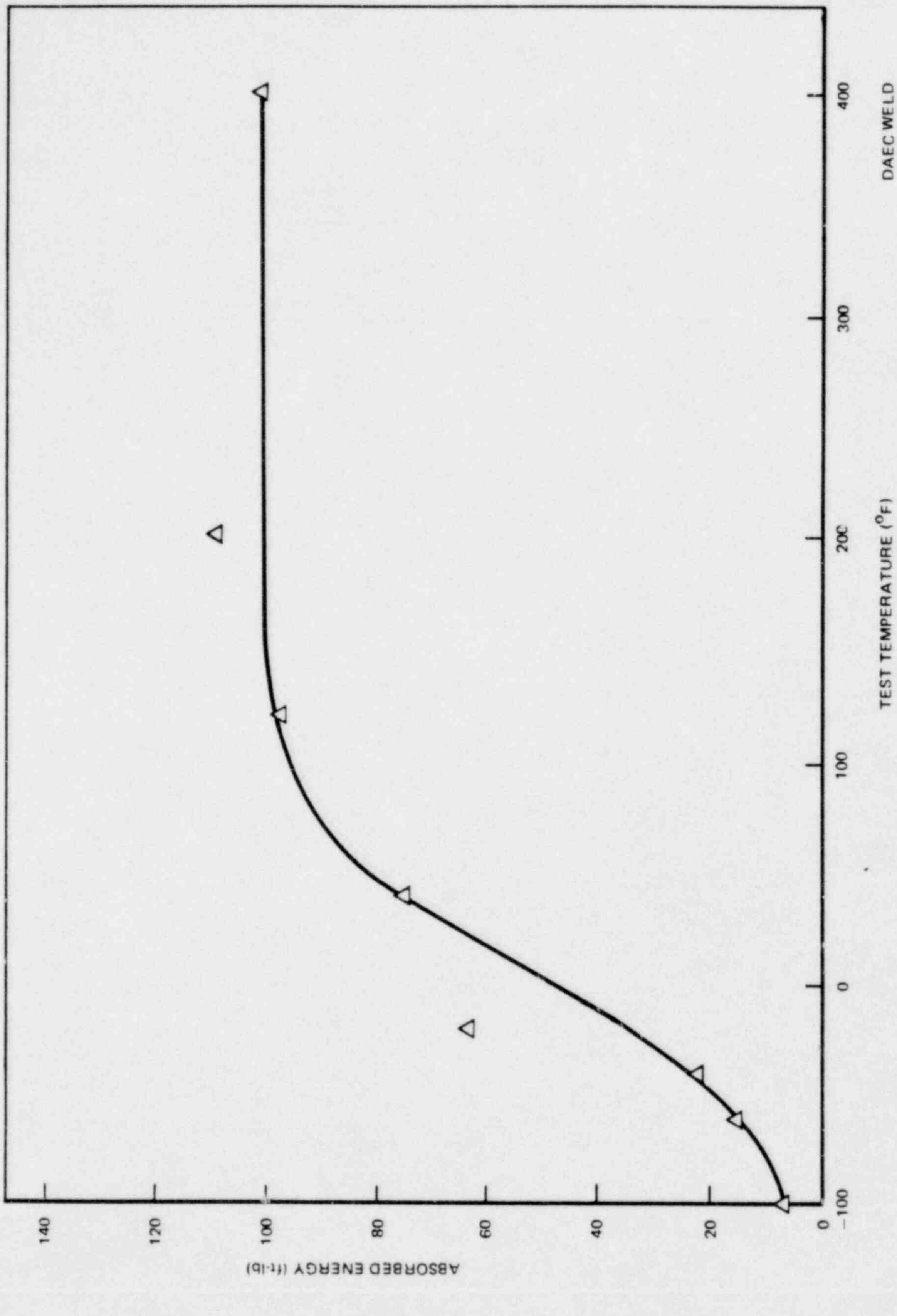


Figure 5-2. DAEC Irradiated Weld Metal Impact Energy

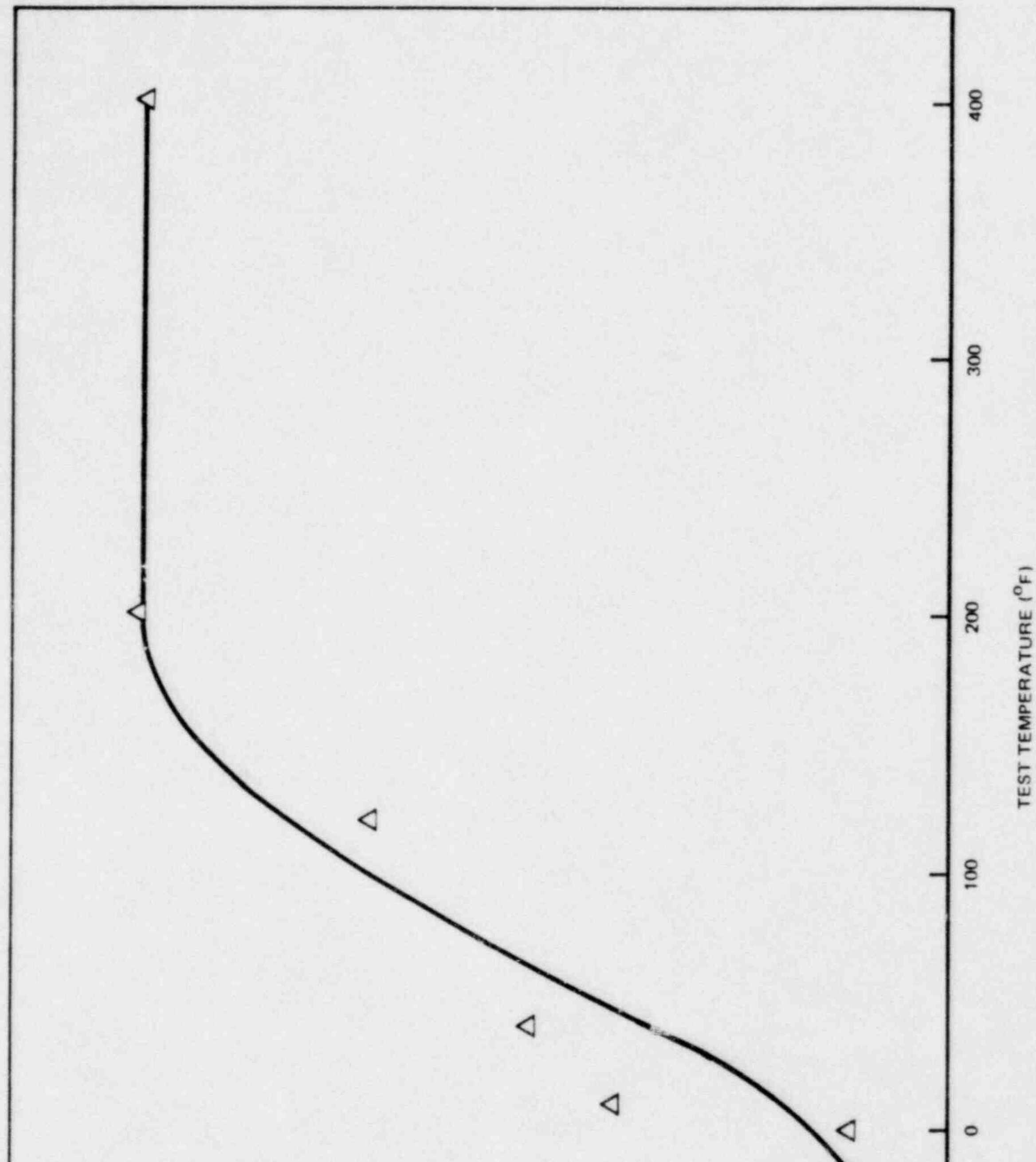


Figure 5-3. DAEC Irradiated HAZ Metal Impact Energy

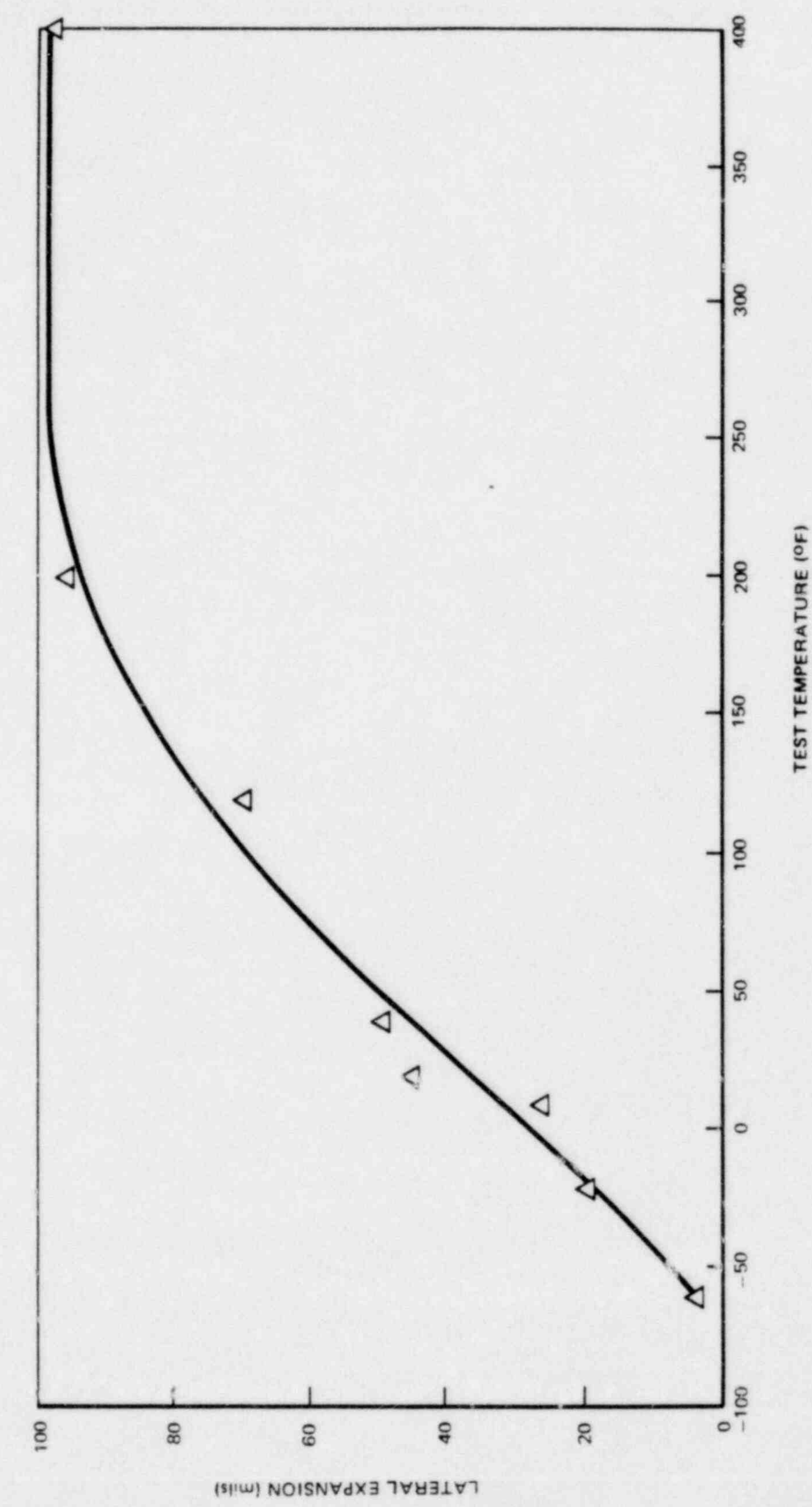


Figure 5-4. DAEC Irradiated Base Metal Lateral Expansion

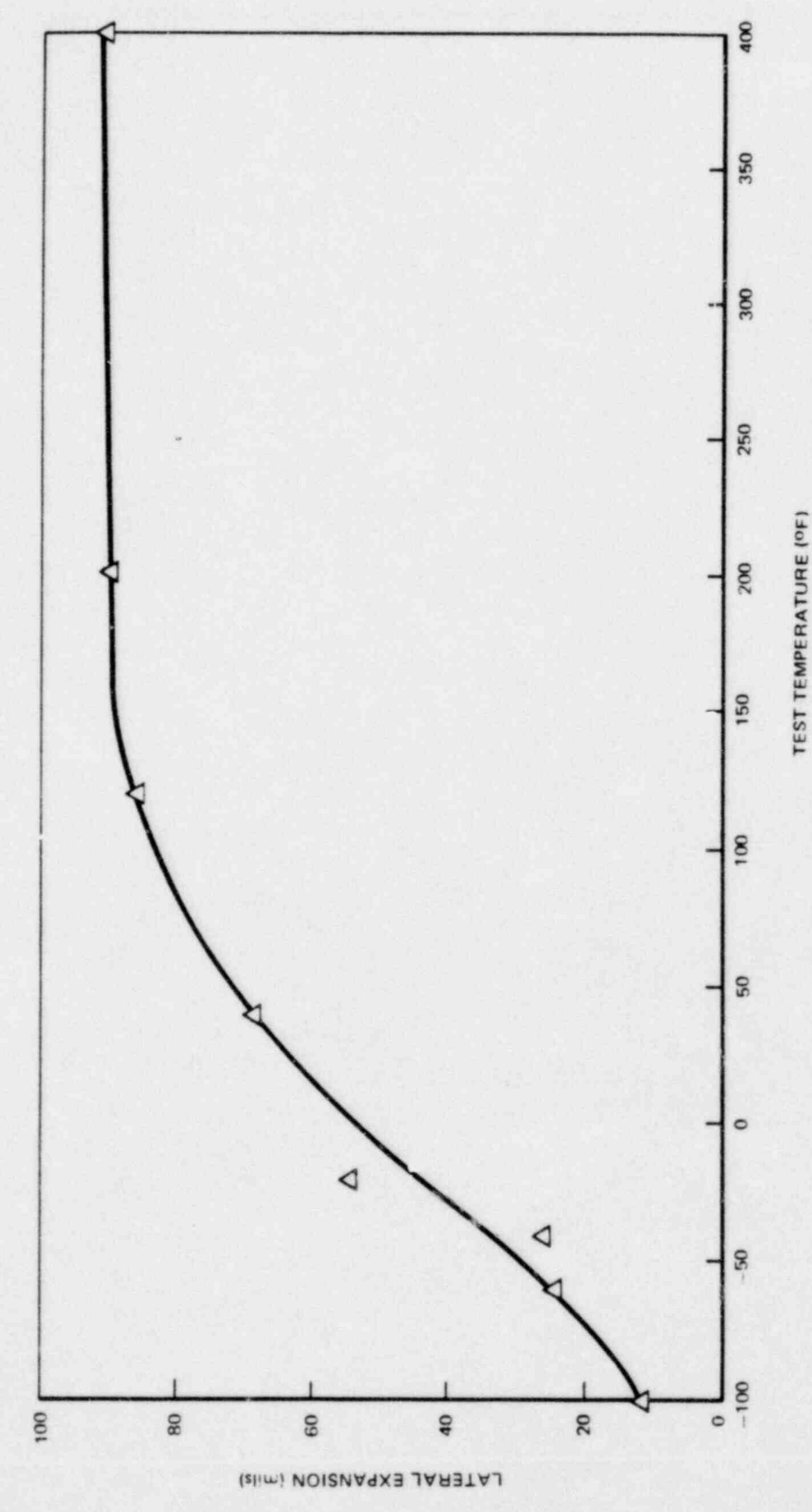


Figure 5-5. DAEC Irradiated Weld Metal Lateral Expansion

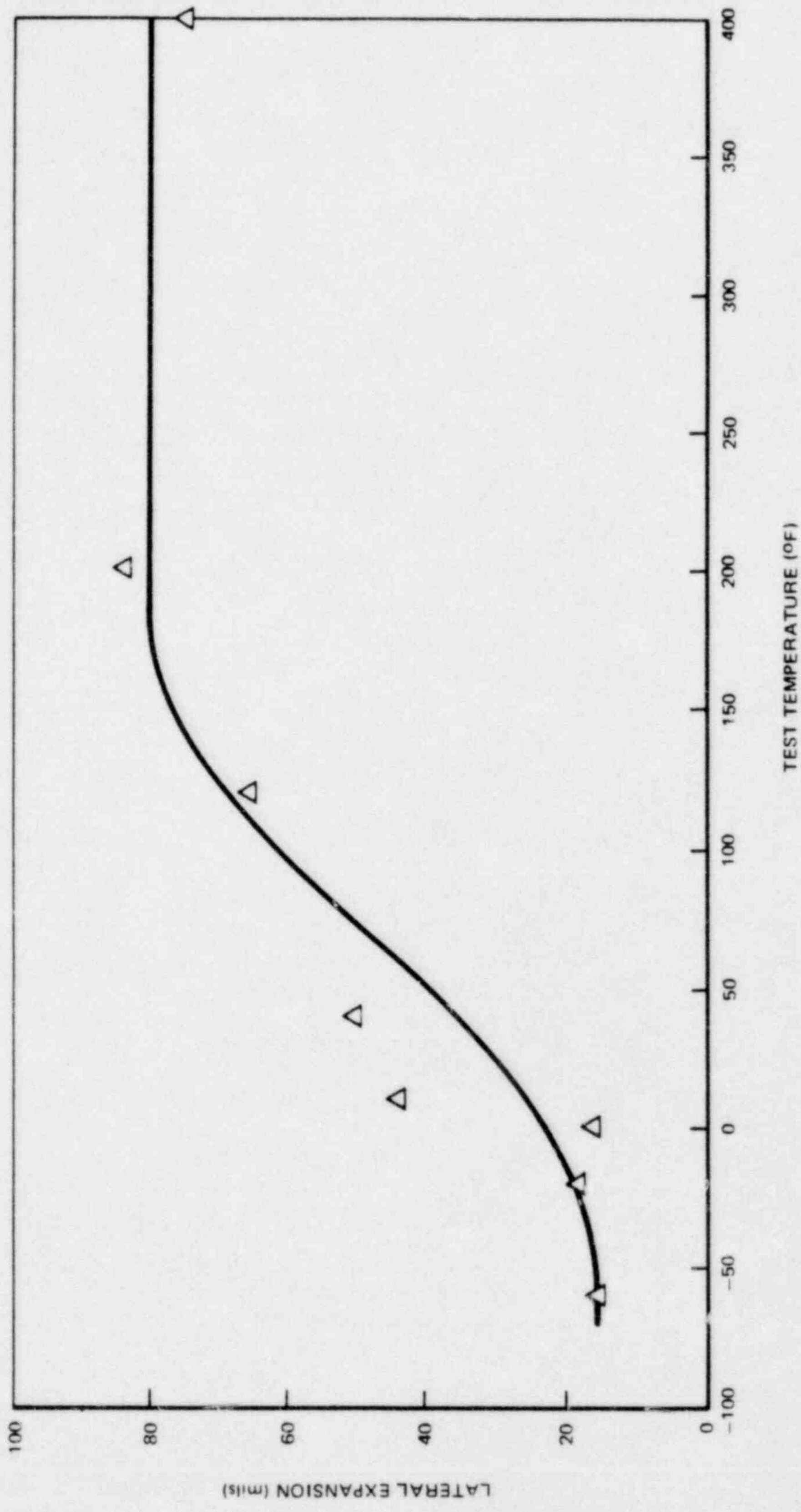


Figure 5-6. DAEC Irradiated HAZ Metal Lateral Expansion

6. TENSILE TESTING

Six round bar tensile specimens were recovered from the surveillance capsule. Uniaxial tensile tests were conducted in air at room temperature and RPV operating temperature. Tests were conducted in accordance with ASTM E8-81 (Reference 11).

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. 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-in. 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 in./min until fracture. A 1-in. span knife edge extensometer was attached directly to each specimen's central gage region and was used to monitor gage extension during test.

The test specimens were machined with a minimum diameter of 0.250 inch at the center of the gage length. Specimens were tested at room temperature (RT = 76°F) and RPV operating temperature (550°F).

The yield strength (YS) and ultimate tensile strength (UTS) were calculated by dividing the nominal 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-in. 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 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 fracture location and local necking behavior.

6.2 RESULTS

Tensile test properties of YS, UTS, RA, uniform elongation (UE) and total elongation (TE) are presented in Table 6-1. Shown in Figure 6-1 is a stress-strain curve for a 550°F base metal specimen typical of the stress-strain characteristics of all the specimens tested. Shown graphically in Figures 6-2 and 6-3 are the data in Table 6-1. Photographs of fracture surfaces and necking behavior are given in Figures 6-4, 6-5 and 6-6 for base, weld and HAZ specimens, respectively.

