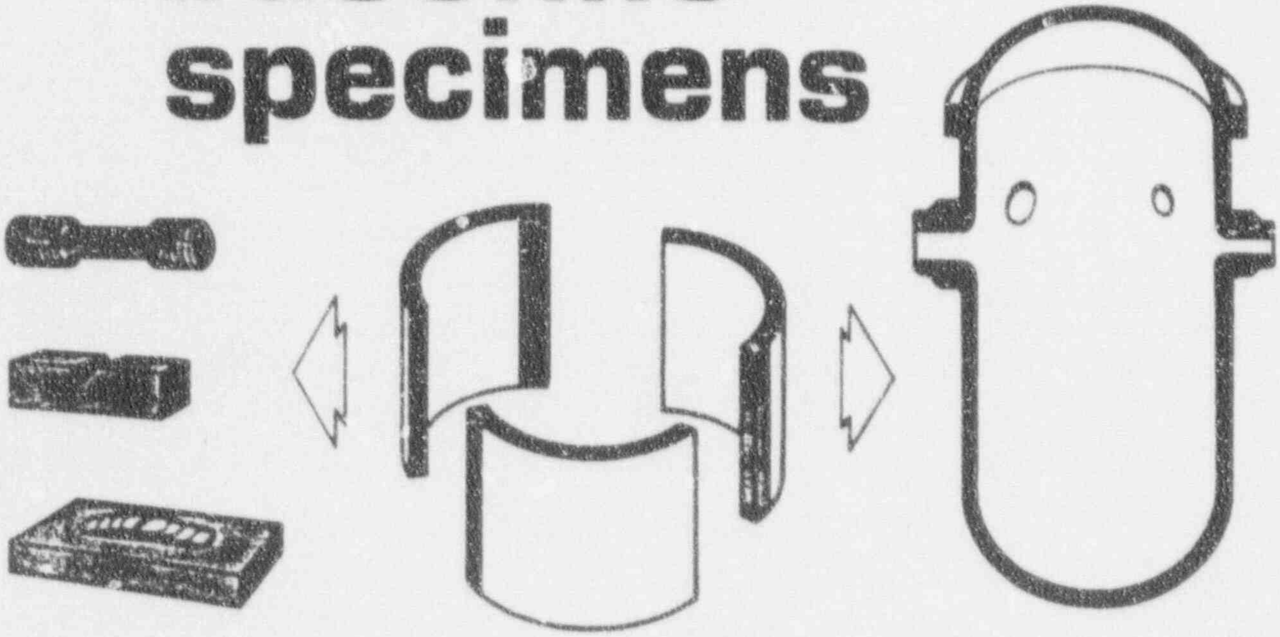
OMAHA
PUBLIC POWER DISTRICT
FORT CALHOUN STATION UNIT no.1

evaluation of baseline specimens



REACTOR VESSEL MATERIALS IRRADIATION SURVEILLANCE PROGRAM

C-E POWER SYSTEMS
COMBUSTION ENGINEERING INC

TR-O-MCD-001

OMAHA PUBLIC POWER DISTRICT FORT CALHOUN STATION UNIT NO. 1

EVALUATION OF BASELINE SPECIMENS REACTOR VESSEL MATERIALS IRRADIATION SURVEILLANCE PROGRAM

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Nuclear Power Systems

COMBUSTION ENGINEERING, INC.

Windsor, Connecticut

List of Symbols and Abbreviations

a = Crack length
a/w = Crack depth ratio
C_s^* = Nondimensional specimen compliance
C_v = Charpy V-Notch
DW = Drop Weight
E_{af} = Energy to cause fracture
E_{dial} = Energy recorded on pendulum dial
E_o = Available impact energy
IC_v = Instrumented Charpy impact
J = J-integral
K_f = Fatigue pre-cracking stress intensity factor
K_{Id} = Dynamic fracture toughness
K_{Bd} = Dynamic fracture toughness by equivalent energy method
K_{Jd} = Dynamic fracture toughness by J-integral method
K_{IR} = Reference fracture toughness
NDTT = Nil-ductility transition temperature
P_{GY} = Yield load
P_M = Maximum load
P_F = Fracture load
PIC_v = Precracked instrumented Charpy
P^* = Equivalent energy load
RW = Longitudinal orientation
R.A. = Reduction of Area
RT_{NDT} = Reference Temperature
σ_{yd} = Dynamic yield strength
σ_{ys} = Static yield strength
t_{GY} = Time to yield
t_M = Time to P_M
T_B = Brittle transition temperature
T_N = Ductility transition temperature
T_D = Ductility temperature
TE = Total Elongation
UE = Uniform Elongation
V_o = Initial impact velocity
w = Specimen thickness
WR = Transverse orientation

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I. SCOPE

Combustion Engineering has developed a detailed program for the Omaha Public Power District (OPPD) to monitor the irradiation induced mechanical property changes of the Fort Calhoun Station Unit No. 1 (Fort Calhoun) reactor vessel beltline materials[1]. The periodic examination of irradiated surveillance capsule materials serves to accurately measure the mechanical property changes experienced by the reactor vessel under service conditions. As a prerequisite for this evaluation the preirradiation or baseline properties of the surveillance materials must be established.

The results of the baseline evaluation of the Fort Calhoun reactor vessel surveillance materials are presented in this report. The materials included in this program are base metal, weld metal and heat-affected-zone (HAZ) metal. Tests conducted on these materials include drop weight, tensile and Charpy impact (both standard and instrumented). In addition to these basic tests, standard Charpy specimens are fatigue precracked and tested to determine fracture toughness parameters for the materials. The basic chemistry analyses for the surveillance materials and metallography characterizing the structure and fracture surface appearances of typical test specimens are also reported. The three appendices to this report contain information concerned with the test equipment used to perform this study.

The information provided by this program will enable OPPD to evaluate the postirradiation surveillance results of the Fort Calhoun reactor vessel using the criteria of 10 CFR 50, Appendix G, "Fracture Toughness Requirements" and Appendix H, "Reactor Vessel Material Surveillance Program Requirements".

By using instrumented Charpy impact test techniques and by incorporating precracked Charpy specimens in the tests, extensive quantitative fracture toughness data characterizing the reactor vessel materials have been obtained. The fracture mechanics approach to analyzing pressure vessels has already been adopted by the ASME and is included in the ASME Boiler and Pressure Vessel Code, Section III, Appendix G, "Protection Against Nonductile Fracture". This code uses quantitative fracture toughness data to set temperature and pressure parameters which insure safe operation of the reactor vessel.

The instrumented Charpy impact test is currently under consideration by ASTM. Subcommittee E 10.02 has decided to include the instrumented Charpy test as part of a revision to ASTM E-184, "Effects of High Energy Radiation on the Mechanical Properties of Metallic Materials", and Subcommittee E 24.03.03 is evaluating the use of the instrumented Charpy test on precracked Charpy impact specimens to obtain dynamic fracture toughness (K_{Id}) values. This test has also been utilized in materials testing programs sponsored by the joint PVRC/MPC Task Group on Fracture Toughness of Materials for Nuclear Components and the Electric Power Research Institute (EPRI). The importance of this program can not be overemphasized because these data form the basis for future testing to be conducted in the Fort Calhoun surveillance program.

REFERENCE

1. "Recommended Program for Irradiation Surveillance of the Fort Calhoun Reactor Vessel Materials," Combustion Engineering, Inc., Feb. 25, 1969, transmitted by letter C-E-750-1011, March 26, 1969.

II. SUMMARY

The Omaha Public Power District has initiated a reactor vessel irradiation surveillance program for the Fort Calhoun reactor vessel. As part of this program, the baseline or preirradiation material properties were determined for the pressure vessel materials, including the base metal, weld metal and heat-affected-zone (HAZ) metal. The material properties were characterized by drop weight tests, tensile tests, instrumented Charpy impact tests (IC_v) and instrumented tests on precracked Charpy specimens (PIC_v). Further material characterization was provided by metallographic examination.

A summary of the baseline test results is provided in Table II-1. Major results from each testing phase are reported, including Charpy impact data, drop weight NDTT and static and dynamic room temperature yield strength values. All reported Charpy impact upper shelf energies exceed the 75 ft-lb minimum requirement of 10 CFR 50, Appendix G. The low preirradiation RT_{NDT} and NDTT (24°F or less) further demonstrate the high degree of toughness of the Fort Calhoun surveillance materials.

Dynamic fracture toughness data were determined from precracked Charpy impact tests. The fracture toughness values for each of the surveillance materials exceed the lower bound toughness requirement of the ASME Code Section III, Appendix G, reference curve. It is evident, by comparison of the static and dynamic yield strength values (Table II-1), that the reactor vessel materials possess significantly higher yield strengths under dynamic loading conditions than under static loads.

The Fort Calhoun surveillance materials are fabricated from SA 533-B, Class 1 steel plate and submerged arc weldments. These materials represent the reactor vessel beltline region and meet ASME Code, Section II and Combustion Engineering (C-E) chemical composition specification.

Metallographic examinations were performed on base metal, weld metal and heat-affected-zone samples from the surveillance program. The base metal exhibited a tempered bainitic structure with an average ASTM grain size of 10. The weld metal was a fine grained ferritic structure. The heat-affected-zone showed a transition structure from tempered bainite of the base metal to fine ferrite of the weld metal. An inclusion content determination, per ASTM E 45-74, was performed on the base metal. An average of four (4) inclusions per field were counted on a transverse microspecimen; the longest inclusion measured on a longitudinal microspecimen was 0.0045 inch. The orientation of the inclusion stringers accounts for the lower transverse Charpy upper shelf impact energy typically found in plate material.

TABLE II-1

SUMMARY OF MATERIAL DATA

Material and Code	C_v Upper Shelf (ft-lb)	30 ft-lb Fix[c] (°F)	50 ft-lb Fix[d] (°F)	35 Mils Lat. Exp. Fix[d] (°F)	NDTT (°F)	RT_{NDT} (°F)	RT Yield Strength (ksi) Static	RT Yield Strength (ksi) Dynamic
Base Metal Plate D-4802-2 (WR)	121	36	78	58	-20	18	69	99
Base Metal Plate D-4802-2 (RW)	137.5	26	52	34	-20	-8[a]	71	99
Weld Metal D-4802-1/D-4802-3	97.5	-18	2	-12	0[b]	0[b].	78	98
HAZ Metal D-4802-2	82	-70	84	58	0[b]	24[b]	67	106

a RT_{NDT} for the RW orientation is not valid per 10 CFR 50, Appendix G and is only reported for information.

b Estimated per Branch Technical Position MTEB 5-2, where NDTT is the higher of 0°F or the 30 ft-lb fix temperature, in the case where drop weight tests were not performed.

c Determined from average impact energy curve.

d Determined from lower bound curve.

III. BACKGROUND

Neutron induced changes in the mechanical properties of ferritic materials are the result of lattice distortion and defect clusters in the material. These distortions and defect clusters act to strengthen the material at the expense of ductility. It is this decrease in ductility which is of major interest to reactor pressure vessel designers.

Ductility and material toughness are characterized by several tests and test parameters. Neutron induced changes in the mechanical properties are determined by comparing test results of unirradiated specimens with results of irradiated specimens. One of the basic tests which demonstrates the toughness of a material and specifically helps to define a ductile to brittle transition behavior is the drop weight test.

The drop weight test uses a large test specimen (refer to Appendix A) to establish the Nil-Ductility Transition (NDT) Temperature of a material. At and below this temperature, the material will fracture in a brittle manner under certain conditions of triaxial stresses. Because these specimens are large, they cannot easily be placed in a reactor environment to be irradiated. Therefore, the drop weight test results are correlated with Charpy V-notch impact test (C_v) results to establish a reference temperature (RT_{NDT}) which can be compared with a similar postirradiation test parameter (adjusted reference temperature) based entirely on Charpy impact data. The comparison will show a temperature increase for this parameter as the specimens are exposed to higher neutron fluence. In other words, the reference temperature increases with irradiation exposure.

The RT_{NDT} and adjusted reference temperature concepts were introduced with the addition of Appendixes G and H to 10 CFR 50 (1973). Prior to that time, material toughness changes were evaluated by noting the temperature change between unirradiated and irradiated Charpy data measured at the 30 ft-lb fix or C_v impact energy level.

This difference was labeled ΔNDTT for nil-ductility transition temperature shift. The newer programs use RT_{NDT} and 30 ft-lb fix techniques together in an attempt to establish a relationship between the two so the RT_{NDT} method can be applied to past data. The advantage of the RT_{NDT} method is that it incorporates drop weight test data and specifically defines what the toughness properties of the material must be at RT_{NDT}.

According to paragraph NB-2331 of the 1974 edition of the ASME Boiler and Pressure Vessel Code, Section III, RT_{NDT} is established as follows:

> At a temperature not greater than (T_{NDT} + 60°F) test three C_v specimens, each of which shall exhibit at least 35 mils of lateral expansion and not less than 50 ft-lb absorbed energy. When these requirements are met, T_{NDT} is the reference temperature, RT_{NDT};
>
> In the event that the above requirements are not met, conduct additional C_v tests in groups of three specimens to determine the temperature T_{cv} at which they are met. In this case, the reference temperature RT_{NDT} = T_{cv} - 60°F. Thus, the reference temperature, RT_{NDT} is the higher of NDT and (T_{cv} - 60°F).
>
> When a C_v test has not been performed at (T_{NDT} + 60°F), or when the C_v test at (T_{NDT} + 60°F) does not exhibit a minimum of 50 ft-lb and 35 mils lateral expansion, a temperature representing a minimum of 50 ft-lb and 35 mils lateral expansion may be obtained from a full C_v impact curve developed from the minimum data points of all C_v tests performed.

The adjusted reference temperature is defined in 10 CFR 50, Appendixes G and H. According to 10 CFR 50, Appendix H:

> The adjusted reference temperature for the base metal, heat-affected zone, and weld metal shall be obtained from the test results by adding to the reference temperature (RT_{NDT}) the amount of temperature shifts in the Charpy test curves between the unirradiated material and the irradiated material measured at the 50 foot-pound level or that measured at the 35 mil lateral expansion level, whichever temperature shift is greater.

Another measurement of the neutron induced changes in mechanical properties is the change in the Charpy impact upper shelf energy. The C_v tests measure the amount of energy required to fracture test specimens at a series of test temperatures. There is a range of temperatures over which the specimen will fracture in a manner that is partially brittle and partially ductile. Below this range, fracture is 100 percent brittle (100 percent cleavage fracture) and absorbed energy values are low; above this range, fracture is 100 percent ductile (100 percent shear fracture) and absorbed energy values are high. The measured impact energy for the 100 percent ductile case is called the upper shelf energy. As a material becomes irradiated and ductility decreases, its upper shelf energy may decrease. 10 CFR 50, Appendix G, specifies that reactor vessel beltline materials (those materials which will experience a minimum 50°F shift in RT_{NDT} over the vessel life) must have minimum initial upper shelf energies of 75 ft-lb unless it can be demonstrated to the Commission that lower values of upper shelf fracture energy still provide adequate margin for deterioration from irradiation. The minimum upper shelf energy allowed after irradiation is 50 ft-lb, because this energy level is required to establish the previously mentioned adjusted reference temperature.

Tensile tests are also employed to characterize radiation effects on materials. The tensile test can determine the amount of radiation strengthening by comparing unirradiated test results with results from irradiated specimens.

Instrumented Charpy impact tests (IC_v) add another dimension to the characterization of ductile-brittle-behavior in ferritic materials. The standard instrumented Charpy test provides information depicted by Figures III-1 through III-4. These figures are representative of oscilloscope traces and data generated by specific tests.

Figure III-1 is a load versus time plot which shows the yield and toughness behavior as a function of time. The entire process, as shown, generally takes place in 5000 microseconds with shorter times experienced for low temperature tests. Values for general yield load (P_{GY}), maximum load (P_M) and fracture load (P_F) are obtainable as indicated.

Figure III-2 shows an integration of the area under the load-time curve (Figure III-1) and represents the energy from initial impact to complete fracture of the specimen. The integration process is performed electronically and the results are superimposed on oscilloscope traces of the individual test records. The integration line starts at the lower left-hand corner of the trace and rises to the right, peaking and leveling off at an energy corresponding to the total impact energy required for complete fracture of the specimen. This curve allows the determination of energies corresponding to any specific time during the test.

Figure III-3 is an idealized plot showing the yield, maximum and fracture loads (taken from a series of traces as shown in Figure III-1) plotted as a function of test temperature. This represents the toughness behavior o. a given material such as base metal, weld metal, or weld heat-affected-zone material. Four temperature regions are shown, each of which is delineated by a distinctly different fracture mode of the material. The dotted line at the bottom represents a typical C_v impact energy versus temperature curve.

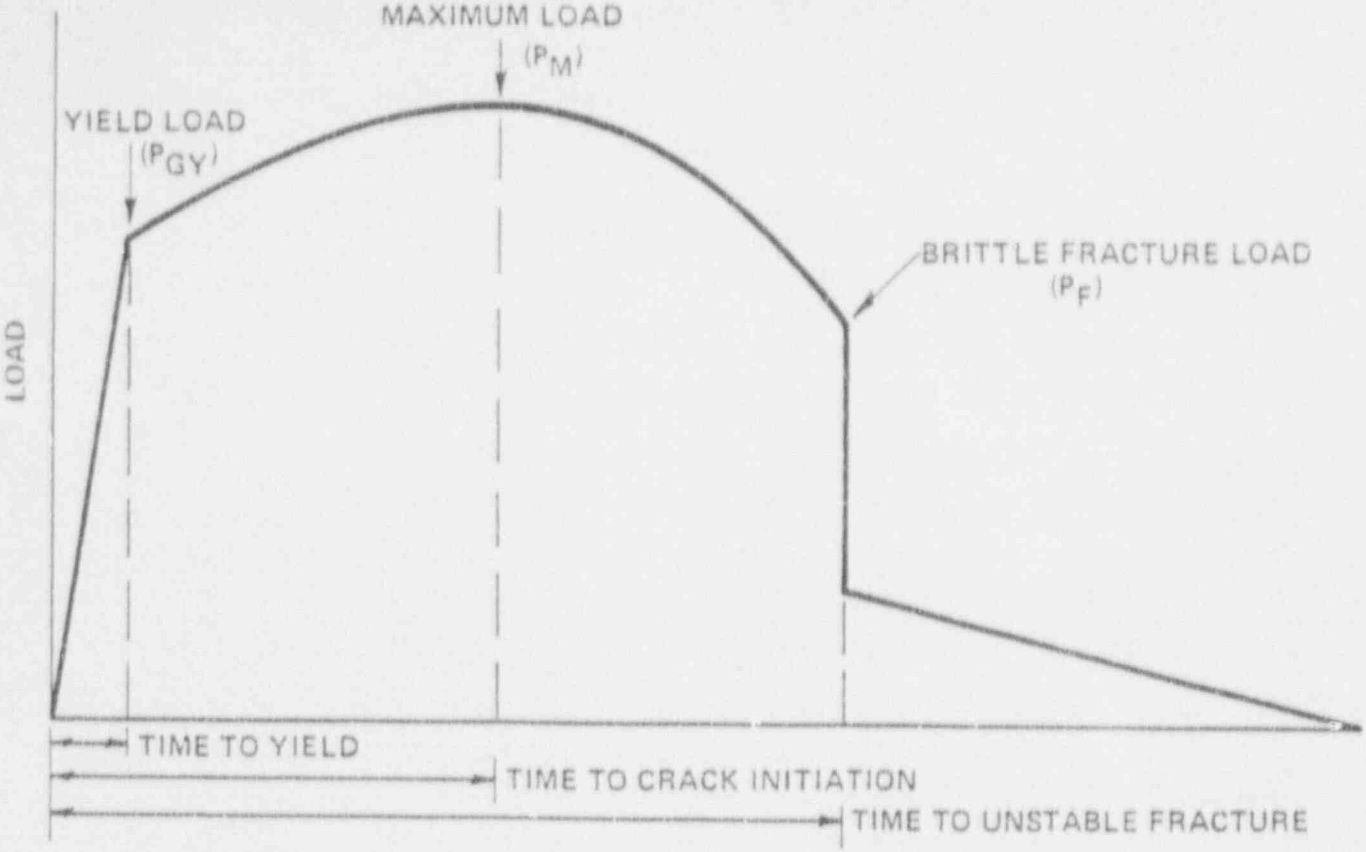


Figure III-1 Idealized Load - Time Record for Instrumented Impact Testing

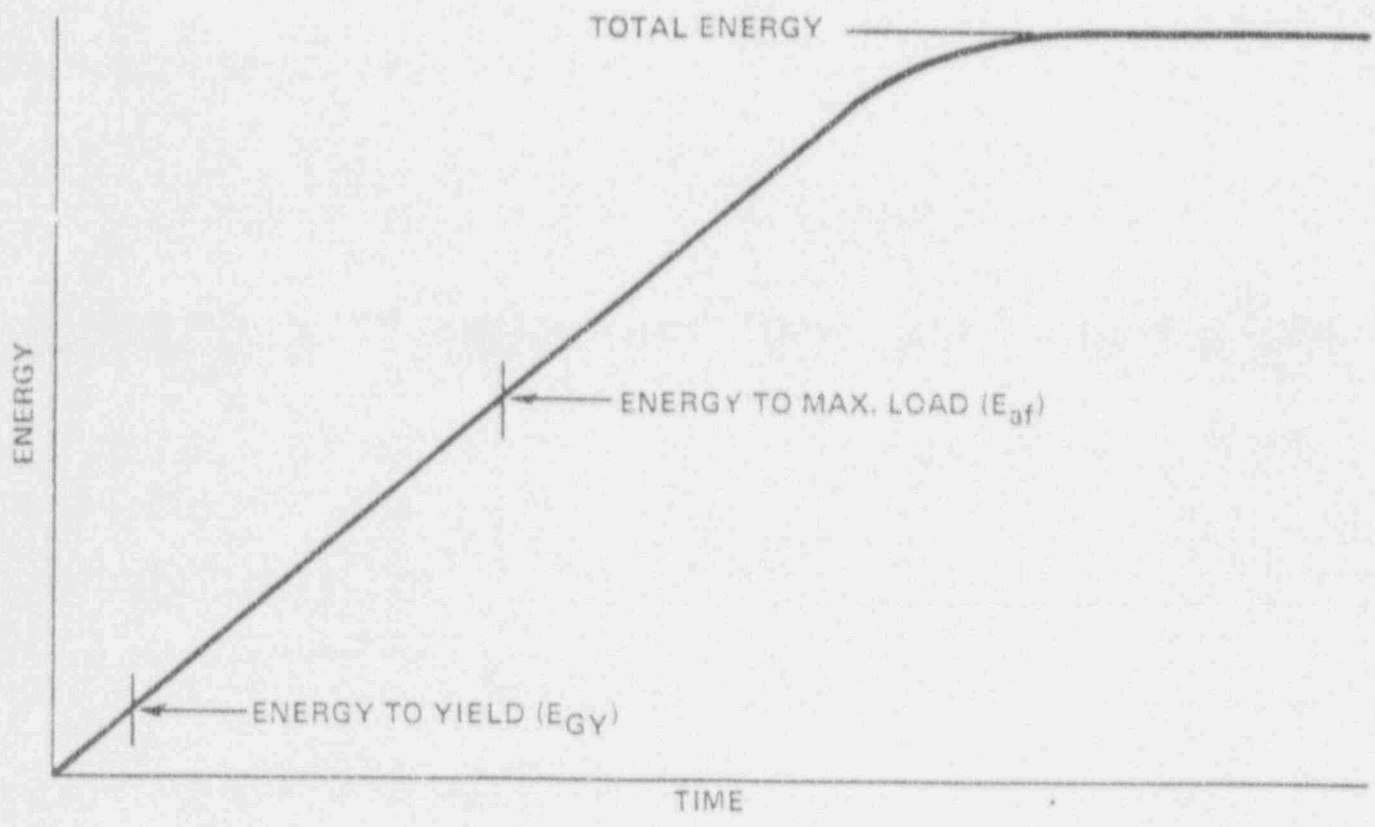


Figure III-2 Idealized Energy - Time Record for Instrumented Impact Testing

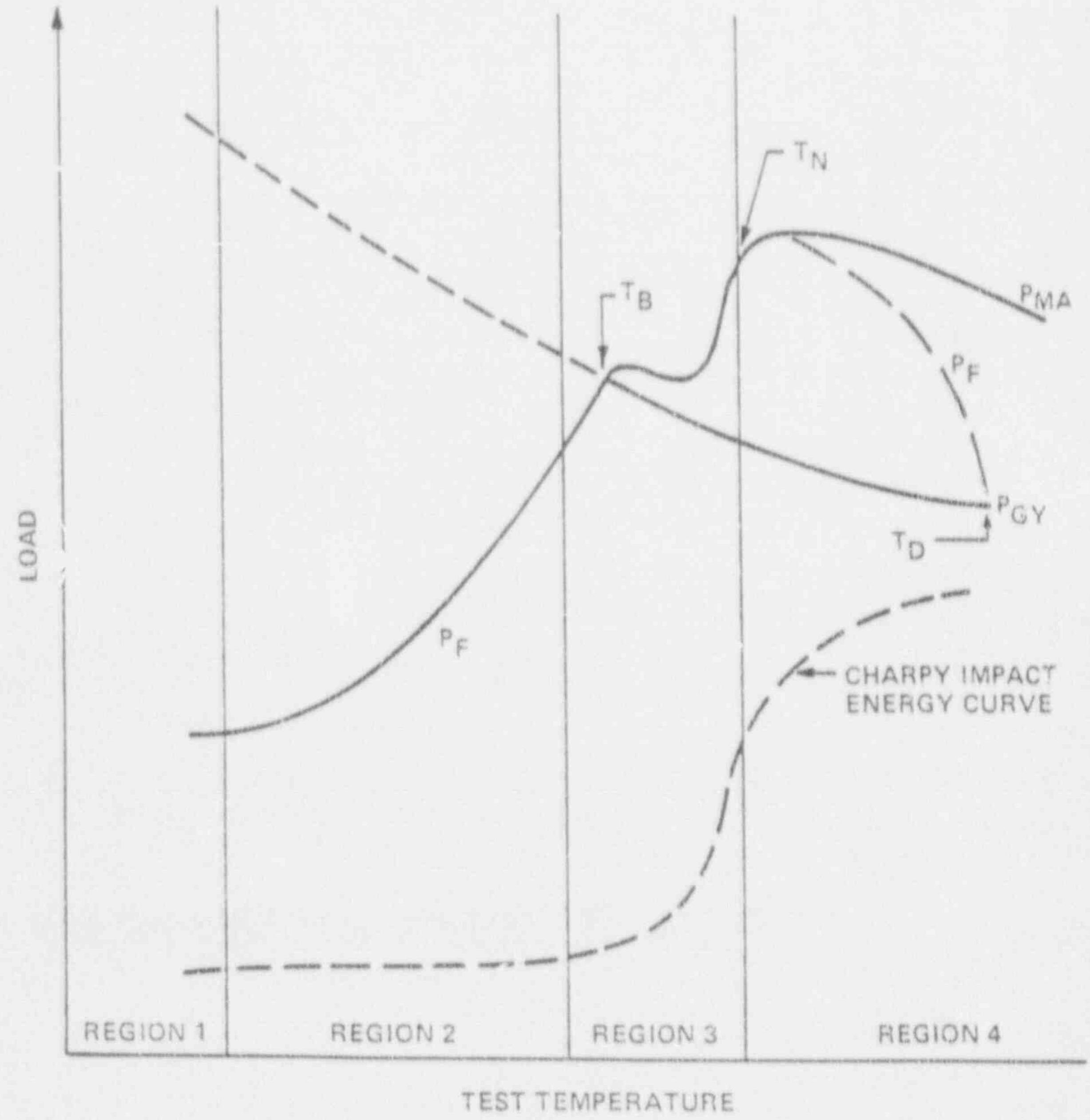


Figure III-3 Variation in Impact Load with Test Temperature for Instrumented Charpy Impact Tests

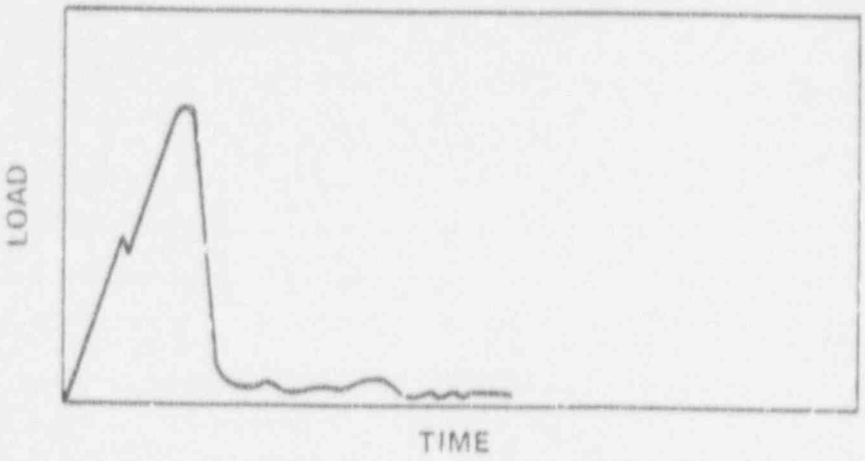


Figure III-4A Temperature Region 2

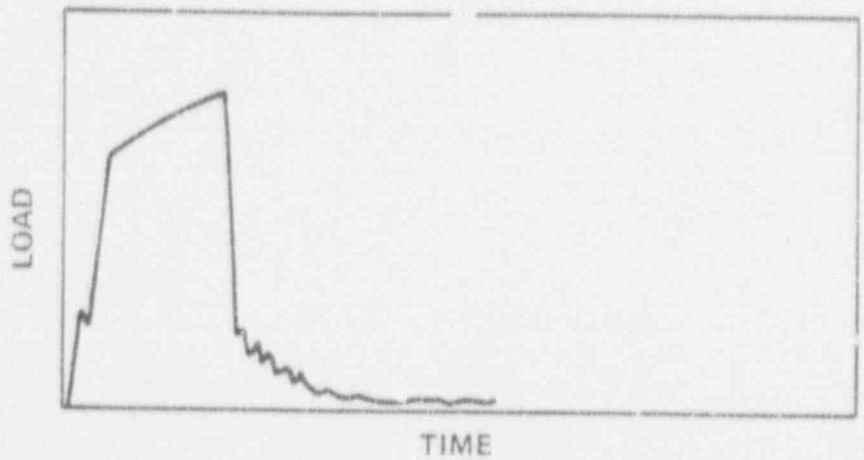


Figure III-4B Temperature Region 3

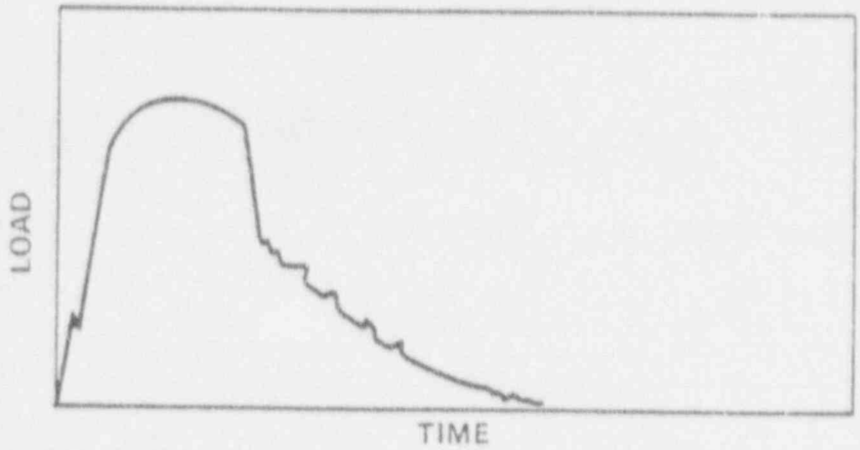


Figure III-4C Temperature Region 4

Figure III-4 Idealized Load vs Time Plots for Instrumented Charpy Impact Tests

At extremely low temperatures, fracture usually initiates by a slip or twinning process in the first grain below the specimen notch. An oscilloscope trace of the test result will differ from those idealized traces discussed and will appear similar to that of Figure III-4A, but with a much lower amplitude. Fracture is completely brittle and the temperature range is indicated as Region 1 in Figure III-3.

When the test temperature is increased to the range of Region 2 (Figure III-3), the load/time trace appears as indicated in Figure III-4A. In this region, the specimen acts primarily in a brittle manner, although there is a very small amount of plastic behavior. For this case the fracture load is approaching the dynamic yield strength of the material. The load read from such a trace is simply P_F - the fracture load.

For tests conducted in the temperature realm of Region 3, the specimen is near its brittle to ductile transition. In this region, the load time plot becomes typical of Figure III-4B and the specimen fractures after yielding at maximum load.

Tests in temperature Region 4 produce load versus time plots indicative of the idealized plots (also shown in Figure III-4C). At these temperatures, the strain required to initiate cleavage fracture becomes so large that it surpasses the ductile fracture strain and fibrous tearing occurs.

Figure III-3 also points out three temperatures of interest. The brittle transition temperature (T_B) occurs at the intersection of P_{GY} values with the P_F curves. Correlation with this value and the C_v energy versus temperature plot (dotted line) shows that T_B compares with the start of the transition region of the C_v curve. In other words, above T_B the Charpy test specimens start to show some ductile behavior so fracture above this temperature will occur after yielding is experienced. The load versus time trace in Figure III-4B illustrates this behavior.

The second temperature, T_N, is called the ductility transition temperature. At this point there is a sharp rise in the maximum load and corresponding fracture tougnness. Comparison with the C_v impact curve (dotted line) shows that this corresponds with the midtransition region. Fracture will occur after maximum load (P_M) is achieved at temperatures above T_N. This is a result of fibrous tearing being experienced. The load versus time trace in Figure III-4C illustrates this behavior.

The third temperature of interest is characterized by T_D - the ductility temperature. This point is defined by the intersection of the P_F curve with P_{GY}. At this temperature fracture is completely ductile and corresponds to the beginning of the upper shelf on the Charpy impact curve (Figure III-3).

Any loss of ductility as a result of irradiation damage will cause these temperatures to increase. The various regions of toughness behavior will also shift and occur at higher temperatures.

As mentioned in Section I, precracking Charpy specimens for instrumented impact testing enables quantitative fracture toughness data to be gleaned from the qualitative C_v test. Among these data are K_{Id} values representing a plane-strain or purely elastic stress intensity factor and K_{Jd} (J-integral) representing a stress intensity factor for material which deforms in an elastic and plastic manner. A third stress intensity factor, K_{Bd} (equivalent energy), is similar to K_{Jd} but employs a different method of calculation. The stress intensity factor, K, relates the magnitude of loading forces to the configuration and size of a crack in a body (within the limits of the linear elastic region). Thus, the stress intensity factor may be interpreted physically as a parameter which reflects the redistribution of stress near the crack tip due to the introduction of a crack, and, in particular, it characterizes the crack instability conditi and field of deformation in a zone surrounding the crack. Beyond the linear elastic region (i.e., at higher temperatures) the relation between the magnitude of loading forces and the crack shape and size (the stress intensity factor) is no longer valid. However, the K_{Jd} and K_{Bd} values approximate the stress field near the crack tip which would cause crack instability under certain loading conditions.

ASTM E 399-74, "Standard Method of Test for Plane Strain Fracture Toughness of Metallic Materials," gives procedures and calculational methods for the determination of the critical stress intensity factor for linear elastic fracture. Standard techniques to determine valid fracture toughness properties from a precracked Charpy specimen are currently being developed by ASTM E 10.02 and ASTM E 24.03. Several techniques were developed in separate programs sponsored by the Electric Power Research Institute (EPRI) and the Pressure Vessel Research Committee/Metal Properties Council (PVRC/MPC) to determine fracture toughness in both the linear elastic region (e.g., Region 2 in Figure III-4A) and the elastic-plastic region (e.g., Regions 3 and 4 in Figures III-4B and III-4C). The analysis of the Fort Calhoun precracked Charpy data employs the EPRI calculational techniques for K_{Id}, K_{Jd} and K_{Bd}.

IV. MATERIALS

A. Selection

The specimens for the Fort Calhoun surveillance program were manufactured from SA 533-B, Class 1 steel pressure vessel plate, weld and heat-affected-zone materials. Selection of the candidate surveillance materials was restricted to the six plates in the intermediate and lower shell courses[1]. Selection criteria followed the general guidelines of ASTM E 185-66, "Standard Recommended Practice For Surveillance Tests For Nuclear Reactor Vessels".

B. Chemistry

The chemical composition of the plate and weld materials for the Fort Calhoun surveillance program is presented in Table IV-1. The chemical analyses were performed on specimens from the quarter thickness (1/4 T) locations. As required by ASTM E 185-73, paragraph 4.1.3, the residual elements phosphorous, sulfur, copper and vanadium are reported as well as other major alloying elements. The chemical composition of the plate and weld conforms to ASME Code, Section II and C-E specifications for SA 533-B, Class 1 material.

C. Specimens

The number of specimens available for testing and their orientation with respect to the major rolling direction of the plate are presented in Table IV-2. The types of specimens included are drop weight, tensile and Charpy V-notch. Additional information concerning these specimens is presented in the Appendixes to this report and in Reference (1).

TABLE IV-1

PLATE AND WELD METAL CHEMICAL ANALYSIS

Element	Weight Percent: Plate D-4802-2	Weight Percent: Weld D-4802-1/D-4802-3
Si	.23	.14
S	.014	.011
P	.009	.013
Mn	1.43	1.57
C	.22	.14
Cr	.04	.03
Ni	.48	.60
Mo	.50	.50
V	<.001	.002
Cb	<.01	<.01
B	.0003	.0002
Co	.007	.014
Cu	.10	.35
Al	.030	.009
W	.02	.02
Ti	<.01	<.01
As	<.01	<.01
Sn	.002	.007
Zr	.002	.002
N_2	.009	.012

TABLE IV-2

SUMMARY OF SPECIMENS AVAILABLE FOR PREIRRADIATION TESTING

Type of Specimen	Orientation(*)	Quantity of Specimens: Base Metal	Weld Metal	HAZ	Total
Drop Weight	RW (Longitudinal)	16	--	--	16
Charpy Impact	RW (Longitudinal)	30	--	--	30
	WR (Transverse)	30	30	30	90
Tensile	RW (Longitudinal)	18	18	--	36
	WR (Transverse)	18	--	18	36
	TOTAL	112	48	48	208

(*) With respect to the plates' major direction of rolling for base metal; with respect to the welding direction for weld and HAZ metal.

D. . Heat Treatment

The heat treatment for the plate material consisted of austenitization at 1600° ±50°F for 4 hours; water quenched and tempered at 1225°F ±25°F for 4 hours. After a 40-hour stress relief at 1150°F ±25°F, the plates were furnace cooled to 600°F. The weldment received a final 40-hour and 30-minute stress relief at 1100°F to 1150°F.

E. Material Structure

A metallographic analysis was performed to provide a record of the microstructures of base, weld and heat-affected-zone metal. This will be valuable reference information for subsequent postirradiation analyses.

The photomicrographs shown in Figures IV-1 through IV-12 represent the base metal, weld metal and HAZ metal. Figures IV-1 and IV-2 show the polished, but unetched base metal in both the transverse and longitudinal direction; these photomicrographs were taken to determine the amount of inclusion content in the base metal, per ASTM E 45-74. An average of four inclusions per field were counted on a transverse mircospecimen; the longest inclusion measured on a longitudina micro was 0.0045 inch. Figures IV-3 through IV-6 are representative of the tempered bainite structure of the base metal in the transverse and longitudinal directions. This structure, with an average ASTM grain size of 10, is typical for SA 533-B, Class 1 thick section steel plate. Figures IV-7 through IV-10 represent the weld metal in the transverse and longitudinal directions. The fine grain ferritic structur with uniform carbide distribution is typical for an automatic submerged arc welding process.

Figures IV-11 and IV-12 show the heat-affected-zone (HAZ). The larger grain area is the heat-affected base metal with its bainitic structure. The fine grain area is the weld metal with well dispersed carbides in the ferrite grains. All specimens were prepared using standard metallographic cutting, grinding and polishing techniques. A Villela's solution was used to etch the specimens for structure determination. Photomicrographs were taken at magnifications of 100x, 500x and 1000x.

REFERENCE

1. "Summary Report on Manufacture of Test Specimens and Assembly of Capsules for Irradiation Surveillance of Fort Calhoun Reactor Vessel Materials", C-E Document CENPD-33 Proprietary Information, dated November 15, 1971.

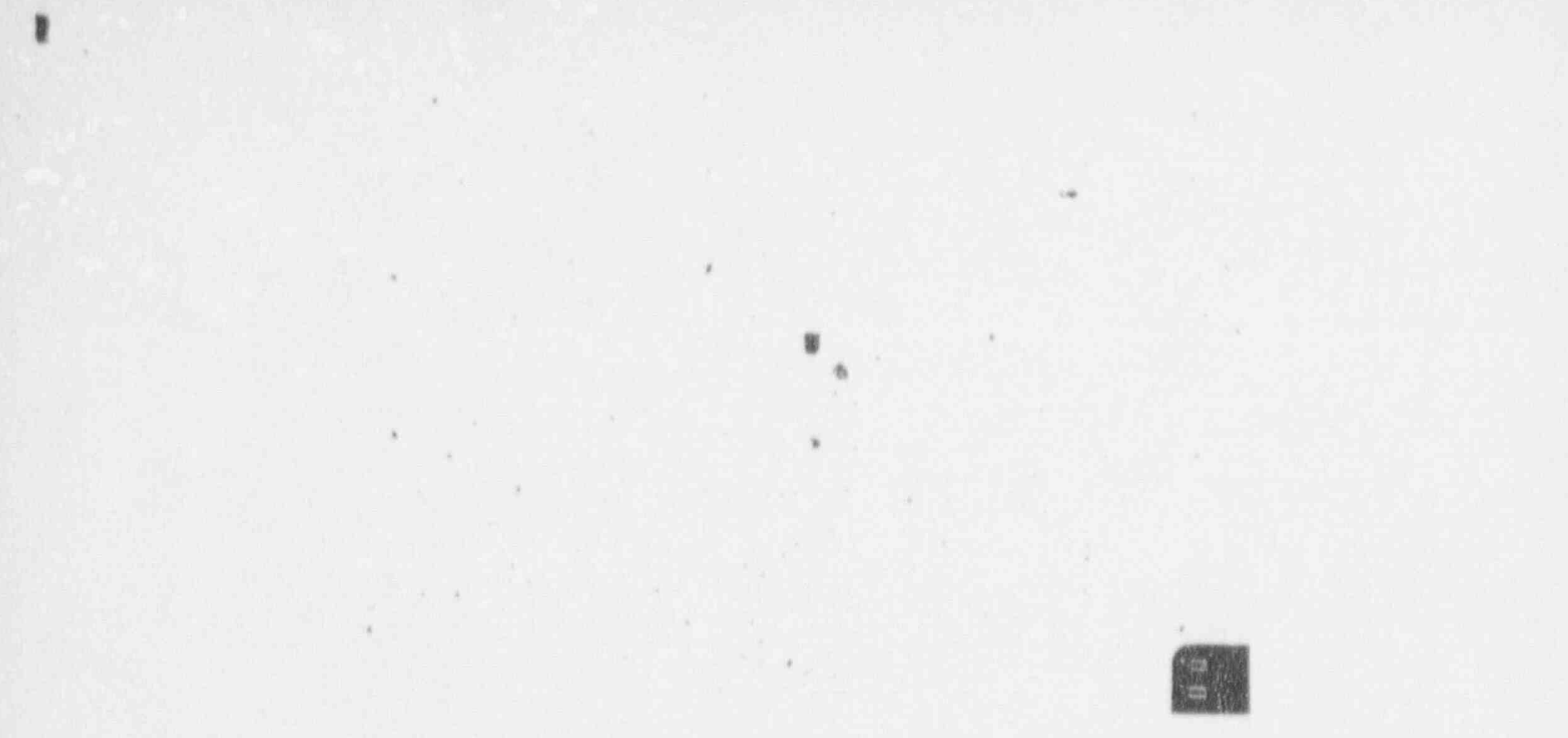


Figure: IV-1 Base Metal (WR) Showing Inclusion Stringer Content and Orientation. Photo Shows Small Amount of Stringers. Not etched. 100x

Figure: IV-2. Base Metal (RW) with Inclusion Distribution for this Orientation. Not etched. 100x

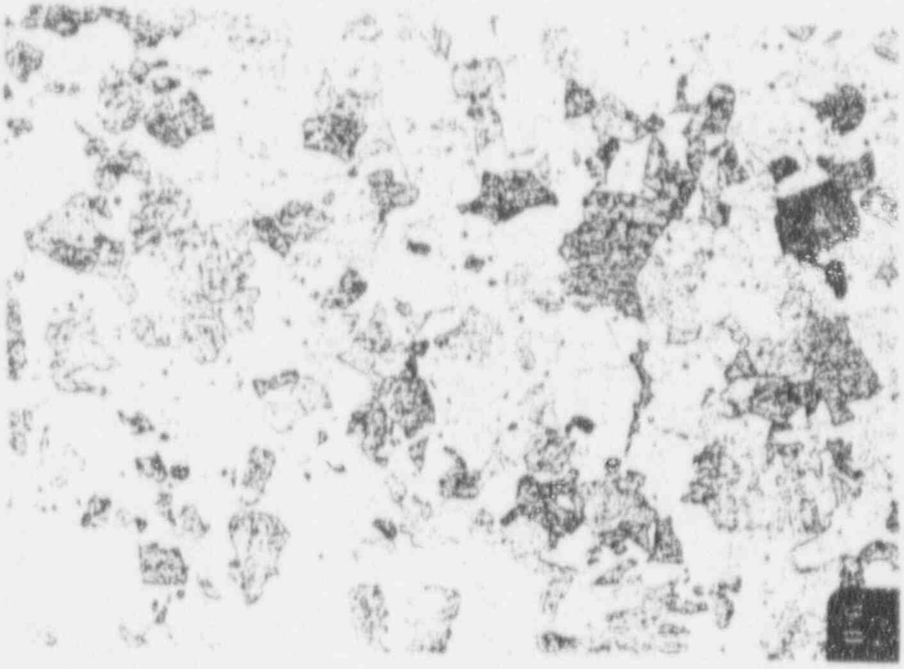


Figure: IV-3. Base Metal (WR). Typical Tempered Bainite Structure of A533-B Material. Vilella's Etch. 500x

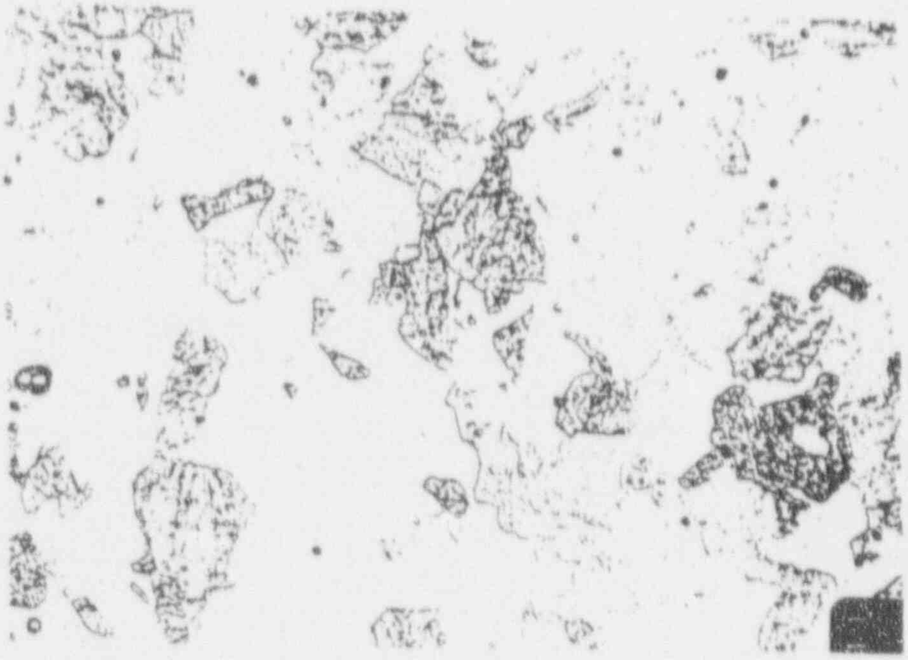


Figure: IV-4. Base Metal (WR). Enlarged View Shows Individual Tempered Bainite Grains. Vilella's Etch. 1000x

Figure: IV-5. Base Metal (RW). Typical Tempered Bainite Structure. Vilella's Etch. 500x

Figure: IV-6. Base Metal (RW). Enlarged View Shows Individual Tempered Bainite Grains. Vilella's Etch. 1000x