The base, weld, and HAZ materials follow the trend of decreasing properties with increasing temperature. The three materials behave very similarly, as seen in Figures 6-2 and 6-3, with the weld material showing the strongest temperature dependence in YS.

6.3 IRRADIATED VERSUS UNIRRADIATED TENSILE PROPERTIES

Unirradiated tensile test data were recovered from QA records for the plate 1-21 material (Heat B0673-1). Data for two 0.505-inch diameter gage tensile specimens from the fabrication test program were averaged to get unirradiated RT base metal YS, UTS and total elongation properties. These are compared in Table 6-2 to the irradiated base metal specimen RT data to determine the degree of radiation strengthening. As seen, the YS and UTS properties increase with irradiation and the irradiated total elongation decreases. These are the expected trends for irradiation embrittlement.

IEL&P has since provided unirradiated base and weld metal tensile specimens to GE for testing. These tests are in progress, and the results will be incorporated for comparison with the irradiated test results in a revision to this report. The new unirradiated data will provide a valid comparison for weld metal and a better comparison for the base metal, because specimens will be the same size (0.250-inch gage section) and testing will be done on the same equipment.

Table 6-1

TENSILE TEST RESULTS FOR IRRADIATED RPV MATERIALS

Specimen Number	Material	Test Temp (°F)	Yield Strength (ksi)	Ultimate Strength (ksi)	Uniform Elongation (%)	Total Elongation (%)	Reduction of Area (%)
ETJ	Base	76	73.4	96.2	9.5	19.7	70.4
ETK	Base	550	67.7	91.7	7.6	15.9	65.9
EU3	Weld	76	79.4	92.9	8.2	17.5	70.0
EU6	Weld	550	65.7	83.5	7.1	15.1	64.0
EY1	HAZ	76	74.2	94.8	9.7	20.7	66.8
EY2	HAZ	550	67.7	87.6	6.6	14.4	59.0

Table 6-2

COMPARISON OF UNIRRADIATED AND IRRADIATED BASE METAL (HEAT B0673-1) TENSILE PROPERTIES AT ROOM TEMPERATURE

	Yield Strength (ksi)	Ultimate Strength (ksi)	Total Elongation (%)	Reduction of Area (%)
Unirradiated [a]	65.0	88.6	25.5	N/A
Irradiated [b]	73.4	96.2	19.7	70.4
Difference [c]	12.9%	8.6%	-22.8%	-

[a] Specimens have 0.505-inch gage diameter.

[b] Specimens have 0.250-inch gage diameter.

[c] Difference = [(Irradiated - Unirradiated)/Irradiated] * 100%

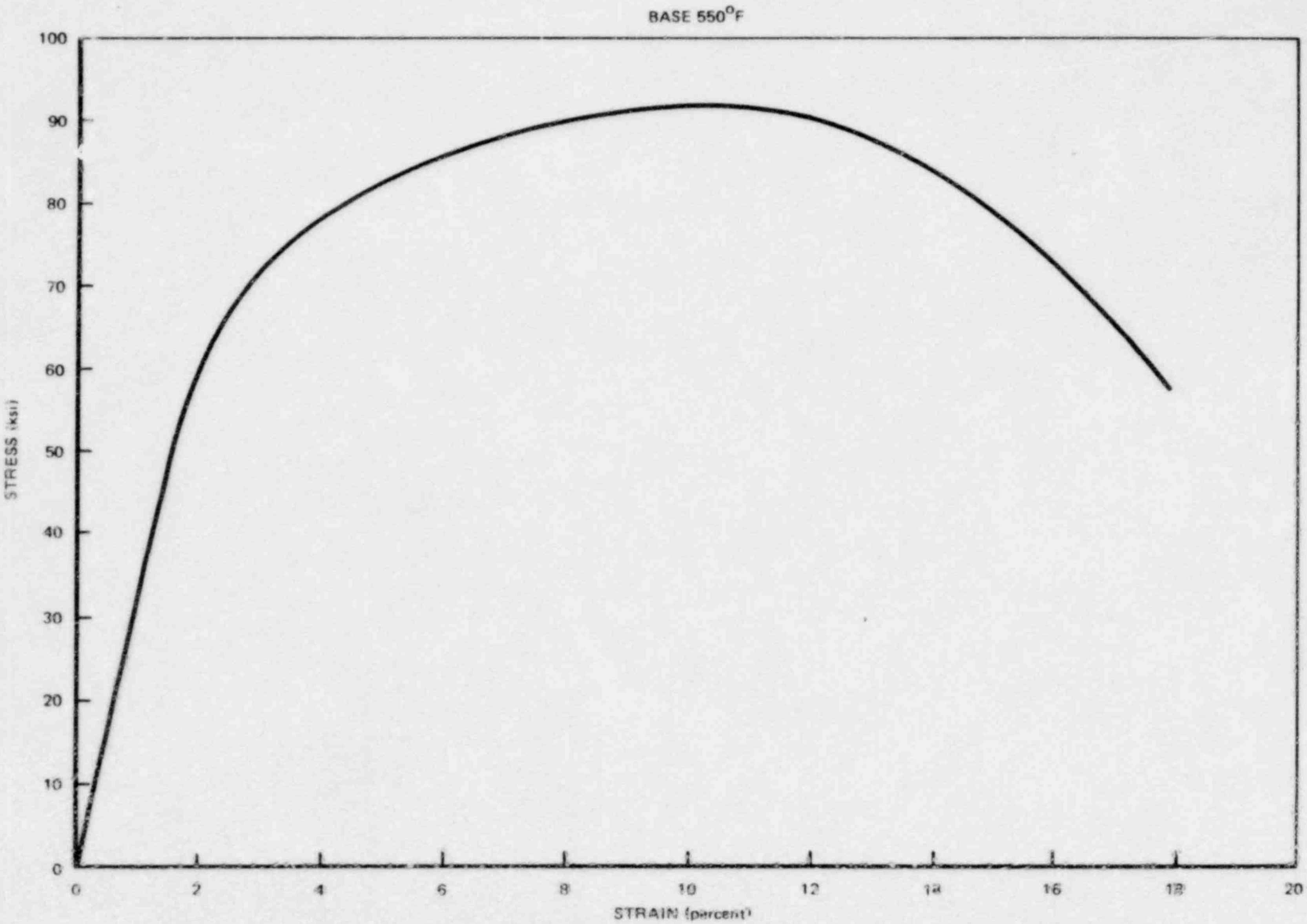


Figure 6-1. Typical Engineering Stress Versus Percent Strain for Irradiated RPV Materials

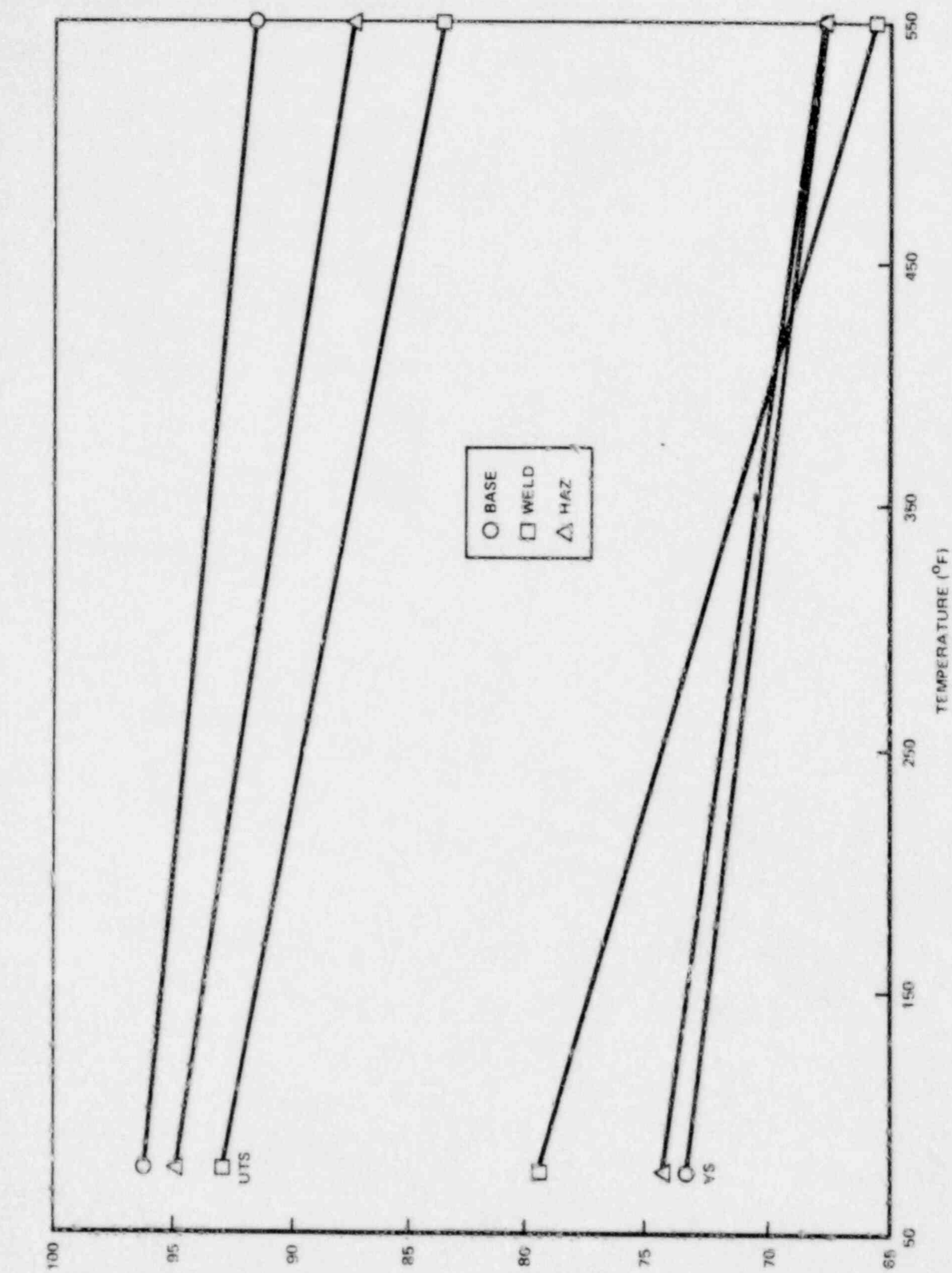


Figure 6-2. Strength Versus Test Temperature for Irradiated Base, Weld, and HAZ Tensile Specimens

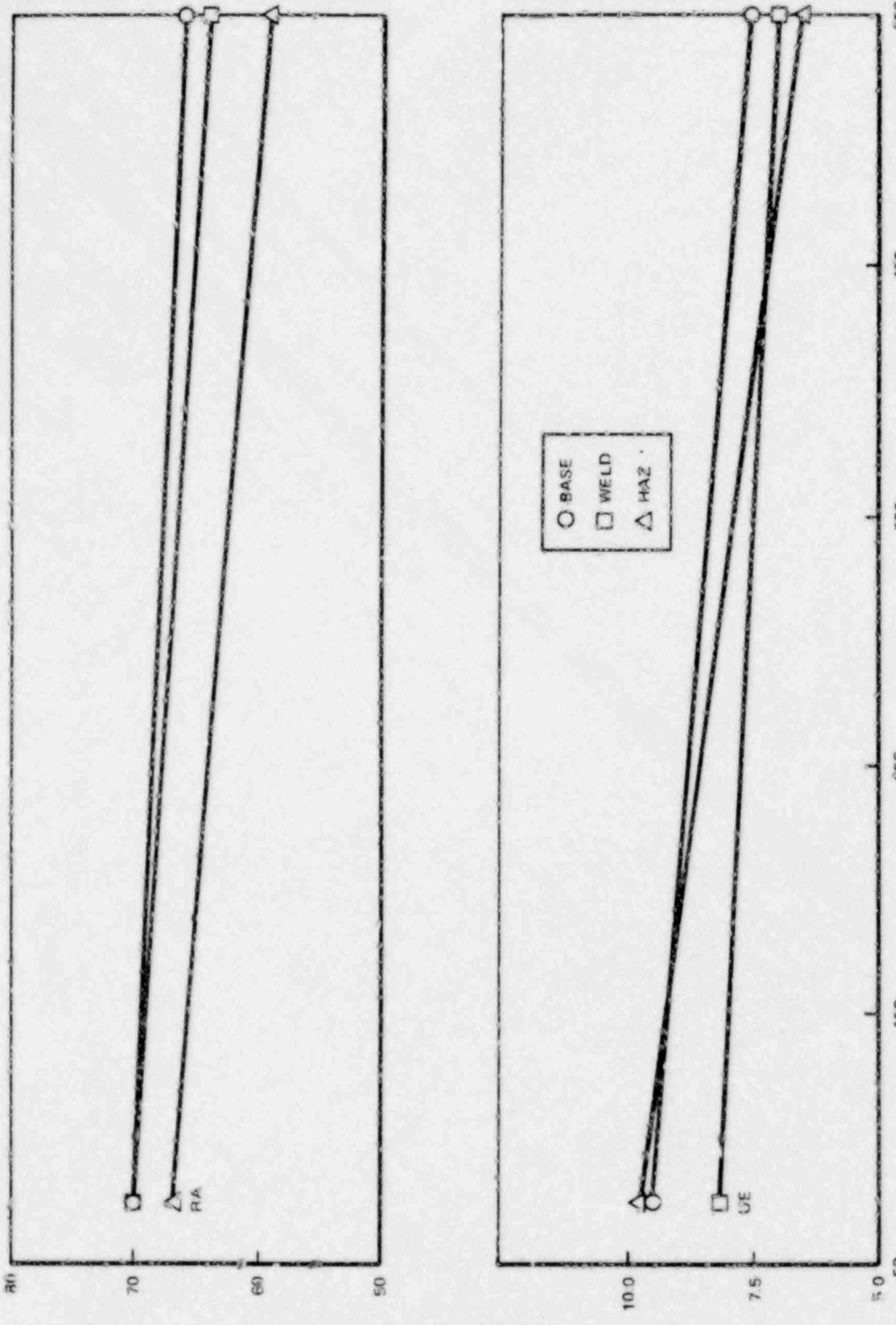
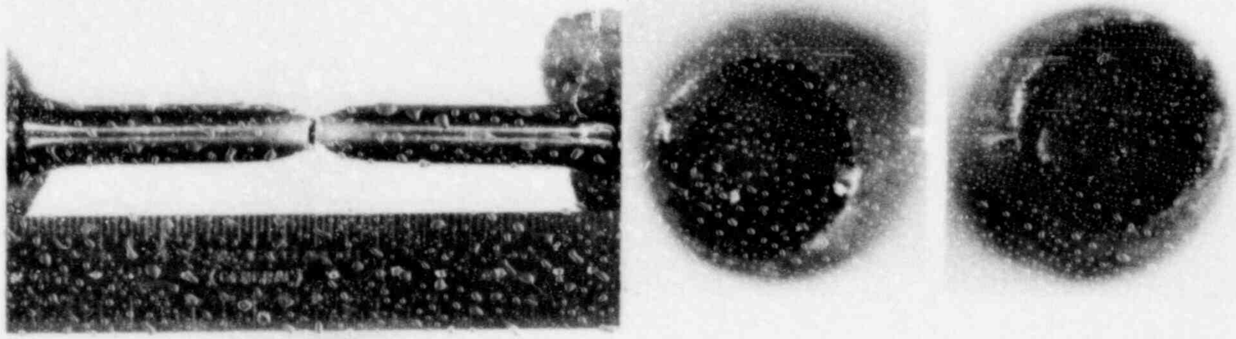
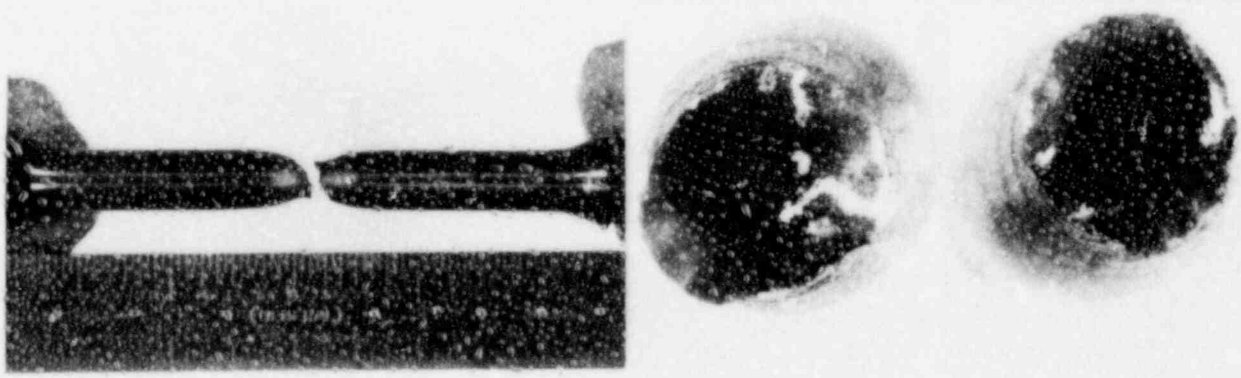