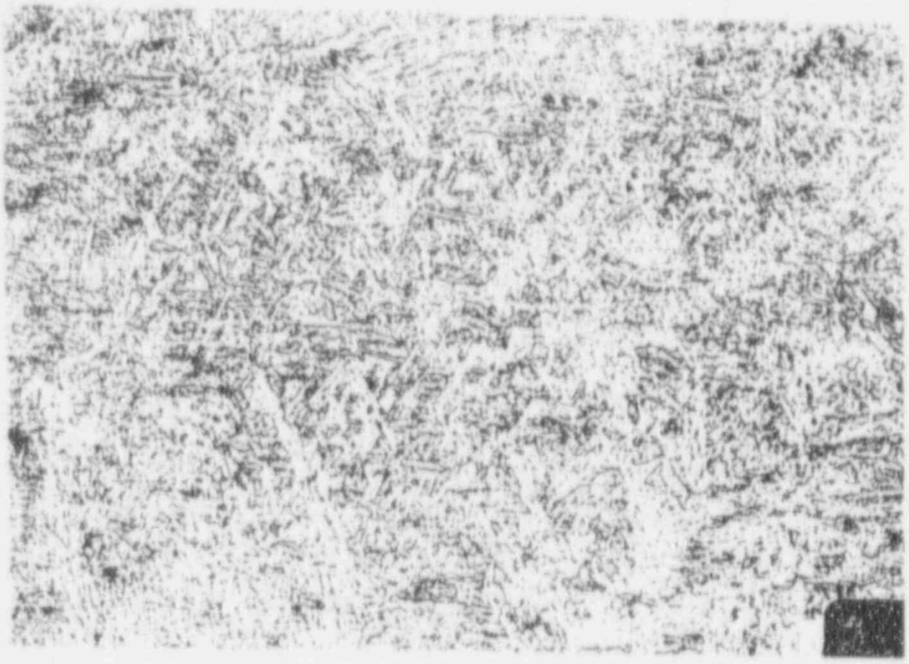


Figure: IV-7. Weld Metal (Transverse Section). Typical Fine G Ferritic Weld Structure of Automatic Sub-Arc Wel Process with Normal Carbide Distribution. Vilel Etch. 500x

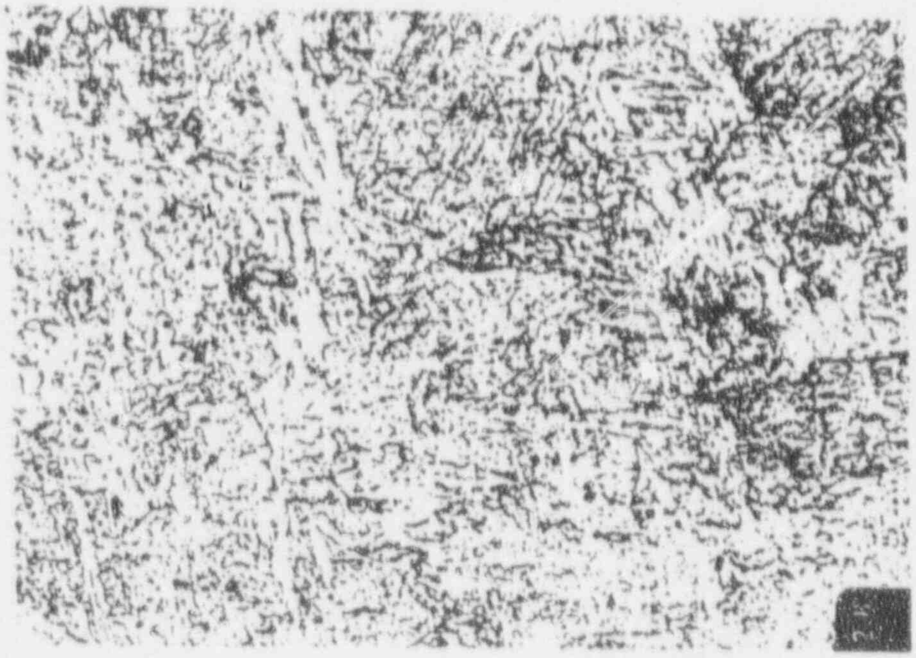


Figure: IV-8. Weld Metal (Transverse Section). Enlarged View o Ferritic Weld Structure. Vilella's Etch. 1000x

Figure: IV-9. Weld Metal (Longitudinal Section). Typical Fine Grain Ferritic Structure. Vilella's Etch. 500x

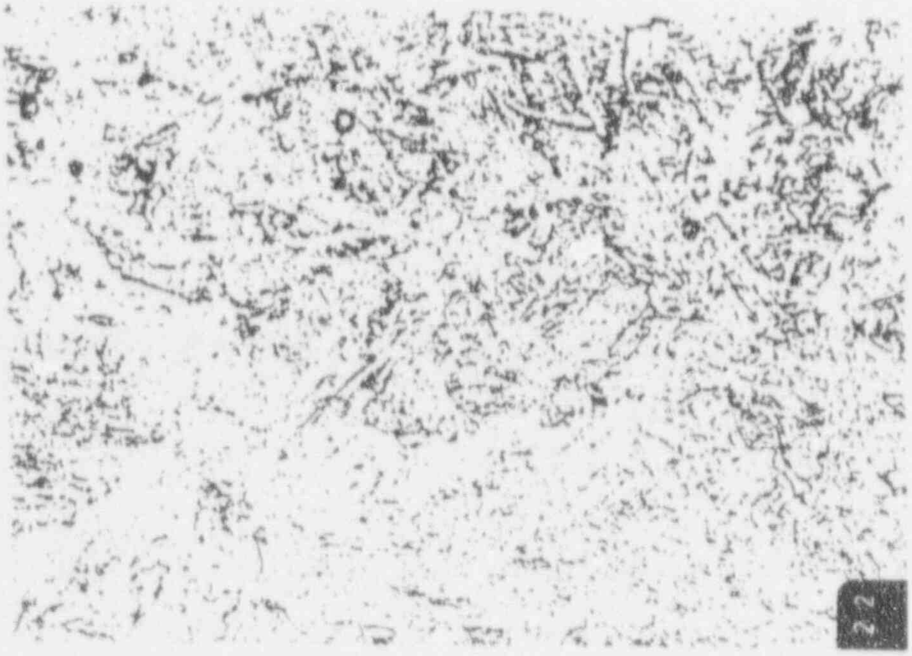


Figure: IV-10. Weld Metal (Longitudinal Section). Enlarged View of Ferritic Structure Showing Good Carbide Distribution. Vilella's Etch. 1000x

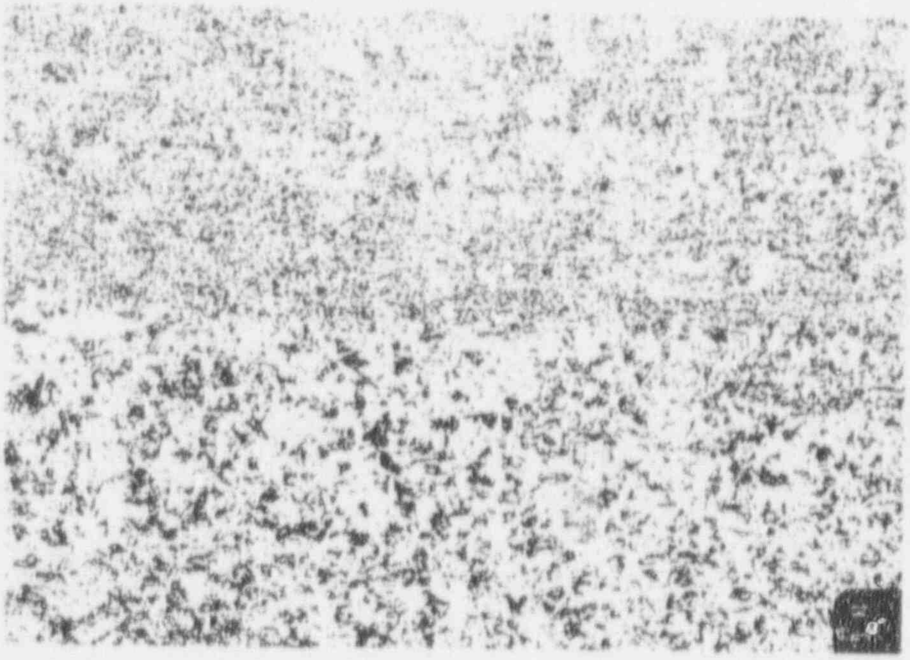


Figure: IV-11. HAZ Metal with Transition from Bainitic Base Metal (Large Grain) to Ferritic Weld Structure. Vilella's Etch. 100x

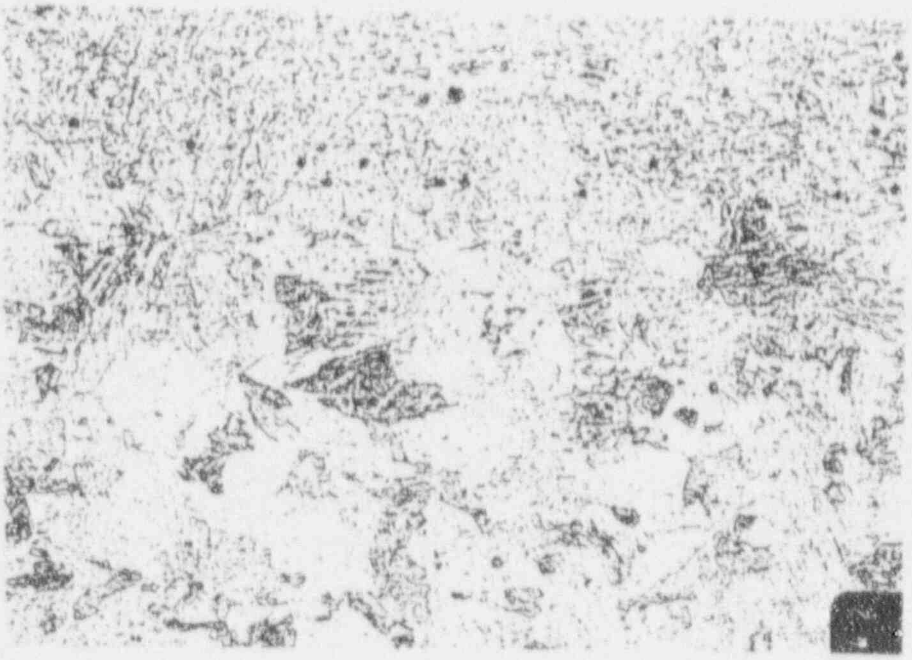


Figure: IV-12. Enlarged View of HAZ Metal Fusion Line of Bainitic Base Metal Grains to Ferritic Grains of Weld. Vilella's Etch. 500x

V. DROP WEIGHT TEST RESULTS

All drop weight tests were conducted according to applicable procedures outlined in the OPPD Test Plan No. 23866-TP-MCD-002. These tests were performed to determine the nil-ductility transition temperature (NDTT) for base metal (RW)*. The results are presented in Table V-1. Drop weight specimens were not available for weld metal and HAZ metal, so the NDTT was determined in accordance with Branch Technical Position METB 5-2, "Fracture Toughness Requirements for Older Plants". MTEB 5-2 states that NDTT "may be assumed to be the temperature at which 30 ft-lb was obtained in Charpy V-notch tests, or 0°F, whichever was higher".

Figure V-1 shows the fracture surfaces of the drop weight specimens. The fracture surface was obtained by heat-tinting the tested specimen, subcooling it in liquid nitrogen, followed by final breakage using the procedure described in Appendix A. The heat-tinted (dark) area of the fracture surface is the original fracture zone (resulting from the test). The lighter untinted area shows the zone of final separation after subcooling.

TABLE V-1

DROP WEIGHT TEST RESULTS

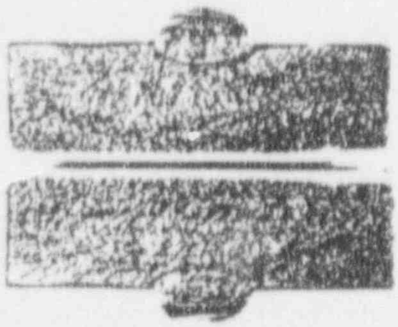
Material	Specimen No.	Individual Test Results	NDTT
Base Metal	1C7	-20°F - Break	
Plate D-4802-2	1C2	-10°F - No Break	-20°F
RW	1C3	-10°F - No Break	
	1C4	0°F - No Break	

*ASTM E 208-69 states that the drop weight test is insensitive to specimen orientation, so transverse (WR) and longitudinal (RW) NDTT are considered equivalent in the determination of RT_{NDT}. Therefore, the NDTT derived from longitudinally oriented drop weight specimens can be used with transverse Charpy impact data to establish RT_{NDT}.

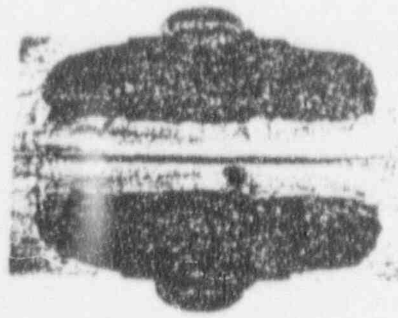
FIGURE V-1

DROP WEIGHT SPECIMEN FRACTURE SURFACES

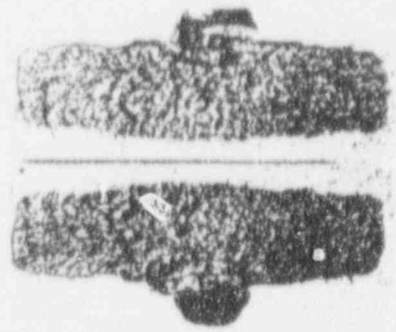
BASE METAL PLATE D-4802-2 (RW)



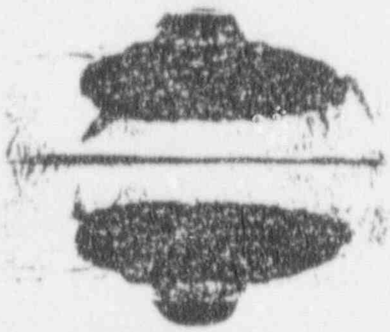
Specimen Code: 1C7
Test Temperature: -20°F
Test Result: Break



Specimen Code: 1C2
Test Temperature: -10°F
Test Result: No Break



Specimen Code: 1C3
Test Temperature: -10°F
Test Result: No Break



Specimen Code: 1C4
Test Temperature: 0°F
Test Result: No Break

VI. TENSILE TEST RESULTS

Tensile tests were conducted according to applicable procedures outlined in the OPPD Test Plan No. 23866-TP-MCD-002. The tests were performed at room temperature (71°F), 250°F and 550°F for base metal (WR and RW), weld metal and HAZ metal. The tensile test data are reported in Tables VI-1 through VI-4, including yield strength, tensile strength, fracture load, fracture strength, fracture stress, reduction in area, uniform elongation and total elongation. The 0.2 percent offset method was used to determine yield strength for those tests that did not exhibit upper and lower yield points. Stress versus strain diagrams have been prepared for typical tests for each material and test temperature. They are presented in Figures VI-1 through VI-12. Photographs of the fracture region and fracture surface of these specimens are presented in Figures VI-13 through VI-16. A description of the test equipment is given in Appendix B.

TABLE VI-1

TENSILE PROPERTIES

BASE METAL PLATE D-4802-2 (WR)

Specimen Code	Test Temp. (°F)	Yield Strength 0.2% or Upper/Lower (ksi)	Ultimate Tensile Strength (ksi)	Fracture Load (lb)	Fracture Strength (ksi)	Fracture Stress (ksi)	Reduction of Area (%)	Elongation (1-inch gage) TE/UE (%)
2D7	71	66.[illegible]/54.3	86.5	2880	58.8	169	65.3	29/11.6
2DU	71	69.2/[illegible]5.1	89.1	2940	60.0	184	67.3	28/11.7
2E1	71	70.4/67.4	90.6	2880	58.8	180	67.3	28/11.3
2E2	250	63.7/62.5	83.0	2760	56.3	173	67.3	25/9.3
2E3	250	64.9/62.5	83.8	2640	53.[illegible]	176	69.3	25/9.6
2DC	250	62.5/60.0	80.0	2760	56.3	162	65.3	26/10.9
2DL	550	55.7/53.9	83.9	30[illegible]	62.5	153	73.5	25/10.5
2DY	550	57.6/56.3	87.1	3120	63.7	173	63.3	23/10.0
2DD	550	55.1/53.9	83.3	2880	58.8	169	65.3	24/9.6

TABLE VI-2

TENSILE PROPERTIES

BASE METAL PLATE D-4302-2 (RW)

Specimen Code	Test Temp. (°F)	Yield Strength 0.2% or Upper/Lower (ksi)	Ultimate Tensile Strength (ksi)	Fracture Load (lb)	Fracture Strength (ksi)	Fracture Stress (ksi)	Reduction of Area (%)	Elongation (1-inch gage) TE/UE (%)
1D5	71	72.2/68.0	91.1	2760	56.3	184	69.4	26/10.1
1E4	71	68.6/63.7	85.5	2640	53.9	189	71.4	31/11.[illegible]
1EP	71	71.6/68.6	90.9	2820	57.6	188	69.4	28/11.1
1DB	250	64.9/63.1	83.8	2580	52.7	172	69.4	26/10.0
1DJ	250	63.7/61.2	81.0	2520	51.4	194	73.5	26/10.2
1D6	250	64.9/63.7	84.1	2640	53.9	203	73.5	25/9.6
1EU	550	58.8/56.3	89.3	2940	60.0	184	67.3	24/10.5
1DZ	550	56.9/55.1	85.7	2760	56.3	173	67.3	22/10.0
1E3	550	55.1/53.9	81.9	2640	53.9	176	69.4	25/10.3

TABLE VI-3

TENSILE PROPERTIES

WELD METAL, PLATE D-4802-1/D-4802-3

Specimen Code	Test Temp. (°F)	Yield Strength 0.2% or Upper/Lower (ksi)	Ultimate Tensile Strength (ksi)	Fracture Load (lb)	Fracture Strength (ksi)	Fracture Stress (ksi)	Reduction of Area (%)	Elongation (1-inch gage) TE/UE (%)
3EP	71	75.3/73.5	90.3	2760	56.3	184	69.4	27/10.0
3EJ	71	74.7/72.2	88.9	2760	56.3	184	69.4	29/10.1
3JA	71	83.9/76.5	91.4	2760	56.3	197	71.4	29/10.6
3EY	250	72.3/69.8	83.5	2580	52.7	172	69.4	25/8.3
3DU	250	69.2/68.6	83.5	2700	55.1	180	69.4	22/8.2
3DP	250	74.7/68.6	82.4	2520	51.4	180	71.4	24/8.7
3DZ	550	68.0/66.1	87.0	3180	64.9	159	59.2	21/9.0
3JK	500	63.7/62.5	83.8	2880	58.8	160	63.3	22/9.3
3E7	550	66.1/63.7	84.7	2880	58.8	169	65.3	23/9.3

TABLE VI-4

TENSILE PROPERTIES

HAZ METAL, PLATE D-4802-2

Specimen Code	Test Temp. (°F)	Yield Strength 0.2% or Upper/Lower (ksi)	Ultimate Tensile Strength (ksi)	Fracture Load (lb)	Fracture Strength (ksi)	Fracture Stress (ksi)	Reduction of Area (%)	Elongation (1-inch gage) TE/UE (%)
4E3	71	64.9/61.2	84.2	3120	63.7	156	59.2	21/10.1
4DJ	71	66.1/63.7	86.9	2820	57.6	176	67.3	22/9.8
4EM	71	69.0/64.2	84.1	2580	52.7	172	70.0	29/10.2
4DL	250	60.0/58.8	79.8	2760	56.3	162	65.3	20/8.1
4DE	250	61.2	80.3	2700	55.1	150	63.3	21/8.0
4DK	250	58.8/58.1	79.4	2880	58.8	152	61.2	19/8.3
4EL	550	54.0/52.8	80.7	2880	58.8	169	60.0	22/8.3
4E5	550	52.7/51.4	81.3	3120	63.7	149	57.1	18/8.7
4D7	550	54.0/52.8	83.5	2940	58.8	163	64.0	24/9.2

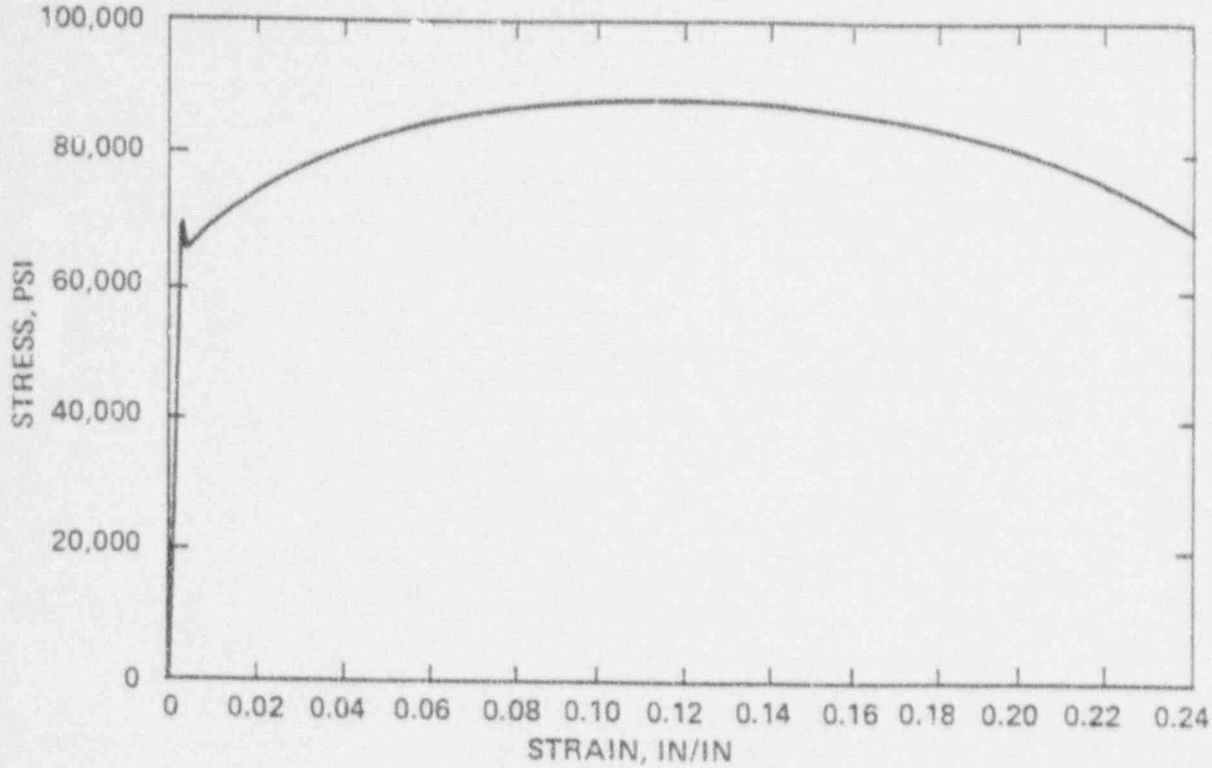


Figure VI-1: Stress-Strain Record of Tensile Test
Base Metal Plate D-4802-2 (WR)
Specimen No. 2DU, Test Temperature: R.T.

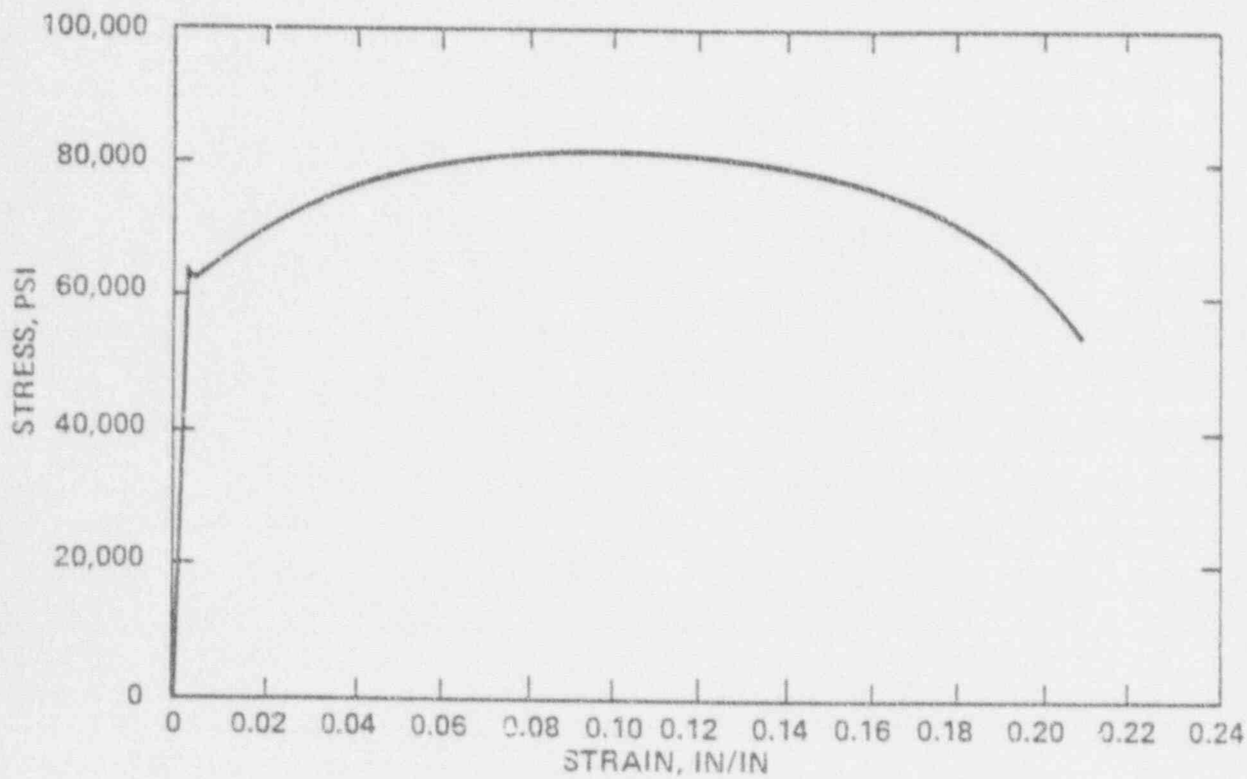


Figure VI-2: Stress-Strain Record of Tensile Test
Base Metal Plate D-4802-2 (WR)
Specimen No. 2E2, Test Temperature: 250°F

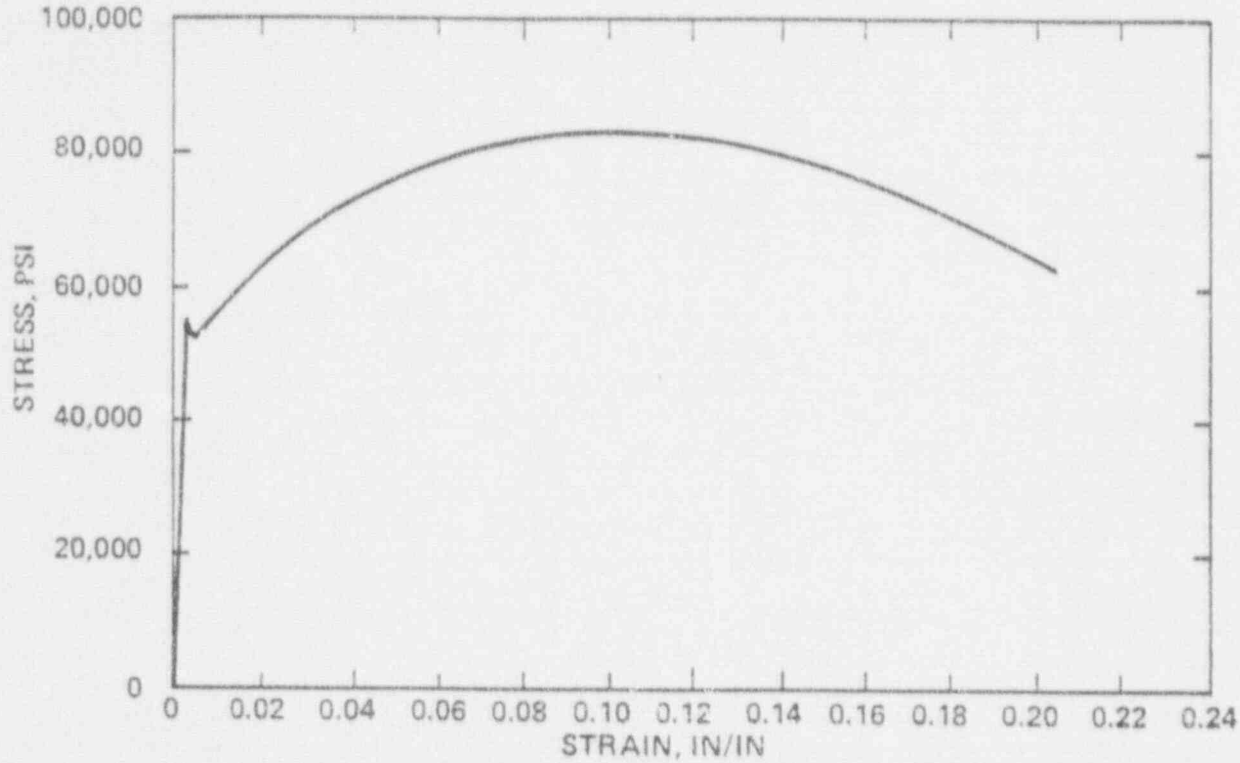


Figure VI-3: Stress-Strain Record of Tensile Test
Base Metal Plate D-4802-2 (WR)
Specimen No. 2DL., Test Temperature: 550°F

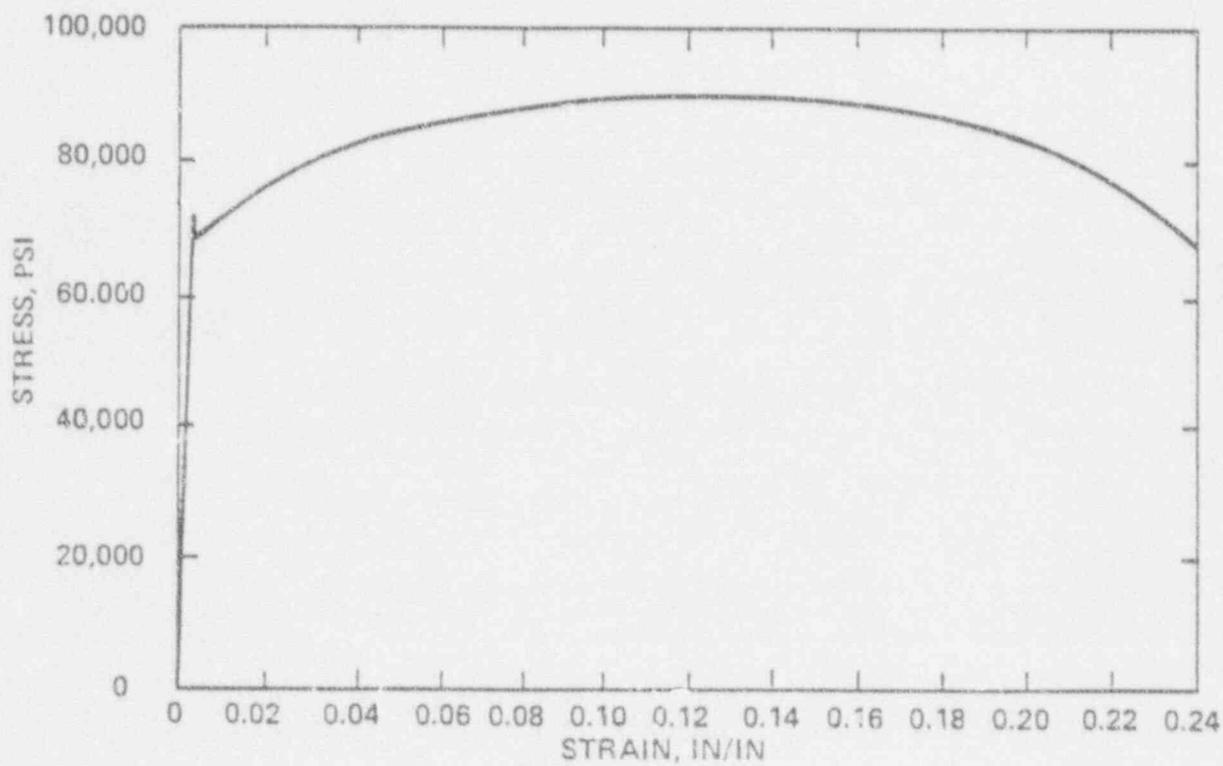


Figure VI-4: Stress-Strain Record fo Tensile Test
Base Metal Plate D-4802-2 (RW)
Specimen No. 1EP, Test Temperature: R.T.

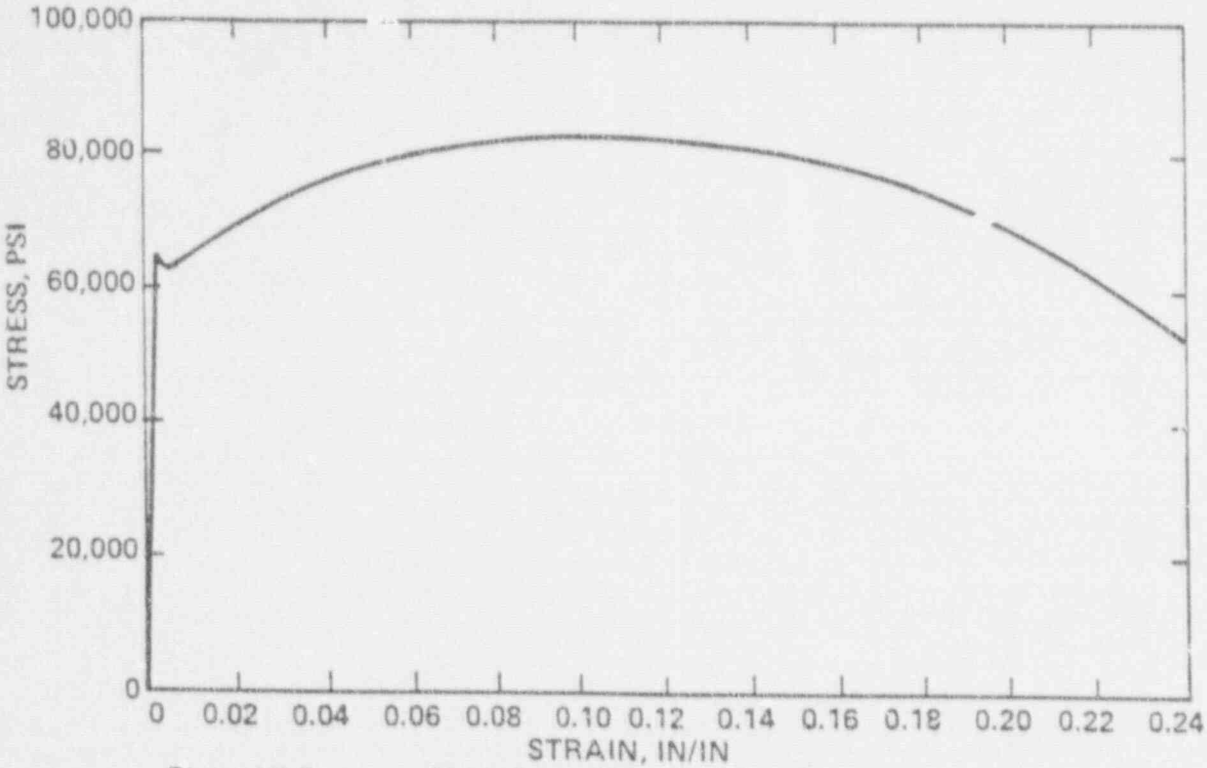


Figure VI-5: Stress-Strain Record of Tensile Test
Base Metal Plate D-4802-2 (RW)
Specimen No. 1DB, Test Temperature: 250°F

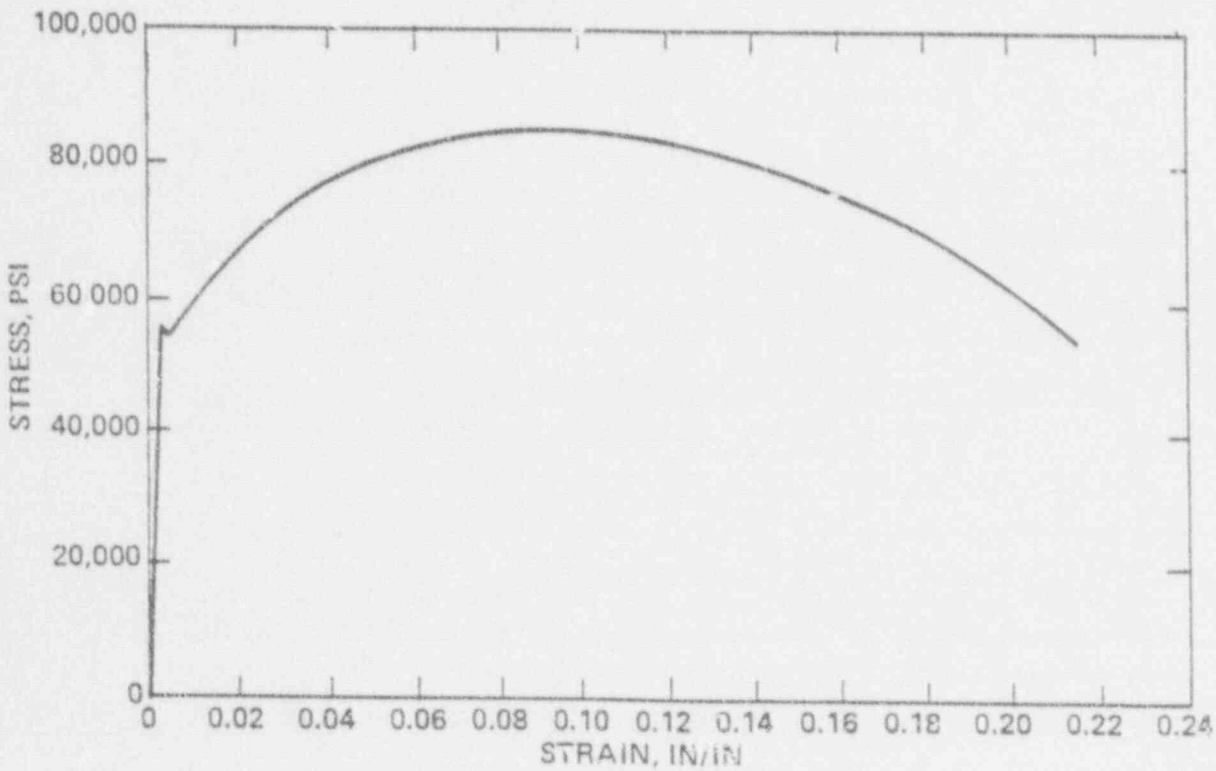


Figure VI-6: Stress-Strain Record of Tensile Test
Base Metal Plate D-4802-2 (RW)
Specimen No. 1DE, Test Temperature: 550°F

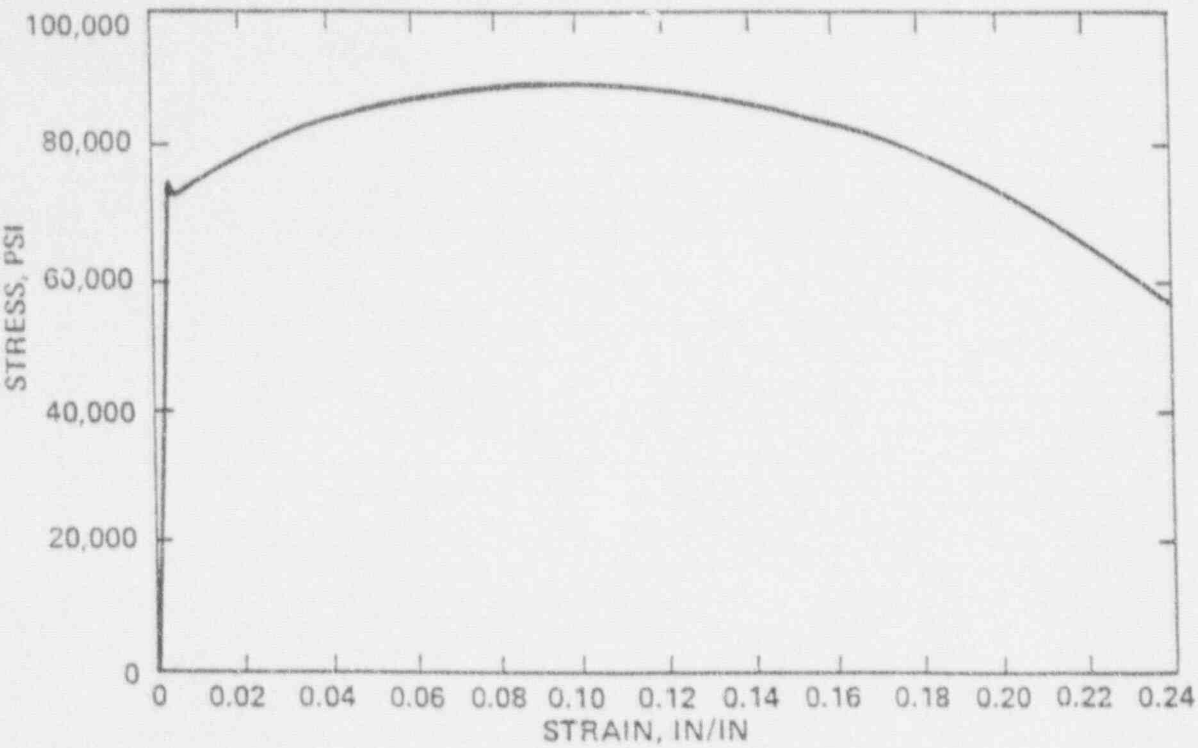


Figure VI-7: Stress-Strain Record of Tensile Test
Weld Metal Plate D-4802-1 / D-4802-3
Specimen No. 3EP, Test Temperature : R.T.

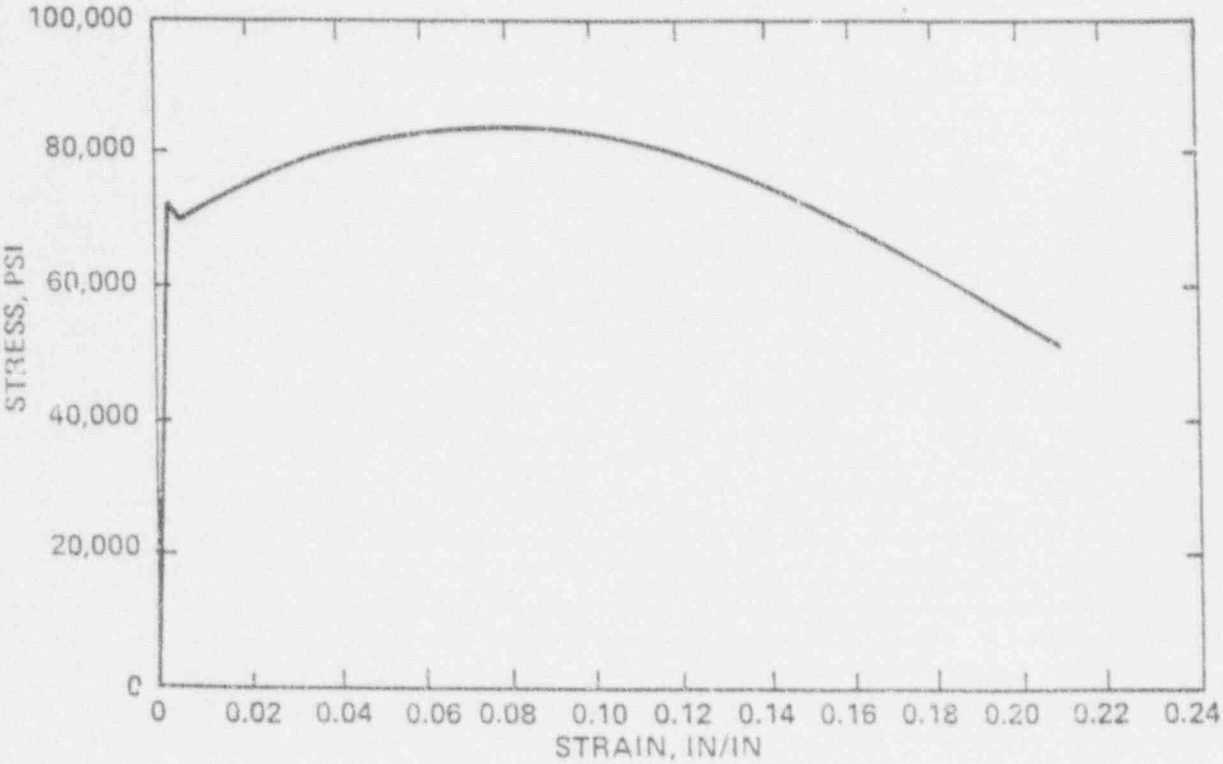


Figure VI-8: Stress-Strain Record of Tensile Test
Weld Metal Plate D-4802-1 / D-4802-3
Specimen No. 3EY, Test Temperature: 250°F

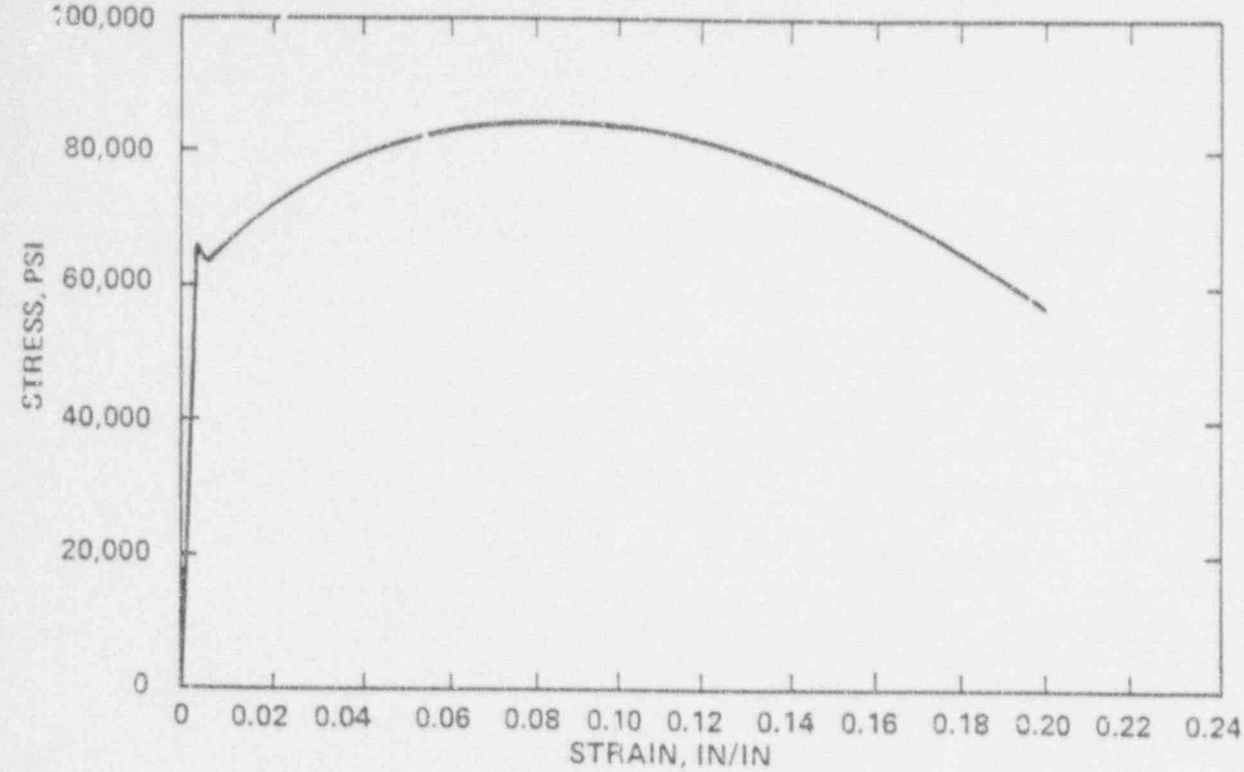


Figure VI-9: Stress-Strain Record of Tensile Test
Weld Metal Plate D-4802-1 / D-4802-3
Specimen No. 3E7, Test Temperature: 550°F

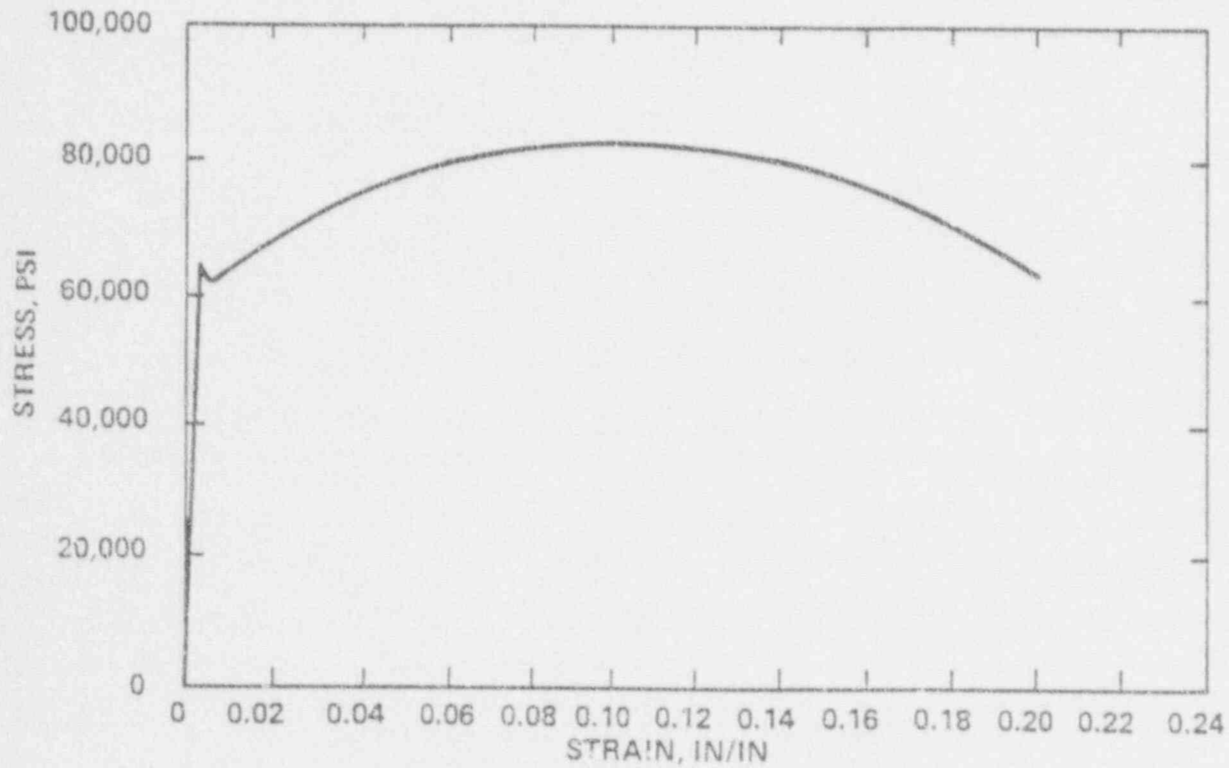


Figure VI-10: Stress-Strain Record of Tensile Test
H.A.Z. Metal Plate D-4802-2
Specimen No. 4E3, Test Temperature: R.T.

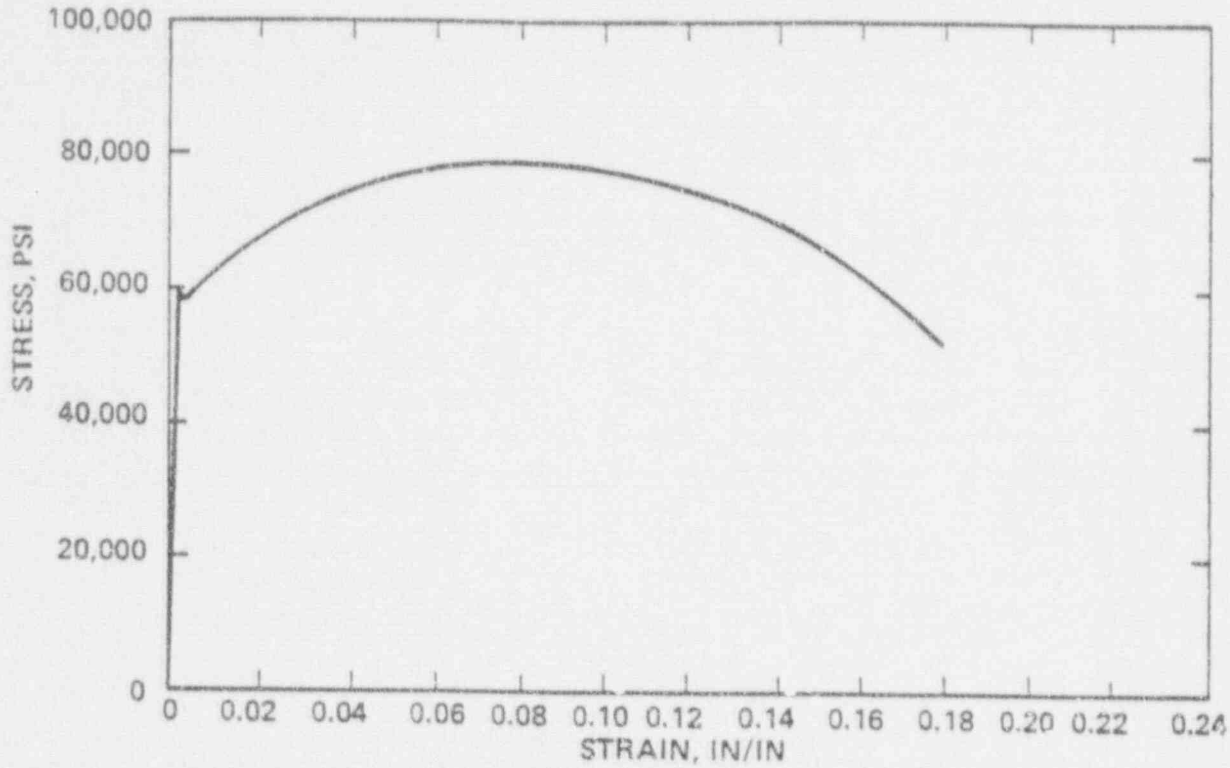


Figure VI-11: Stress-Strain Record of Tensile Test
H.A.Z. Metal Plate D-4802-2
Specimen No. 4DL, Test Temperature: 250°F

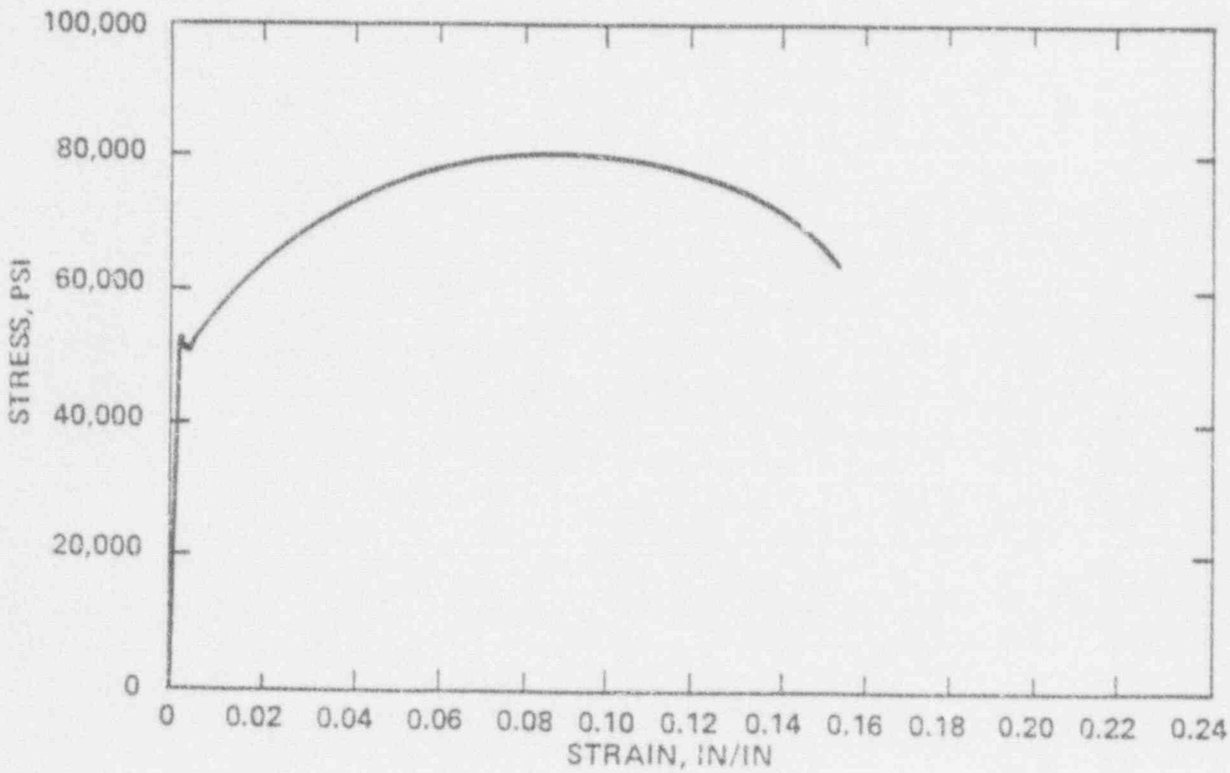


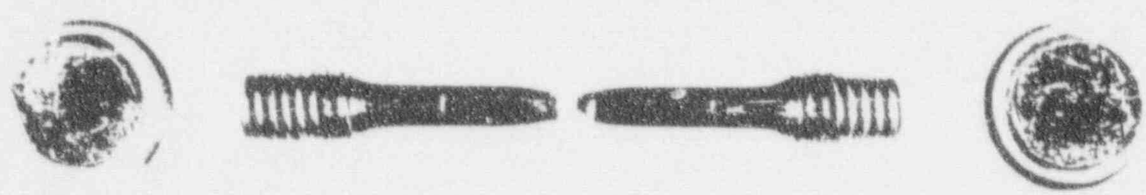
Figure VI-12: Stress-Strain Record of Tensile Test
H.A.Z. Metal Plate D-4802-2
Specimen No. 4E5, Test Temperature: 550°F

FIGURE VI-13

TENSILE SPECIMEN FRACTURE SURFACES
BASE METAL PLATE D-4802-2 (WR)

Specimen No. 2DU, Test Temp. 71°F

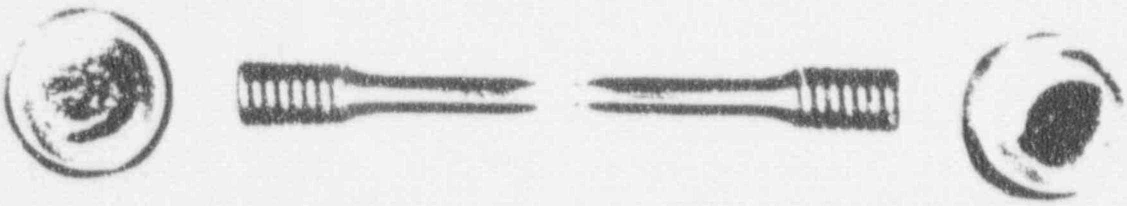
Specimen No. 2E2, Test Temp. 250°F



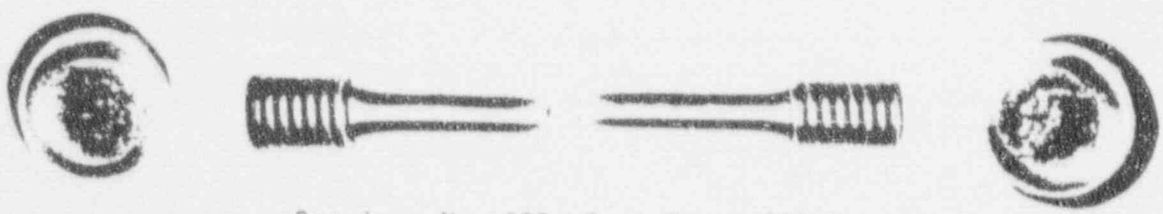
Specimen No. 2DL, Test Temp. 550°F

FIGURE VI-14

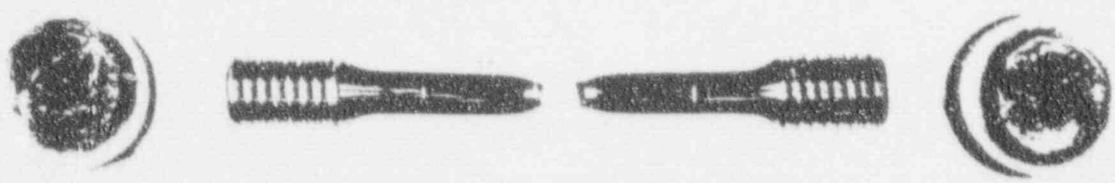
TENSILE SPECIMEN FRACTURE SURFACES
BASE METAL PLATE D-4802-2 (RW)



Specimen No. 1EP, Test Temp. 71°F



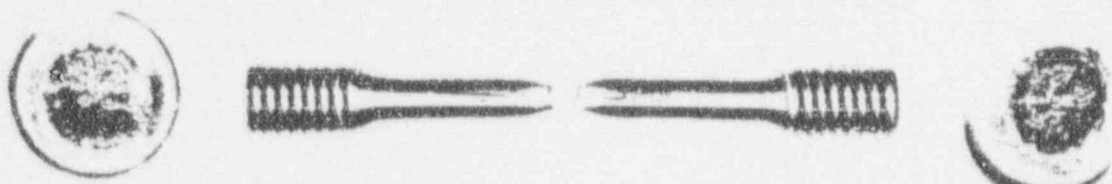
Specimen No. 1DB, Test Temp. 250°F



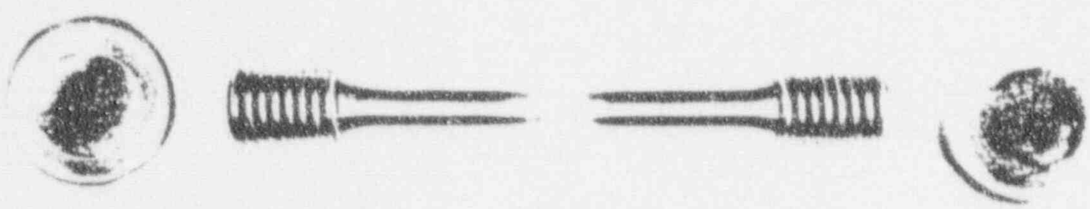
Specimen No. 1DE, Test Temp. 550°F

FIGURE VI-15

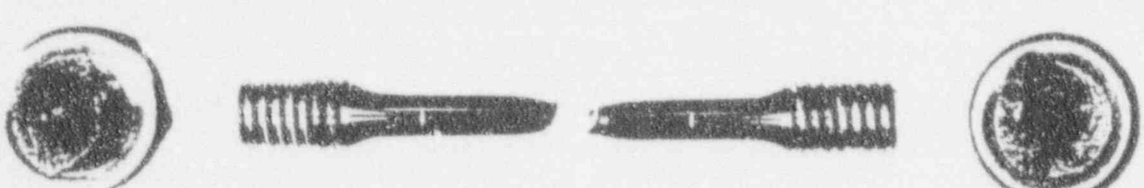
TENSILE SPECIMEN FRACTURE SURFACES
WELD METAL, PLATE D-4802-1/D-4802-3



Specimen No. 3EP, Test Temp. 71°F



Specimen No. 3EY, Test Temp. 250°F



Specimen No.3E7, Test Temp. 550°F

FIGURE VI-16

TENSILE SPECIMEN FRACTURE SURFACES
HAZ METAL, PLATE D-4802-2

Specimen No. 4E3, Test Temp. 71°F

Specimen No. 4DL, Test Temp. 250°F

Specimen No. 4E5, Test Temp. 550°F

VII. CHARPY IMPACT TEST RESULTS

The instrumented Charpy (IC_V) impact tests were performed in accordance with applicable procedures outlined in the OPPD Test Plan No. 23866-TP-MCD-002.

Tests were performed on base metal (WR and RW), weld metal and HAZ metal. For each material, both standard and instrumented Charpy impact data were determined. The standard C_V data are reported in Tables VII-1, -3, -5 and -7 including the RT_{NDT}, determined from lower bound impact test results, and the NDTT from drop weight test results. From the oscilloscope trace for each impact test, the loads corresponding to yielding, maximum load and fracture were determined (refer to Section III) as shown in Tables VII-2, -4, -6 and -8. The data from Tables VII-1 through VII-8 are shown as a function of test temperature in Figures VII-1 through VII-16. From these curves, the brittle transition temperature (T_B), the ductility transition temperature (T_N) and the ductility temperature (T_D) were determined as shown in Figure III-3 in Section III. These temperatures as well as RT_{NDT}, NDTT and the upper shelf energy (minimum impact energy corresponding to 100 percent shear for two tests at one test temperature) are reported in the IC_V tables for each material. (Note that RT_{NDT} for longitudinally oriented base metal materials is not strictly valid and provided for reference purposes only). Fix temperatures, as reported in Sections II and IX, were determined from the lower bound curves for 50 ft-lb and 35 mils lateral expansion and from the average curves for 30 ft-lb.

Figures VII-1 through VII-16 present impact load, impact energy, lateral expansion and shear, all as a function of test temperature. Fracture surface photographs and oscilloscope traces for typical specimens from each test series are provided in Figures VII-17 through VII-36.

A description of the testing equipment is given in Appendix C.

TABLE VII-1

IMPACT TEST RESULTS

BASE METAL PLATE D-4802-2 (WR)

Specimen No.	Test Temp. (°F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear %
23D	-80	4	3	0
23E	-40	6.5	8	10
22P	-40	8.5	10	10
233	0	17	18	20
247	0	26.5	27	25
21E	40	30	30	30
21U	40	32	32	30
21C	80	60	43	40
22T	80	62.5	53	55
242	120	78.5	66	60
21B	120	96.5	74	75
22C	160	94.5	76	90
23B	160	102.5	74	95
21T	190	121	85	100
22U	210	122.5	83	100
24D	210	125	84	100
217	230	110.5	83	100

RT_{NDT} = 18°F (Determined from lower bound curve)

NDTT = -20°F

Upper Shelf Energy = 121 ft-lb

TABLE VII-2

INSTRUMENTED IMPACT TEST RESULTS

BASE METAL PLATE D-4802-2 (WR)

Specimen No.	Test Temp. (°F)	Impact Energy Dial (ft-lb)	Impact Loads		
			P_{GY} (lb)	P_M (lb)	P_F (lb)
23D	-80	4	--	--	2800
23E	-40	6.5	--	--	3200
22P	-40	8.5	--	--	3500
233	0	17	3100	3500	--
247	0	26.5	3100	3900	--
21E	40	30	2800	3600	--
21U	40	32	2900	3700	--
21C	80	60	2800	3800	--
22T	80	62.5	2800	4000	3900
242	120	78.5	2700	3800	3700
21B	120	96.5	2700	3800	3400
22C	160	94.5	2600	3700	--
23B	160	102.5	2500	3700	--
21T	190	121	2400	3600	--
22U	210	122.5	2500	3700	--
24D	210	125	2400	3500	--
217	230	110.5	2400	3600	--

T_B = -40°F

T_N = 80°F

T_D = 160°F

TABLE VII-3

IMPACT TEST RES' .S

BASE METAL PLATE D-[illegible]-2 (RW)

Specimen No.	Test Temp. (°F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear (%)
12D	-80	4.5	1	0
15K	-40	7	8	10
13J	-40	9	8	10
15P	0	20.5	21	20
13E	0	25.5	24	25
11C	40	41.5	38	35
162	40	45.5	39	35
11M	80	78	62	50
151	80	79	60	50
11P	120	115	85	80
12E	120	132.5	90	85
11D	160	137.5	94	100
11T	160	140	93	100
13Y	190	147.5	90	100
11E	210	133.5	90	100
15L	210	144.5	90	100

RT_{NDT} = -8°F (Determined from lower bound curve)

NDTT = -20°F

Upper Shelf Energy = 137.5 ft-lb

TABLE VII-4

INSTRUMENTED IMPACT TEST RESULTS

BASE METAL PLATE D-4802-2 (RW)

Specimen No.	Test Temp. (°F)	Impact Energy Dial (ft-lb)	Impact Loads		
			P_{GY} (lb)	P_M (lb)	P_F (lb)
12D	-80	4.5	--	--	3100
15K	-40	7	--	--	3400
13J	-40	9	--	--	3500
15P	0	20.5	3200	3600	--
13E	0	25.5	3300	3900	--
11C	40	41.5	3100	4000	--
162	40	45.5	3000	4000	--
11M	80	78	2700	3900	3700
151	80	79	2700	3800	3700
11P	120	115	2600	3800	2800
12E	120	[illegible]	2600	4000	2400
11D	160	137.5	2600	3800	--
11T	160	140	2600	3700	--
13Y	190	147.5	2600	3800	--
11E	210	133.5	2400	3800	--
15L	210	144.5	2400	3700	--

T_B = -22°F

T_N = 52°F

T_D = 120°F

TABLE VII-5

IMPACT TEST RESULTS

WELD METAL, PLATE D-4802-1/D-4802-3

Specimen No.	Test Temp. (°F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear (%)
364	-120	5.5	4	0
35U	-80	5.5	9	10
32Y	-80	18.5	17	15
332	-40	20.5	21	30
31L	-40	30	28	35
35E	0	49.5	41	40
32E	0	55	47	50
35T	40	66.5	55	65
31Y	40	74	64	70
33C	80	97.5	83	100
324	80	105.5	86	100
35P	120	92.5	81	100
33D	120	105	89	100
346	160	105.5	83	100
31U	160	115	89	100

RT_{NDT} = 0°F (Determined from Lower Bound Curve)

NDTT = 0°F (Estimated per Branch Technical Position MTEB 5-2)

Upper Shelf Energy = 97.5 ft·lb

TABLE VII-6

INSTRUMENTED IMPACT TEST RESULTS

WELD METAL, PLATE D-4802-1/D-4802-3

Specimen No.	Test Temp. (°F)	Impact Energy Dial (ft-lb)	Impact Loads		
			P_{GY} (lb)	P_M (lb)	P_F (lb)
364	-120	5.5	--	--	3500
35U	-80	5.5	--	--	3400
32Y	-80	18.5	3400	4000	--
332	-40	20.5	3300	3800	--
31L	-40	30	3200	4000	--
35E	0	49.5	3100	4000	3800
33E	0	55	3100	4000	3900
35T	40	66.5	3000	3900	3500
31Y	40	74	3000	3800	3600
33C	80	97.5	2900	3800	--
324	80	105.5	2800	3800	--
35P	120	92.5	2700	3700	--
33D	120	105	2800	3800	--
346	160	105.5	2600	3700	--
31U	160	115	2600	3700	--

T_B = -112°F

T_N = -30°F

T_D = 80°F

TABLE VII-7

IMPACT TEST RESULTS

HAZ METAL, PLATE D-4802-2

Specimen No.	Test Temp. (°F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear (%)
444	-160	3	1	0
42L	-140	13.5	11	10
423	-115	28	23	25
43C	-80	20	20	25
46A	-80	34.5	28	25
44Y	-40	28.5	32	35
44B	-40	70.5	50	40
43D	0	83.5	68	80
431	0	110	73	80
45E	40	30.5	30	45
415	40	101.5	67	80
417	80	113.5	81	80
45D	120	65.5	60	85
416	120	126	84	90
45Y	160	82	73	100
467	160	87	68	100
466	200	93	67	100

RT_{NDT} = 24°F (Determined from lower bound curve)

NDTT = 0°F (Estimated per Branch Technical Position MTEB 5-2)

Upper Shelf Energy = 82 ft-lb

TABLE VII-8

INSTRUMENTED IMPACT TESTS RESULTS

HAZ METAL, PLATE D-4802-2

Specimen No.	Test Temp. (°F)	Impact Energy Dial (ft-lb)	Impact Loads P_{GY} (lb)	Impact Loads P_M (lb)	Impact Loads P_F (lb)
444	-160	3	--	--	2500
42L	-120	13.5	4200	4300	--
423	-115	28	4000	4300	--
43C	-80	20	3700	3900	--
46A	-80	34.5	3700	4200	--
44Y	-40	28.5	3300	3600	--
44B	-40	70.5	3300	4200	4000
43D	0	83.5	3200	4000	3800
431	0	110	3200	4200	2800
45E	40	30.5	3100	3500	--
415	40	101.5	3100	4200	3900
417	80	113.5	3000	4200	3600
45D	120	65.5	2800	3600	3200
416	120	129	2900	4100	--
45Y	160	82	2700	3800	--
467	160	87	2700	3700	--
466	200	93	2600	3700	--

T_B = -140°F

T_N = -40°F

T_D = 160°F

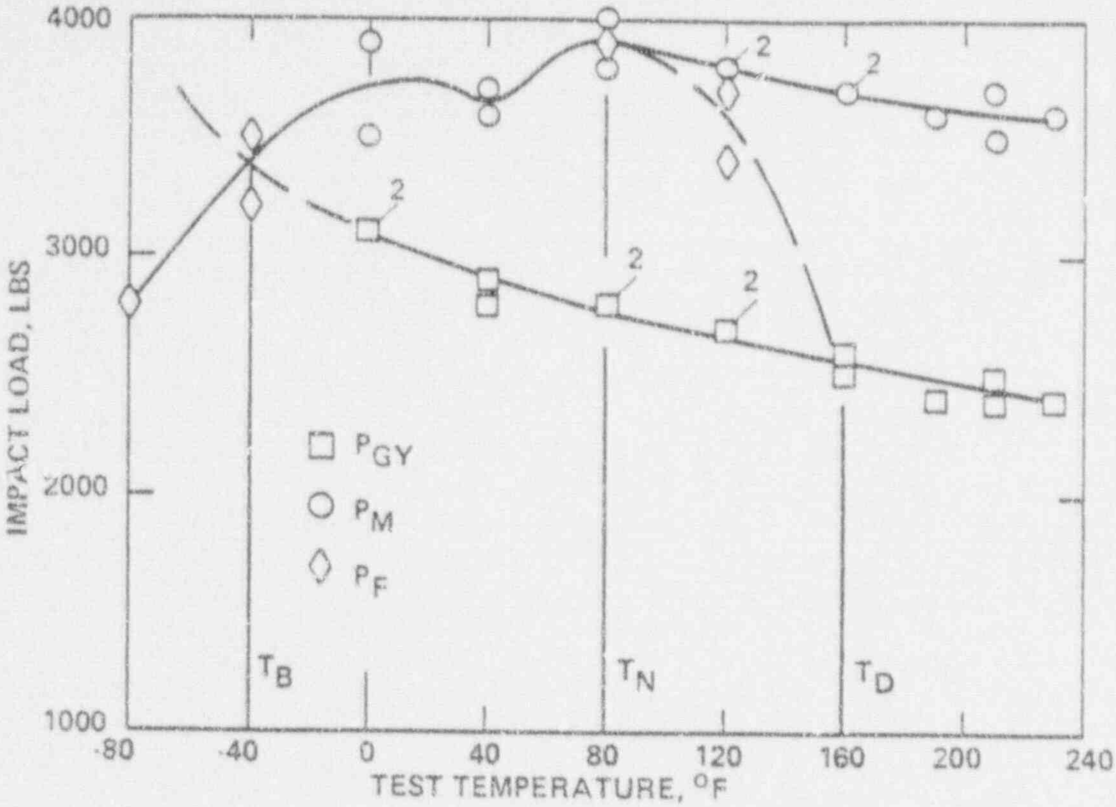


Figure VII-1: IMPACT LOAD vs TEMPERATURE
BASE METAL PLATE D-4802-2 (WR)

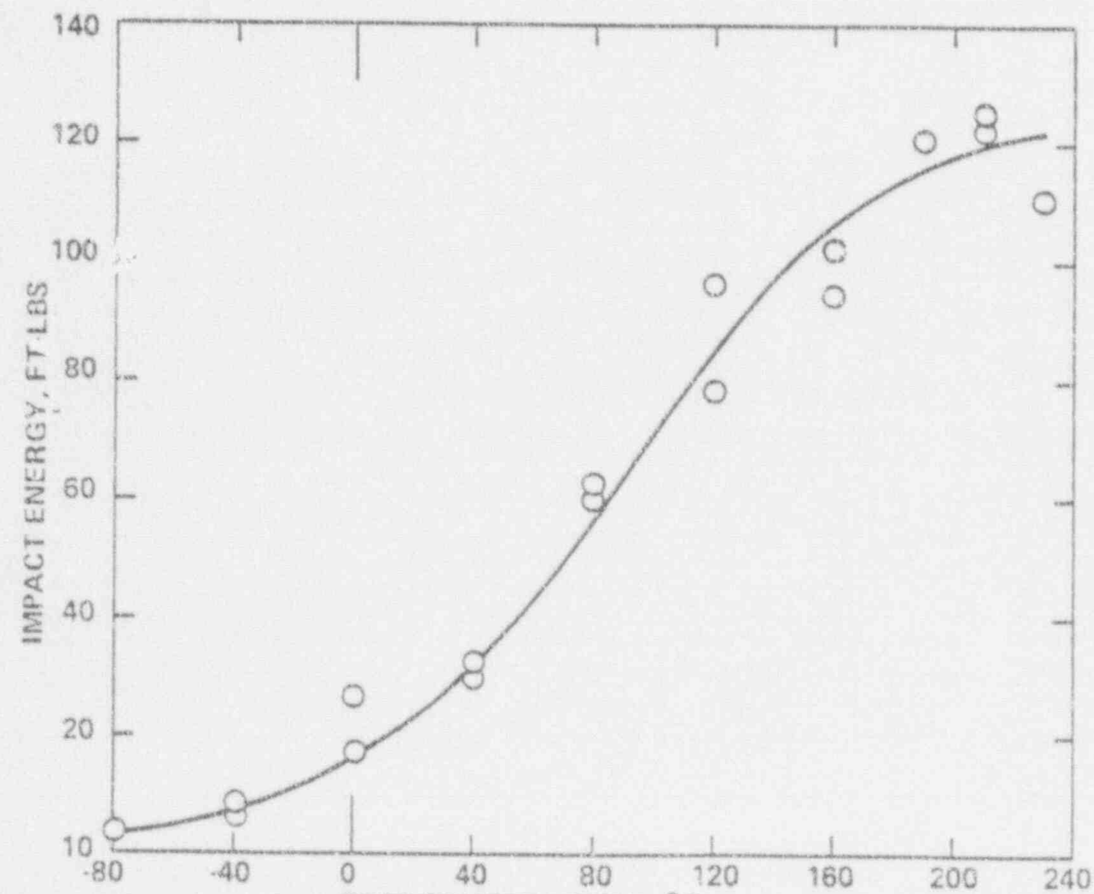


Figure VII-2: IMPACT ENERGY vs TEMPERATURE
BASE METAL PLATE D-4802-2 (WR)

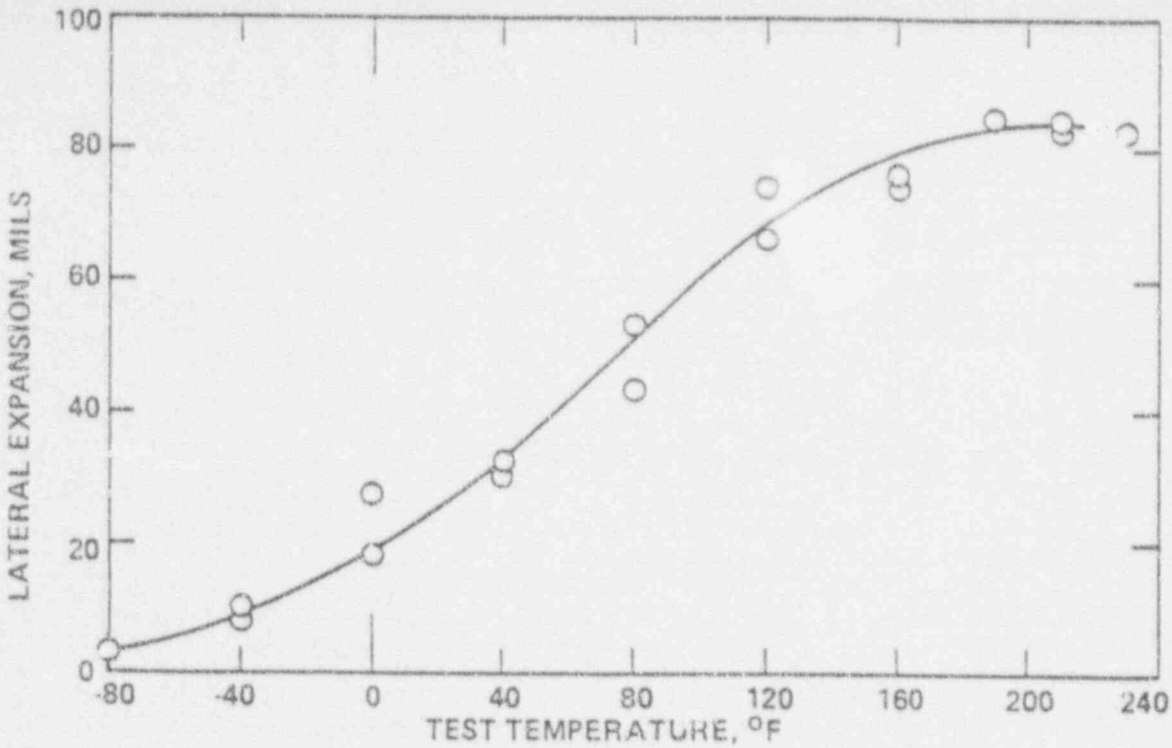


Figure VII-3: LATERAL EXPANSION vs TEMPERATURE
BASE METAL PLATE D-4802-2 (WR)

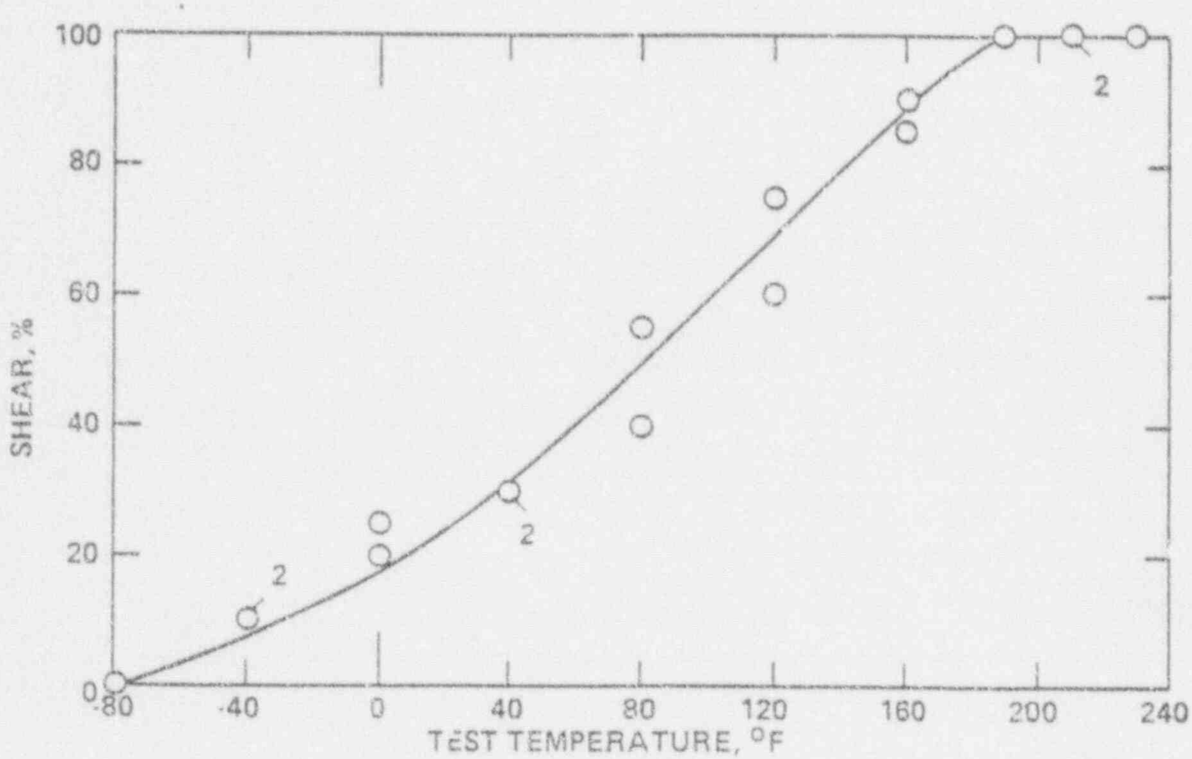


Figure VII-4: SHEAR vs TEMPERATURE
BASE METAL PLATE D-4802-2 (WR)

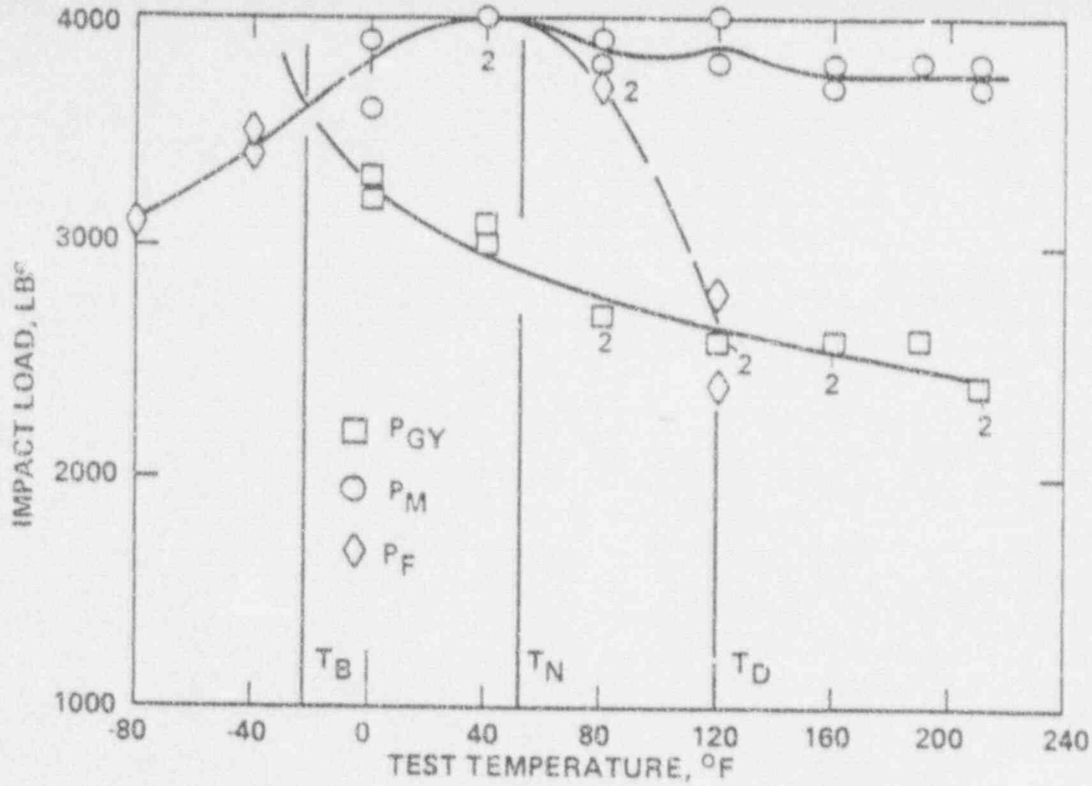


Figure VII-5: IMPACT LOAD vs TEMPERATURE
BASE METAL PLATE D-4802-2 (RW)

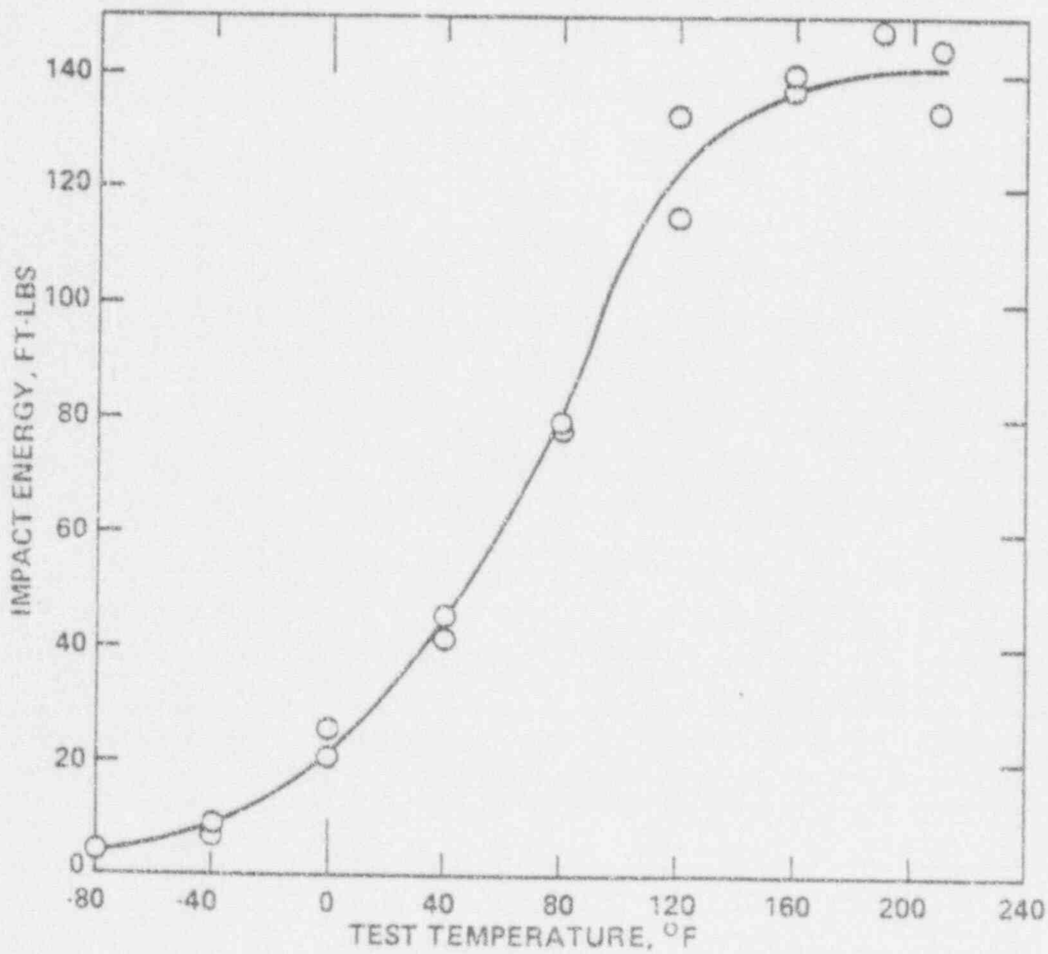


Figure VII-6: IMPACT ENERGY vs TEMPERATURE
BASE METAL PLATE D-4802-2 (RW)

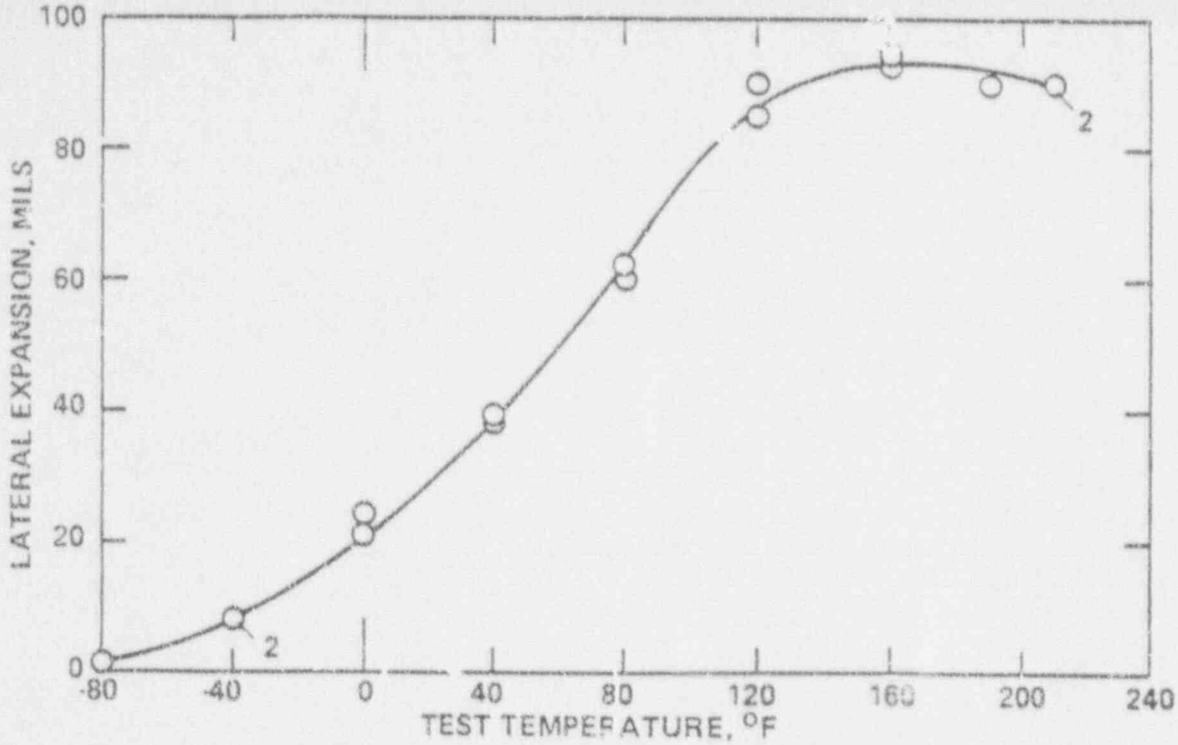


Figure VII-7: LATERAL EXPANSION vs TEMPERATURE
BASE METAL PLATE D-4802-2 (RW)

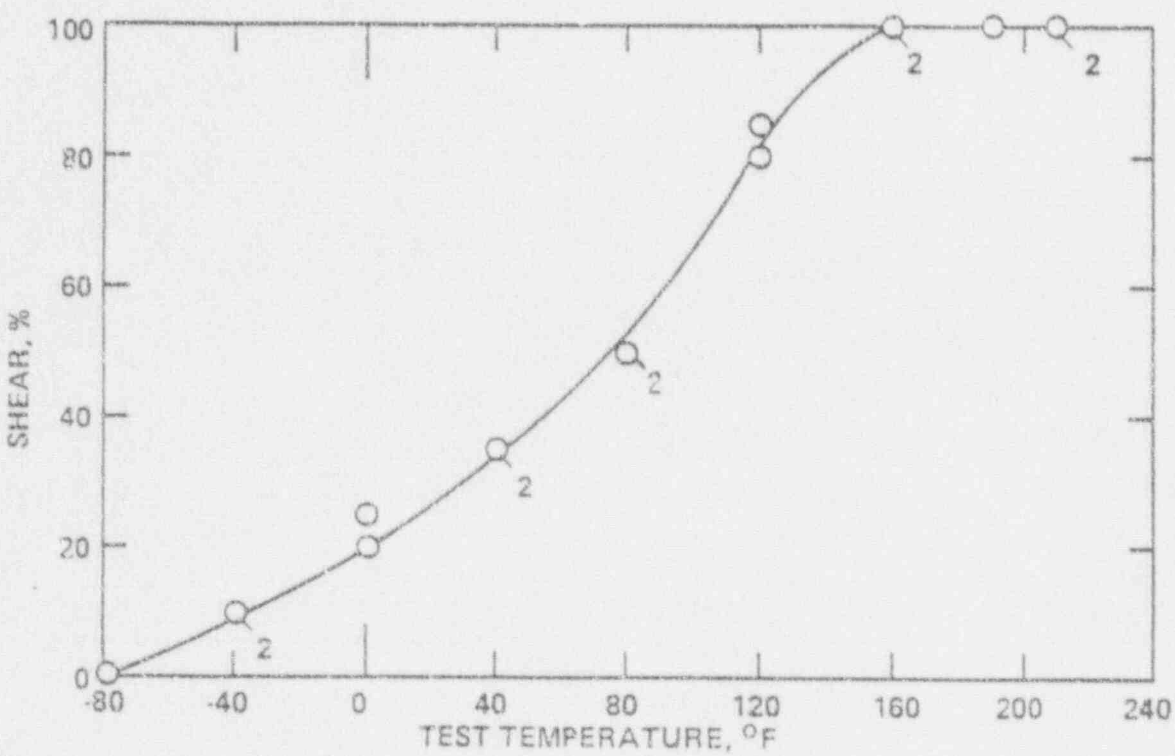


Figure VII-8: SHEAR vs TEMPERATURE
BASE METAL PLATE D-4802-2 (RW)