Figure 6-3. Ductility Versus Test Temperature for Irradiated Base, Weld, and HAZ Tensile Specimens



ETJ 76°F



ETK 550°F

Figure 6-4. Fracture Location, Necking Behavior, and Fracture Appearance for Irradiated Base Metal Tensile Specimens

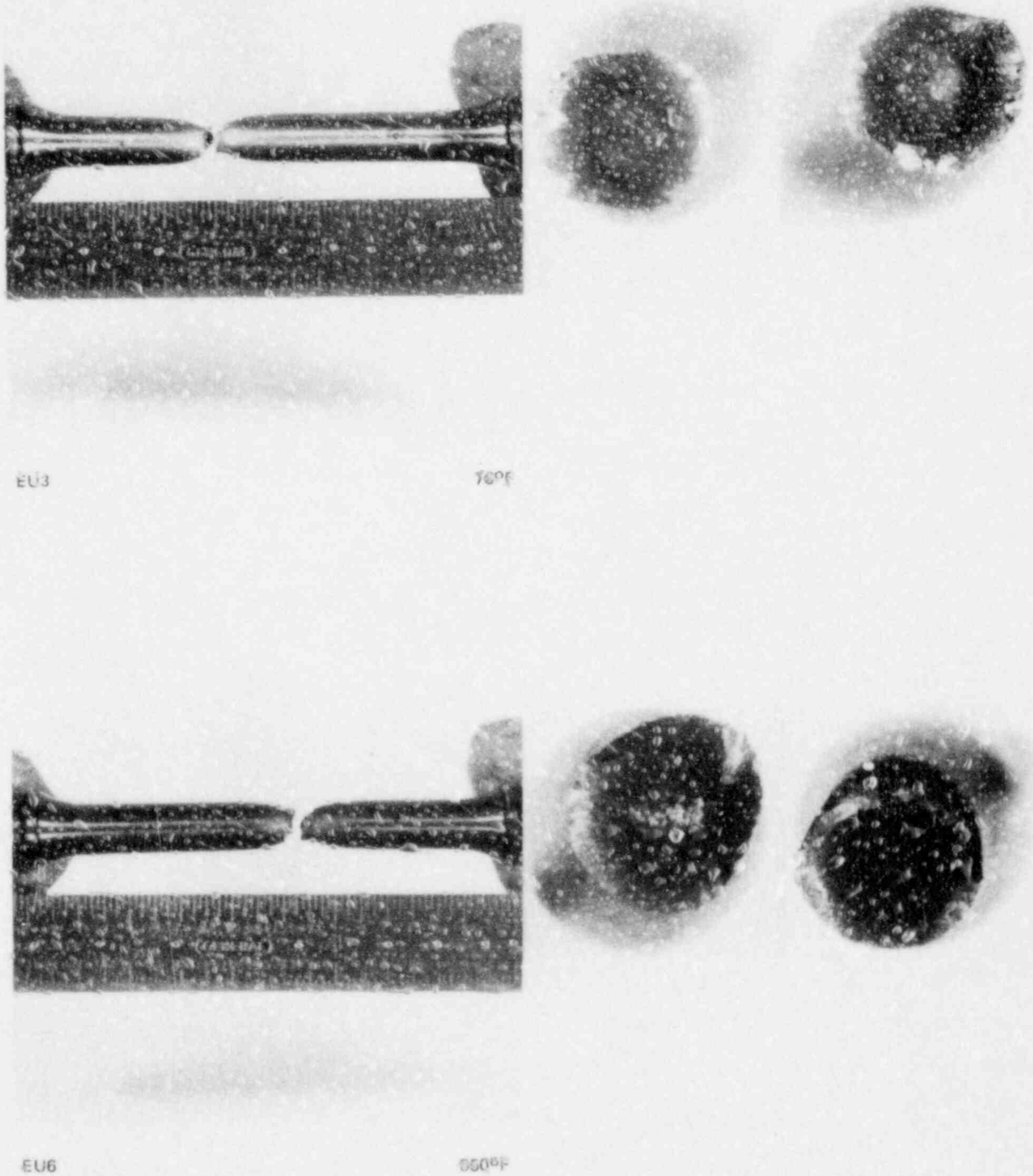
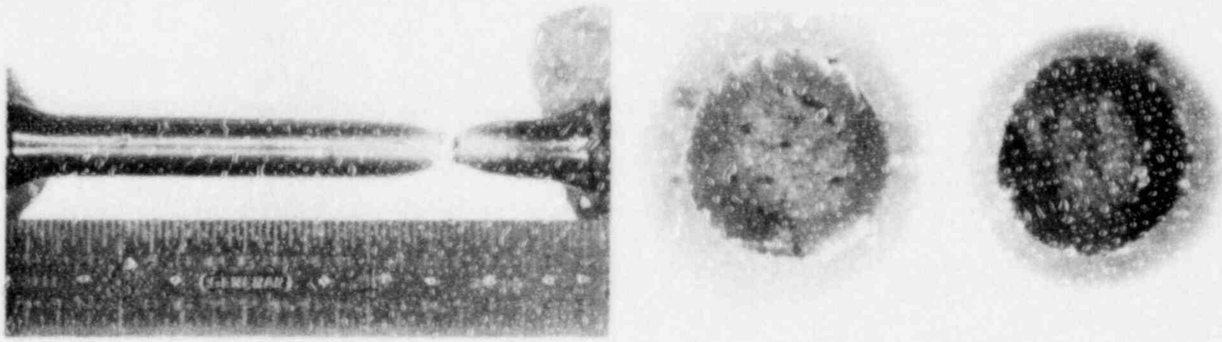
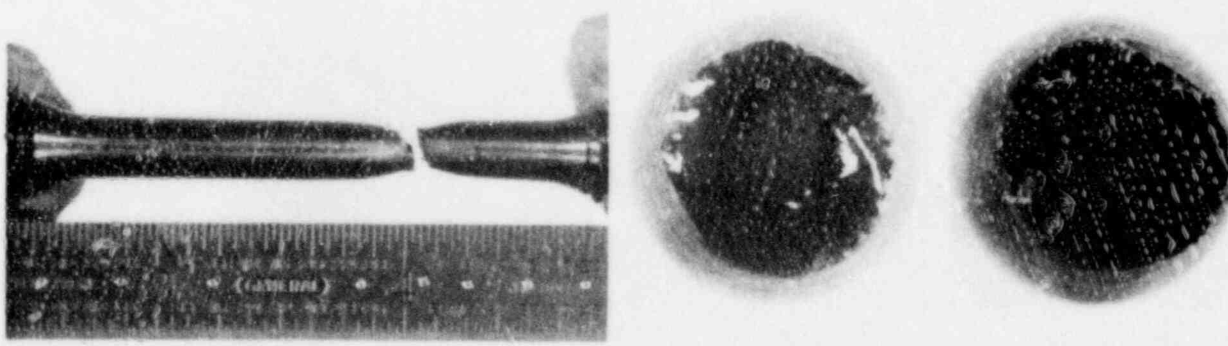


Figure 6-5. Fracture Location, Necking Behavior, and Fracture Appearance for Irradiated Weld Metal Tensile Specimens



EY1 76°F



EY2 550°F

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

7. PREDICTED END-OF-LIFE CONDITIONS

Reference 1 states several conditions which, if exceeded, require that vessel thermal annealing be performed. The conditions relate to RT_{NDT} and USE as follows:

a. The adjusted reference temperature (ART), which is the initial RT_{NDT} plus the irradiation shift, must be less than 200°F for the most limiting beltline material.

b. The USE for all beltline materials must be greater than 50 ft-lb at EOL, accounting for reductions due to irradiation.

7.1 ADJUSTED REFERENCE TEMPERATURE

The ART of the beltline was calculated in Reference 6, using the methods of Reference 5. The results from Reference 6 (ART = 126°F) are conservative because of the Cu-P values and fluence used. The Cu-P values taken for the beltline plates were the highest values of any plates in the beltline, rather than the highest combination for a single beltline plate. These Cu-P values were used with the highest initial RT_{NDT} of the beltline plates, all of which yield a conservative ART. In addition, the EOL fluence used in Reference 6 of 4.4×10^{18} n/cm² is conservative compared to the EOL fluence from Section 4 of 3.6×10^{18} n/cm².

These conservatisms, which also affect the size of the beltline shift in the operating limits curves, will be corrected once the actual irradiation shifts of the surveillance materials are established. The EOL shift will be predicted based on the actual chemistry and RT_{NDT} values for each plate, taking into account the shift of the surveillance specimens compared to the shift predicted by Reference 5.

7.2 UPPER SHELF ENERGY

Even though there are no unirradiated USE data for the surveillance specimen materials, the USE at EOL can be predicted using the Reference 5 methods with the irradiated USE values from Section 5. Figure 2 of Reference 5 shows percent decrease of USE as a function of Cu content and fluence. The irradiated USE values were used with their corresponding Cu contents and the fluence of 4.9×10^{17} n/cm² to calculate what their unirradiated USE values should have been, according to Reference 5. The EOL values were then predicted using the same methods. The results are shown in Table 7-1.

In addition to the surveillance specimen data, Charpy data were available for beltline plate 1-20 (Heat B0436-2). These data were generated by CB&I as part of the fabrication test program. The Charpy tests were performed up to temperatures of 200°F, which provides a reasonable and conservative estimate of the USE. The unirradiated USE for plate 1-20 is included in Table 7-1.

The USE values in Table 7-1 are based on longitudinal Charpy specimens. Reference 7 recommends a correction factor of 65% to estimate the transverse Charpy USE of plates. No correction is required for weld metal, which has no orientation effect. As seen in Table 7-1, the corrected transverse USE for the plate materials and the USE for the weld are above the minimum of 50 ft-lb at EOL.

Table 7-1

END-OF-LIFE UPPER SHELF ENERGY

Material	USE (ft-lb) for f = 0 (longitudinal)	USE (ft-lb) for $f = 4.9x10^{17}$ (longitudinal)	USE (ft-lb) for $f = 3.6x10^{18}$ (long./trans.)
Plate 1-21	182	160 [a]	147/95
Plate 1-20	134 [a]	118	108/70
Weld	110	100 [a]	95

[a] These are measured values. All others are calculated using methods from References 5 and 7.