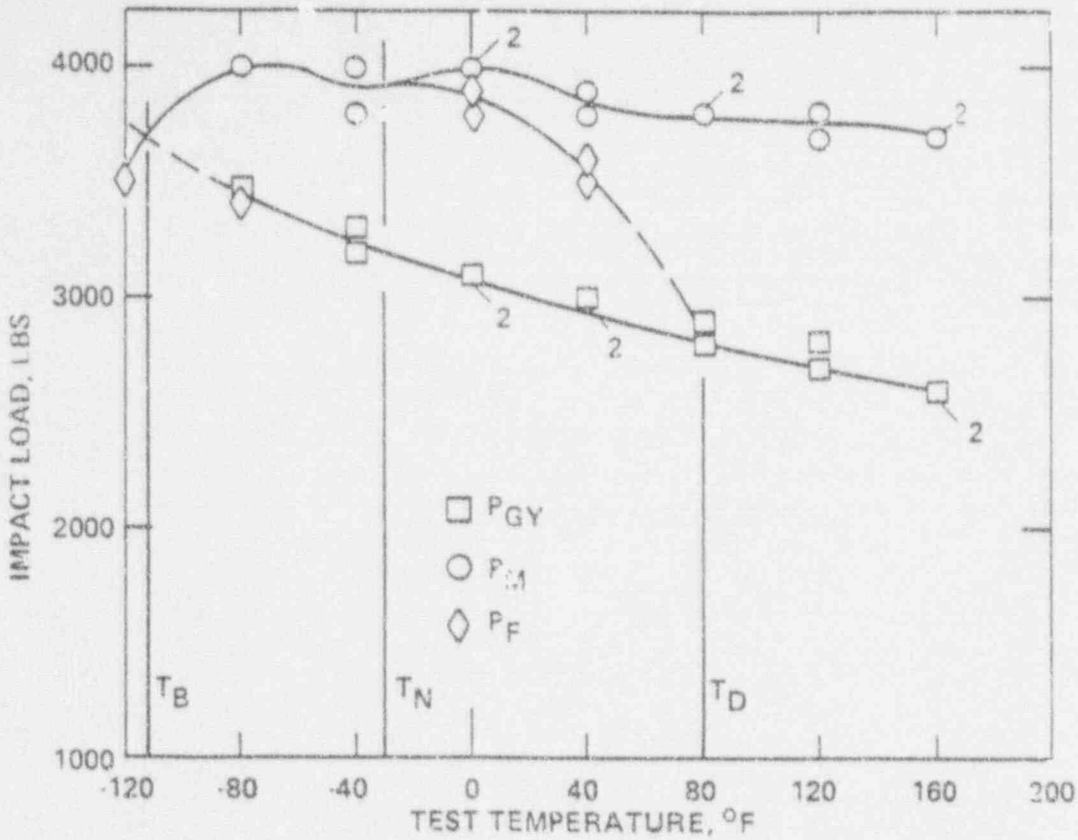


Figure VII-9: IMPACT LOAD vs TEMPERATURE
WELD METAL, PLATE D-4802-1/D-4802-3

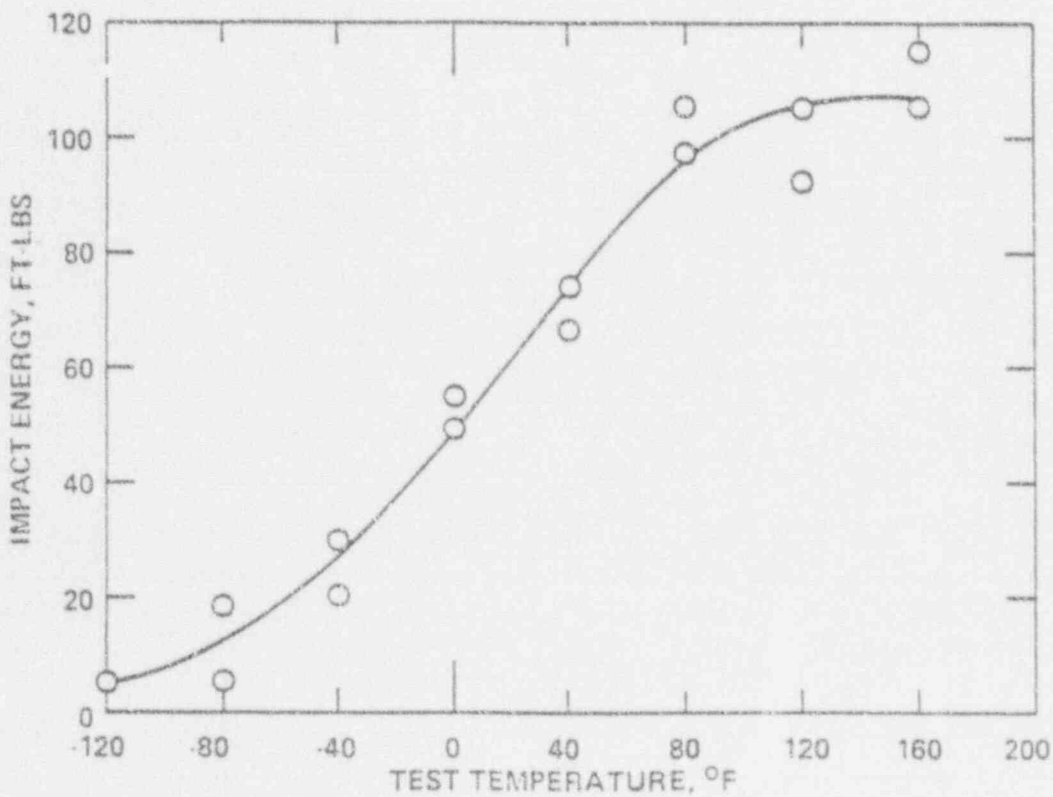


Figure VII-10: IMPACT ENERGY vs TEMPERATURE
WELD METAL, PLATE D-4802-1/D-4802-3

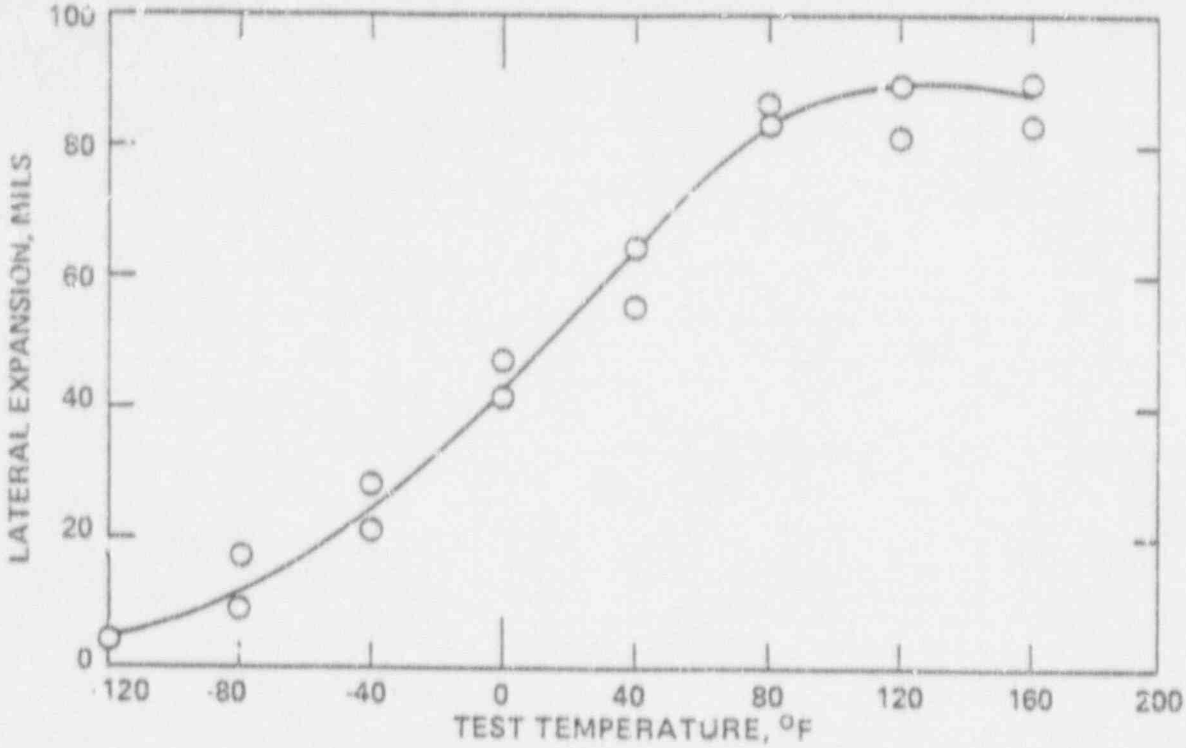


Figure VII-11: LATERAL EXPANSION vs TEMPERATURE
WELD METAL, PLATE D-4802-1/D-4802-3

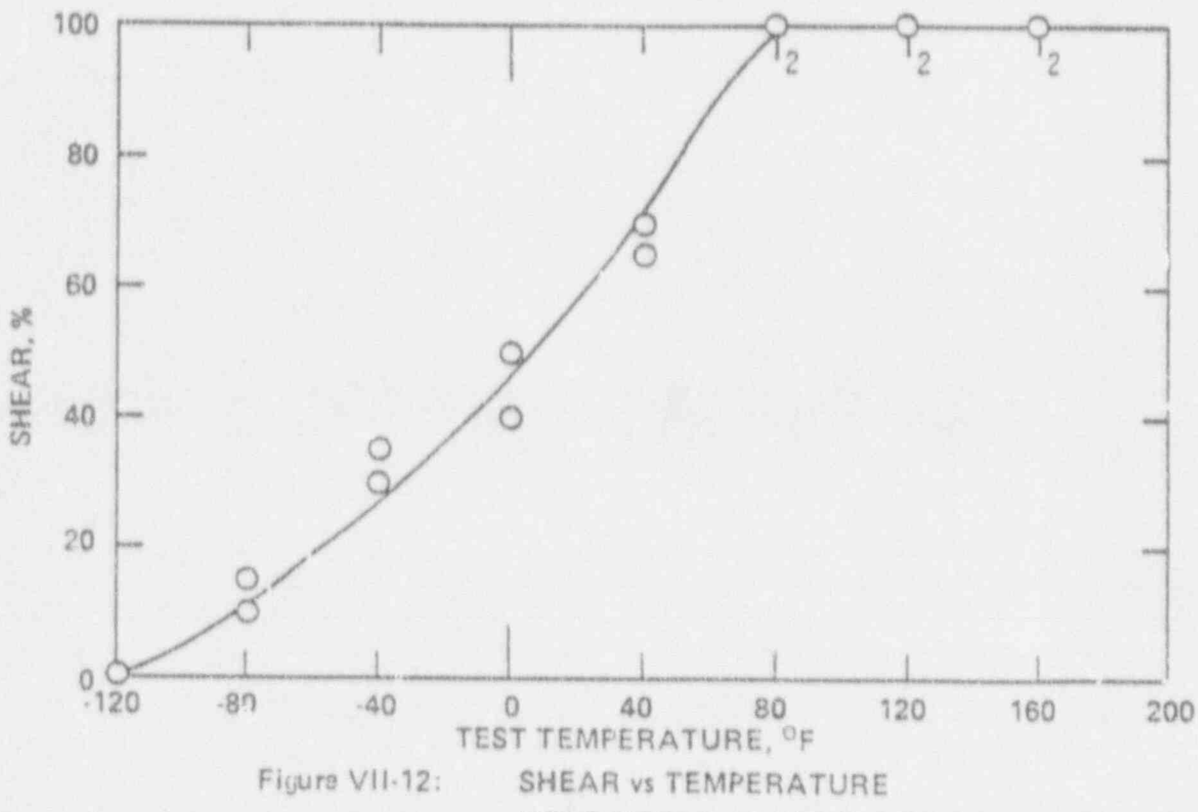


Figure VII-12: SHEAR vs TEMPERATURE
WELD METAL, PLATE D-4802-1/D-4802-3

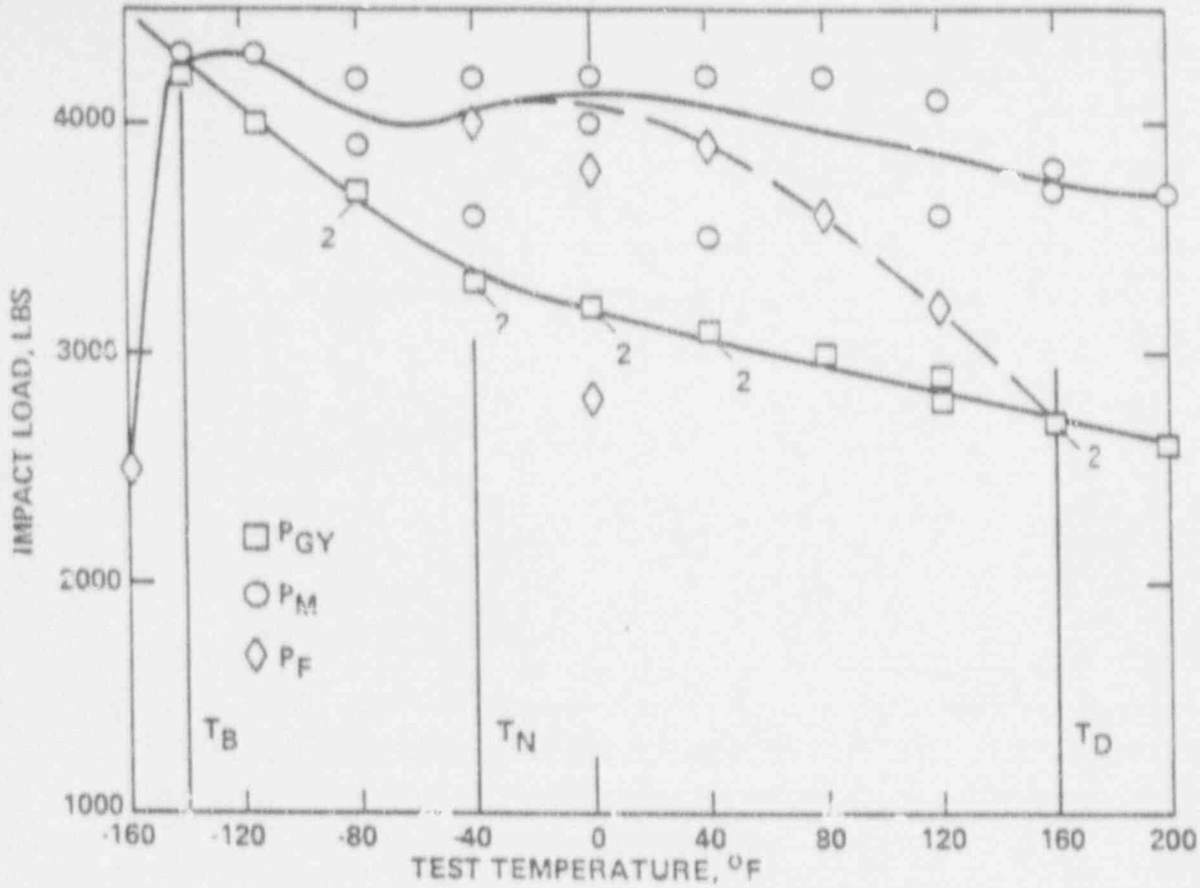


Figure VII-13: IMPACT LOAD vs TEMPERATURE
HAZ METAL, PLATE D-4802-2

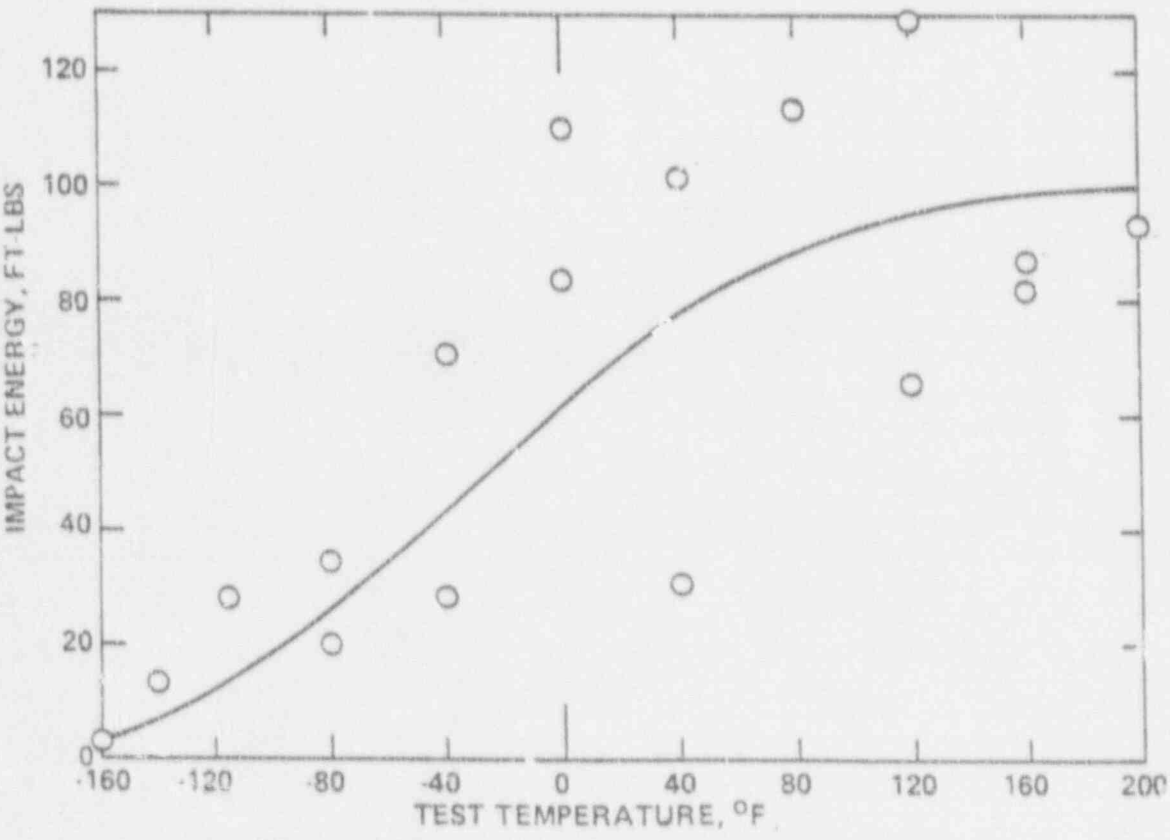


Figure VII-14: IMPACT ENERGY vs TEMPERATURE
HAZ METAL, PLATE D-4802-2

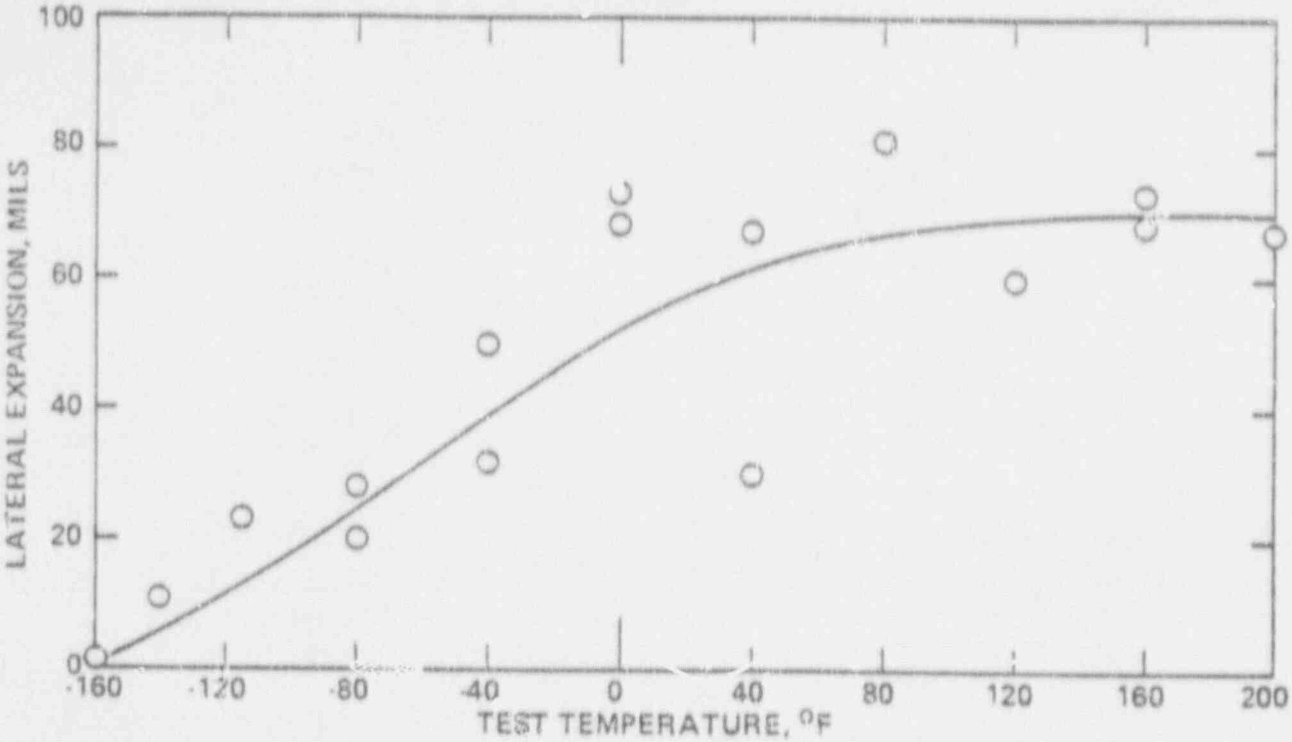


Figure VI-15: LATERAL EXPANSION vs TEMPERATURE
HAZ METAL, PLATE D-4802-2

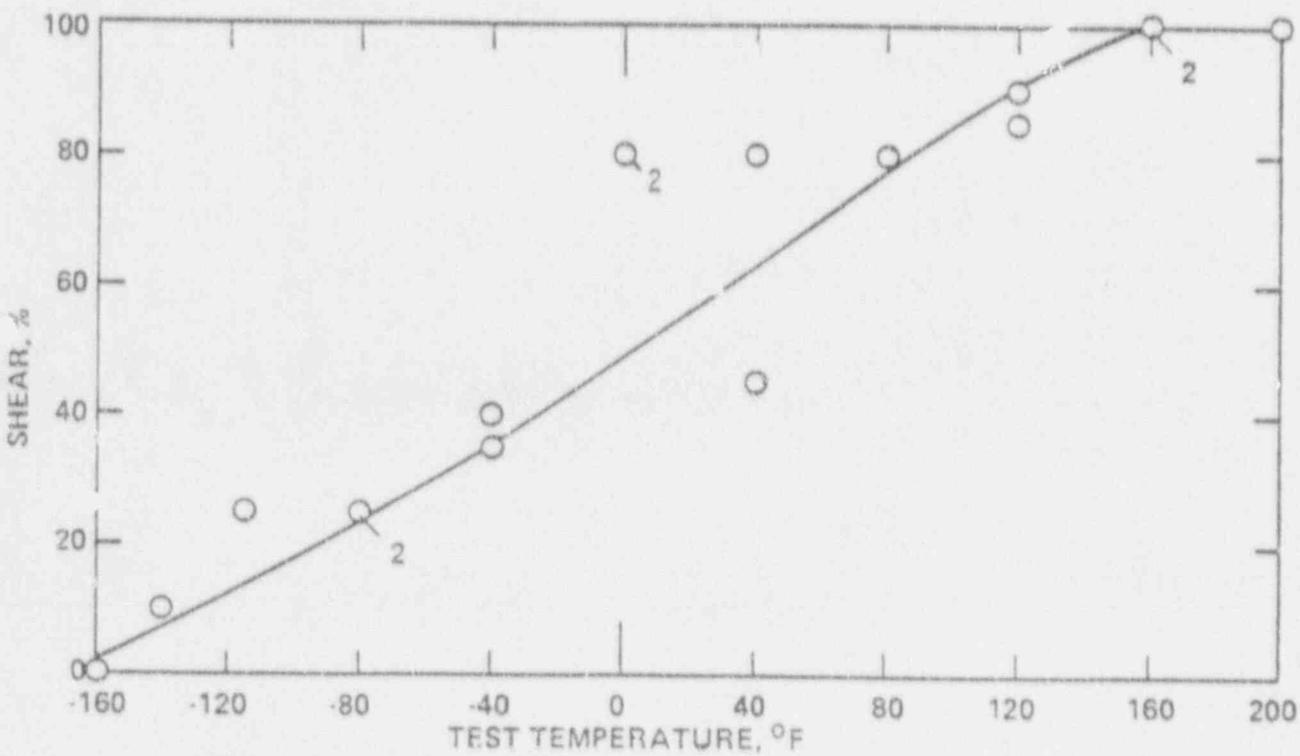
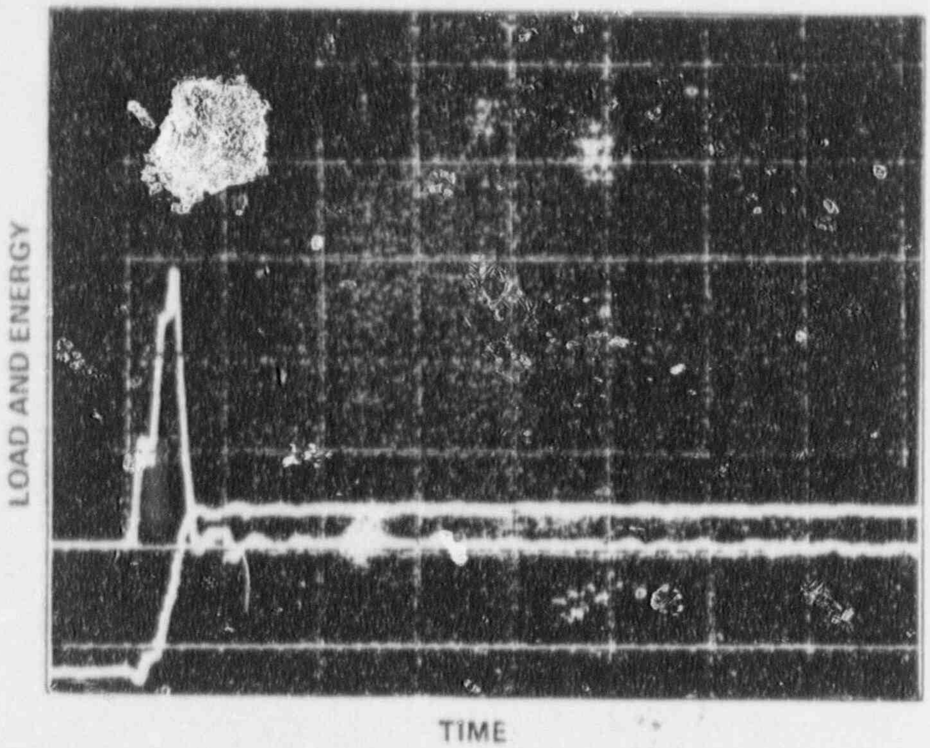
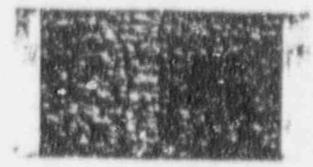


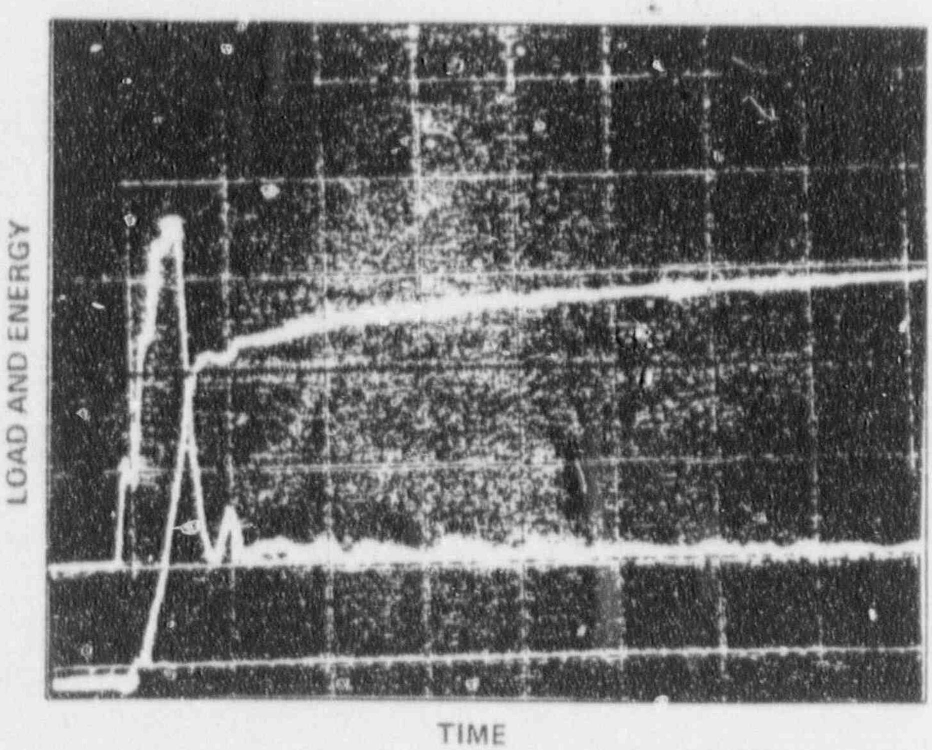
Figure VII-16: SHEAR vs TEMPERATURE
HAZ METAL, PLATE D-4802-2



SPECIMEN No. 23D

TEST TEMP. -80 °F

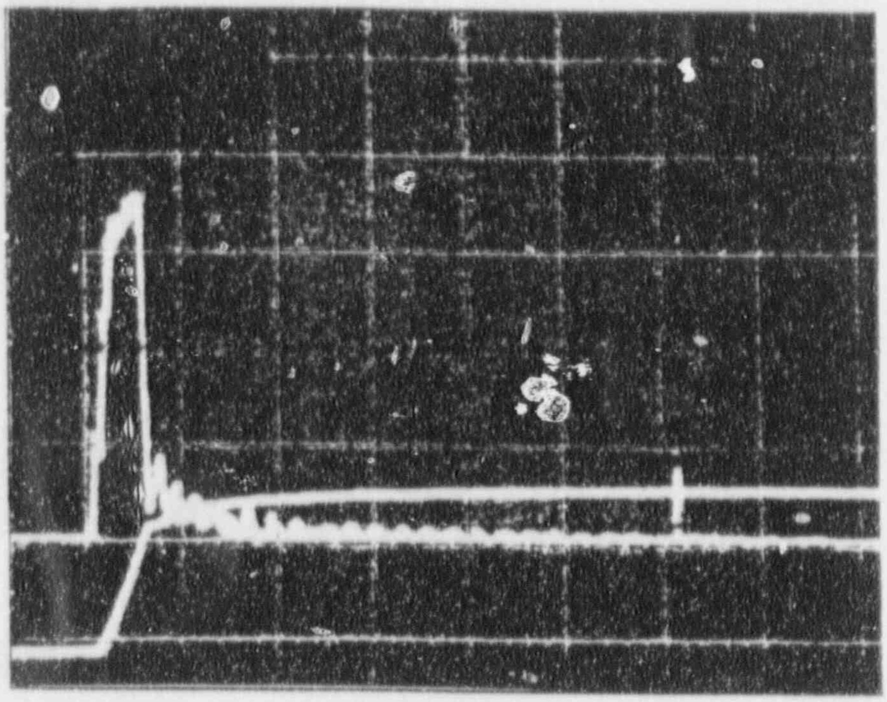




SPECIMEN No. 22P

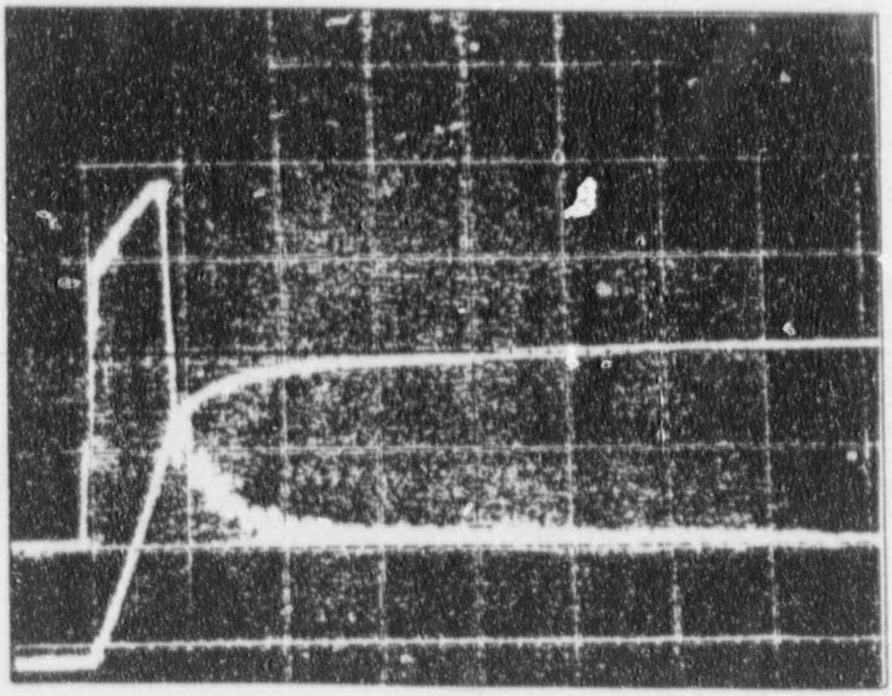
TEST TEMP -40 °F

Figure. VII - 17: Instrumented Charpy Impact Load Records and Specimen Fracture Surfaces of Base Metal - WR - Plate D-4802-2



SPECIMEN No. 233

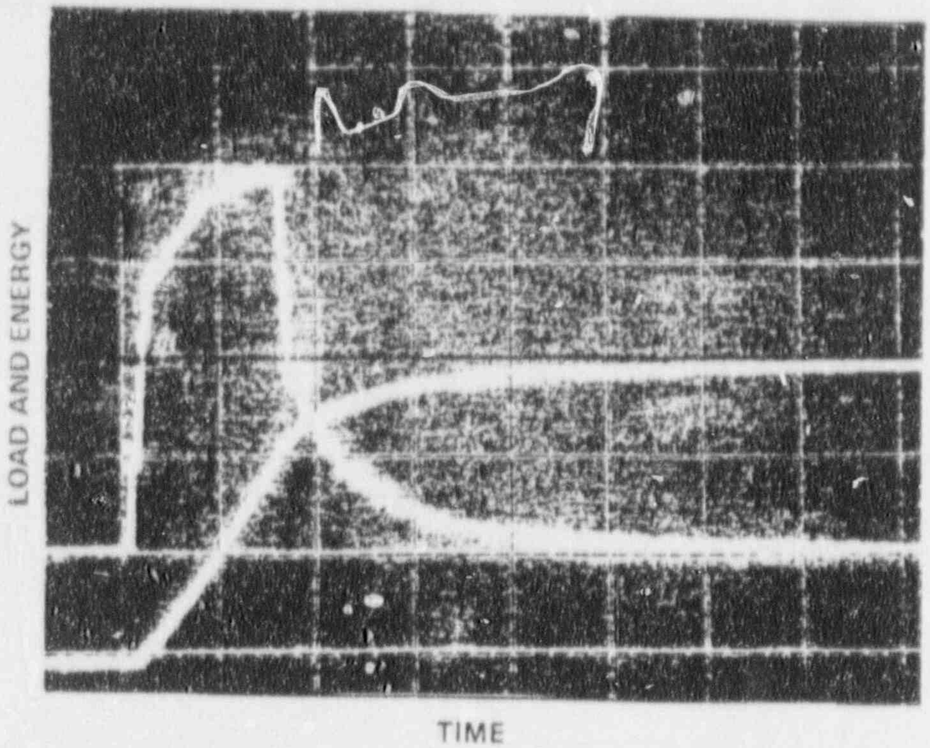
TEST TEMP. 0 °F



SPECIMEN No. 21U

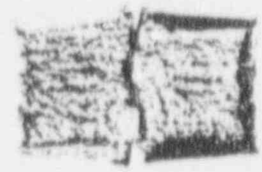
TEST TEMP. 40 °F

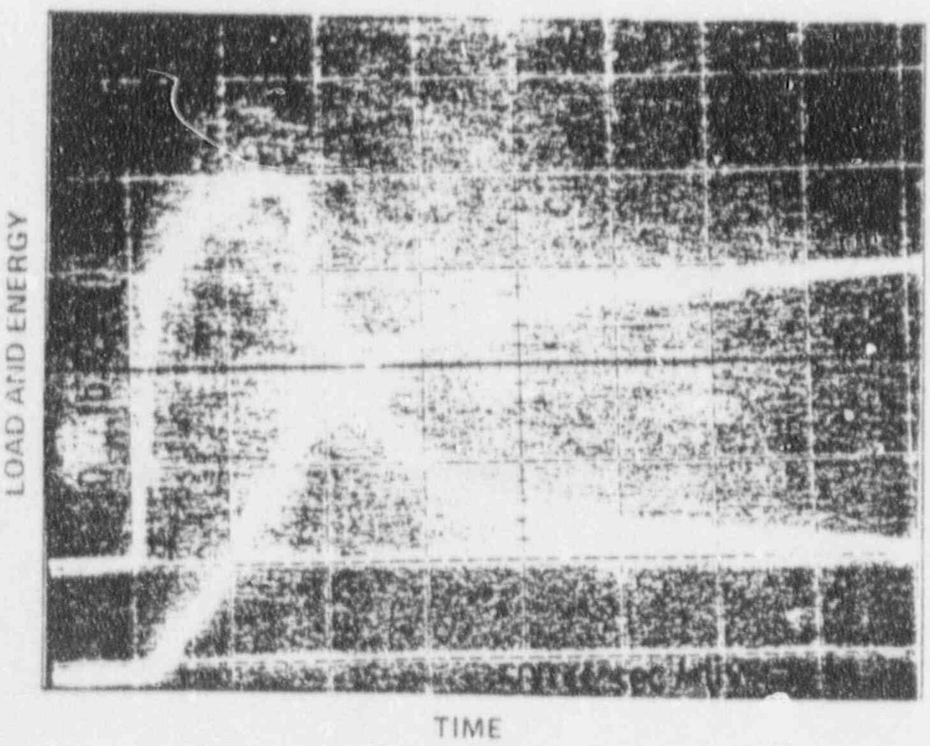
Figure: VII - 18: Instrumented Charpy Impact Load Records and Specimen Fracture Surfaces of Base Metal - WR - Plate D-4802-2



SPECIMEN No. 21C

TEST TEMP. 80 °F





SPECIMEN No. 242

TEST TEMP. 120 °F

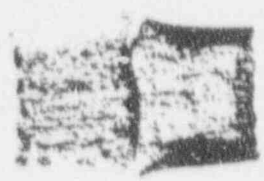
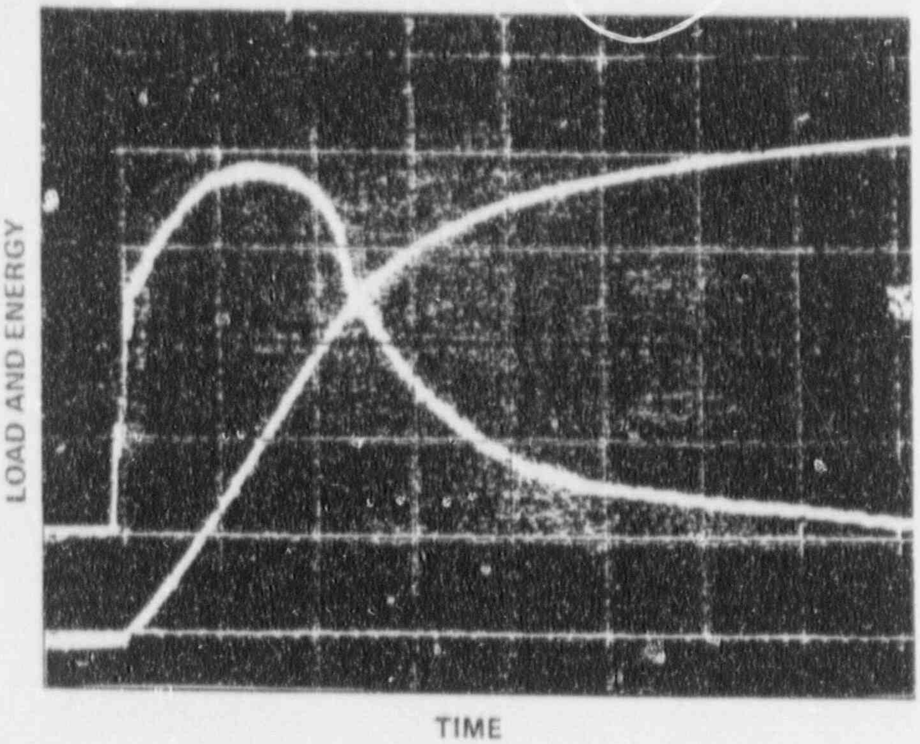
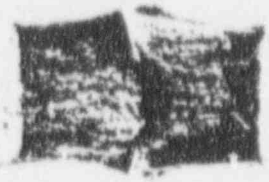


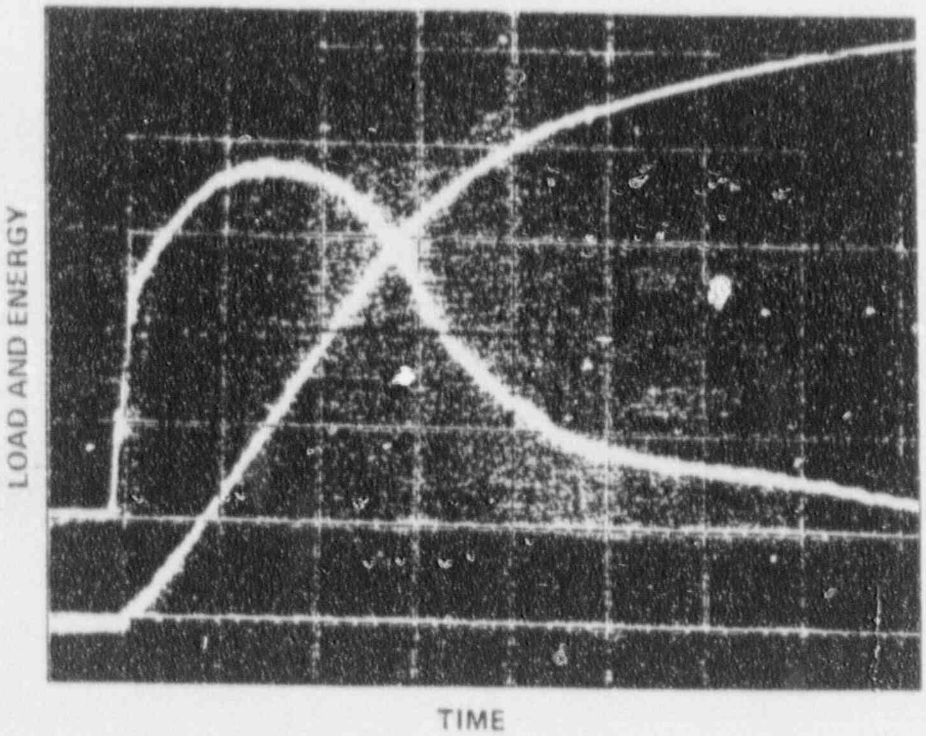
Figure: VII - 19: Instrumented Charpy Impact Load Records and Specimen Fracture Surfaces of Base Metal - WR - Plate D-4802-2



SPECIMEN No. 23B

TEST TEMP. 160 °F





SPECIMEN No 21T

TEST TEMP. 190 °F

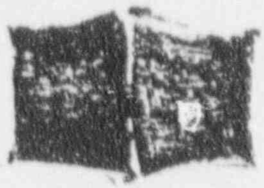


Figure: VII - 20: Instrumented Charpy Impact Load Records and Specimen Fracture Surfaces of Base Metal - WR - Plate D-4802-2

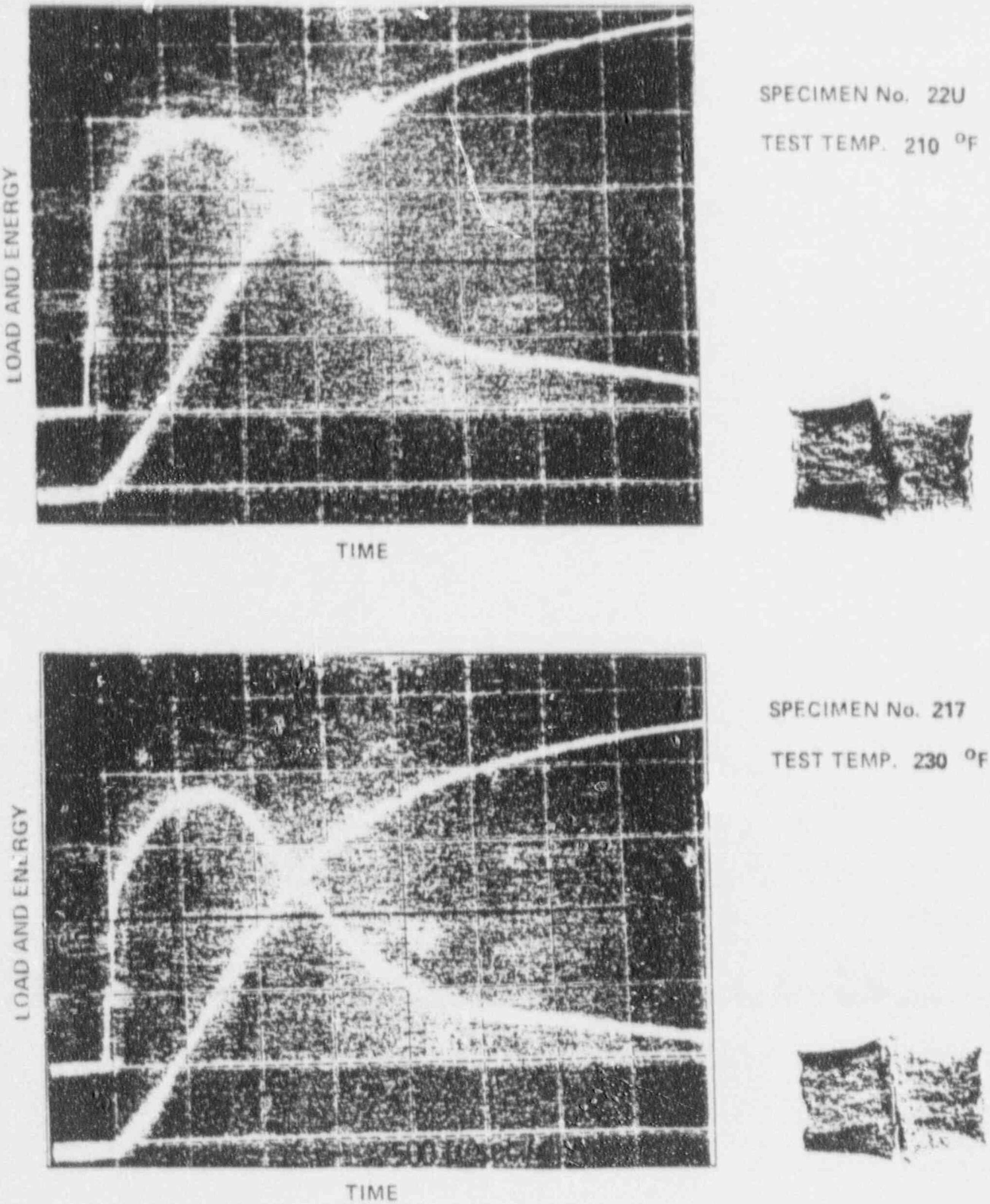
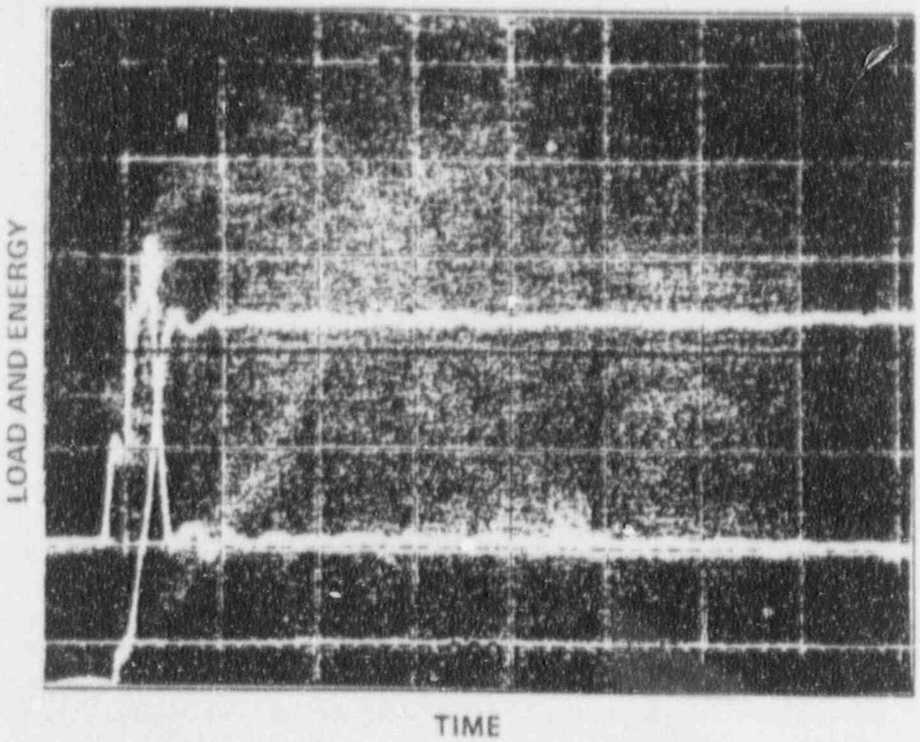
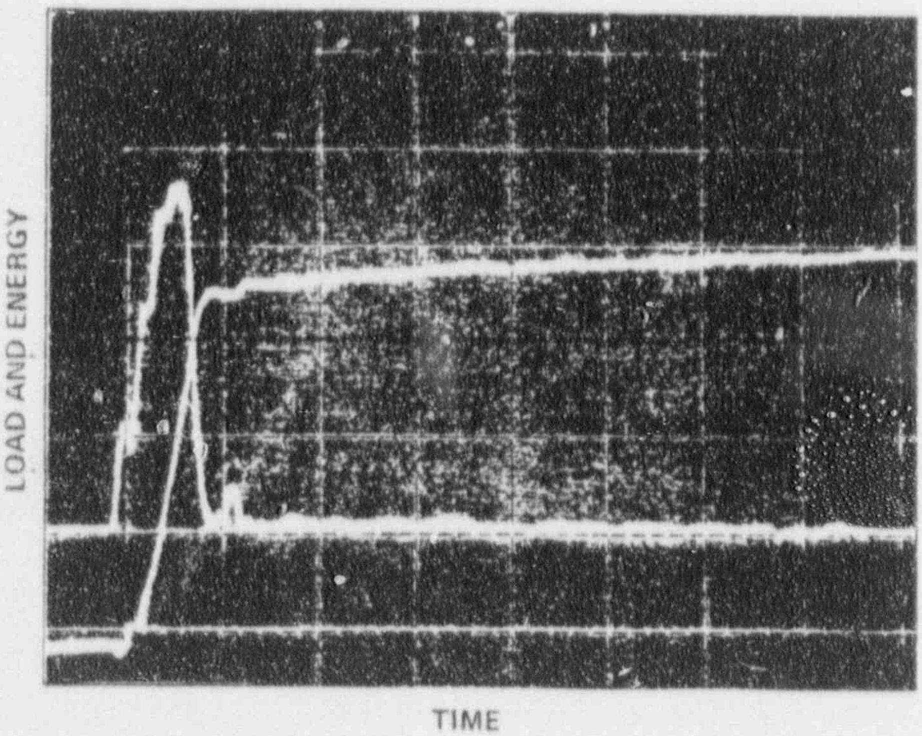