8. REFERENCES

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

2. "Protection Against Non-Ductile Failure," Appendix G to Section III of the ASME Boiler & Pressure Vessel Code, Addenda to and including Winter 1985.

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

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

5. "Effects of Residual Elements on Predicted Radiation Damage to Reactor Vessel Materials," USNRC Regulatory Guide 1.99, Revision 1, April 1977.

6. "DAEC RPV Fracture Toughness Analysis to 10CFR50 Appendix G, May 1983," General Electric Company, NEDC-30839, December 1984.

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

8. "Drilled Hole Pattern," General Electric Drawing 117C4942, Revision 2, April 1971.

9. "Surveillance Test," Chicago Bridge & Iron Drawings T4 - T12.

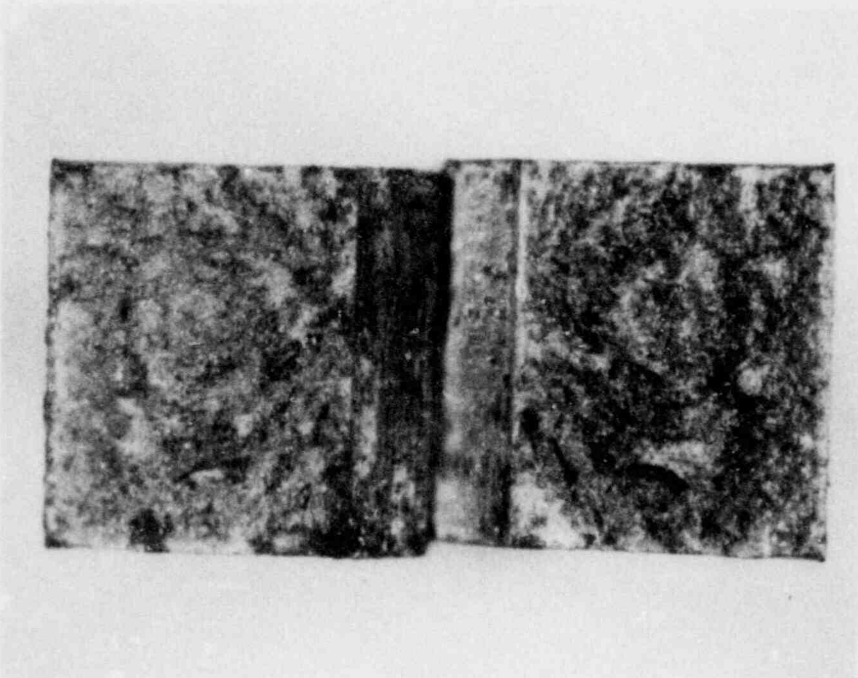
10. "Standard Methods for Notched Bar Impact Testing of Metallic Materials," Annual Book of ASTM Standards, E23-82, March 1982.

11. "Standard Methods of Tension Testing of Metallic Materials," Annual Book of ASTM Standards, E8-81.

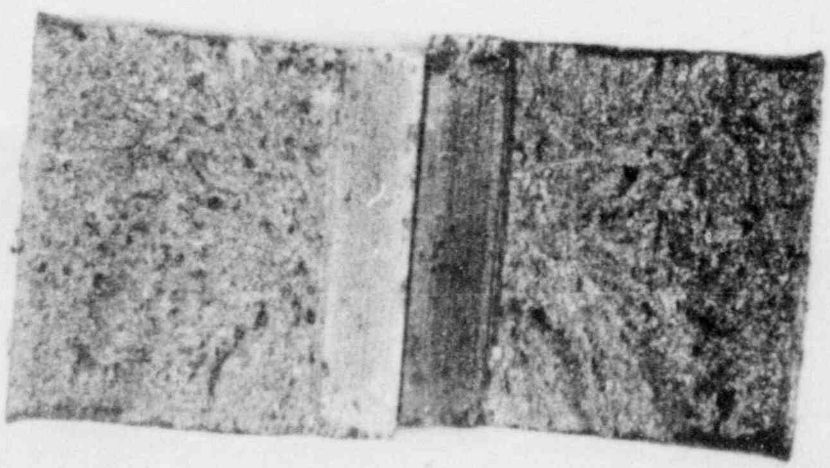
APPENDIX A

CHARPY V-NOTCH FRACTURE SURFACE PHOTOGRAPHS

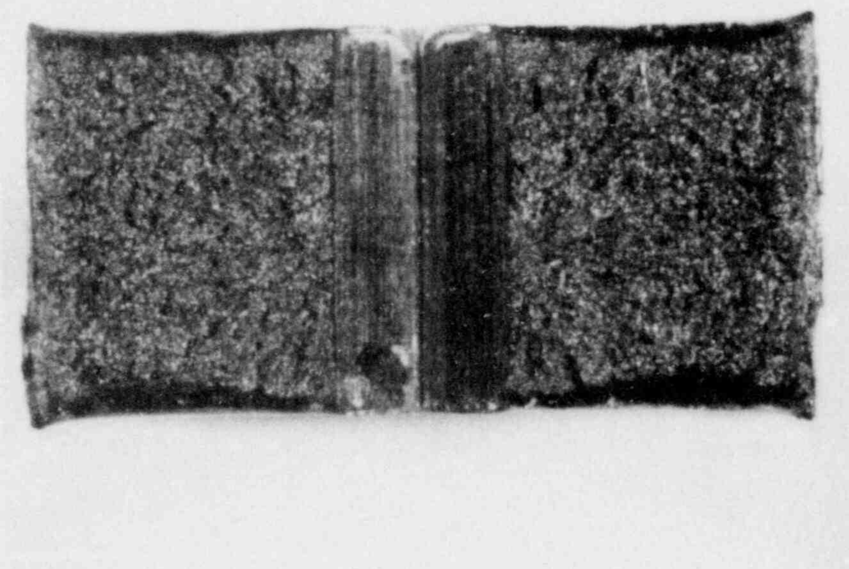
Photographs of each Charpy specimen fracture surface were taken to facilitate the determination of percent shear, and to comply with the requirements of ASTM E185-82. The pages following show the fracture surface photographs along with a summary of the Charpy test results for each specimen. The pictures are arranged by increasing test temperature for each material, with the materials in the order of base, weld and HAZ.



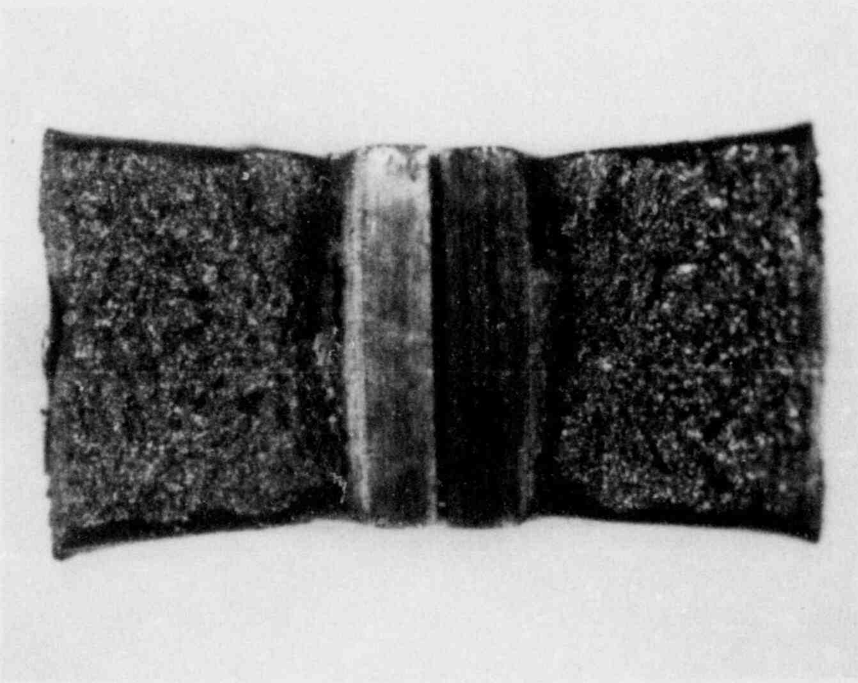
BASE: EPU
TEMP: $-60^{o}F$
ENERGY: 4.0 ft-lb
MLE: 4
% SHEAR: 0



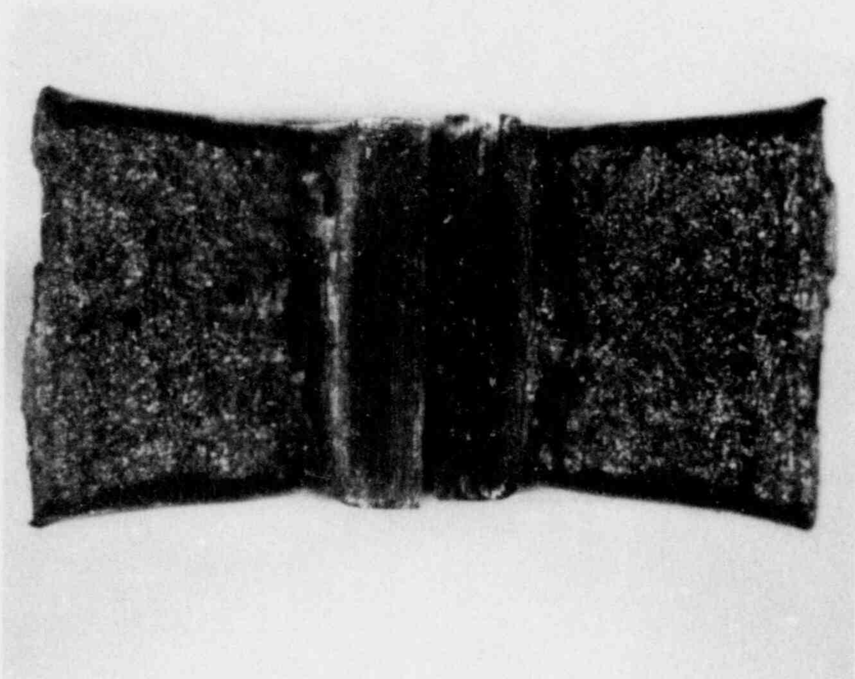
BASE: EBP
TEMP: $-20^{o}F$
ENERGY: 15.0 ft-lb
MLE: 19
% SHEAR: 0



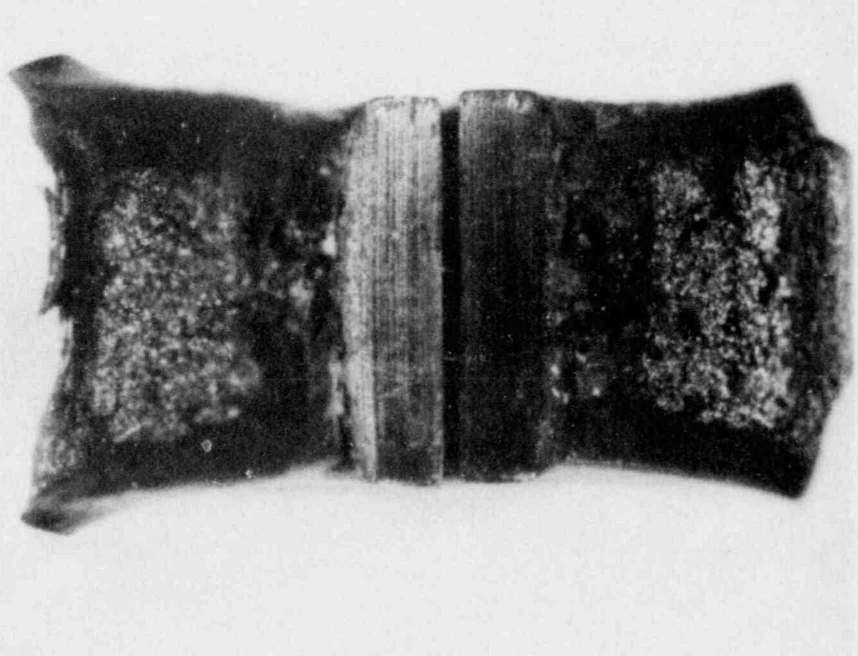
BASE:	EBT	MLE:	26
TEMP:	10°F	% SHEAR:	40
ENERGY:	15.5 ft-lb		