Figure: VII - 21: Instrumented Charpy Impact Load Records and Specimen Fracture Surfaces of Base Metal - WR - Plate D-4802-2



SPECIMEN No. 12D

TEST TEMP. -80 °F



SPECIMEN No. 13J

TEST TEMP. -40 °F

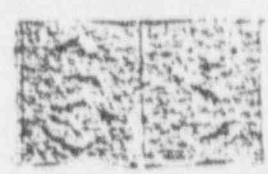
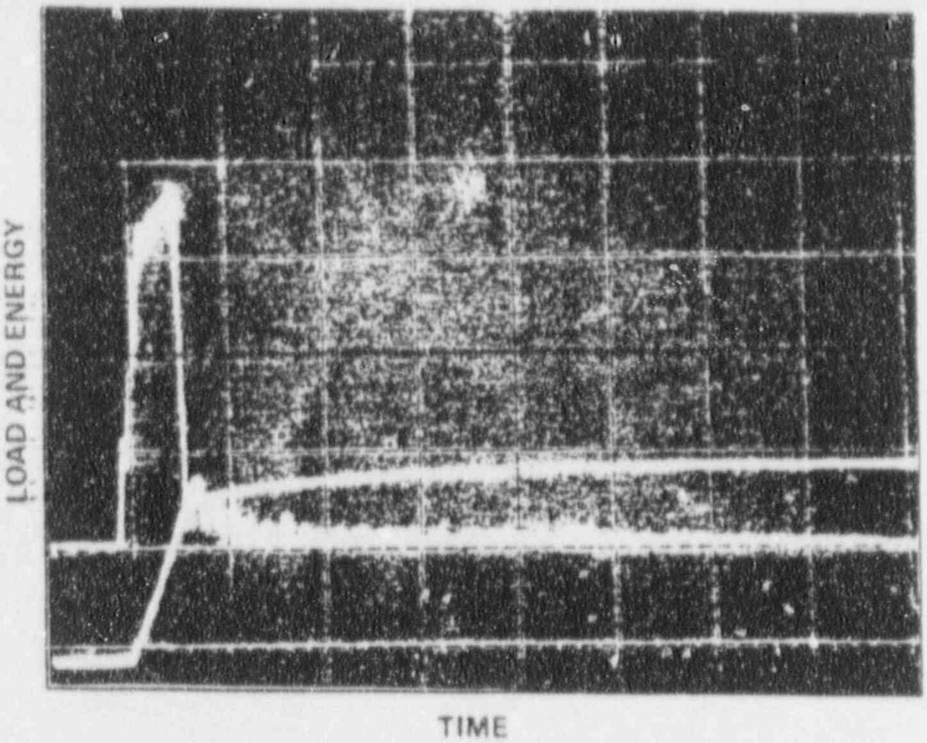
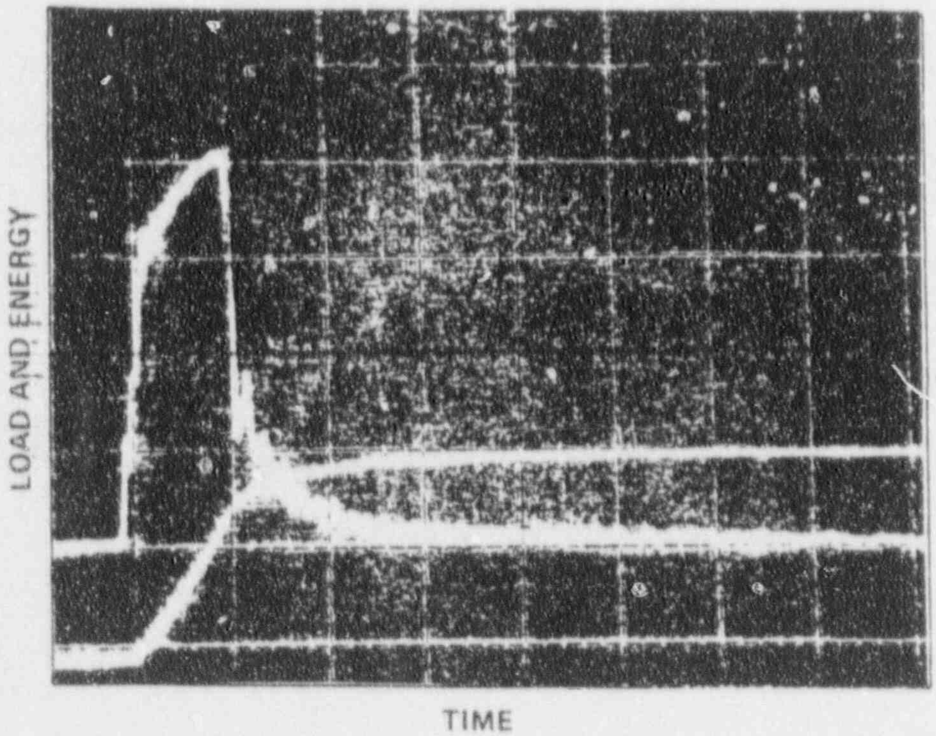


Figure: VII - 22: Instrumented Charpy Impact Load Records and Specimen Fracture Surfaces of Base Metal - RW - Plate D-4802-2



SPECIMEN No. 15P

TEST TEMP. 0 °F



SPECIMEN No. 11C

TEST TEMP. 40 °F

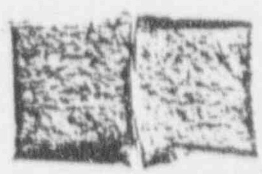
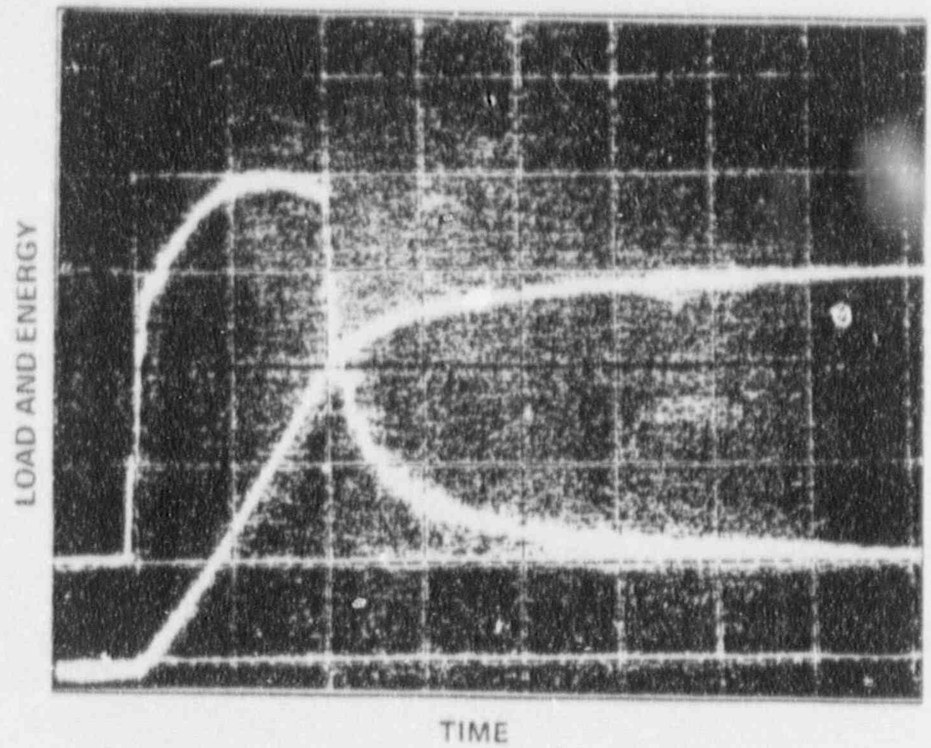
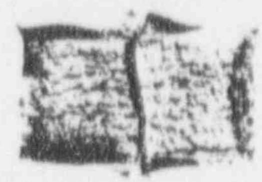


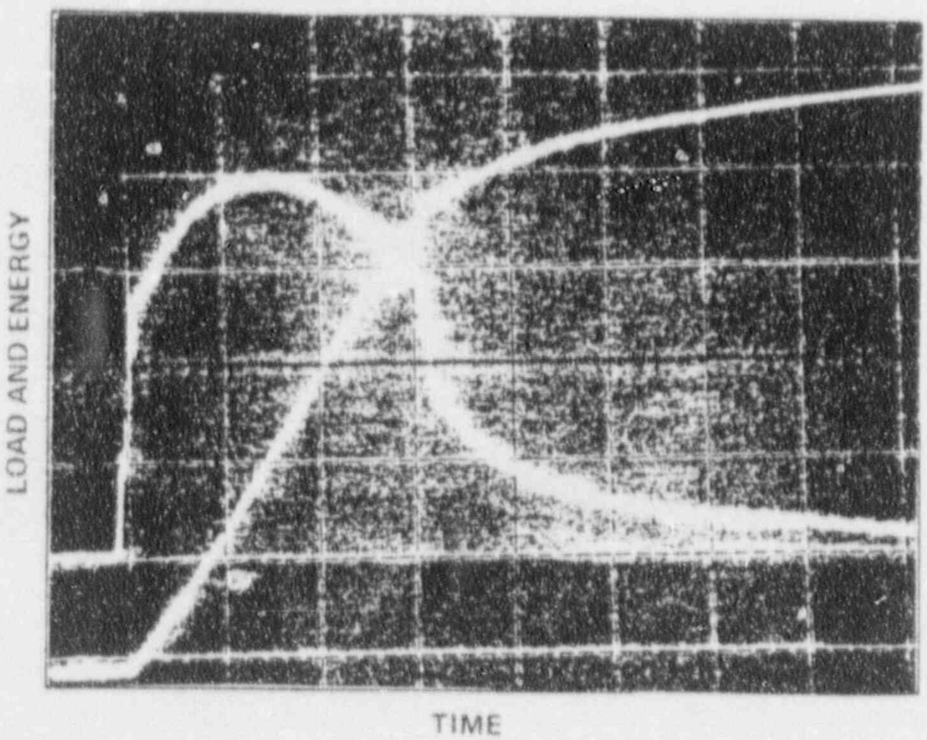
Figure: VII - 23: Instrumented Charpy Impact Load Records and Specimen Fracture Surfaces of Base Metal - RW - Plate D-4802-2



SPECIMEN No. 151

TEST TEMP. 80 °F





SPECIMEN No. 11P

TEST TEMP. 120 °F

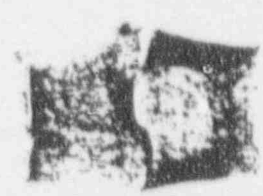
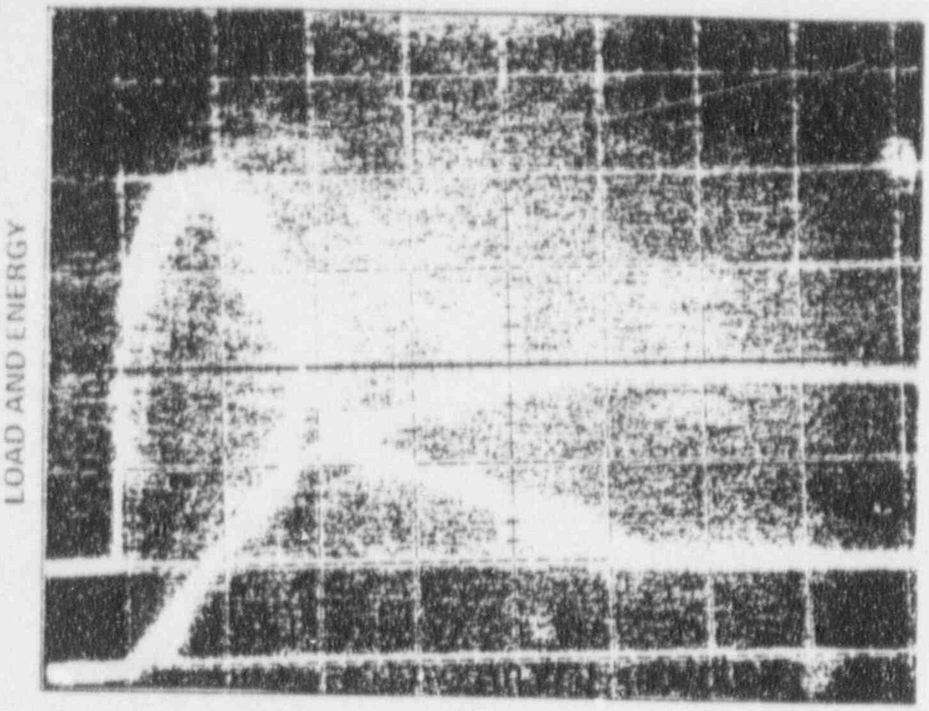
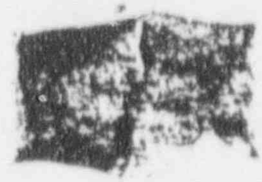


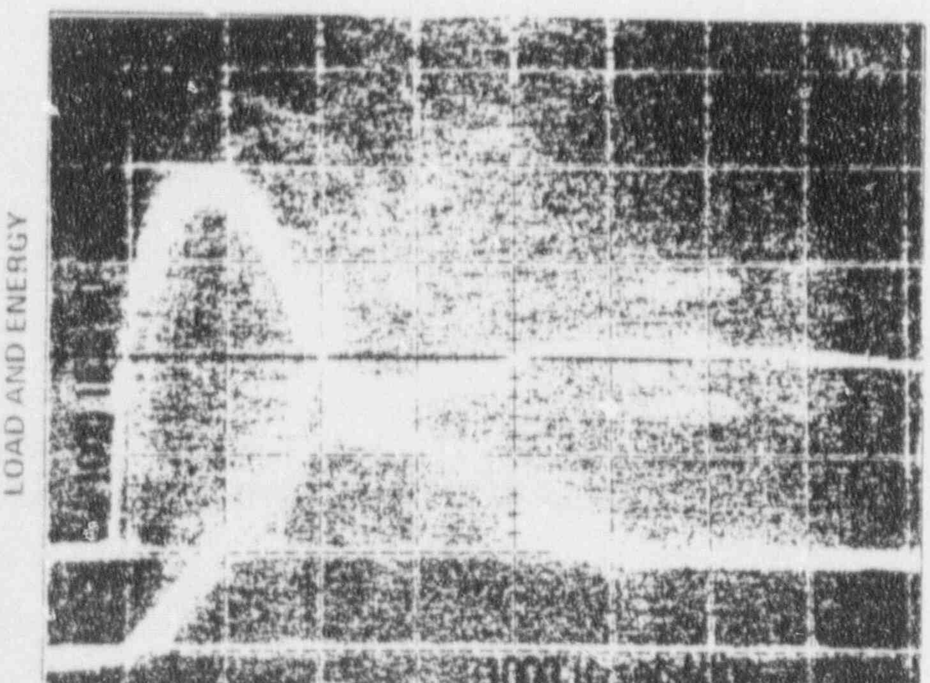
Figure: VII - 24: Instrumented Charpy Impact Load Records and Specimen Fracture Surfaces of Base Metal - RW - Plate D-4802-2



SPECIMEN No. 11D

TEST TEMP. 160 °F





SPECIMEN No. 15L

TEST TEMP. 210 °F

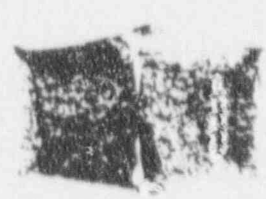
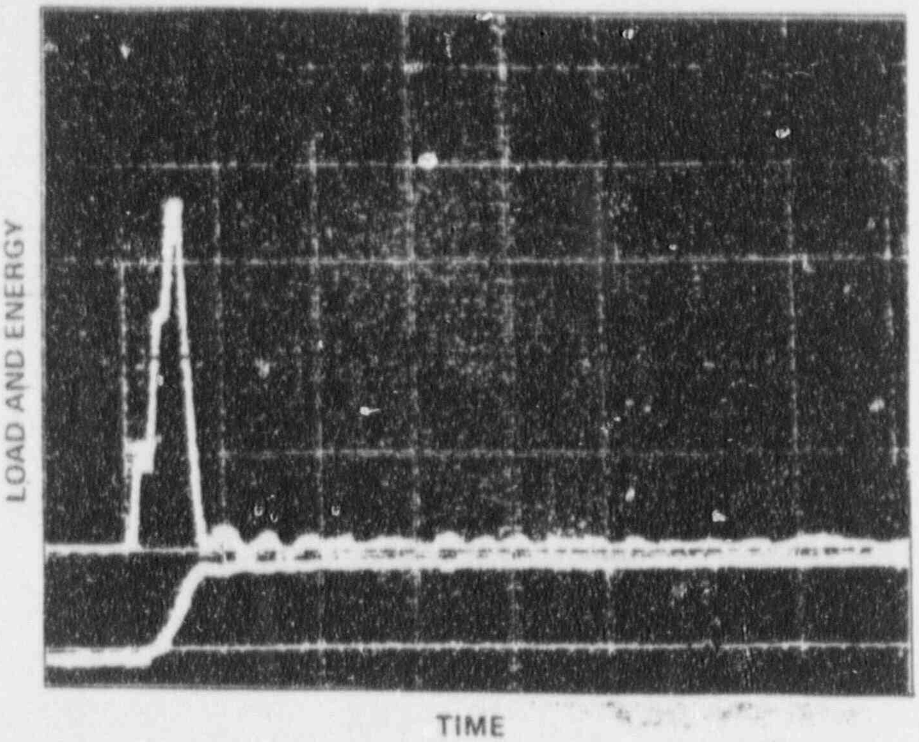
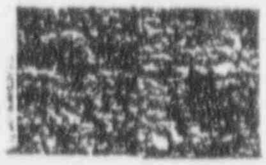


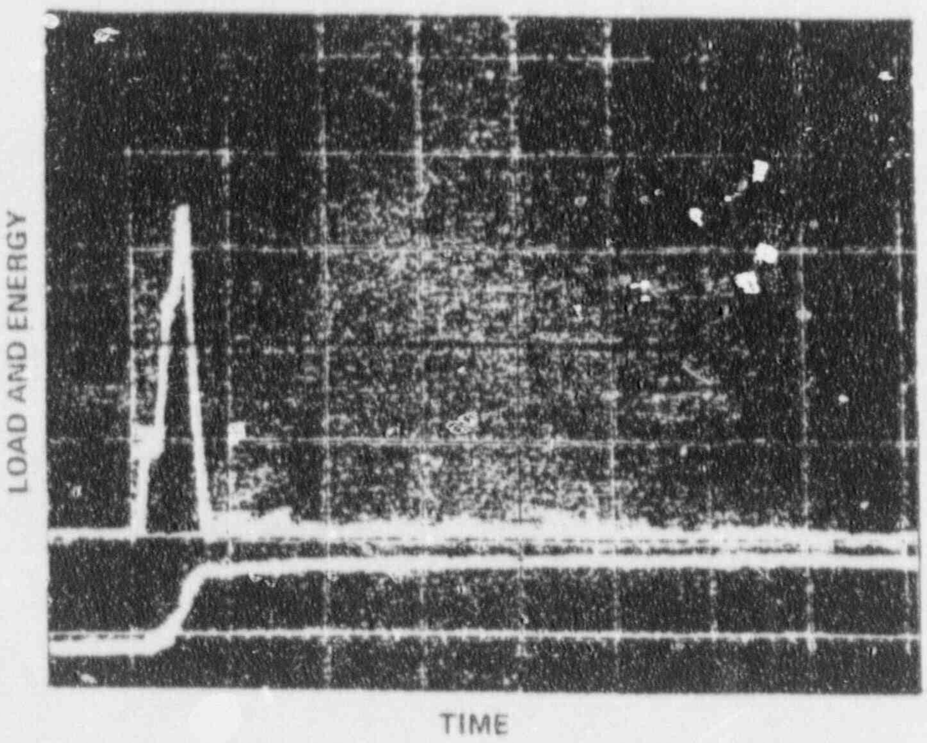
Figure: VII - 25: Instrumented Charpy Impact Load Records and Specimen Fracture Surfaces of Base Metal - RW - Plate D-4802-2



SPECIMEN No. 364

TEST TEMP. -120 °F

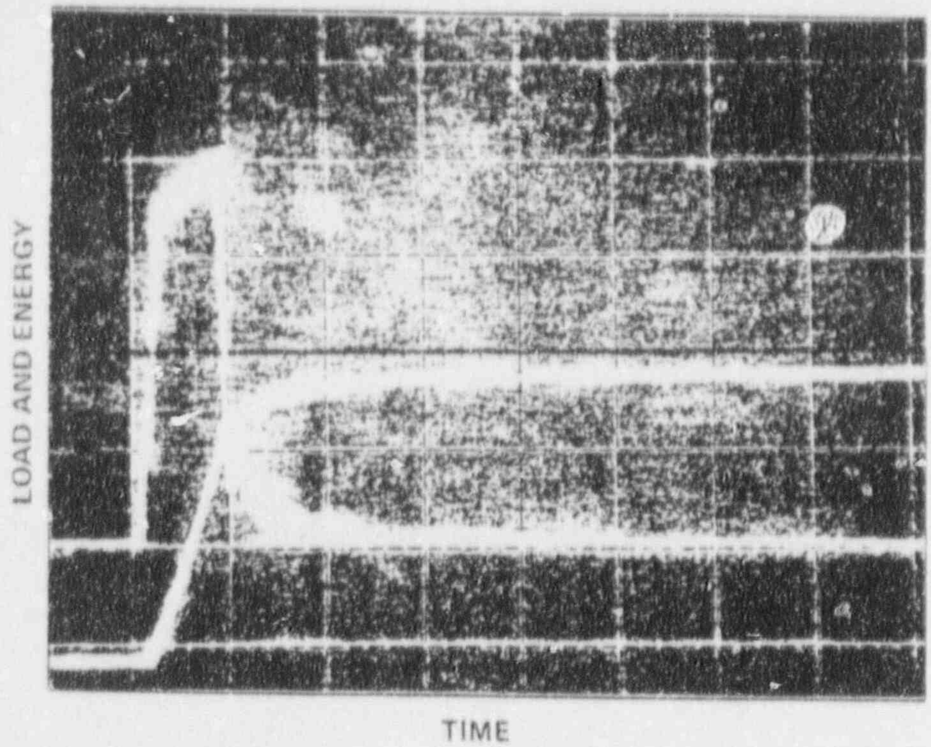




SPECIMEN No. 35U

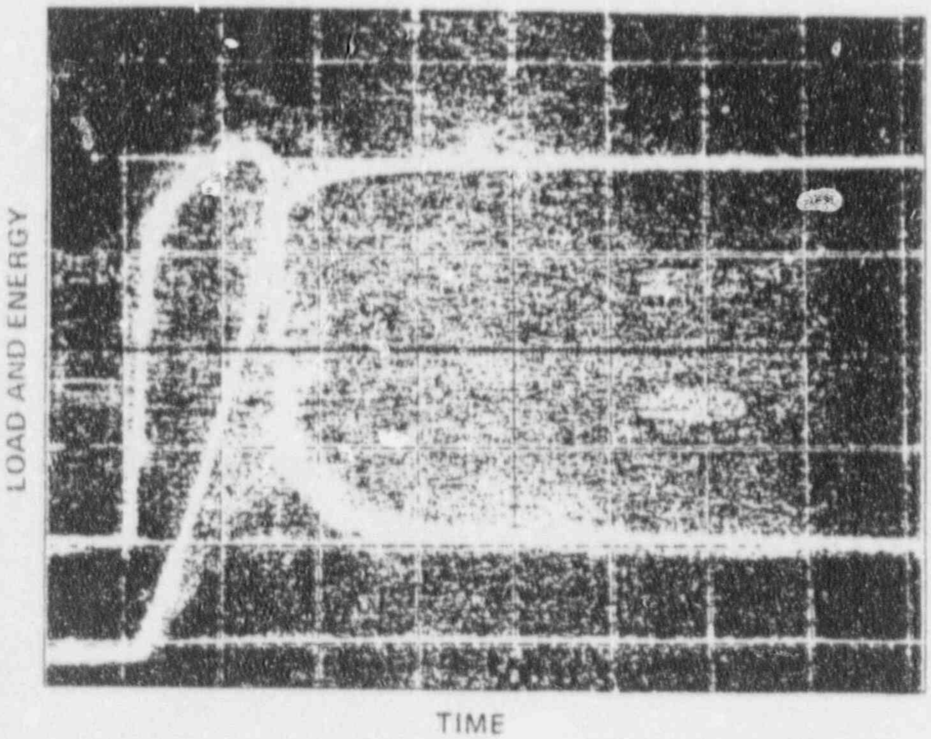
TEST TEMP. -80 °F

Figure: VII - 26: Instrumented Charpy Impact Load Records and Specimen Fracture Surfaces of Weld Metal, D-4802-1/D-4802-3



SPECIMEN No. 31L

TEST TEMP. -40 °F



SPECIMEN No. 35E

TEST TEMP. 0 °F

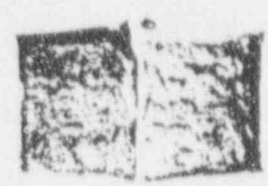
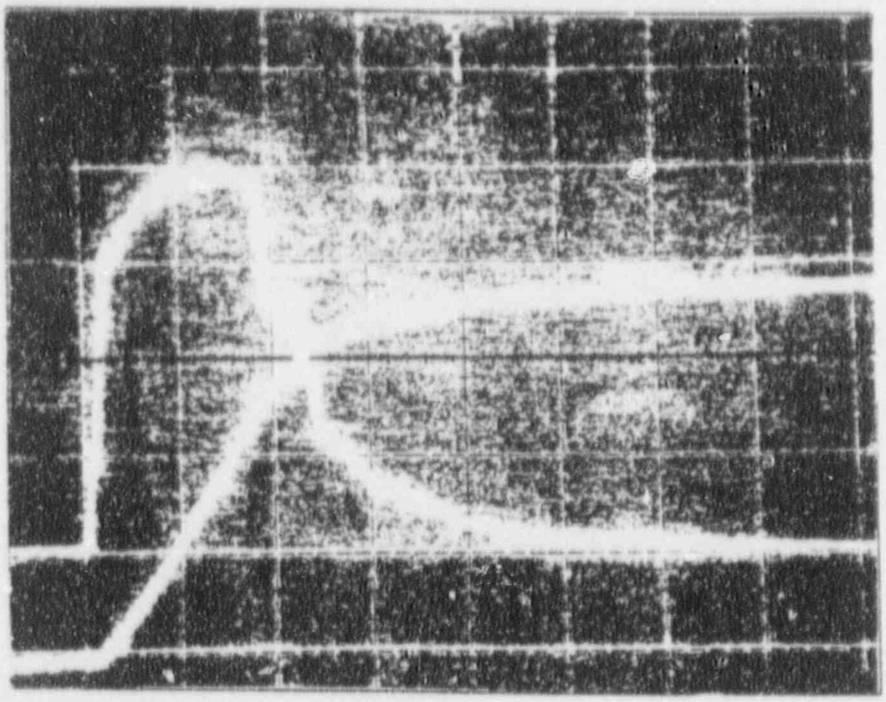
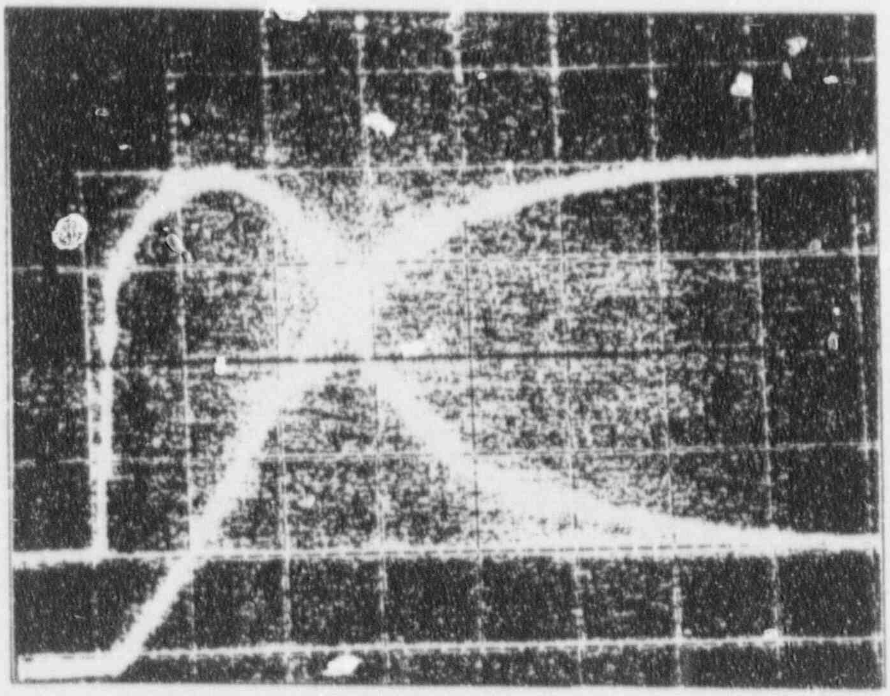


Figure: VII - 27: Instrumented Charpy Impact Load Records and Specimen Fracture Surfaces of Weld Metal, D-4802-1/D-4802-3



SPECIMEN No. 31Y

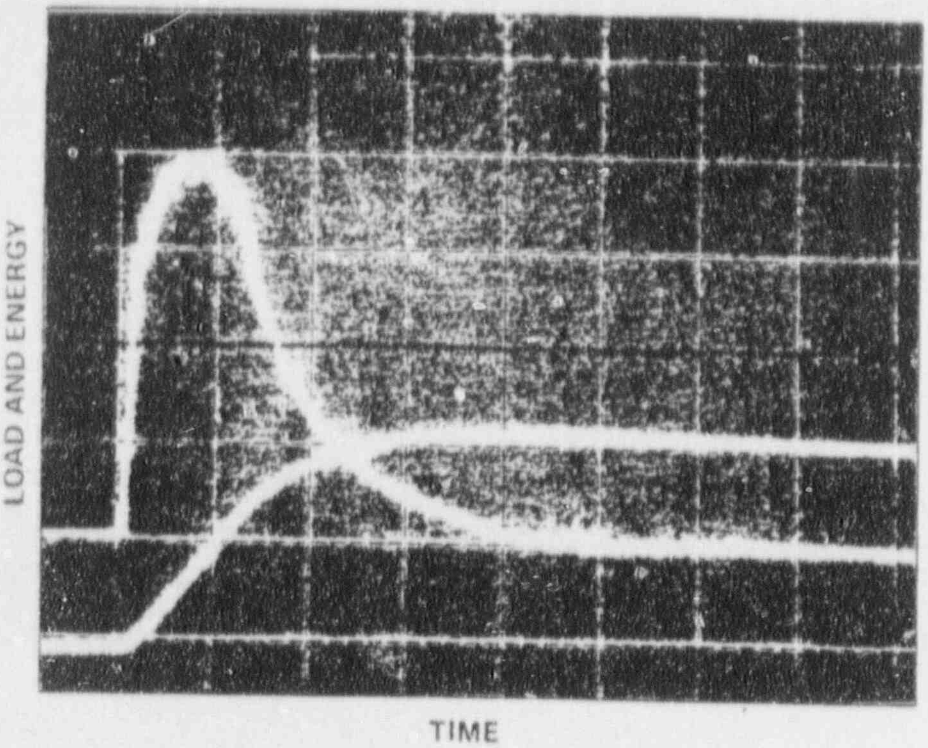
TEST TEMP. 40 °F



SPECIMEN No. 33C

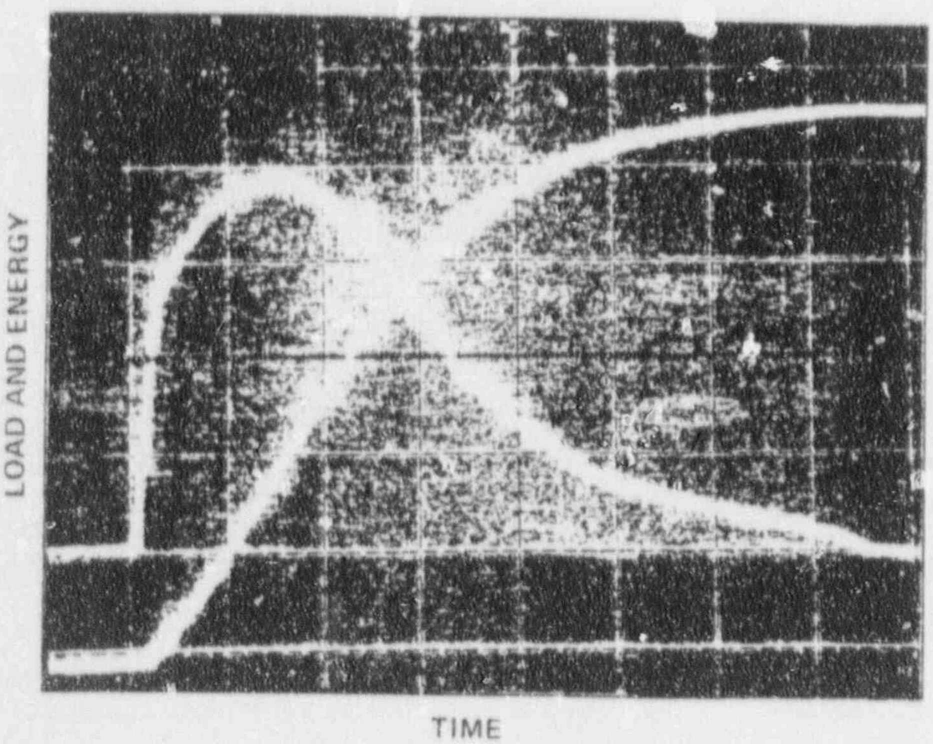
TEST TEMP. 80 °F

Figure: VII - 28: Instrumented Charpy Impact Load Records and Specimen Fracture Surfaces of Weld Metal, D-4802-1/D-4802-3



SPECIMEN No. 33D

TEST TEMP. 120 °F



SPECIMEN No. 346

TEST TEMP. 160 °F

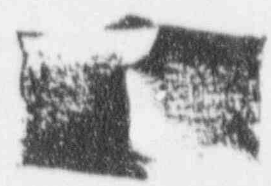
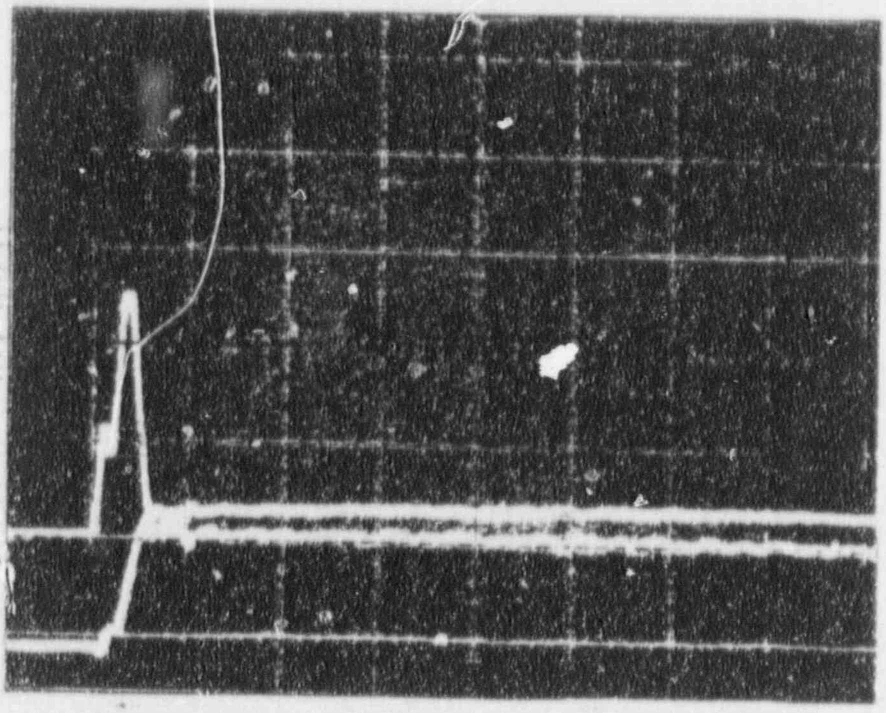
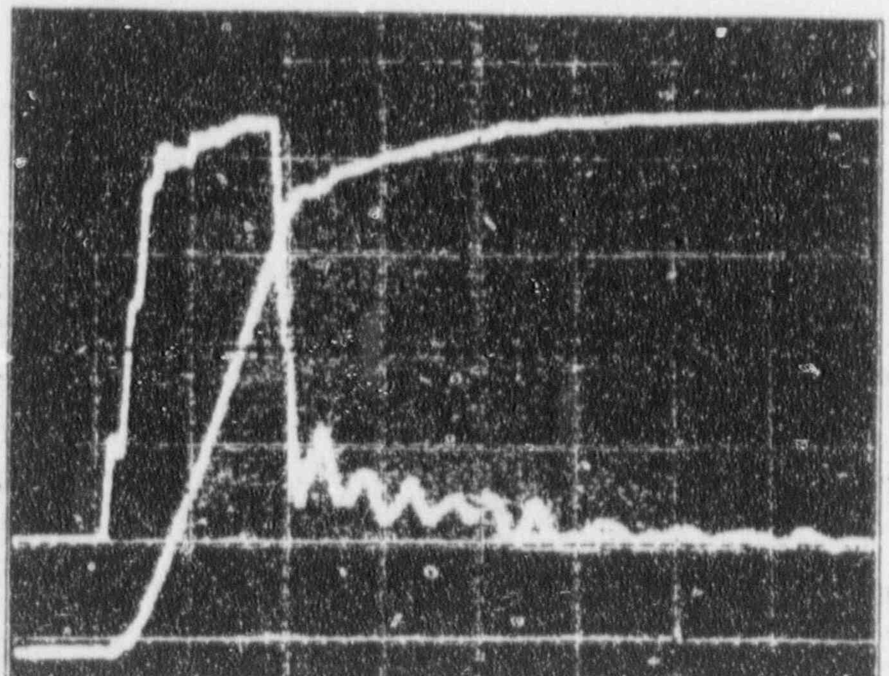


Figure: VII - 29: Instrumented Charpy Impact Load Records and Specimen Fracture Surfaces of Weld Metal, D-4802-1/D-4802-3



SPECIMEN No. 444

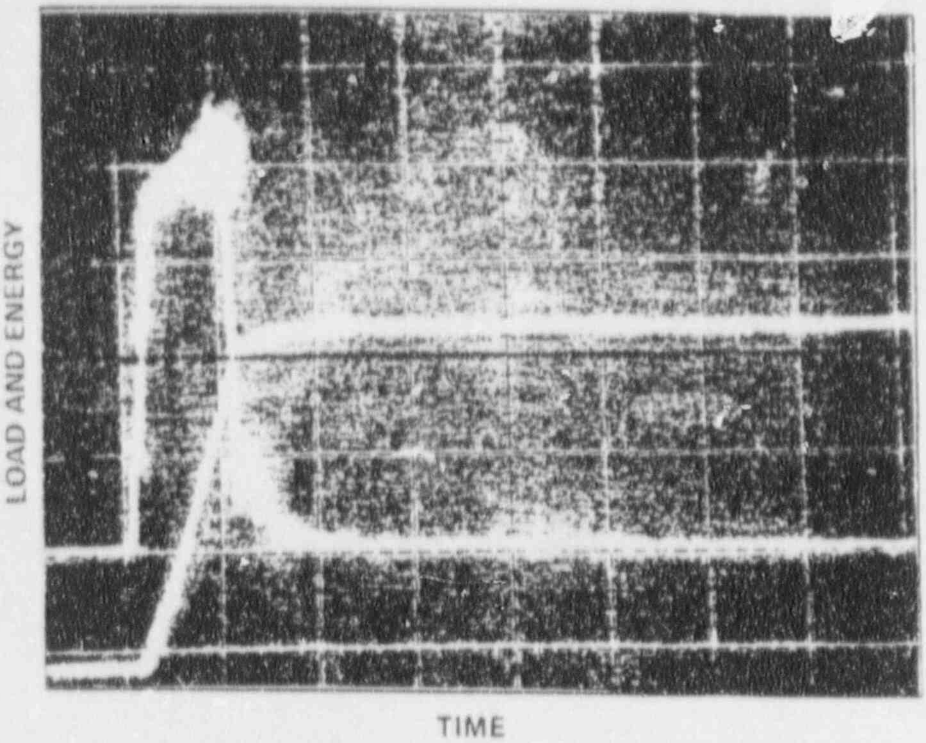
TEST TEMP. -160 °F



SPECIMEN No. 423

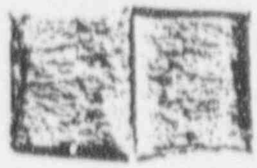
TEST TEMP. -115 °F

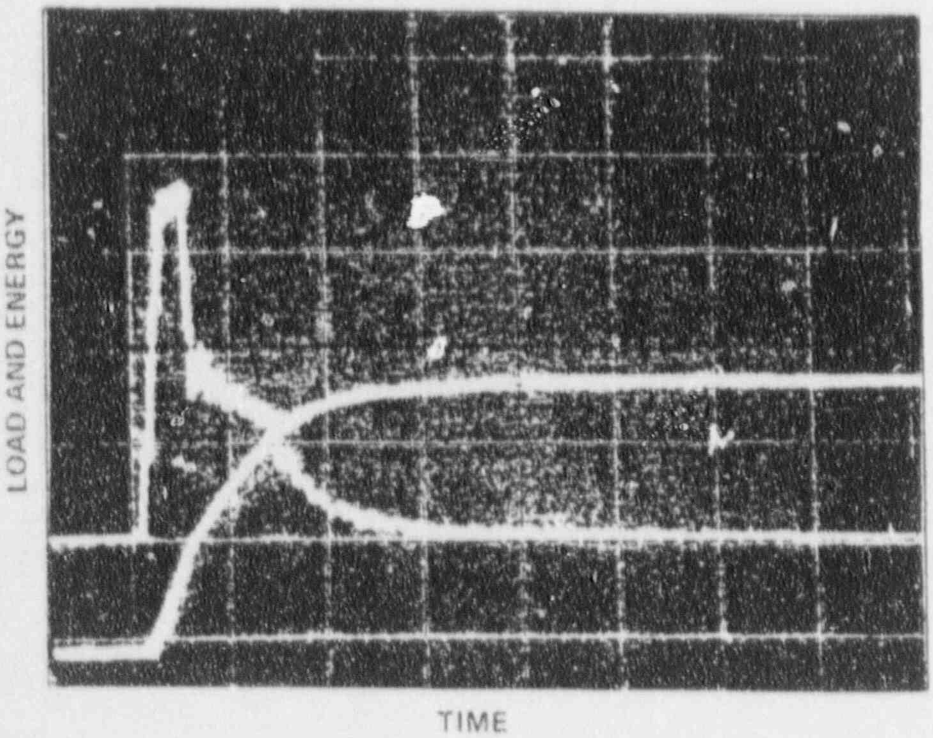
Figure: VII - 30: Instrumented Charpy Impact Load Records and Specimen Fracture Surfaces of HAZ Metal, D-4802-2



SPECIMEN No. 46A

TEST TEMP. -80 °F





SPECIMEN No. 44Y

TEST TEMP. -40 °F

Figure: VII - 31: Instrumented Charpy Impact Load Records and Specimen Fracture Surfaces of HAZ Metal, D-4802-2

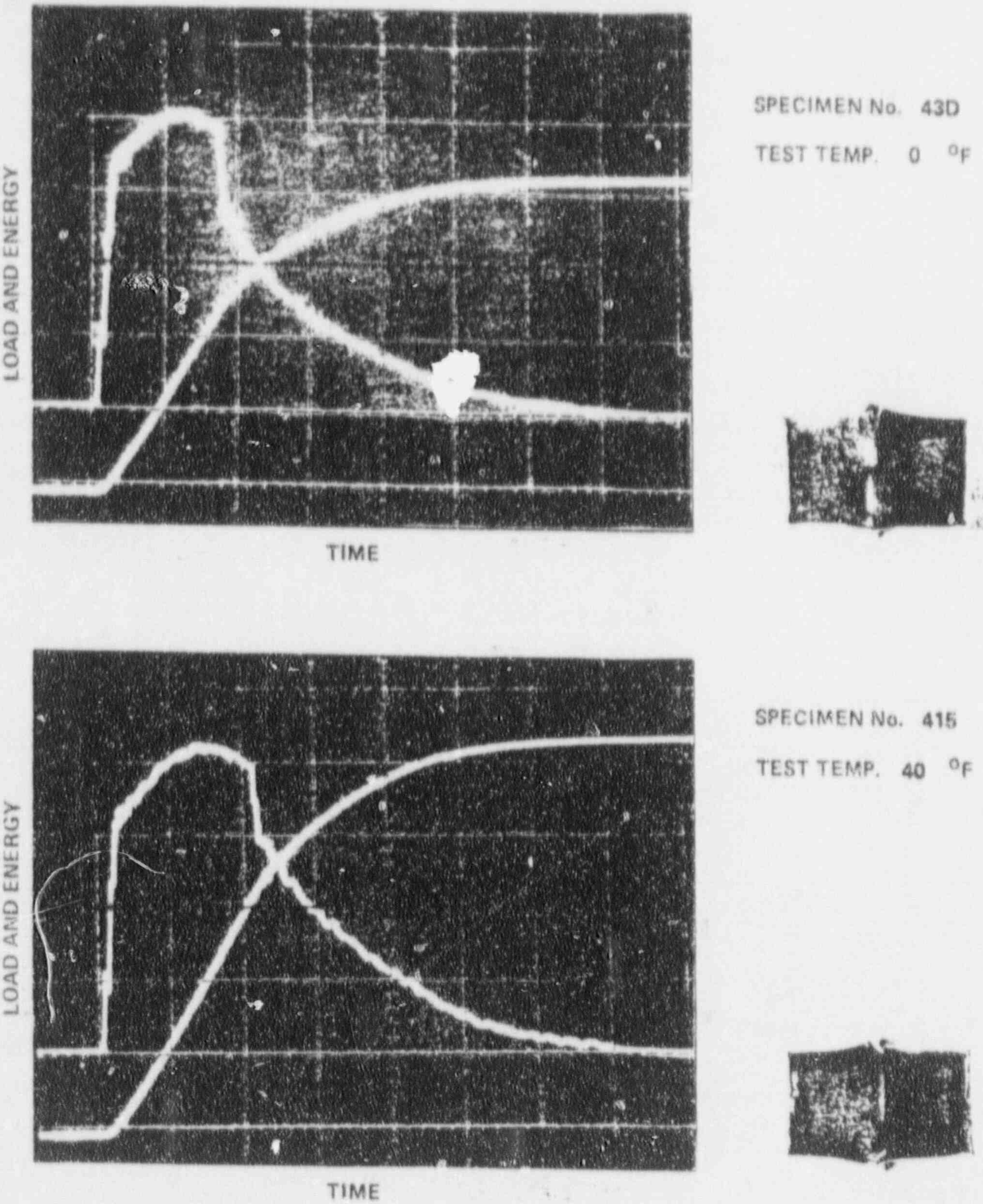
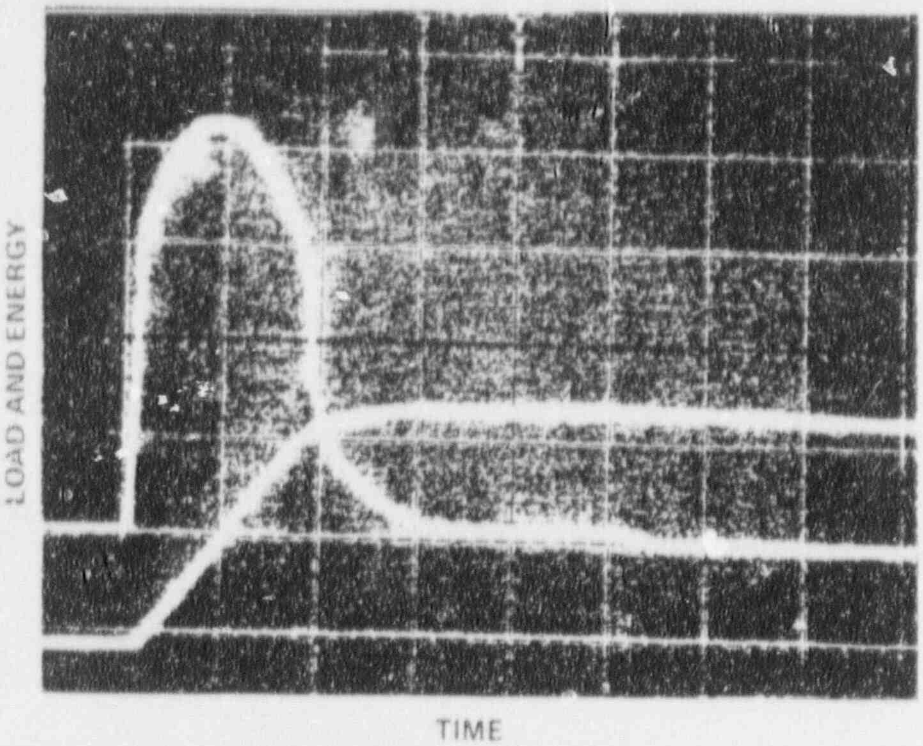
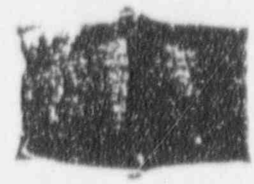