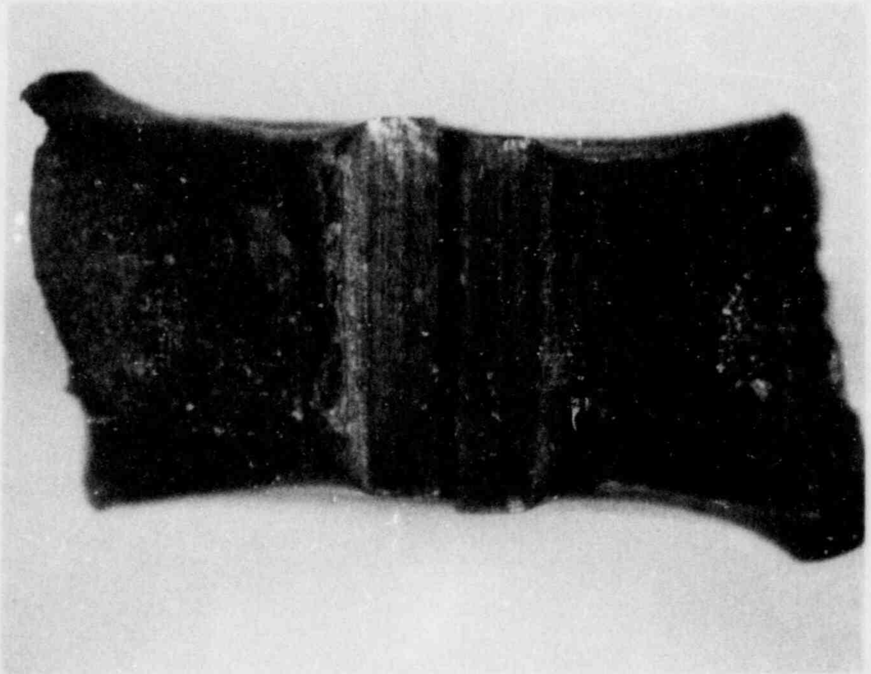
BASE:	ECI	MLE:	45
TEMP:	20°F	% SHEAR:	40
ENERGY:	49.5 ft-lb		



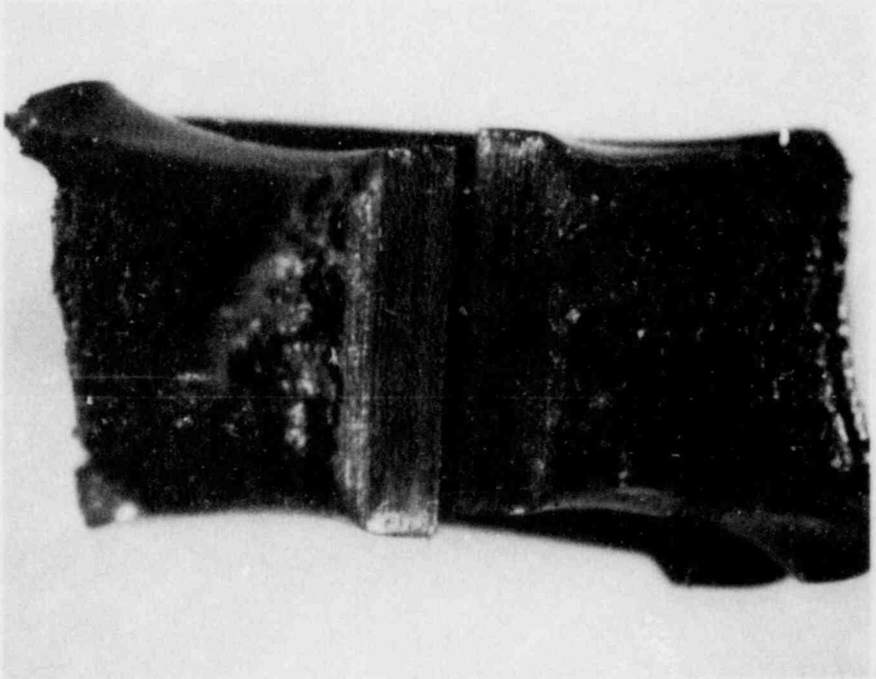
BASE: EBK
TEMP: 40°F
ENERGY: 60.0 ft-lb
MLE: 49
% SHEAR: 40



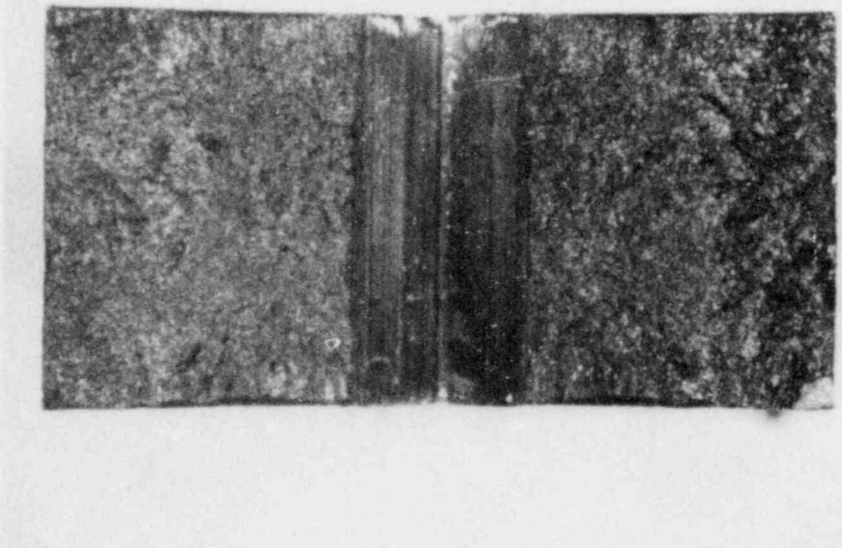
BASE: EBJ
TEMP: 120°F
ENERGY: 101.5 ft-lb
MLE: 70
% SHEAR: 70



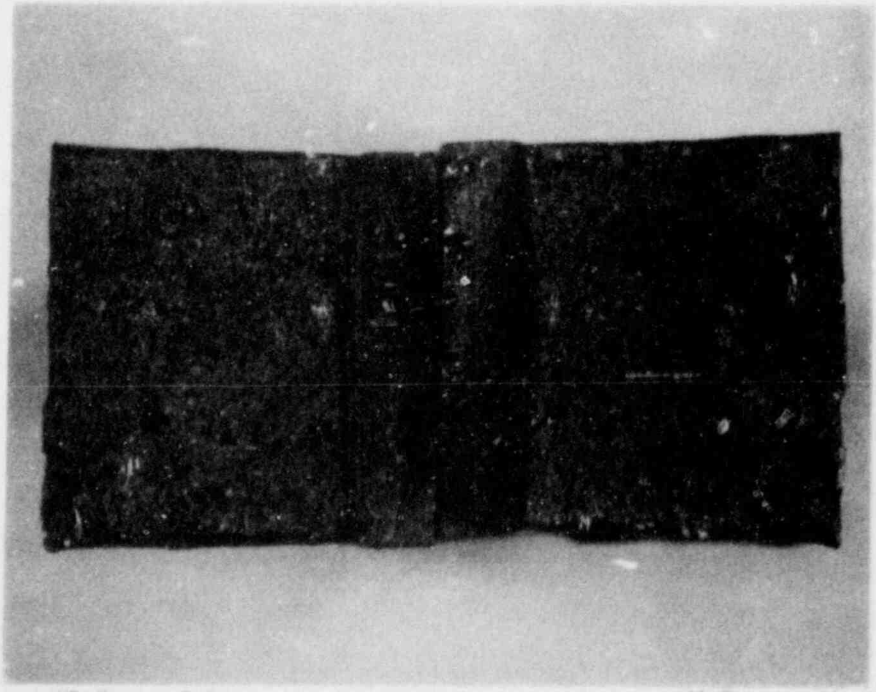
BASE: EBL
TEMP: 200°F
ENERGY: 144.5 ft-lb
MLE: 95
% SHEAR 90



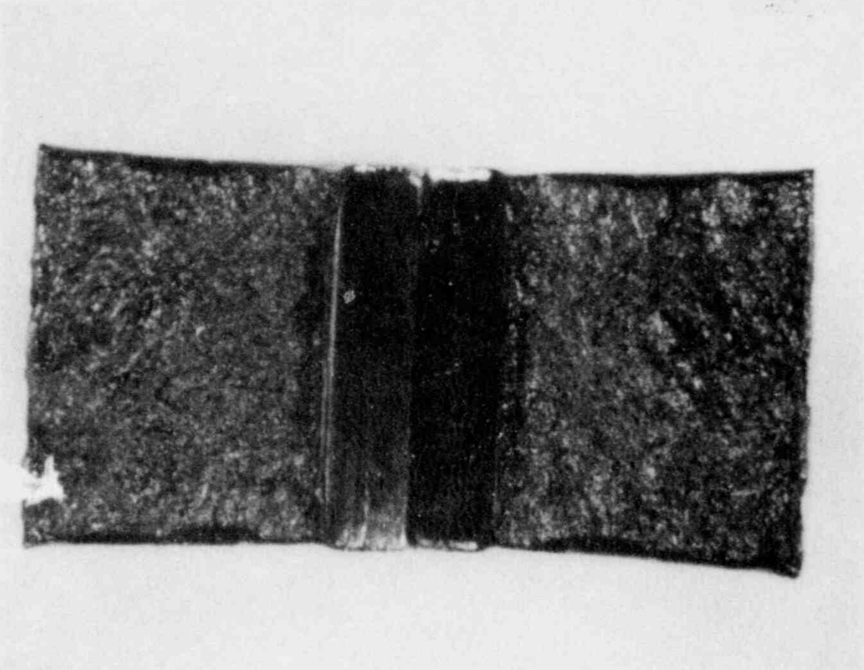
BASE: EBY
TEMP: 400°F
ENERGY: 160 ft-lb
MLE: 98
% SHEAR 90



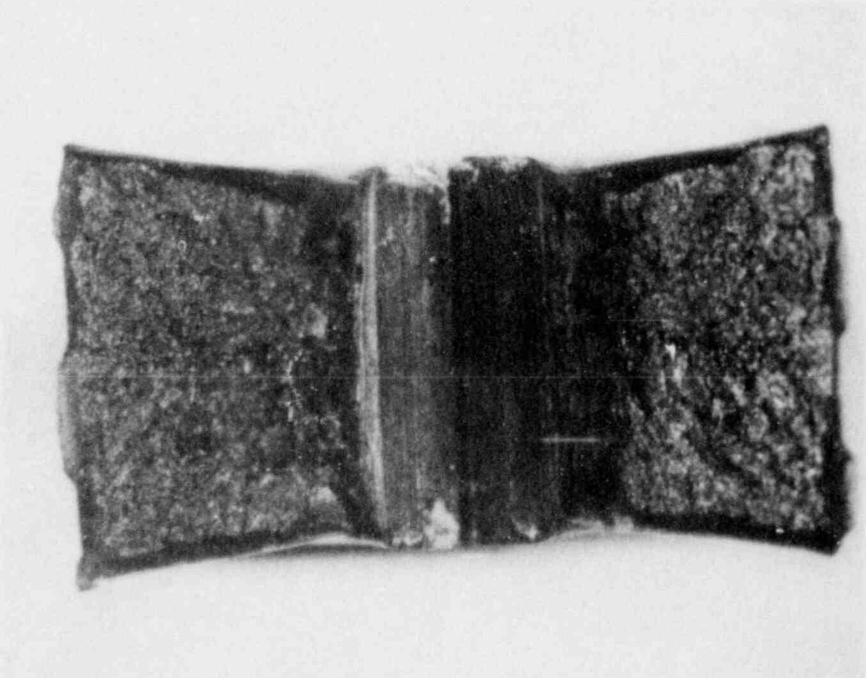
WELD: EJ1
TEMP: −100°F
ENERGY: 6.5 ft-lb
MLE: 11
% SHEAR: 0



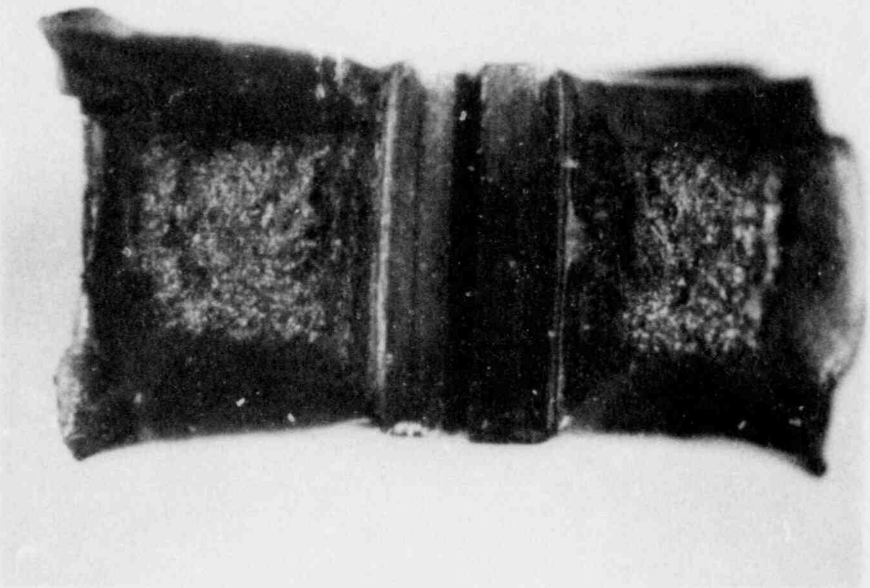
WELD: EJ2
TEMP: −60°F
ENERGY: 15.3 ft-lb
MLE: 24
% SHEAR: 10



WELD: EJ4
TEMP: −40°F
ENERGY: 22.0 ft-lb
MLE: 26
% SHEAR: 10

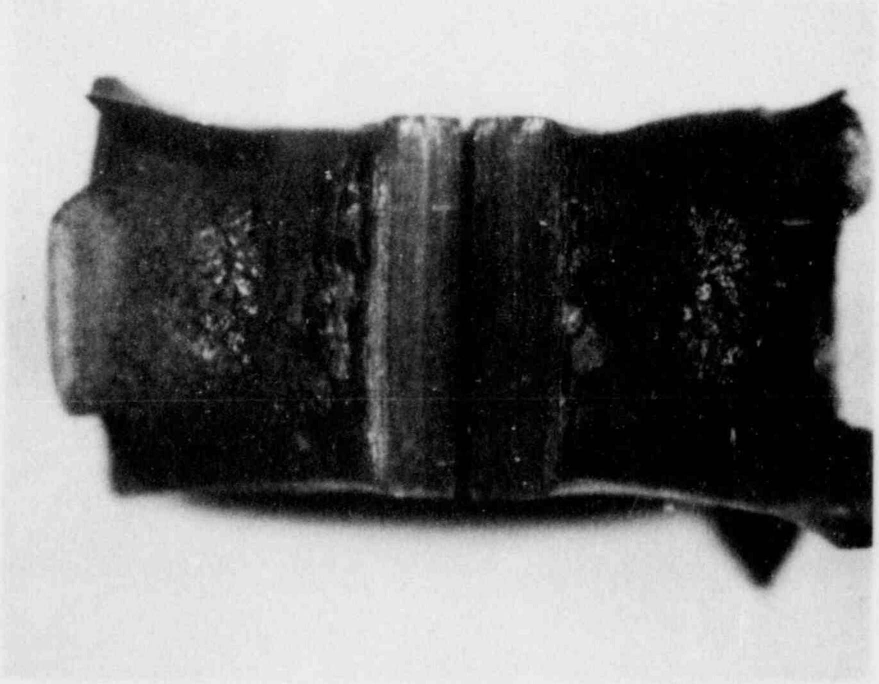


WELD: EE5
TEMP: −20°F
ENERGY: 63.5 ft-lb
MLE: 54
% SHEAR: 40



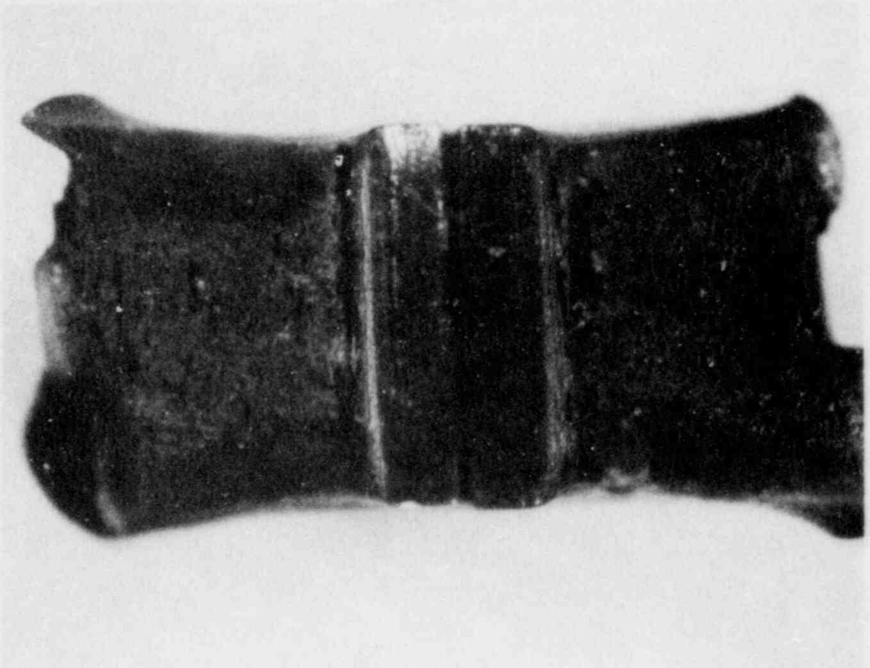
WELD: EE2
TEMP: 40°F
ENERGY: 75.2 ft-lb

MLE: 69
% SHEAR: 60

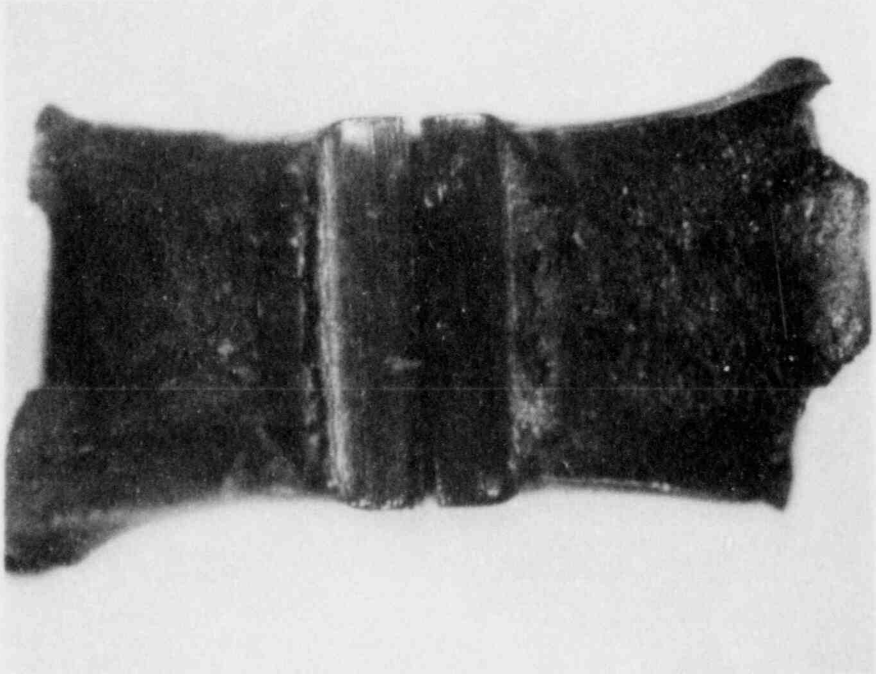


WELD: EE3
TEMP: 120°F
ENERGY: 97.2 ft-lb

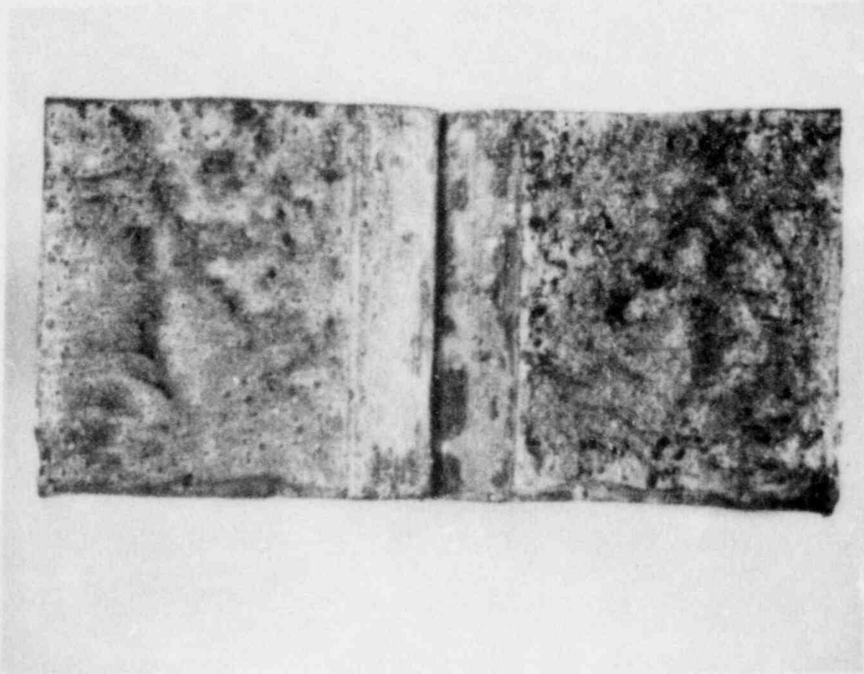
MLE: 86
% SHEAR: 80



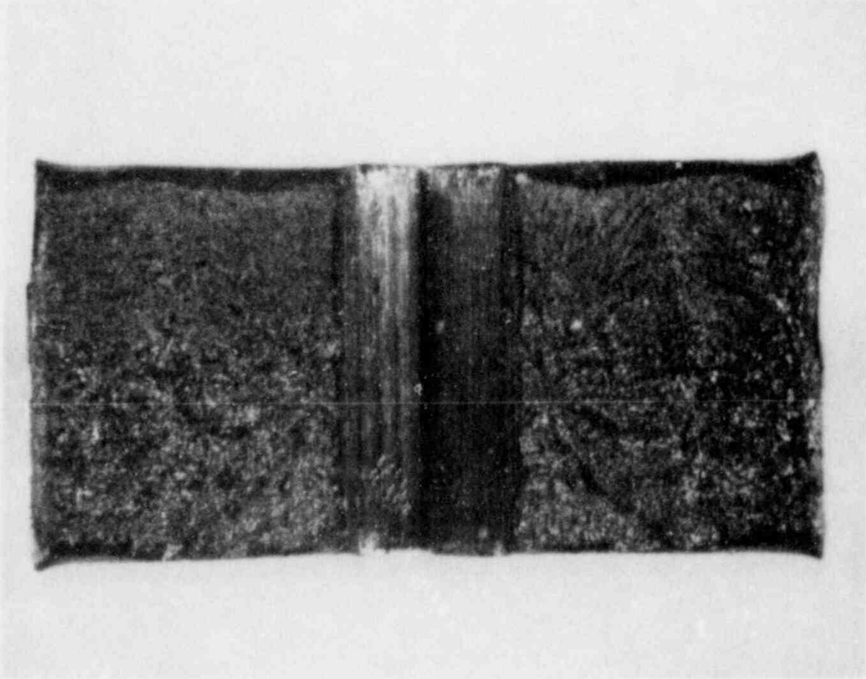
WELD:	EE4	MLE:	90
TEMP:	200°F	% SHEAR:	70
ENERGY:	109.0 ft-lb		