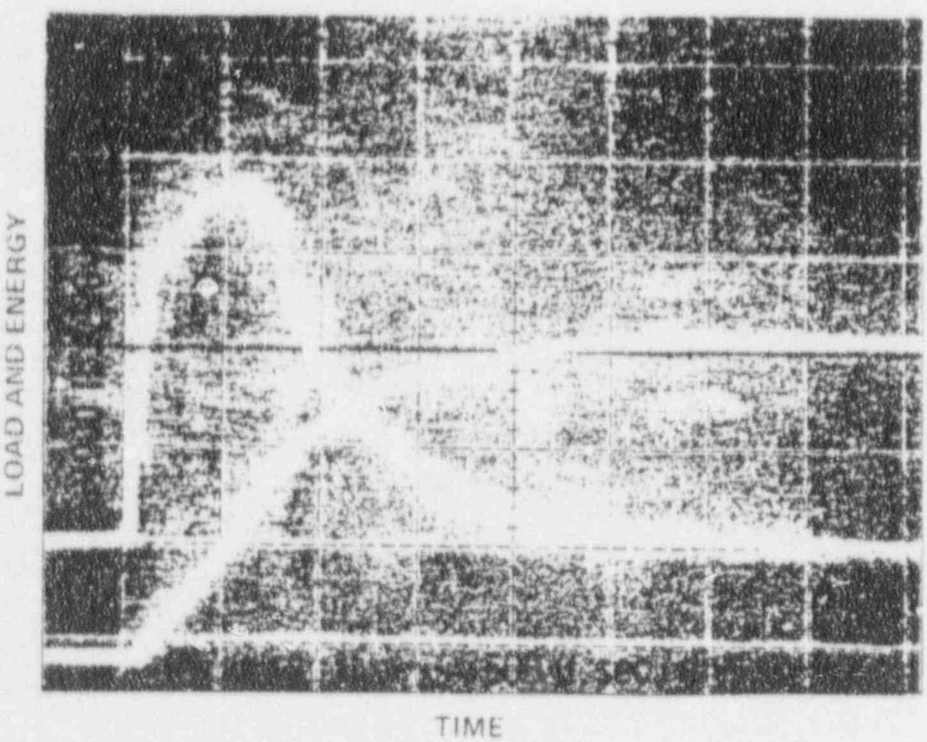
Figure: VII - 32: Instrumented Charpy Impact Load Records and Specimen Fracture Surfaces of HAZ Metal, D-4802-2



SPECIMEN No. 417

TEST TEMP. 80 °F

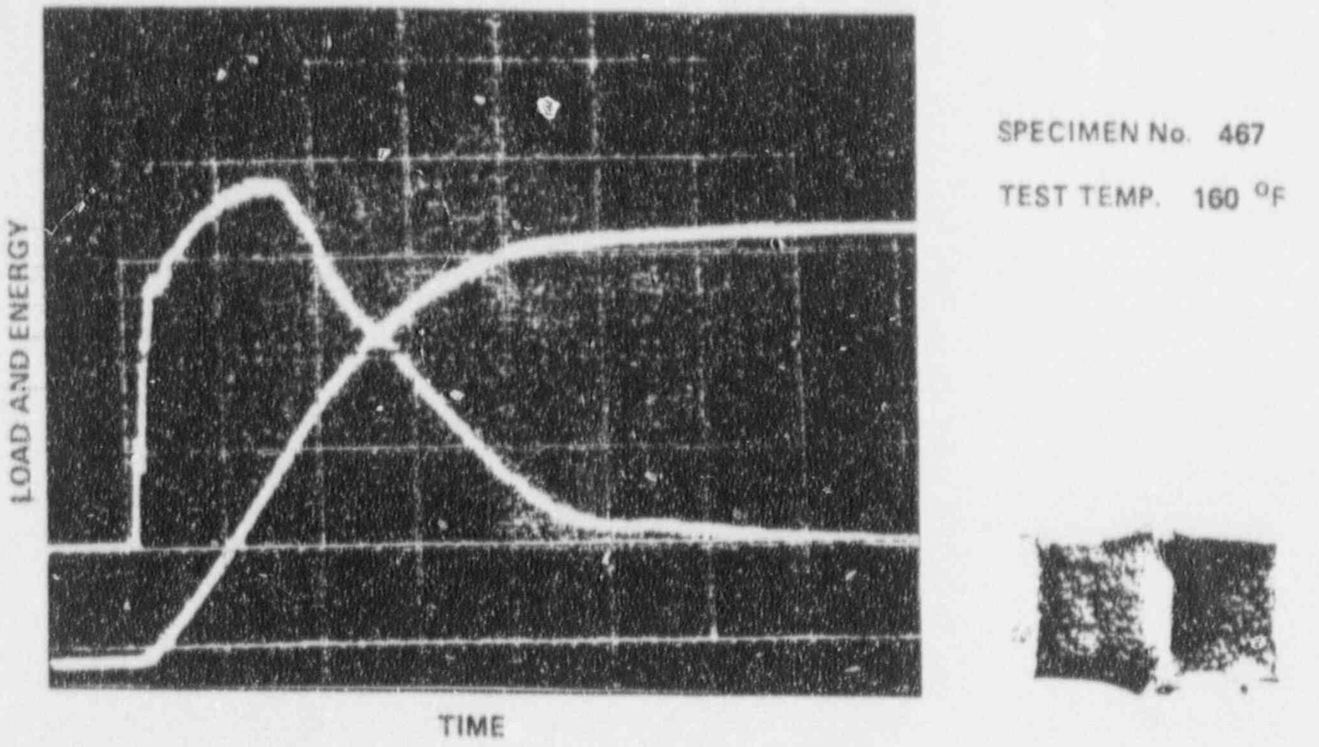




SPECIMEN No. 45D

TEST TEMP. 120 °F

Figure: VII - 33: Instrumented C..arpy Impact Load Records and Specimen Fracture Surfaces of HAZ Metal, D-4802-2



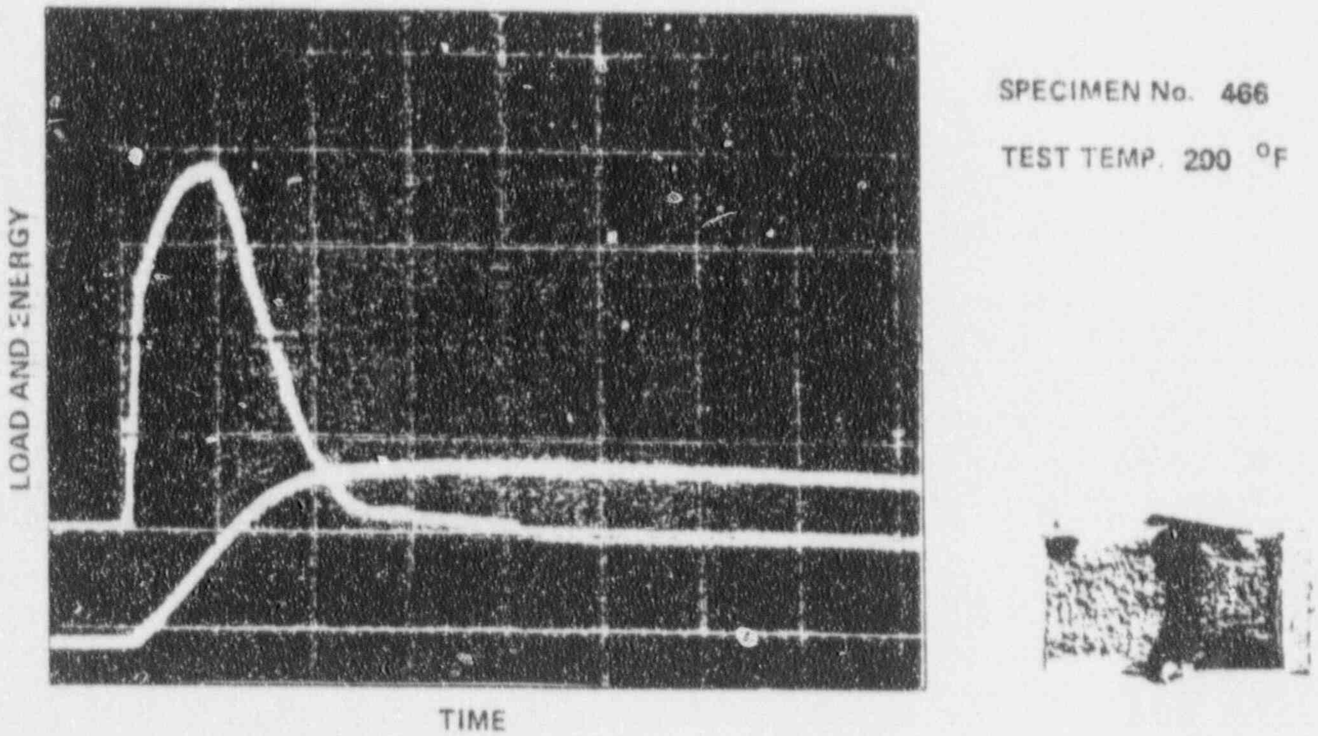


Figure: VII - 34: Instrumented Charpy Impact Load Records and Specimen Fracture Surfaces of HAZ Metal, D-4802-2

VIII. PRECRACKED CHARPY TEST RESULTS

Precracked Charpy impact tests for Fort Calhoun were performed on base metal (WR and RW), weld metal and heat-affected-zone metal. The testing and precracking methods used to perform these tests are described in Appendix C.

The computer input data necessary for the computation of fracture toughness parameters and the calculated results are listed in Tables VIII-1 through VIII-4. The computer plot of the impact load signals for each test and the fracture surface appearances of the specimens are shown in Figures VIII-1 through VIII-32. Figure VIII-33 provides a comparison of the calculated K_{Id} and K_{Bd} values to the reference stress-intensity factor (K_{IR}) versus temperature curve provided by the ASME Boiler and Pressure Vessel Code, Section III, Appendix G, "Protection Against Nonductile Failure". This ASME Code presents the procedure for obtaining the allowable loadings for ferritic pressure-retaining materials in Class 1 components based on principles of fracture mechanics.

TABLE VIII-1

PRECRACKED INSTRUMENTED CHARPY IMPACT TEST RESULTS

BASE METAL PLATE D-4802-2 (WR)

Test Data													Calculated Results			
Test No.	Specimen No.	Test Temp. (°F)	C_S*	V_o (in./sec)	t_{GY} (μs)	P_{GY} (lb)	t_M (μs)	P_M (lb)	E_{af} (in.-lb)	E_o (in.-lb)	a (in.)	a/w	K_{Id} ksi $\sqrt{in.}$	K_{Bd} ksi $\sqrt{in.}$	K_{Jd} ksi $\sqrt{in.}$	σ_{yd} ksi
2670	22B	-80	56.7	40.8	170	932	170	932	3	113	.197	.50	40.0	--	--	79
2671	21D	-40	51.3	55.2	140	1101	140	1101	3	207	.187	.47	43.5	--	--	85
2673	243	0	50.3	62.4	140	1350	140	1350	4	265	.185	.47	52.6	--	--	102
2674	231	40	50.6	69.6	200	1401	200	1401	9	329	.185	.47	54.8	--	--	106
2672	21Y	80	51.8	87.6	132	1271	214	1279	15	521	.188	.48	--	87	88	99
2675	241	120	51.6	93.6	109	1155	518	1481	57	595	.187	.48	--	189	191	89
2677	216	160	51.3	103.2	90	1176	772	1635	110	724	.187	.47	--	264	266	90
2676	21P	210	50.9	103.2	106	1078	876	1558	117	724	.186	.47	--	259	262	82

TABLE VIII-2

PRECRACKED INSTRUMENTED CHARPY IMPACT TEST RESULTS

BASE METAL PLATE D-4802-2 (RW)

Test Data											Calculated Results					
Test No.	Specimen No.	Test Temp. (°F)	C_S*	V_o (in./sec)	t_{GY} (μs)	P_{GY} (lb)	t_M (μs)	P_M (lb)	E_{af} (in.-lb)	E_o (in.-lb)	a (in.)	a/w	K_{Id} ksi $\sqrt{in.}$	K_{Bd} ksi $\sqrt{in.}$	K_{Jd} ksi $\sqrt{in.}$	σ_{yd} ksi
2678	152	-80	58.3	40.8	200	1094	200	1094	4	113	.200	.51	48.0	--	--	96
2679	15M	-40	55.8	40.8	220	1222	220	1222	5	113	.195	.50	51.7	--	--	102
2681	11U	0	54.1	69.6	140	1182	140	1182	4	329	.192	.49	48.8	--	--	96
2680	13K	40	55.6	78.0	[illegible]	1350	200	1350	11	413	.195	.49	57.0	--	--	113
2683	163	80	52.8	93.6	113	1253	404	1492	42	595	.190	.48	--	170	172	99
2682	13U	120	52.3	93.6	99	1177	820	1684	[illegible]	595	.189	.48	--	262	264	92
2684	14Y	160	56.0	103.2	105	1090	884	1556	116	724	.196	.50	--	284	285	91
2685	12C	210	51.3	110.4	95	1130	936	1647	143	828	.187	.47	--	287	290	87

TABLE VIII-3

PRECRACKED INSTRUMENTED CHARPY IMPACT TEST RESULTS

WELD METAL, PLATE D-4802-1/D-4802-3

Test Data												Calculated Results				
Test No.	Specimen No.	Test Temp. (°F)	C_S*	V_o (in./sec)	t_{GY} (μs)	P_{GY} (lb)	t_M (μs)	P_M (lb)	E_{af} (in.-lb)	E_o (in.-lb)	a (in.)	a/w	K_{Id} ksi $\sqrt{in.}$	K_{Rd} ksi $\sqrt{in.}$	K_{Jd} ksi $\sqrt{in.}$	σ_{yd} ksi
2697	31M	-120	52.6	40.8	220	1222	220	1222	4	113	.189	.48	49.3	--	--	96
2699	331	-80	56.7	55.2	160	1215	160	1215	4	207	.197	.50	52.2	--	--	103
2696	363	-40	50.1	69.6	120	1266	120	1265	3	329	.184	.47	49.1	--	--	95
2694	34P	0	49.7	87.6	117	1400	623	1725	76	521	.183	.47	--	223	226	104
2695	362	40	52.8	87.6	133	1317	563	1607	61	521	.190	.48	--	205	206	104
2698	34M	80	50.0	93.6	105	1304	813	1721	111	595	.184	.47	--	264	267	98
2701	347	120	49.2	103.2	122	1314	772	1727	114	724	.182	.46	--	264	267	97
2700	35J	160	51.6	110.4	119	1239	673	1618	99	828	.187	.48	--	249	252	96

TABLE VIII-4

PRECRACKED INSTRUMENTED CHARPY IMPACT TEST RESULTS

HAZ METAL, PLATE D-4802-2

Test Data												Calculated Results					
Test No.	Specimen No.	Test Temp. (°F)	C_S*	V_o (in./sec)	t_{GY} (μs)	P_{GY} (lb)	t_M (μs)	P_M (lb)	E_{af} (in.-lb)	E_o (in.-lb)	a (in.)	a/w	K_{Id} ksi $\sqrt{in.}$	K_{Bd} ksi $\sqrt{in.}$	K_{Jd} ksi $\sqrt{in.}$	σ_{yd} ksi
2689	442	-120	63.6	55.2	160	1148	160	1148	4	207	.208	.53	54.0	--	--	109
2686	43B	-80	59.9	55.2	320	1570	320	1570	17	207	.202	.51	70.4	--	--	141
2690	41J	-40	57.5	78.0	130	1440	1085	1748	127	413	.198	.50	--	301	302	124
2693	42K	0	54.5	93.6	133	1484	489	1603	58	595	.193	.49	--	202	203	121
2688	443	40	57.1	93.6	156	1328	742	1572	92	595	.198	.50	--	244	245	114
2687	42J	80	54.3	110.4	112	1297	758	1604	113	828	.193	.49	--	276	278	106
2687	422	120	53.4	130.8	102	1311	802	1680	149	1162	.191	.48	--	316	319	105
2691	434	160	54.9	130.8	115	1275	784	1619	139	1162	.194	.4	--	308	310	105

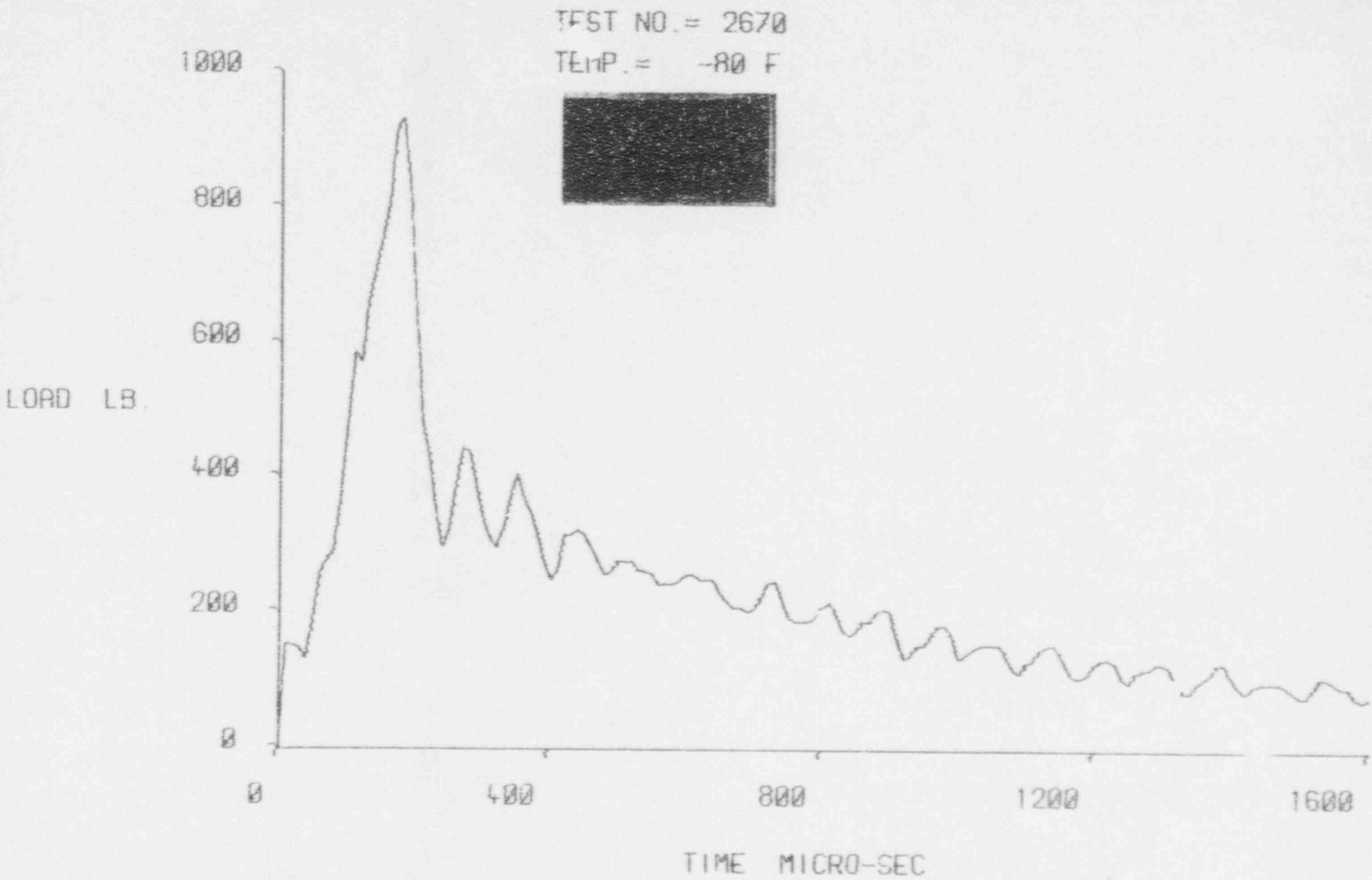


Figure VIII-1: PIC_V Load Record for Base Metal Plate D-4802-2 (WR)

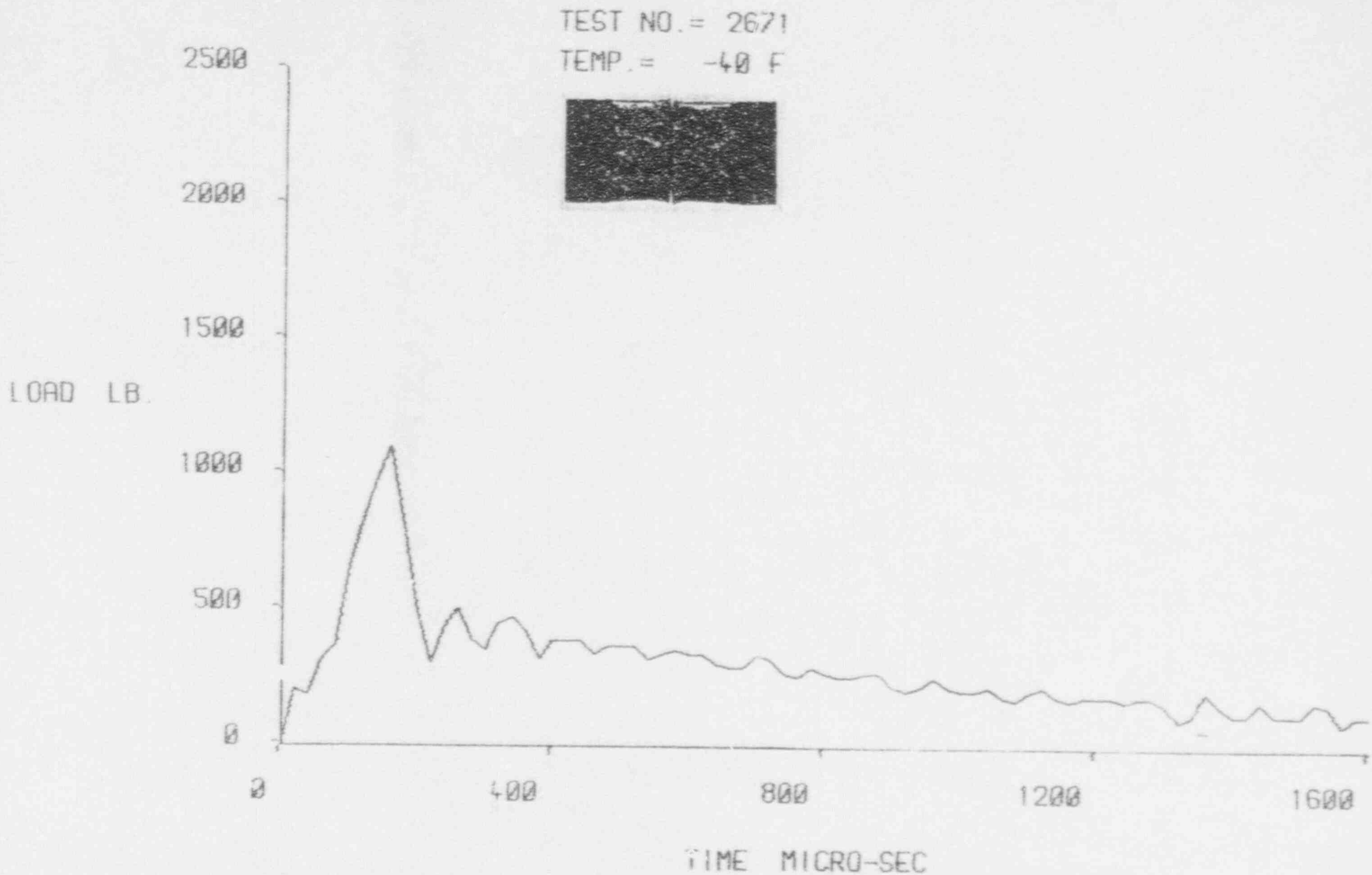


Figure VIII-2: PIC_V Load Record for Base Metal Plate D-4802-2 (WR)

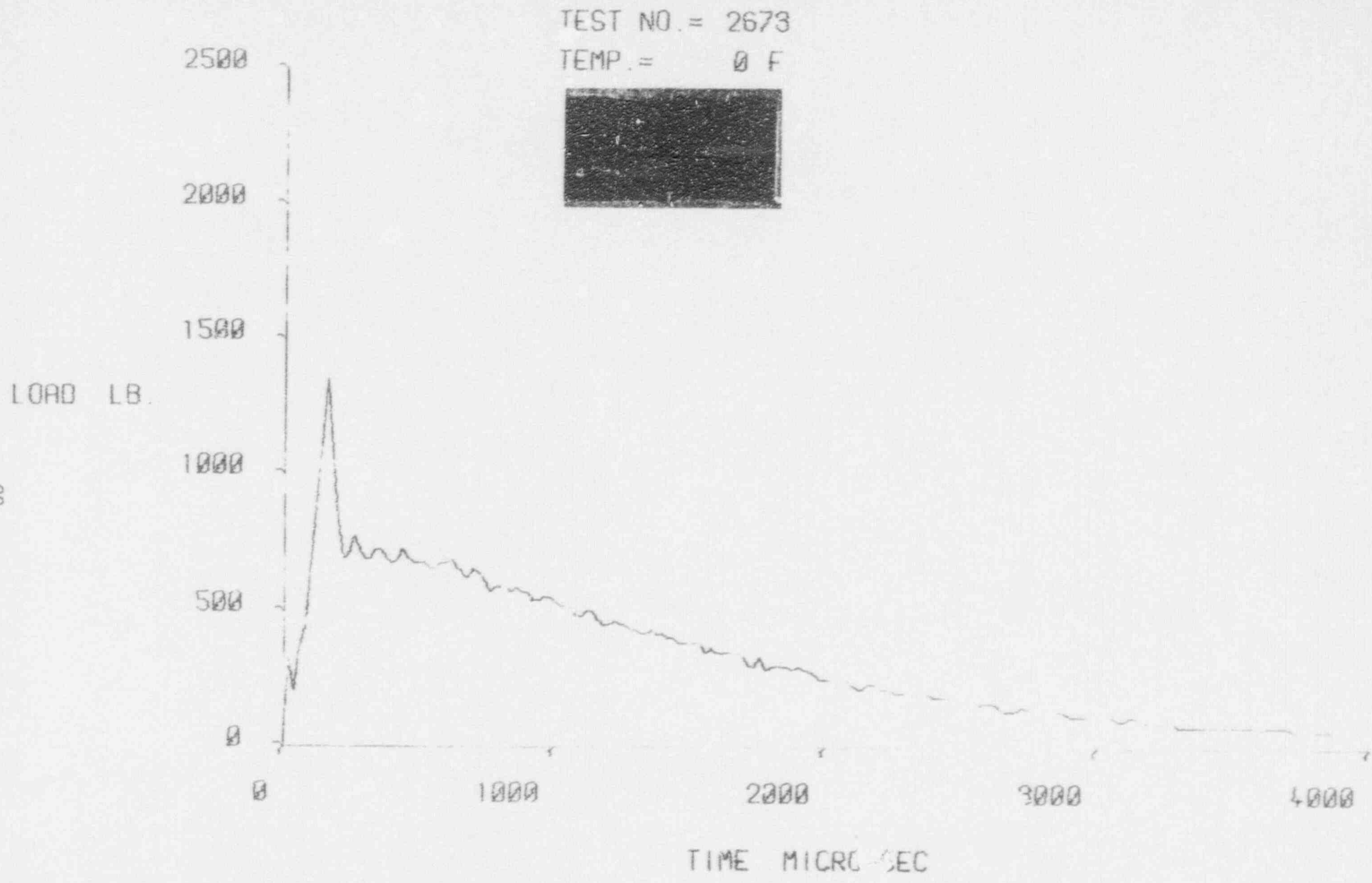


Figure VIII-3: PIC_V Load Record for Base Metal Plate D-4802-2 (WR)

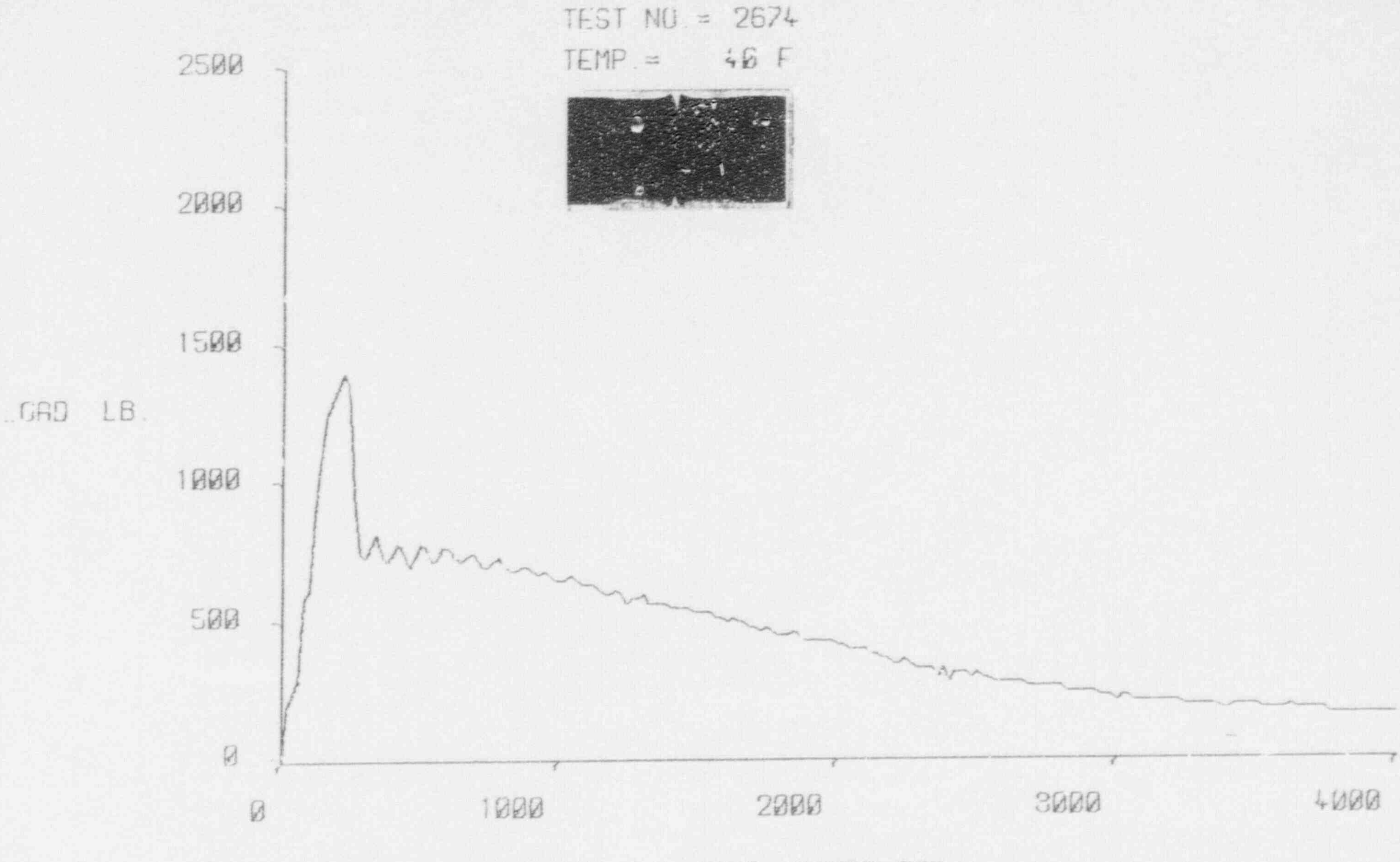
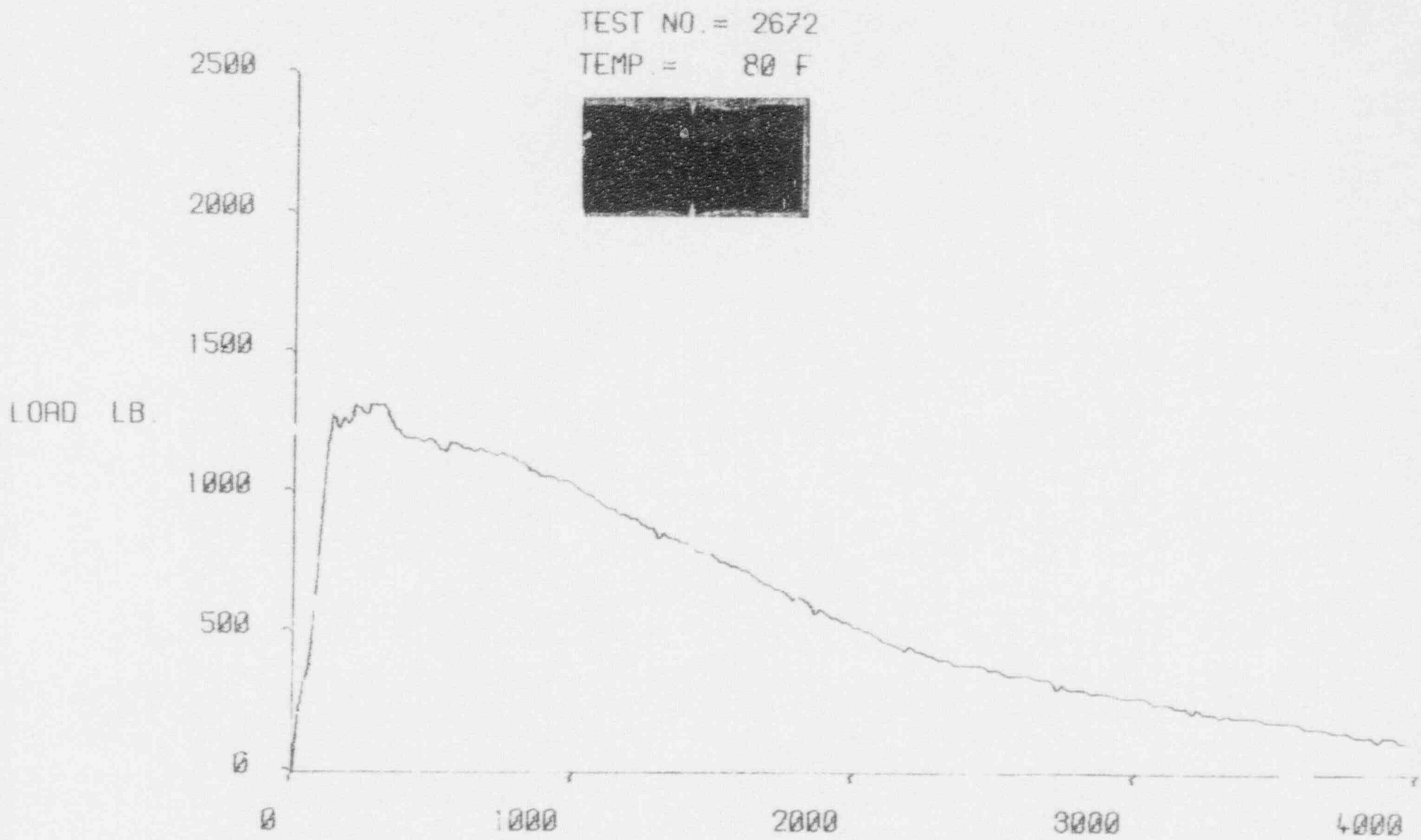


Figure VIII-4: PIC$_V$ Load Record for Base Metal Plate D-4802-2 (WR)


TEST NO. = 2672
TEMP. = 80 F
LOAD LB.
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000

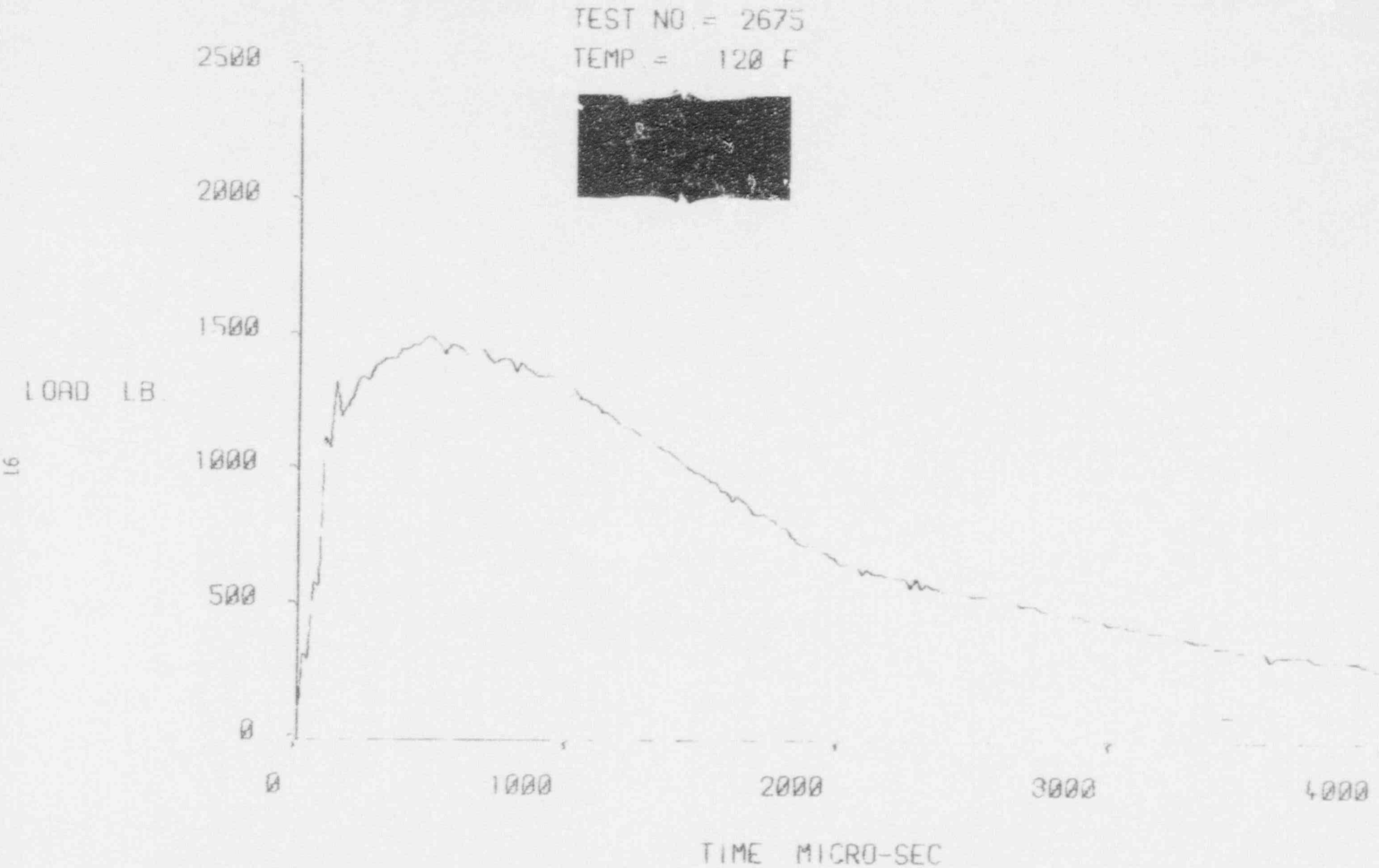
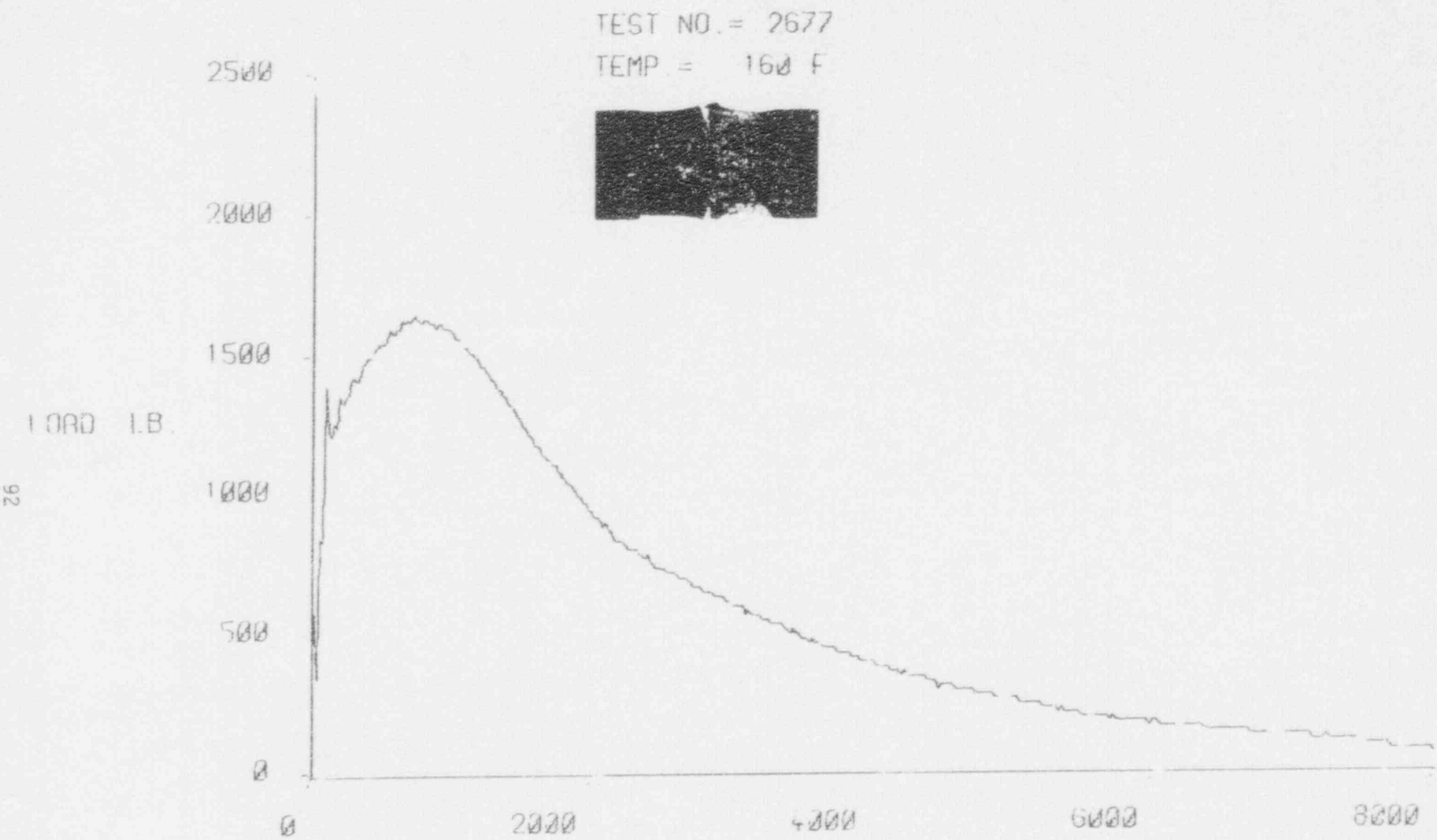


Figure VIII-6: PIC_V Load Record for Base Metal Plate D-4802-2 (WR)



TEST NO.= 2677
TEMP = 160 F
LOAD LB.
2500
2000
1500
1000
500
0
0
2000
4000
6000
8000

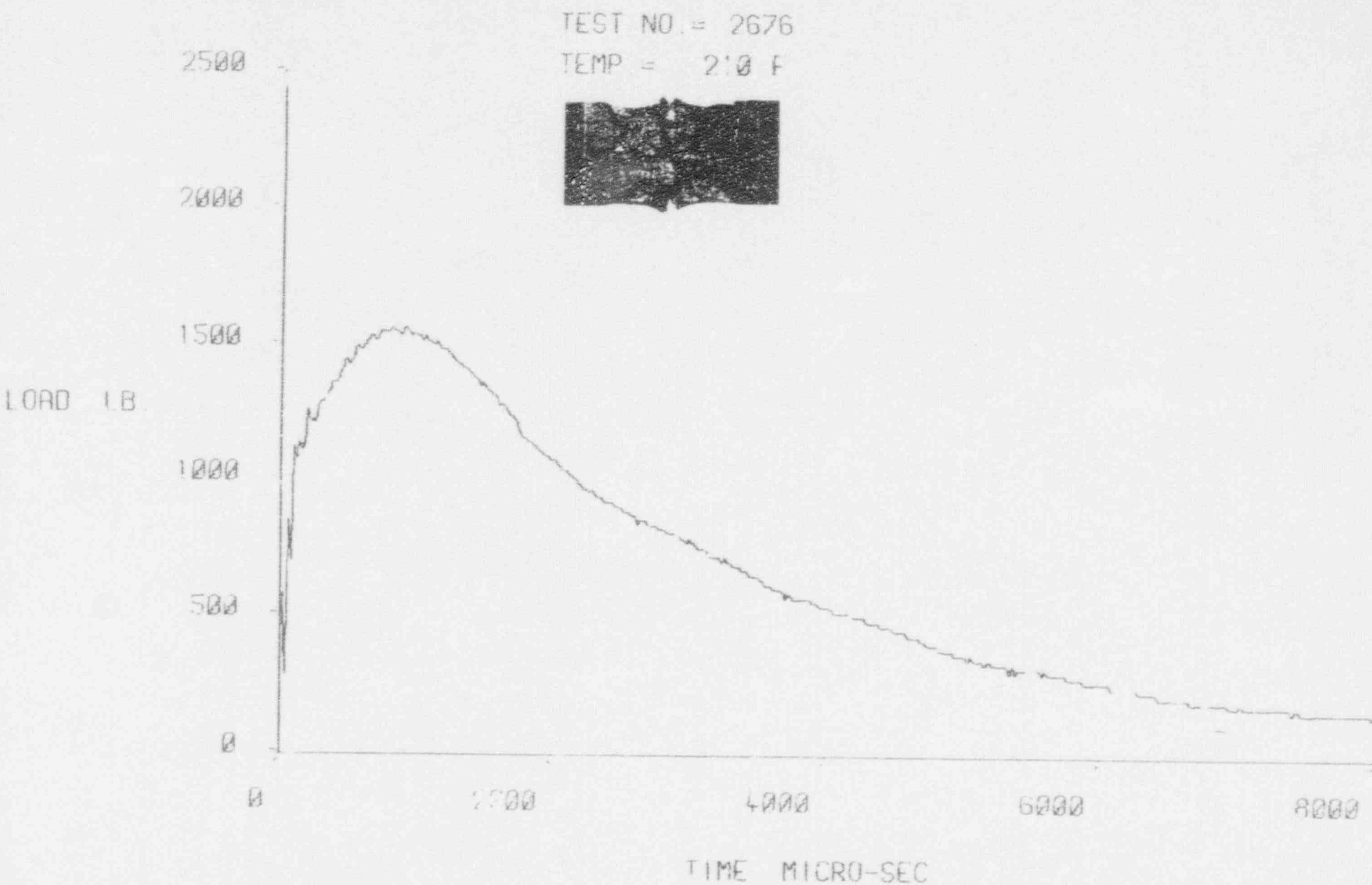
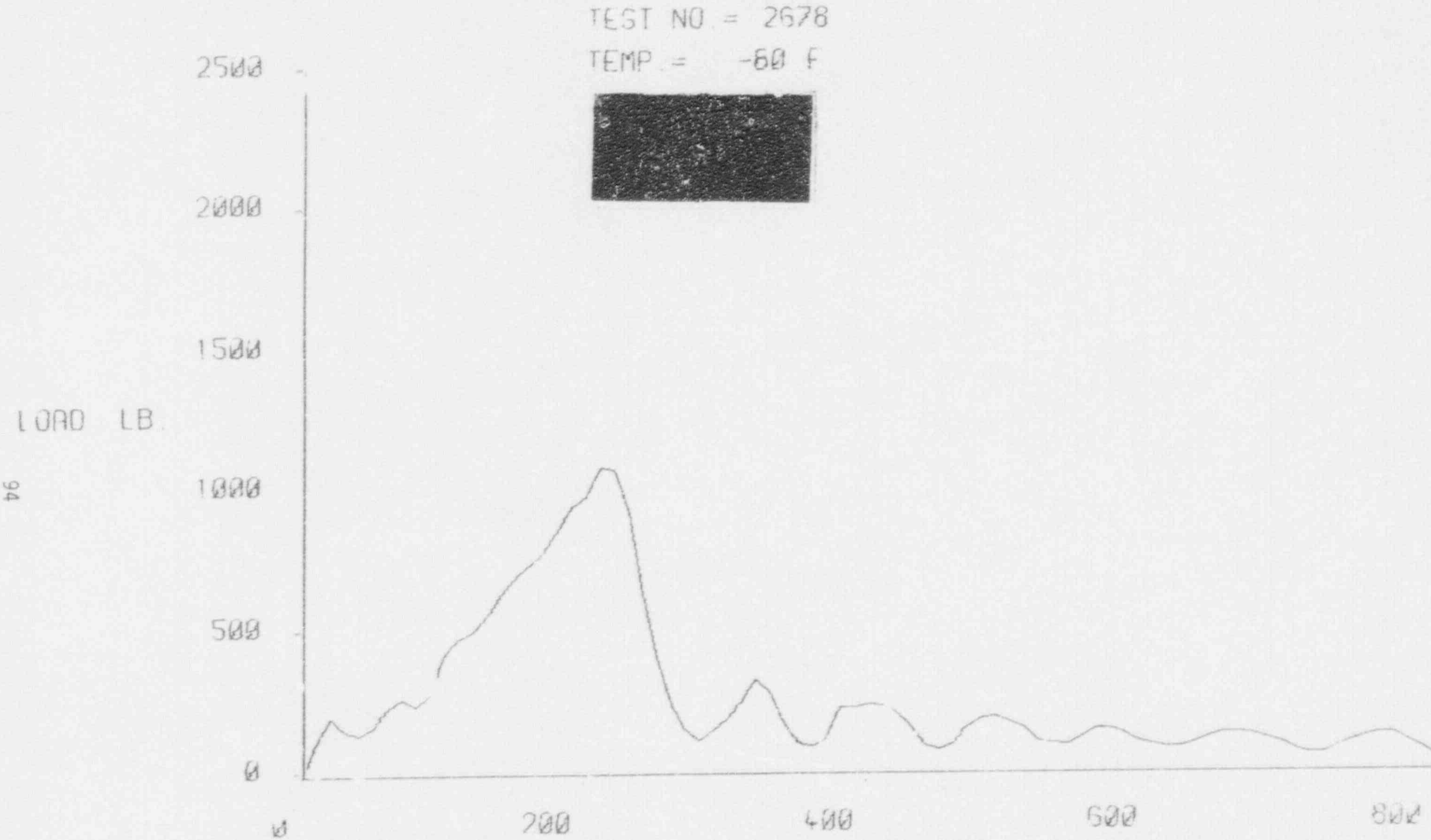