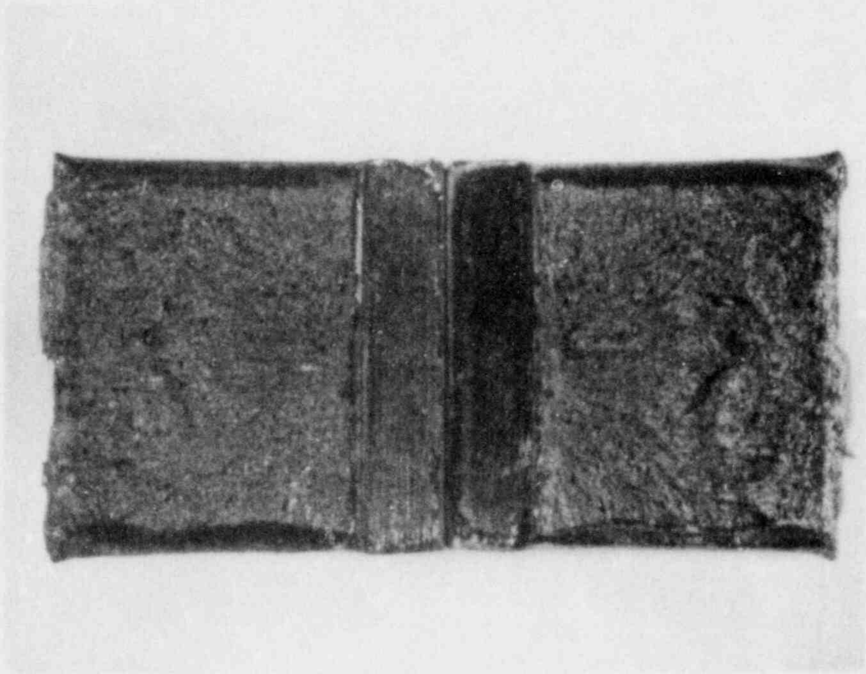
WELD:	EJ3	MLE:	91
TEMP:	400°F	% SHEAR:	100
ENERGY:	101.0 ft-lb		



HAZ:	ELY	MLE:	15
TEMP:	−60°F	% SHEAR:	0
ENERGY:	8.0 ft-lb		

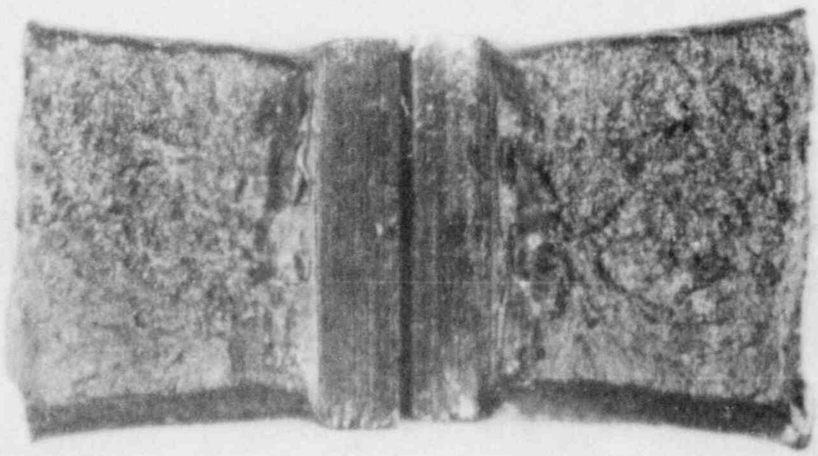


HAZ:	ELP	MLE:	18
TEMP:	−20°F	% SHEAR:	20
ENERGY:	13.5 ft-lb		



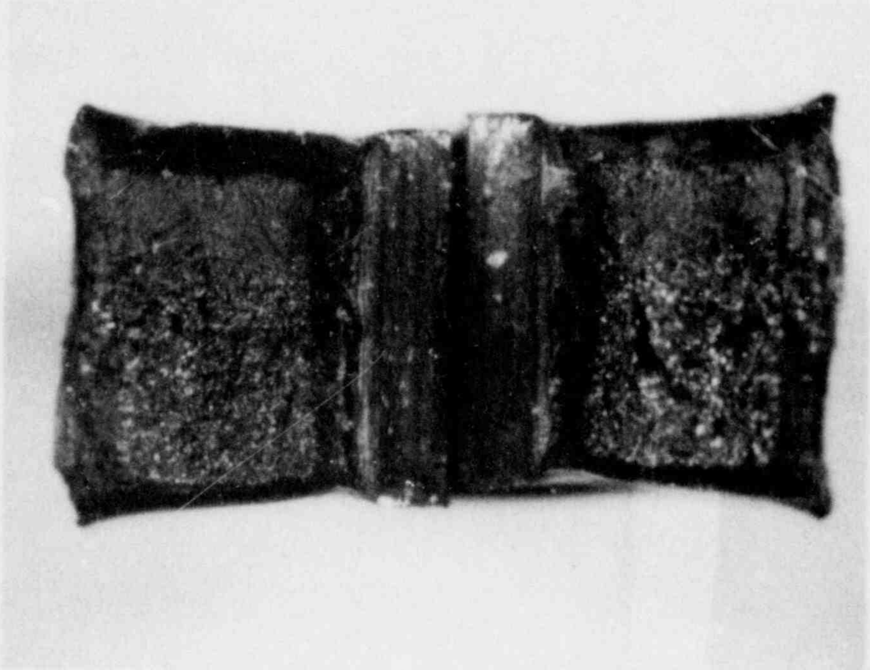
HAZ: EMY
TEMP: 0°F
ENERGY: 15.0 ft-lb

MLE: 16
% SHEAR: 30



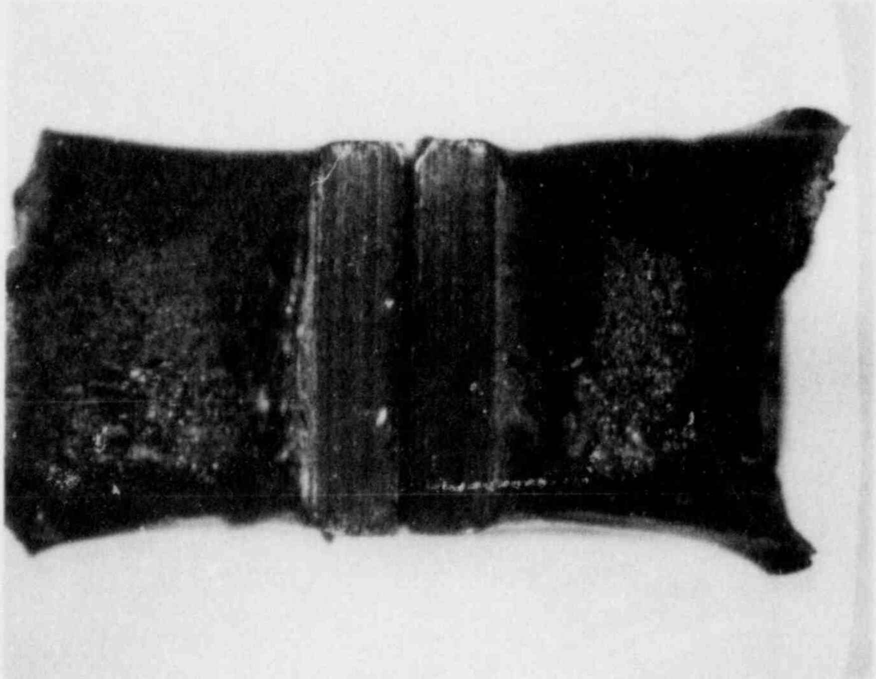
HAZ: ELT
TEMP: 10°F
ENERGY: 51.7 ft-lb

MLE: 43
% SHEAR: 40



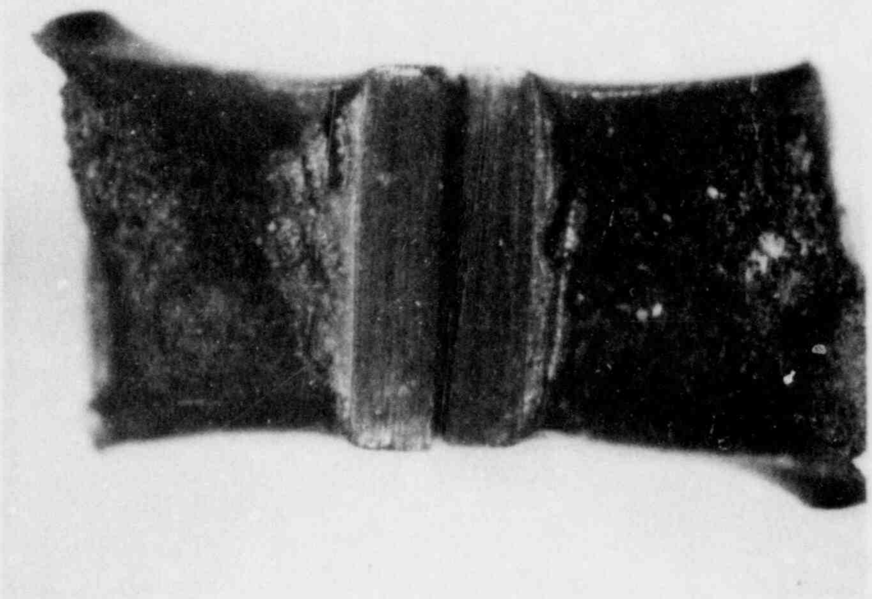
HAZ: ELK
TEMP: 40°F
ENERGY: 65.0 ft-lb

MLE: 50
% SHEAR: 50

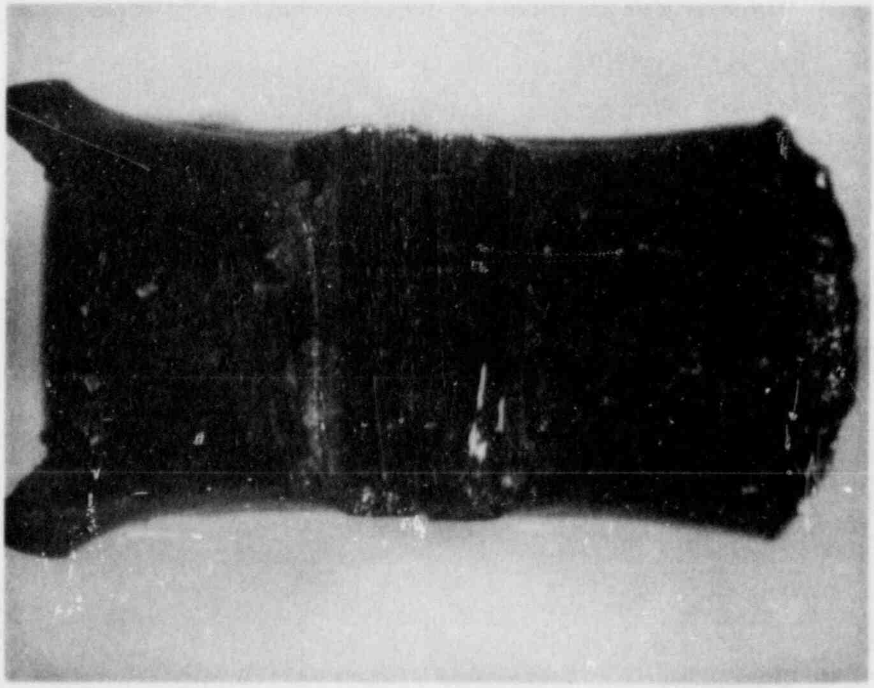


HAZ: ELL
TEMP: 120°F
ENERGY: 90.1 ft-lb

MLE: 66
% SHEAR: 70



HAZ:	ELM	MLE:	84
TEMP:	200°F	% SHEAR:	90
ENERGY:	126.5 ft-lb		



HAZ:	EMT	MLE:	75
TEMP:	400°F	% SHEAR:	100
ENERGY:	124.5 ft-lb		

GENERAL ELECTRIC