Figure VIII-8: PIC_y Load Record for Base Metal Plate D-4802-2 (WR)


TEST NO. = 2678
TEMP. = -60 F
[redacted]
LOAD LB.
2500
2000
1500
1000
500
0
0
200
400
600
800

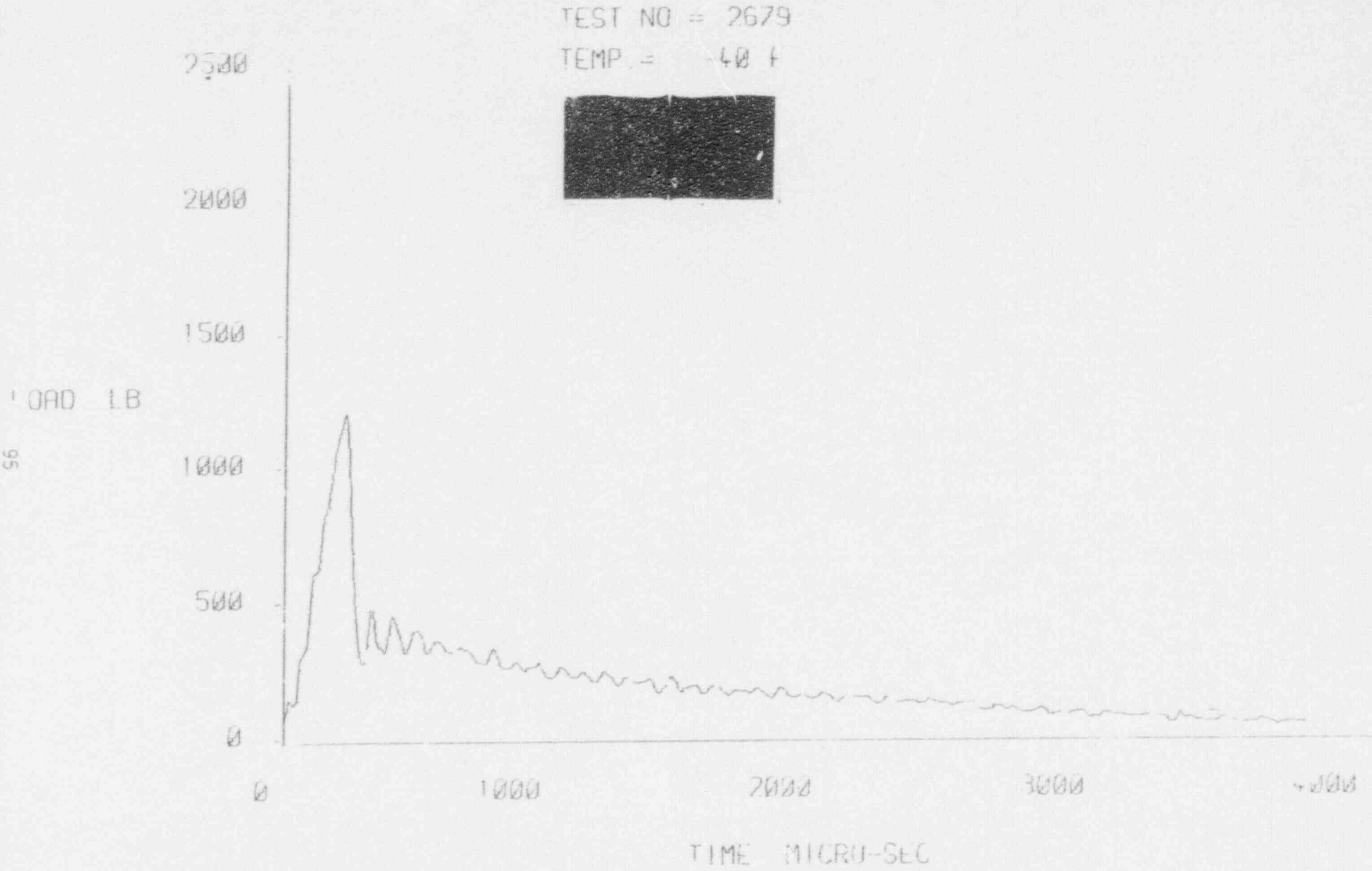
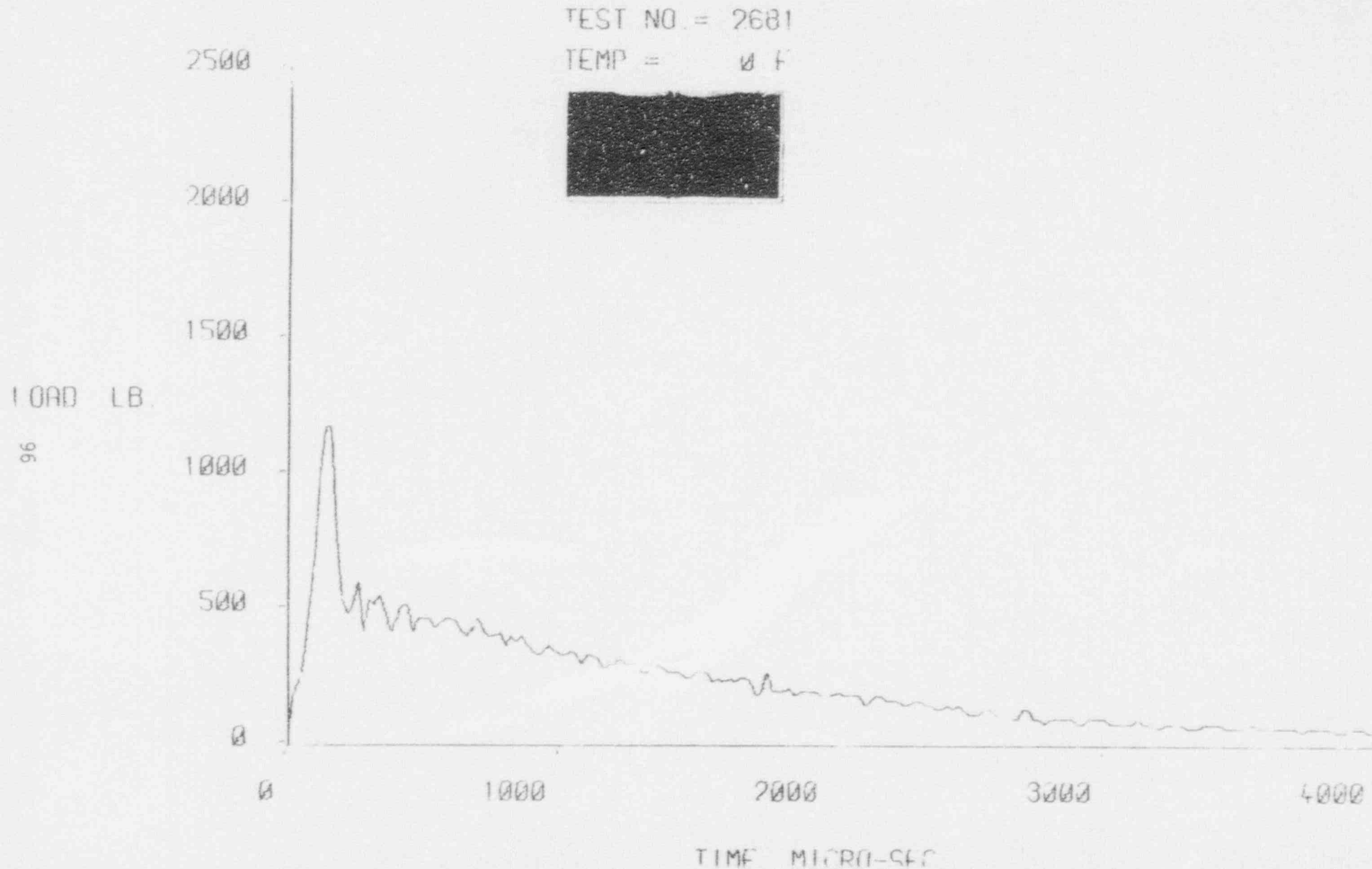


Figure VIII-10: PIC_V Load Record for Base Metal Plate D-4802-2 (RW)


TEST NO. = 2681
TEMP = 0 F
[redacted]
LOAD LB.
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
TIME MICRO-SEC

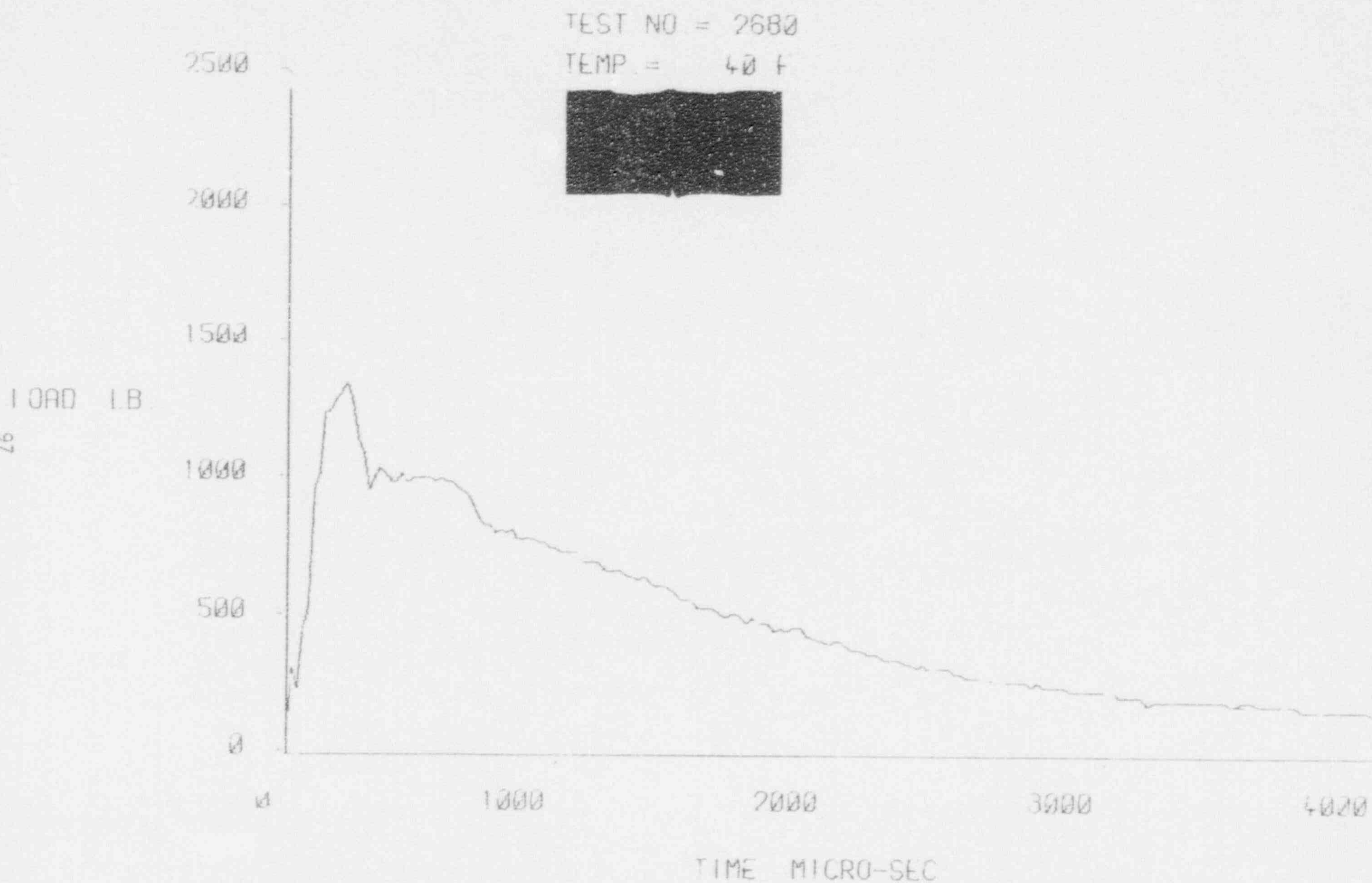
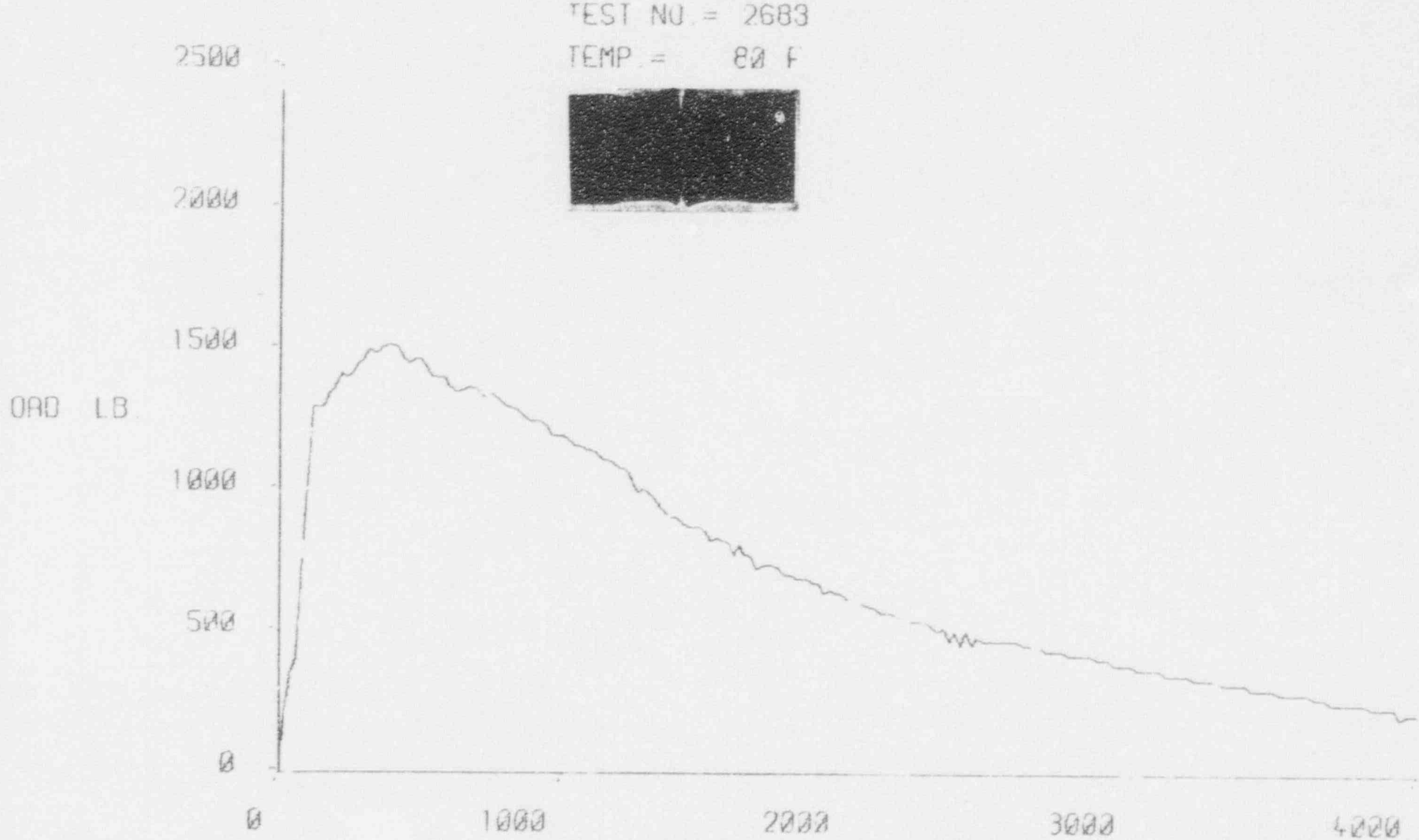


Figure VIII-12: PIC_V Load Record for Base Metal Plate D-4802-2 (RW)


TEST NO. = 2683
TEMP. = 80 F
LOAD LB.
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000

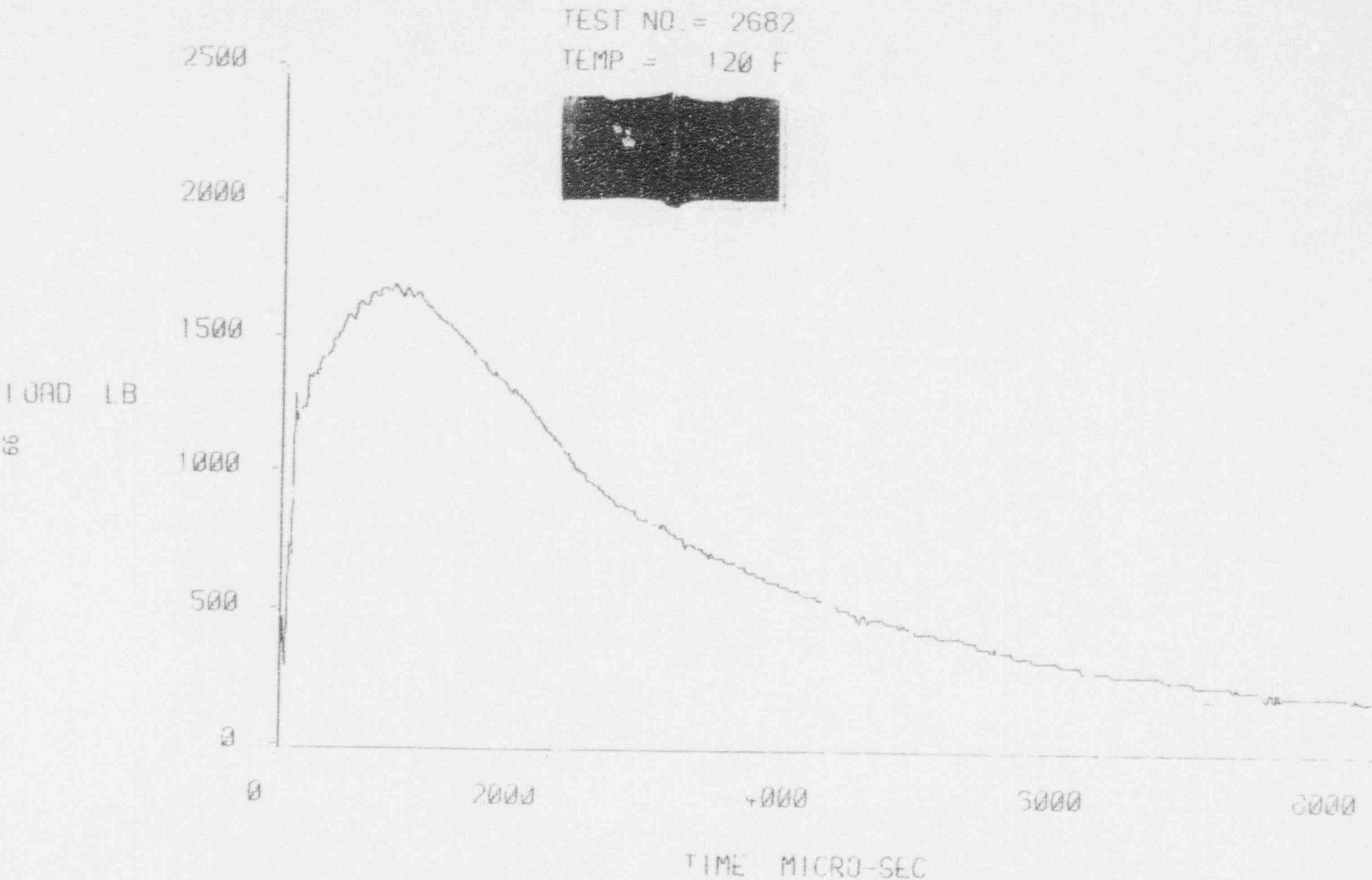
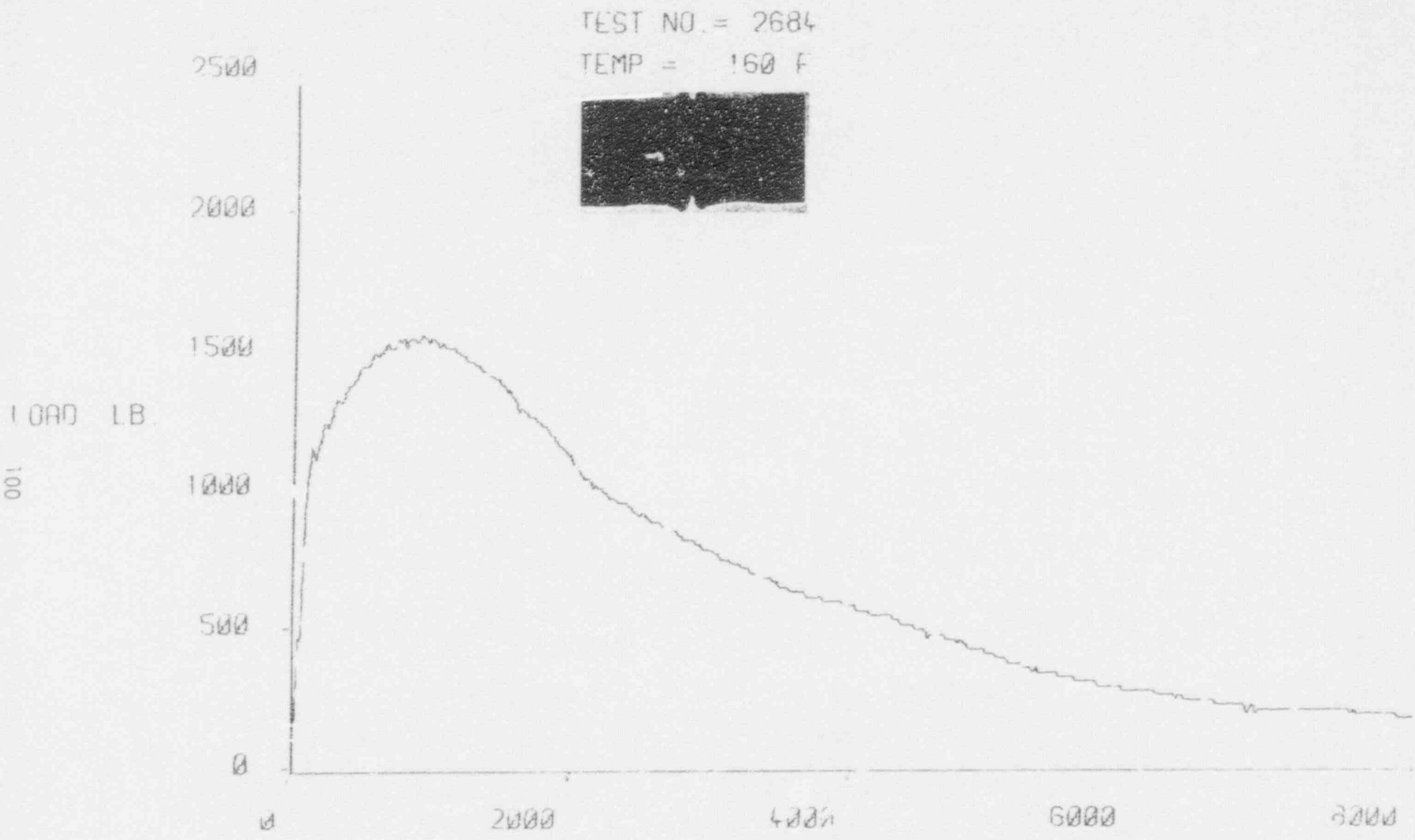


Figure VIII-14: PIC_V Load Record for Base Metal Plate D-4802-2 (RW)


TEST NO. = 2684
TEMP = 160 F
LOAD LB.
2500
2000
1500
1000
500
0
0
2000
4000
6000
8000

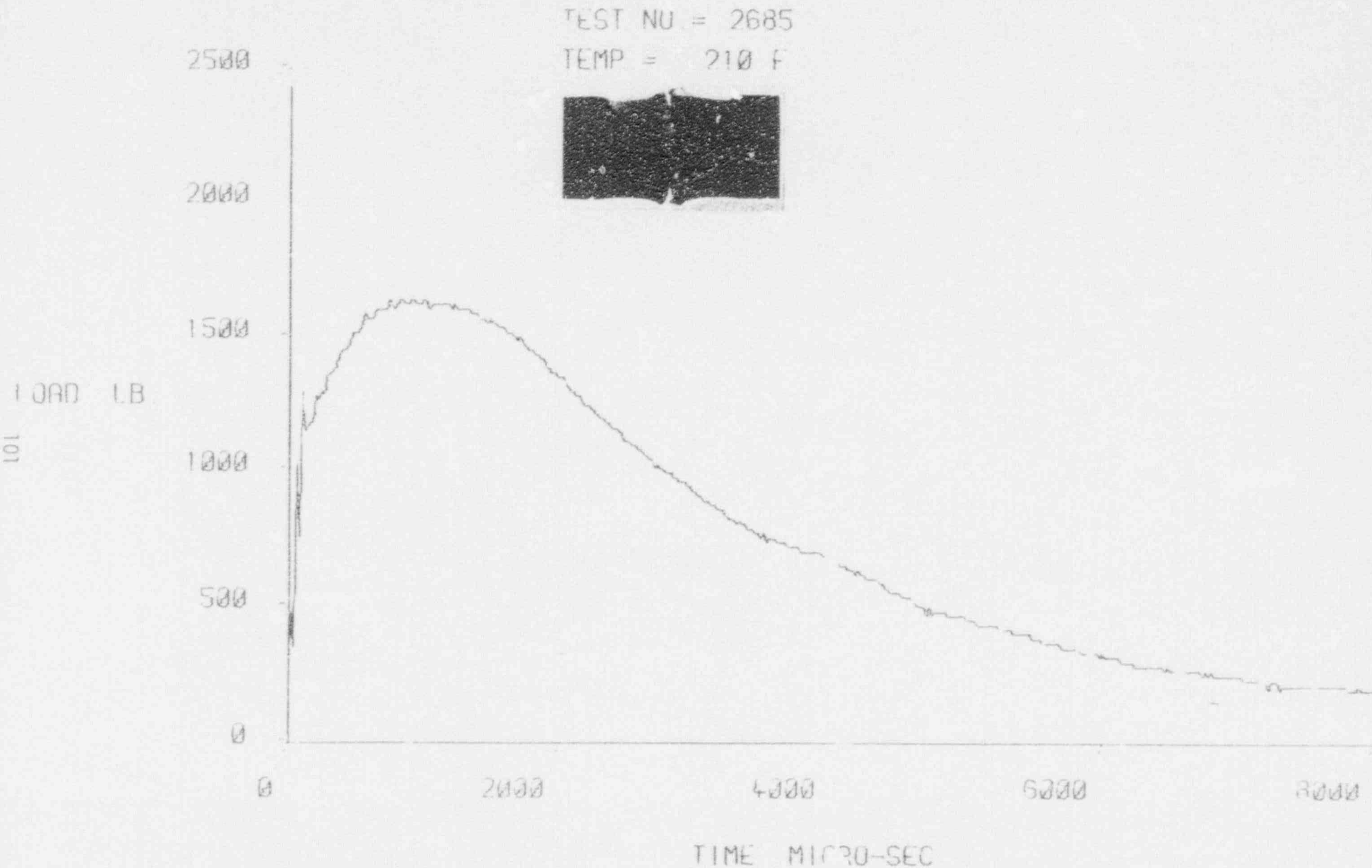
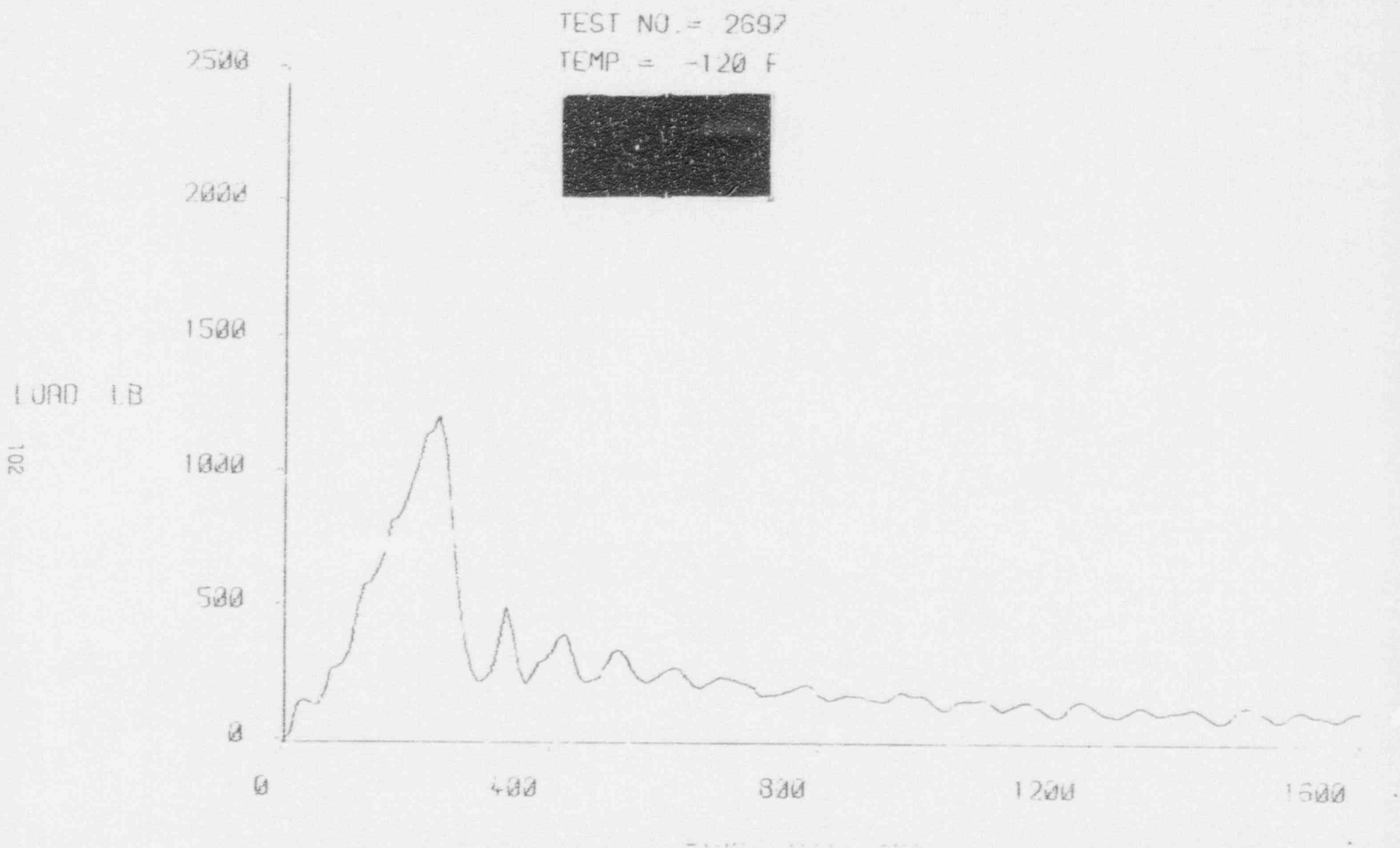


Figure VIII-16: PIC_V Load Record for Base Metal Plate D-4802-2 (RW)


TEST NO. = 2697
TEMP = -120 F
[redacted]
LOAD LB
2500
2000
1500
1000
500
0
0
400
800
1200
1600

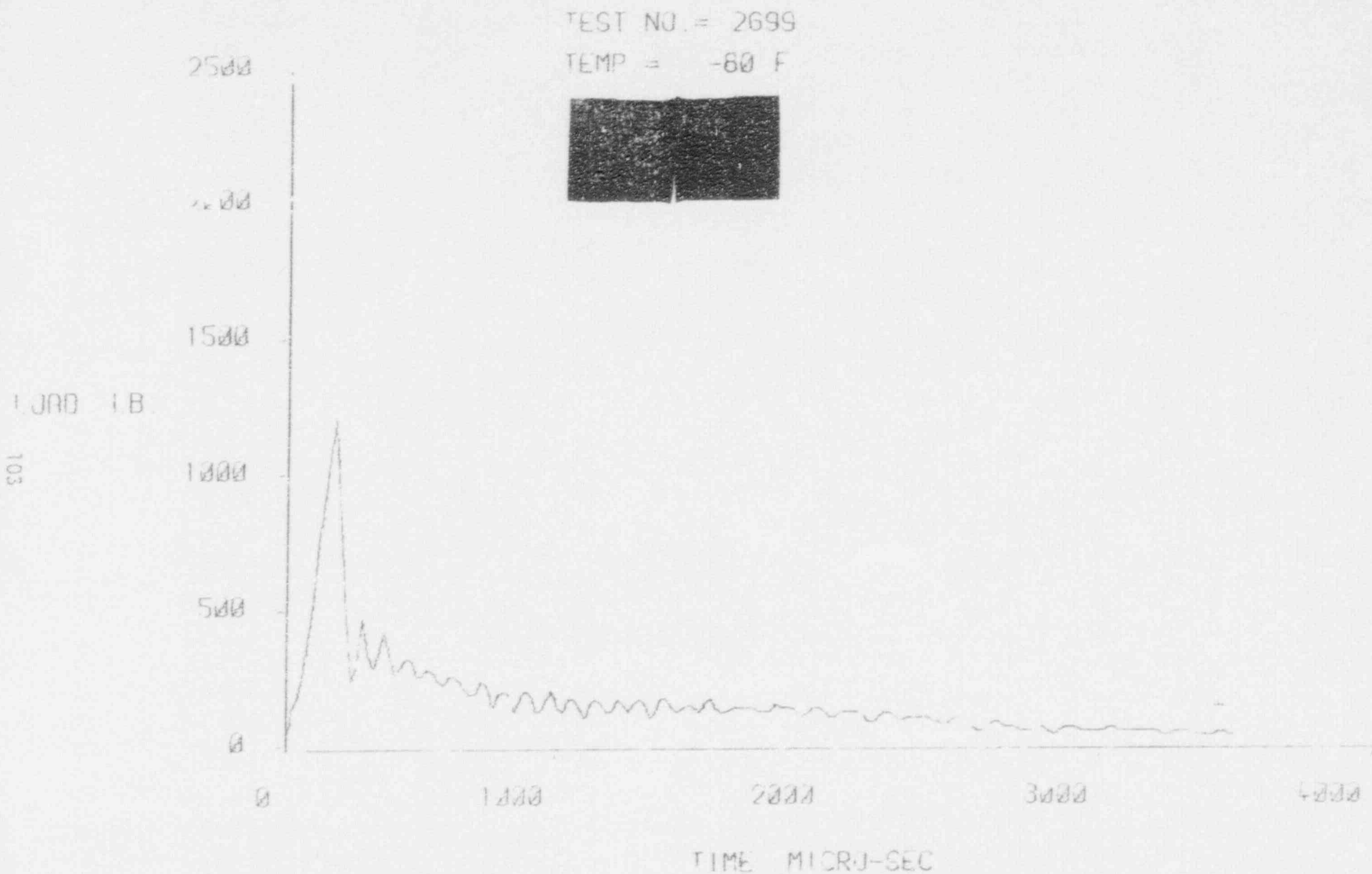
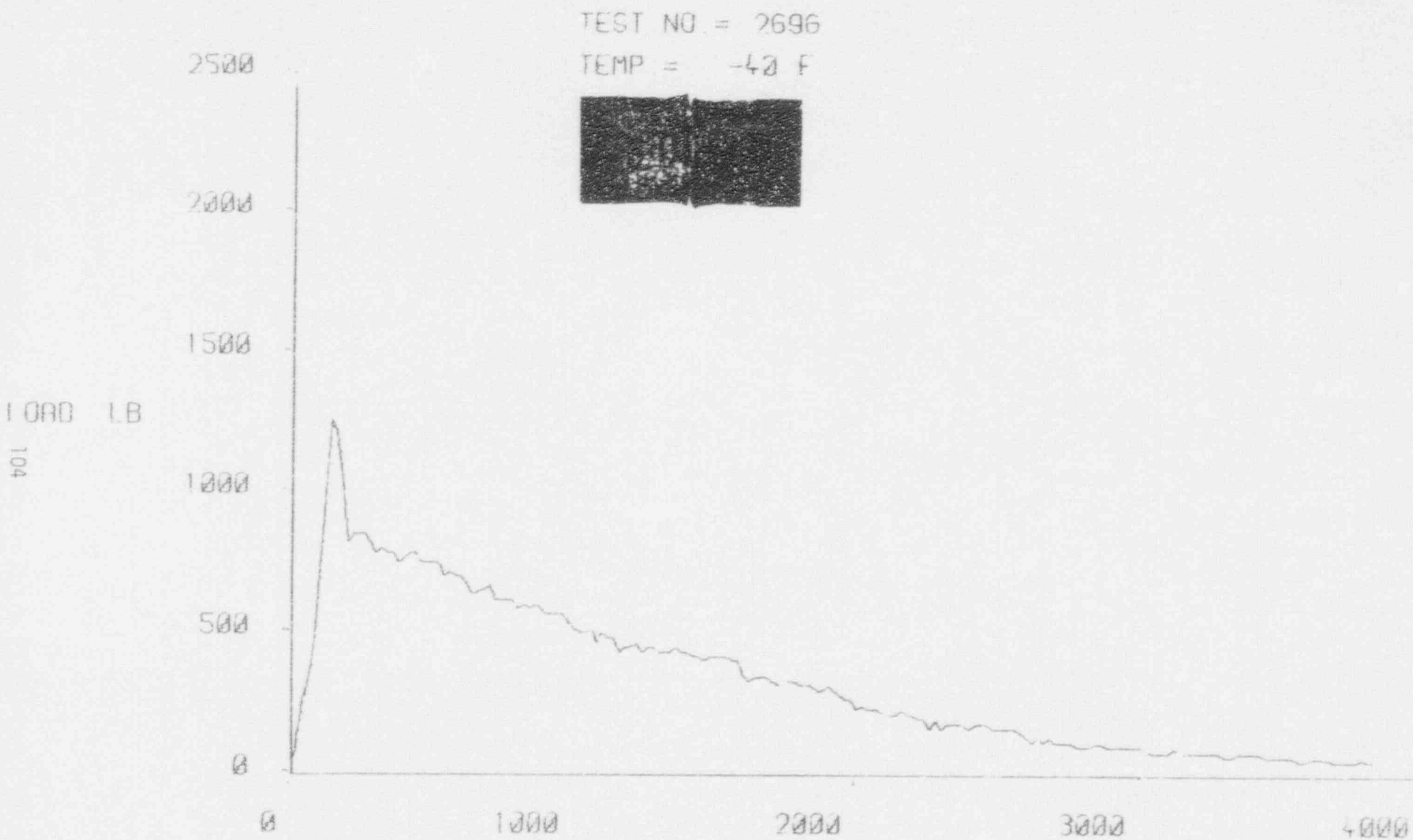


Figure VIII-13: PIC_V Load Record for Weld Metal, Plate D-4802-1/D-4802-3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LOAD LB
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2000
1500
1000
500
0
0
1000
2000
3000
4000

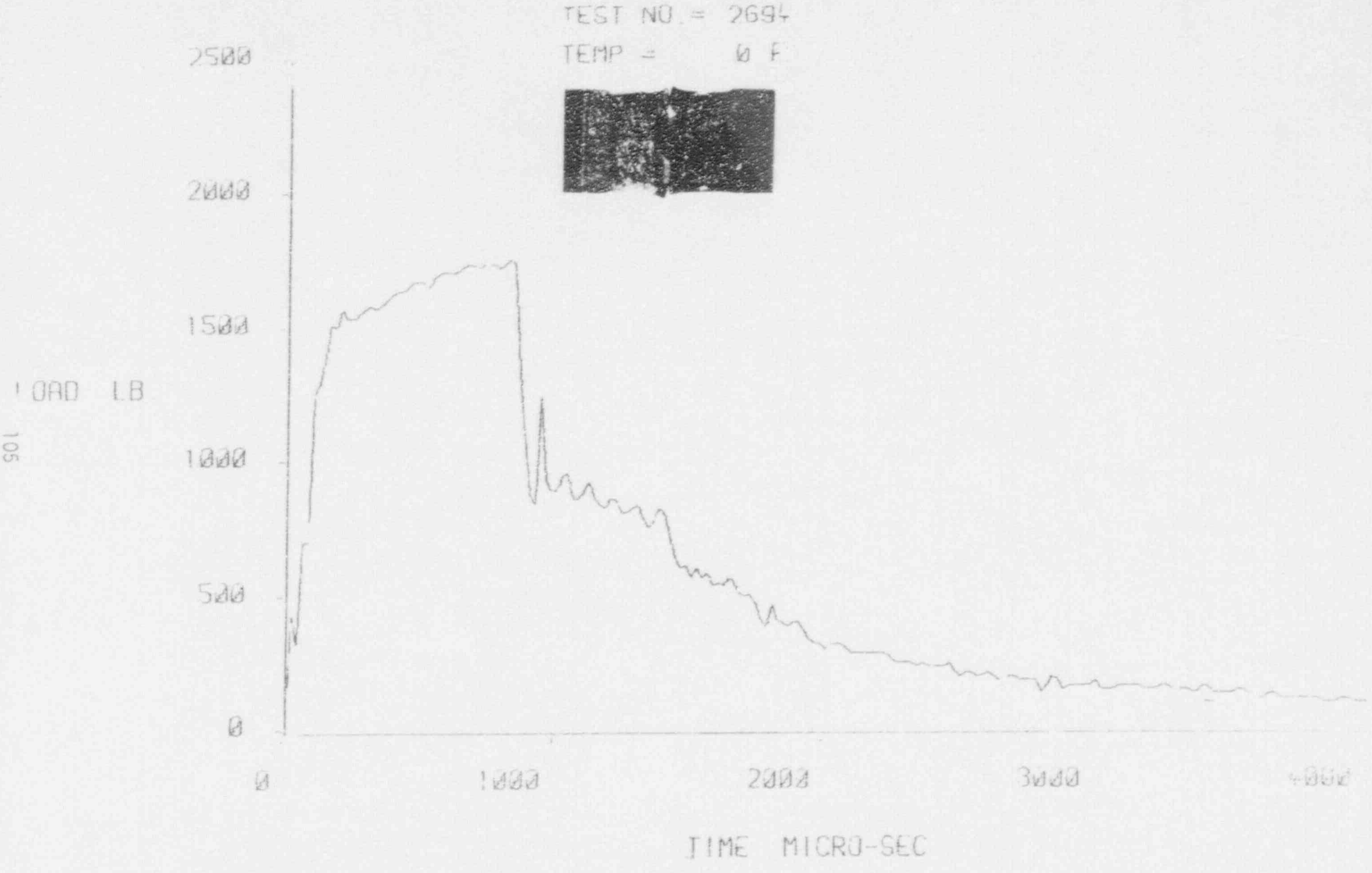
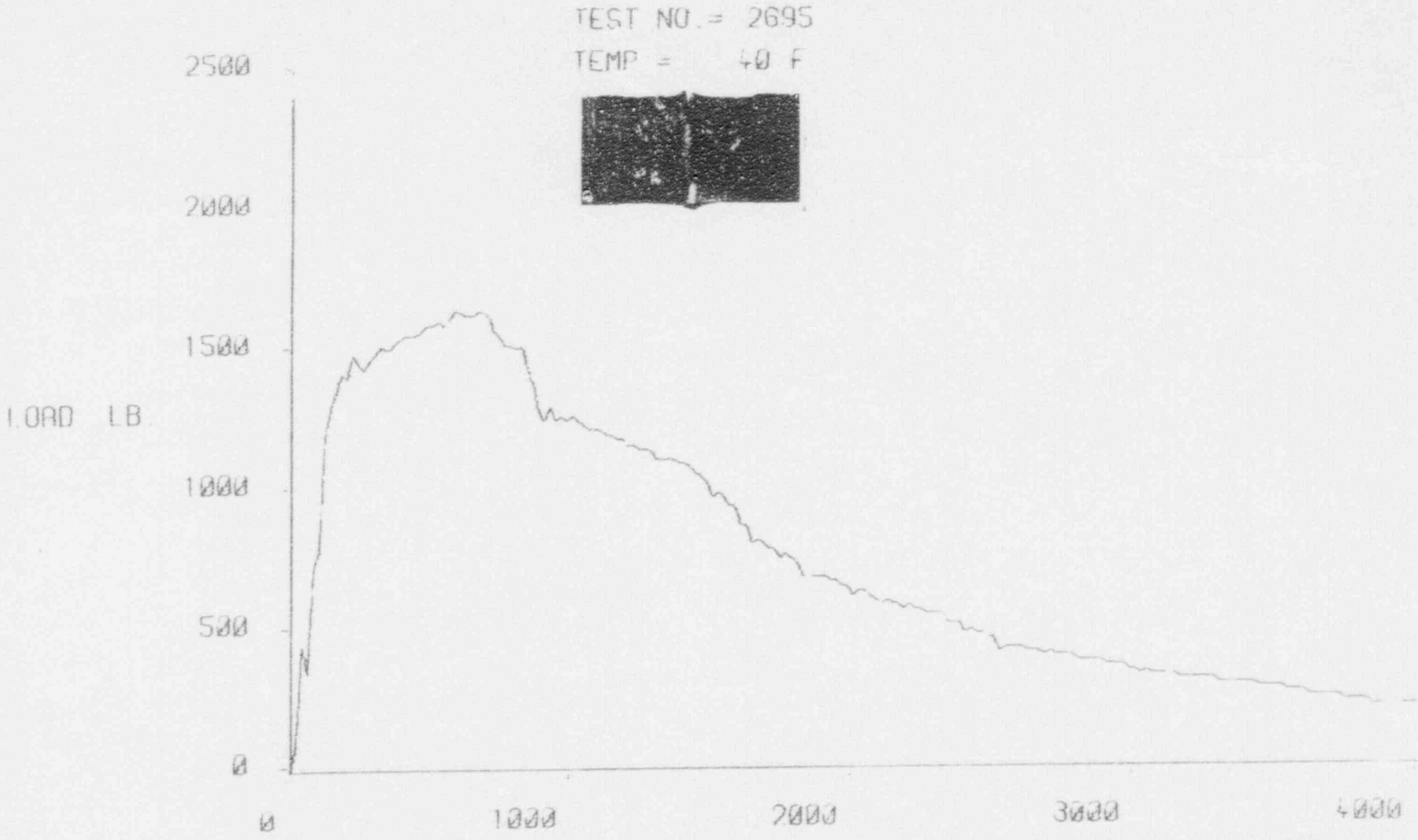


Figure VIII-20: PIC_V Load Record for Weld Metal, Plate D-4802-1/D-4802-3


TEST NO. = 2695
TEMP = 40 F
LOAD LB.
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2000
1500
1000
500
0
0
1000
2000
3000
4000

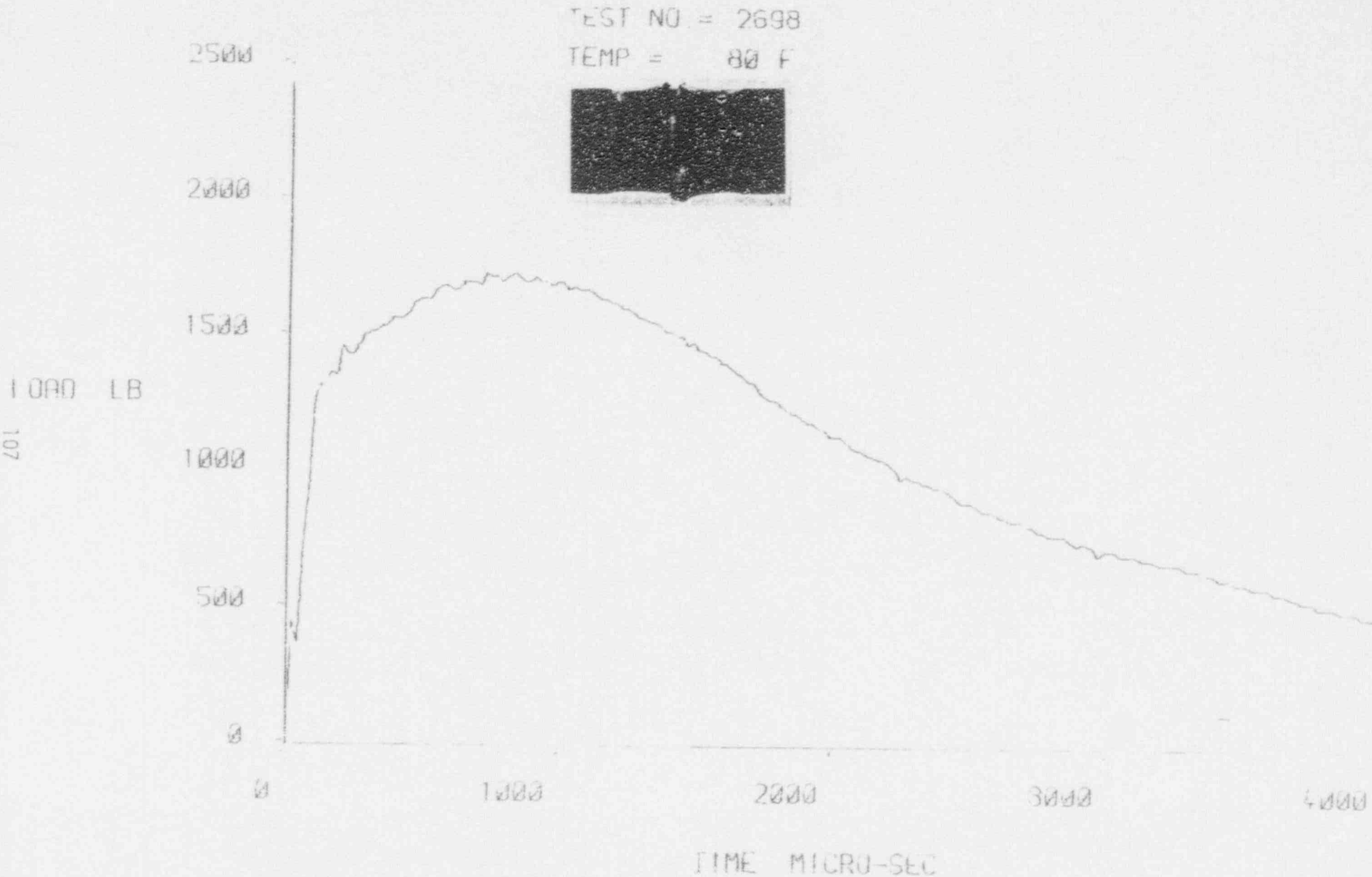
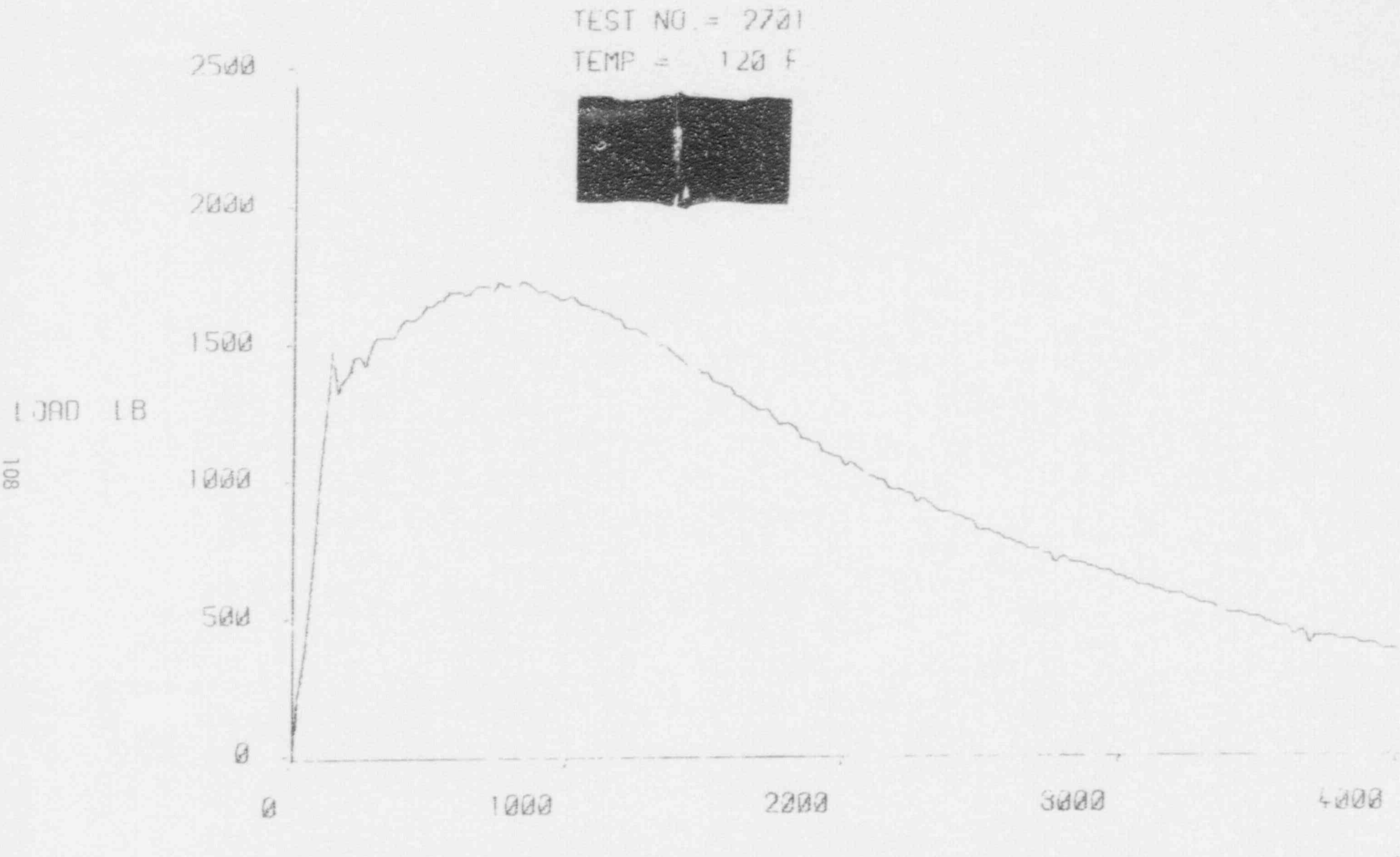


Figure VIII-22: PIC_V Load Record for Weld Metal, Plate D-4802-1/D-4802-3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0
1000
2000
3000
4000

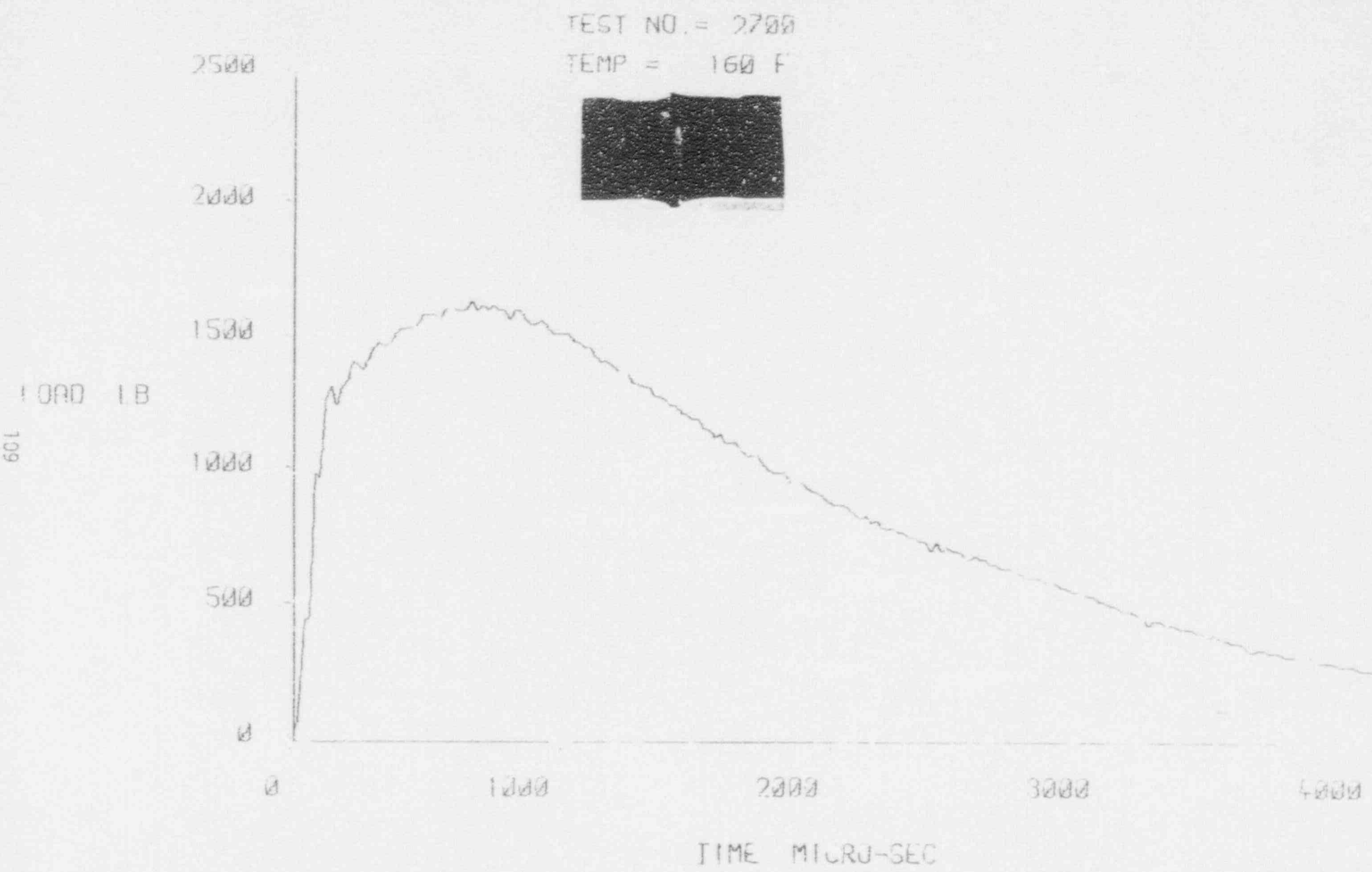
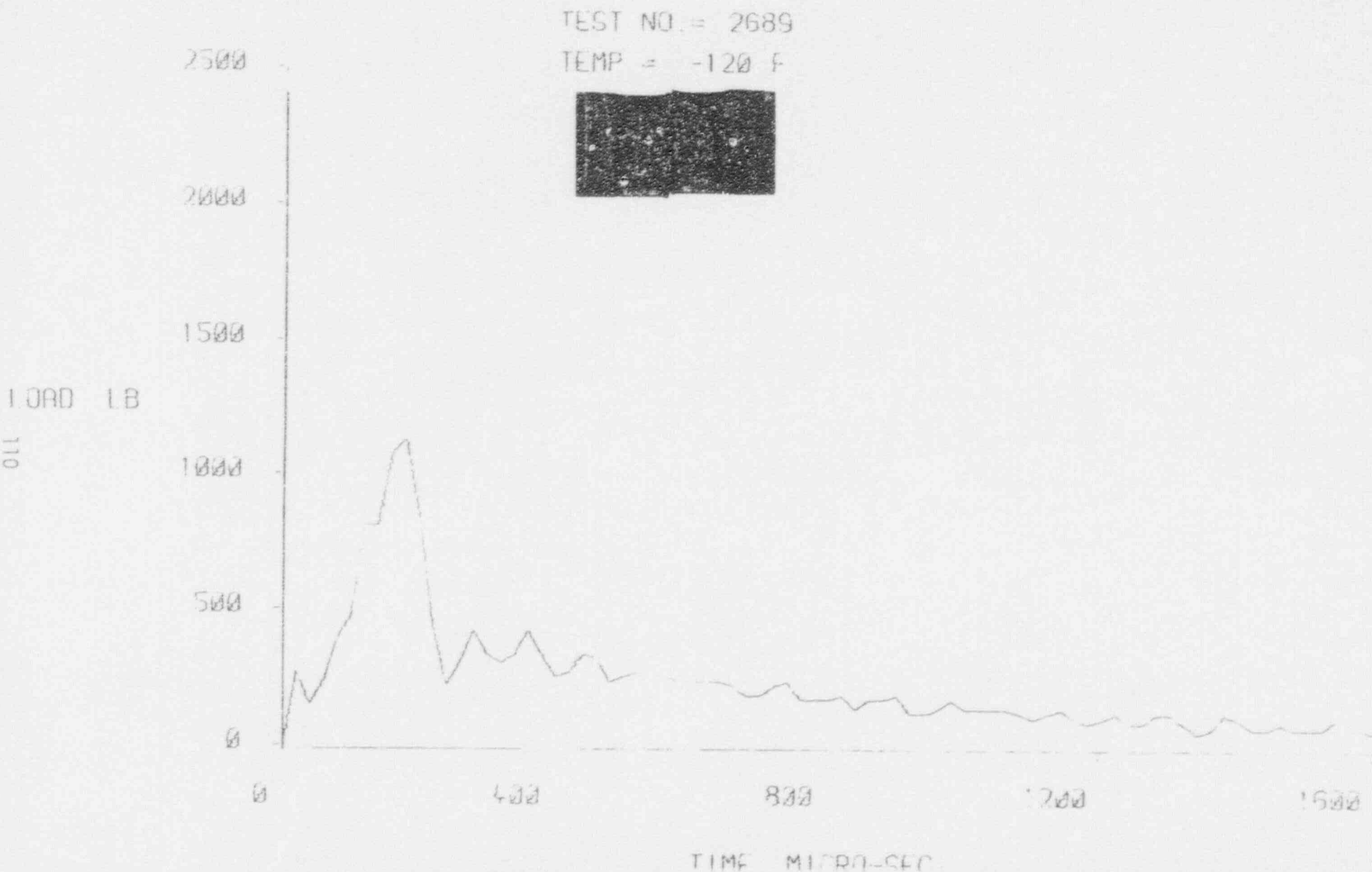


Figure VIII-24: PIC_V Load Record for Weld Metal, Plate D-4802-1/D-4802-3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800
1200
1600
TIME MICRO-SEC

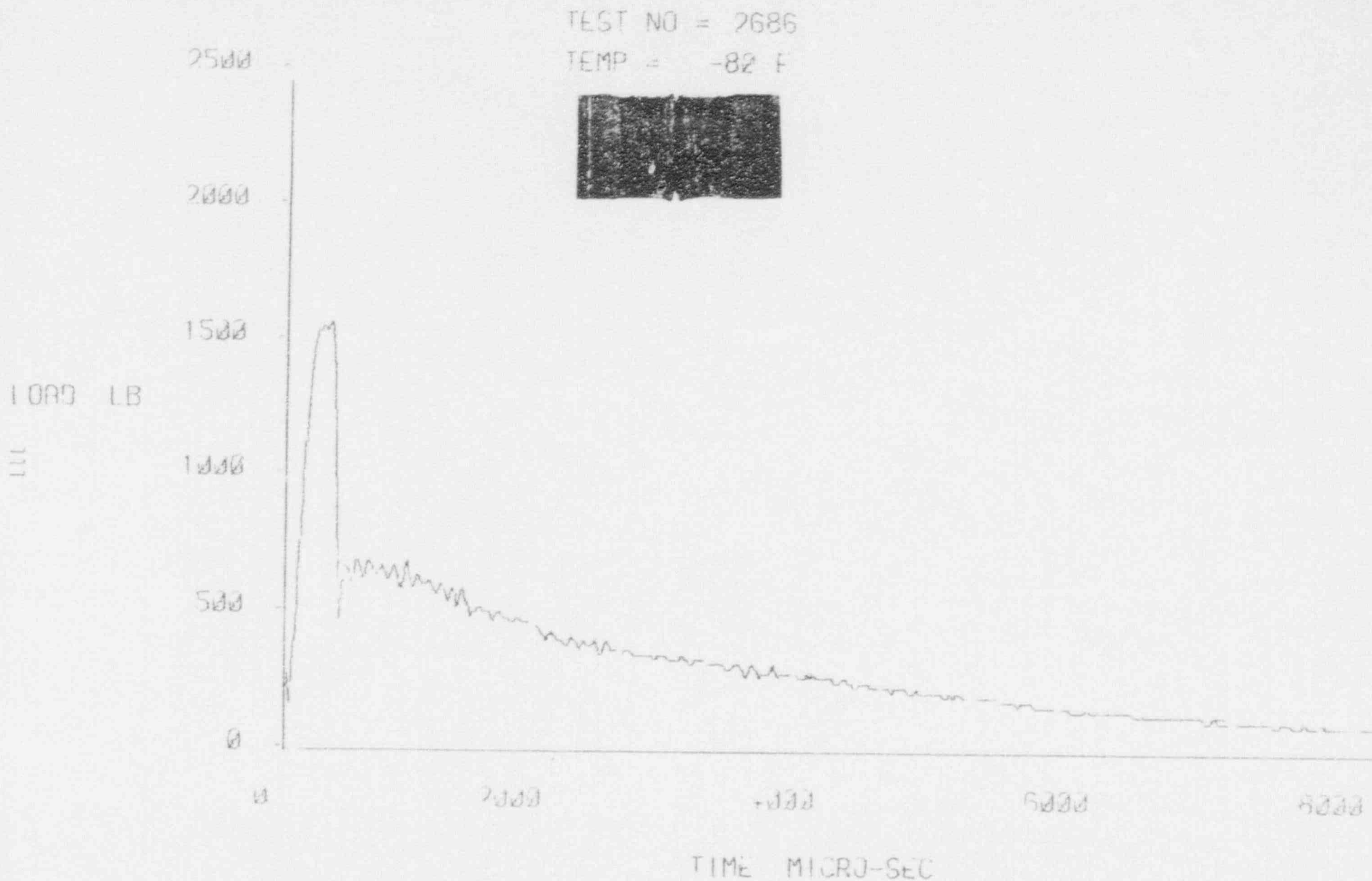
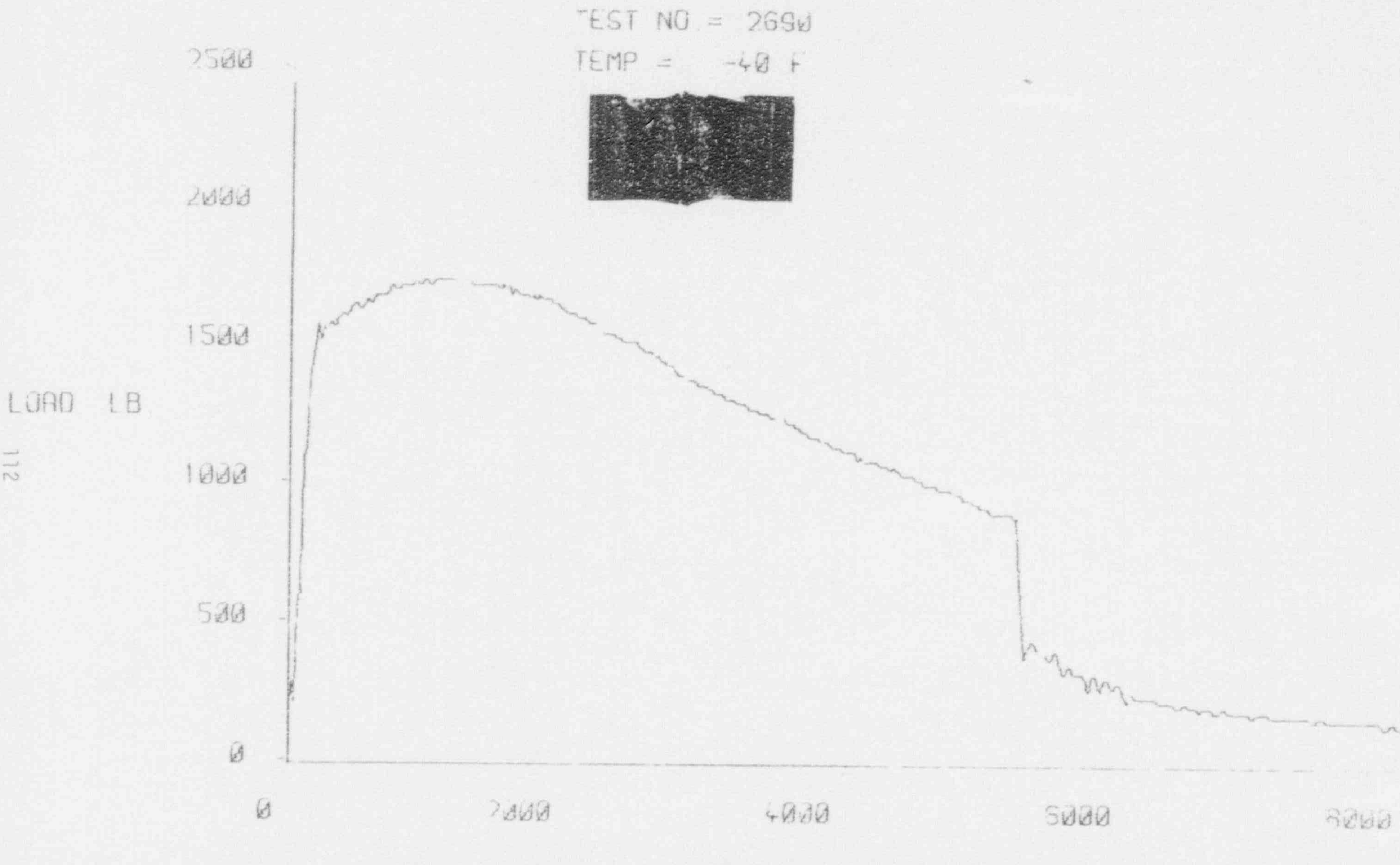


Figure VIII-26: PIC_v Load Record for HAZ Metal, Plate D-4802-2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LOAD LB
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2000
4000
6000
8000

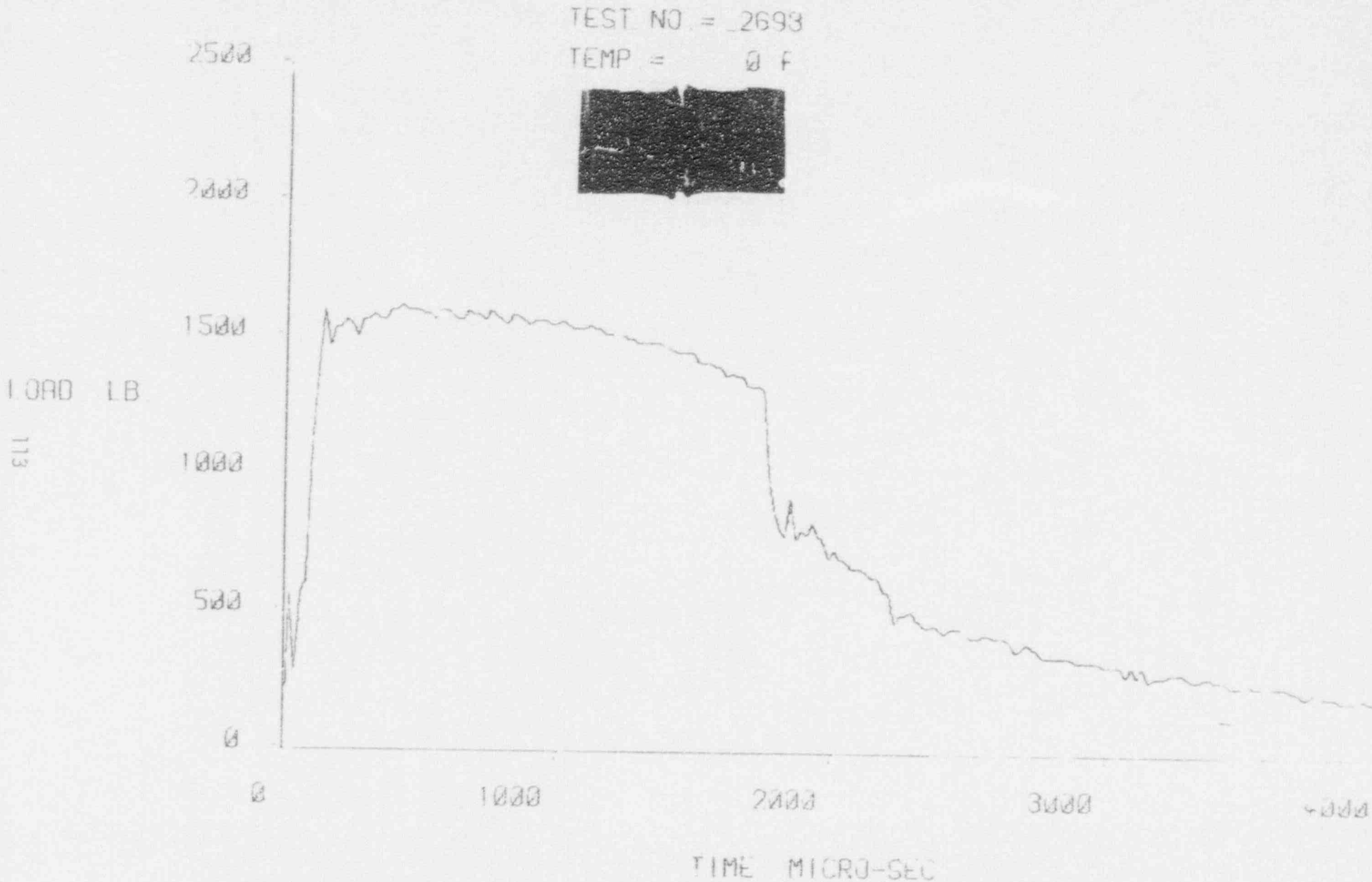
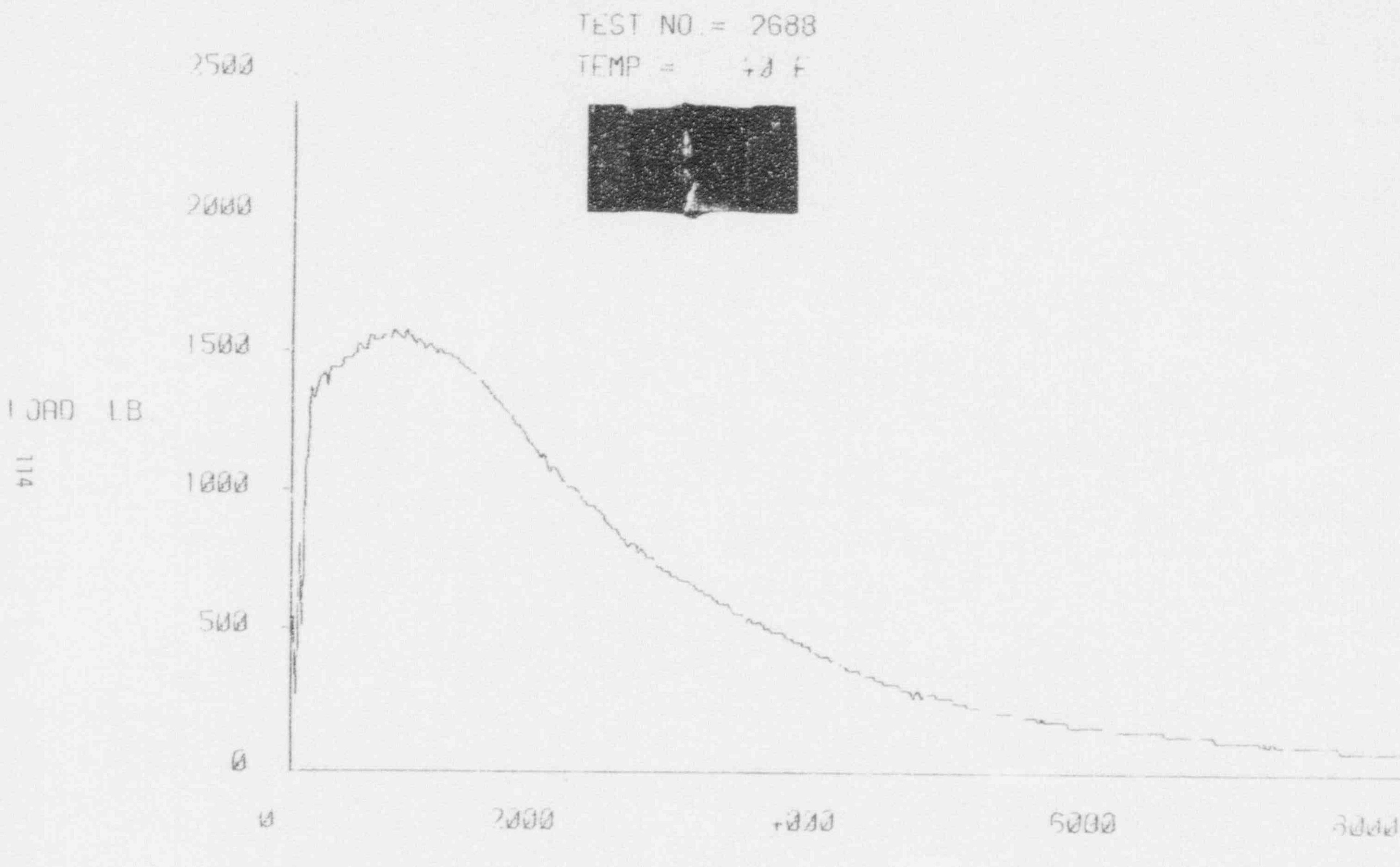


Figure VIII-28: PIC_V Load Record for HAZ Metal, Plate D-4802-2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1500
1000
500
0
0
2000
4000
6000
8000
TIME MICRO-SEC

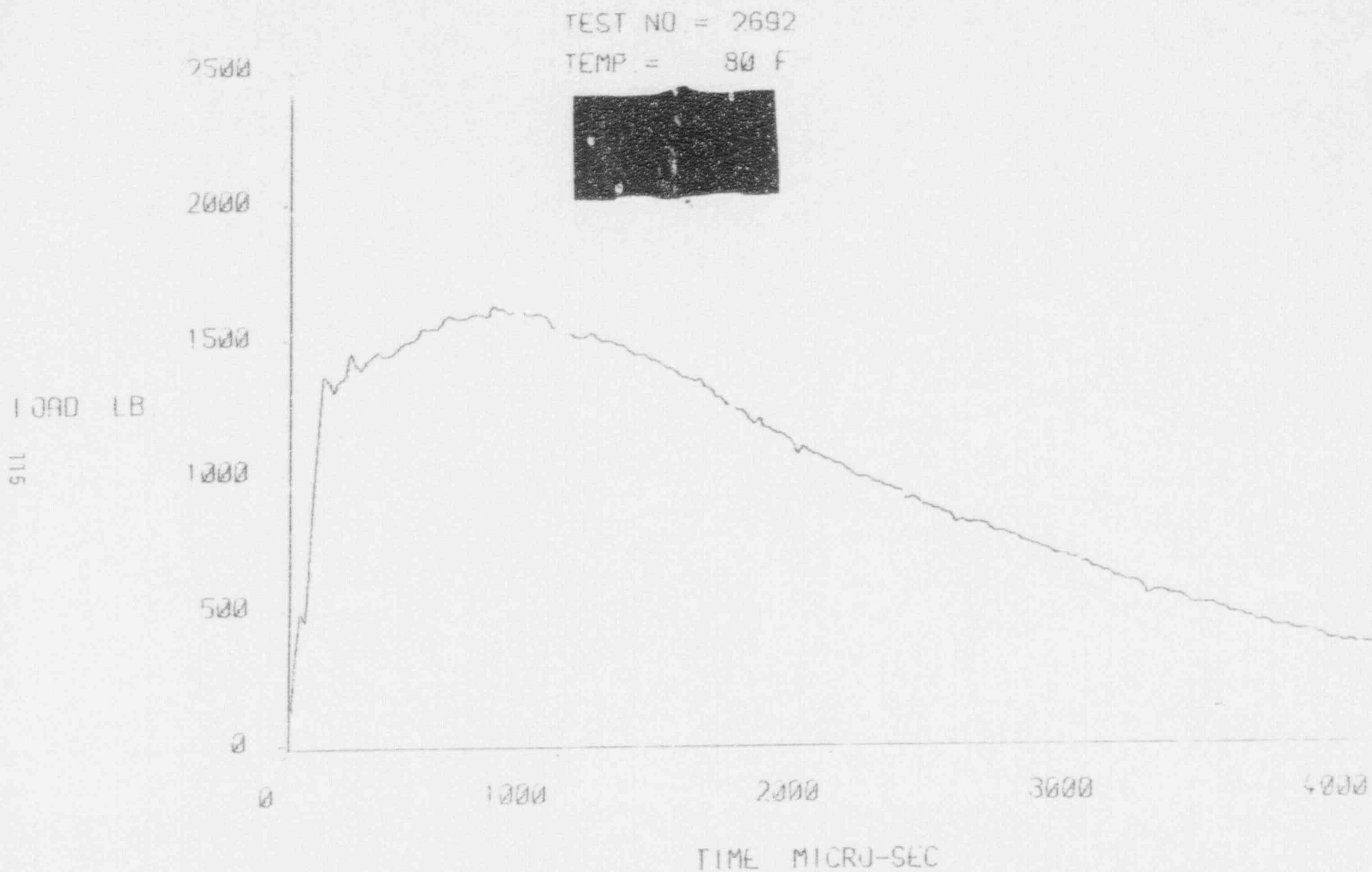
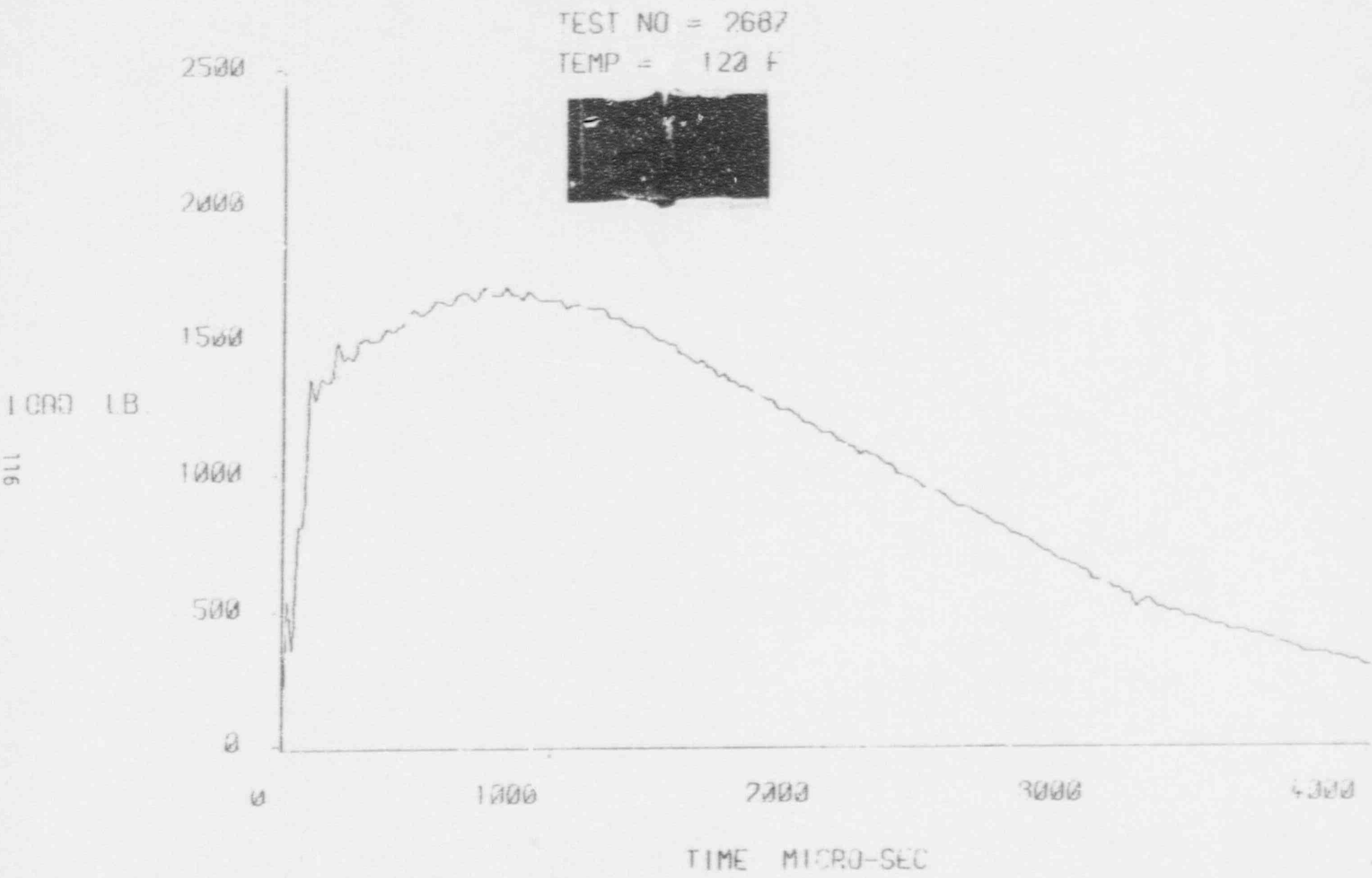


Figure VIII-30: PIC_V Load Record for HAZ Metal, Plate D-4802-2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4000
TIME MICRO-SEC

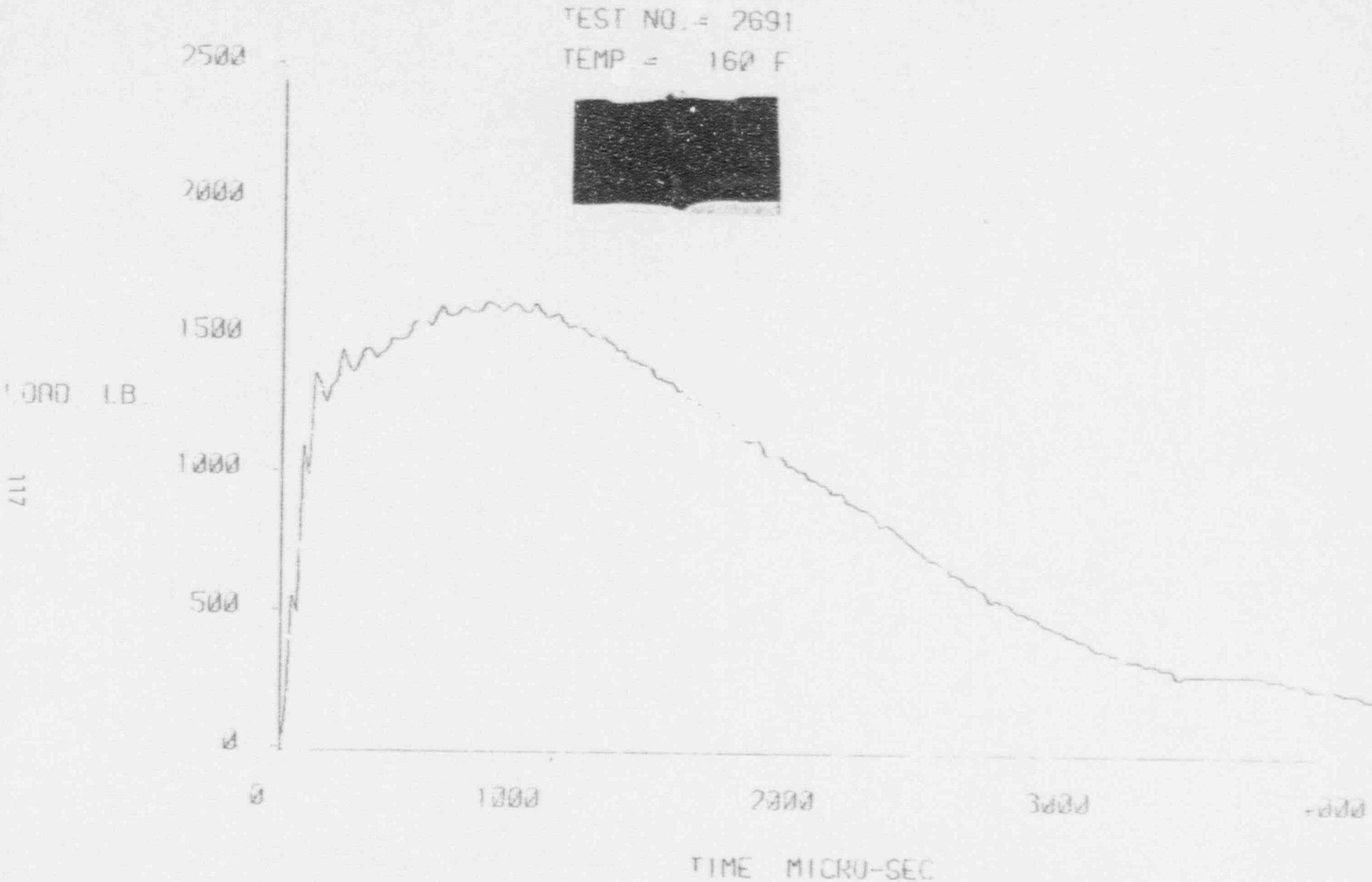

Figure VIII-32: PIC_V Load Record for HAZ Metal, Plate D-4802-2

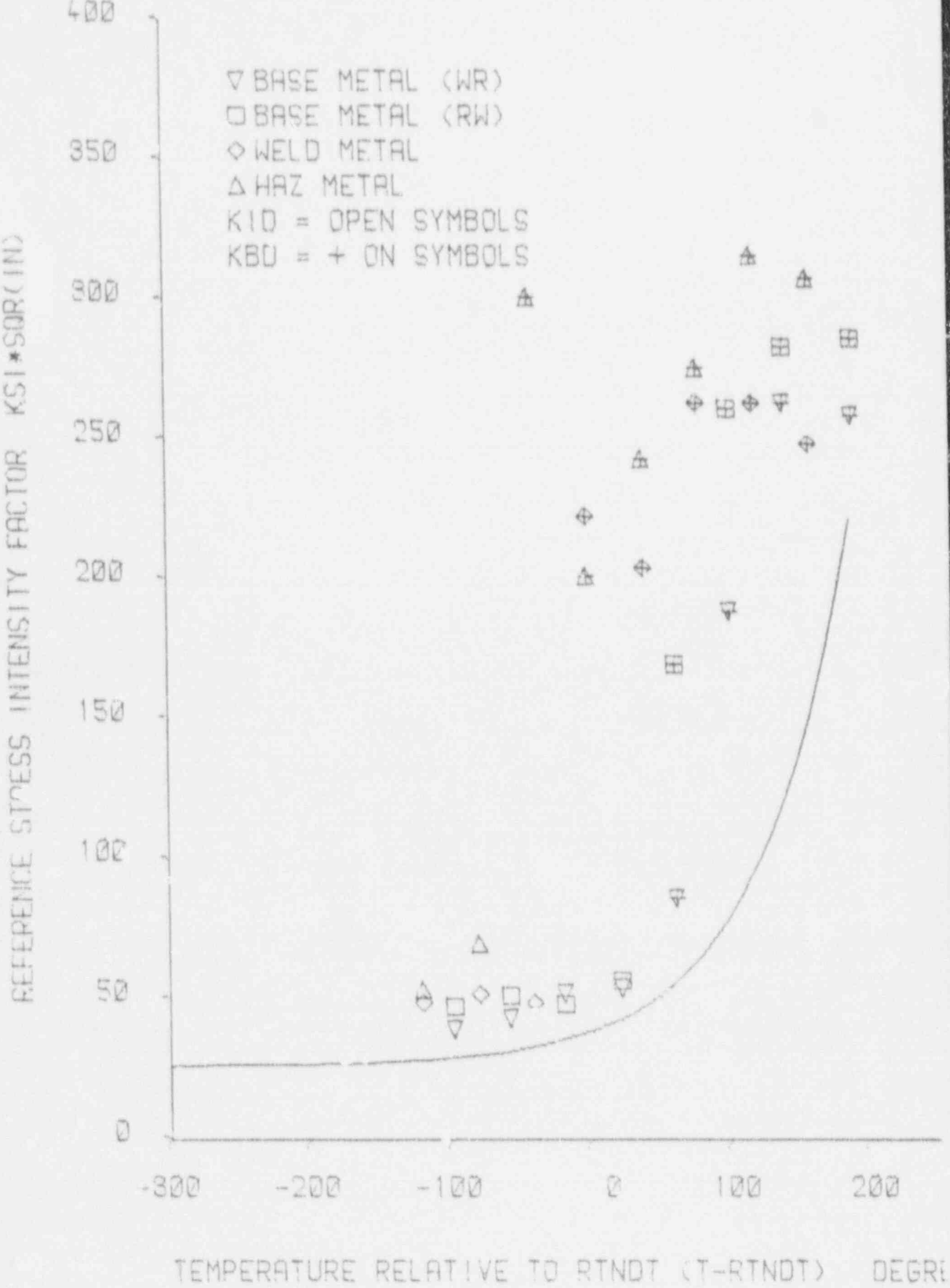

Figure VIII-33: Fracture Toughness Values for Dynamic PIC_V Tests

IX. DISCUSSION

A summary of all major test results is provided in Table IX-1. This table serves as the basis for the following discussion of each of the phases of evaluation of baseline specimens from reactor vessel materials, as part of the irradiation surveillance program.

A. Materials

The Fort Calhoun surveillance materials consist of SA 533-B, Class 1 plate, weld and HAZ fabricated from sections of the vessel shell plate which would first appear to limit the operation of the reactor vessel. The chemical composition conforms to ASME Code Section II and C-E specifications for reactor vessel plates and weldments.

A metallographic examination was performed to characterize the structure of the surveillance materials. The tempered bainite structure for the base metal and ferrite structure for the weld metal are typical for thick section SA 533-B steel in the quenched and tempered condition. A small amount of inclusion stringers was found in the base metal; the stringers were oriented parallel to the major rolling direction. This accounts for the difference in toughness normally experienced between longitudinally and transversely oriented Charpy specimens. In a longitudinal specimen, toughness is not affected because the advancing crack must cross the stringer. In transverse specimens, the stringers are oriented parallel to the advancing crack, offering a path of low resistance, thereby reducing the toughness relative to a longitudinally oriented specimen. As seen in Table II-1, this difference in toughness appears as a lower upper shelf energy for transversely (WR) oriented base metal.

B. Drop Weight Tests

Drop weight tests were performed to establish an NDTT value of the vessel base metal. The baseline NDTT value is used in conjunction with Charpy impact data to determine the reference temperature, RT_{NDT}, for the material. NDTT for the base metal (RW), was -20°F, demonstrating the excellent toughness of the vessel plate. NDTT for the weld and HAZ was conservatively estimated as 0°F using Branch Technical Position MTEB 5-2.

In addition to the NDTT determination, the fracture surfaces of each specimen were heat tinted to show the extent of crack extension after impact. The extent of crack extension (shown as a dark, heat-tinted area in Figure V-1) decreases with increasing temperature. The fracture surface photographs also confirm the break-no break performance determined prior to heat-tinting.

C. Tensile Tests

The results of the tensile tests show that all materials exceed the yield strength, tensile strength and elongation requirements of the ASME Specification for SA 533-B, Class 1 pressure vessel steel at all test temperatures. In addition to the ASME requirements, the fracture load, fracture strength, fracture stress, reduction of area (R.A.) and the uniform elongation (UE) are reported as required by ASTM E 185 in order to more fully define the material properties. A comparison of the material tensile properties shows that the weld metal exhibited the highest yield strength of all materials. The other materials had similar properties.

D. Charpy Impact Tests

Charpy impact tests were performed on plate, weld and HAZ surveillance material to provide baseline data for subsequent comparison to irradiated surveillance material.

Standard Charpy data are summarized in Tables II-1 and IX-1, including upper shelf energy, RT_{NDT}*, and fix temperatures corresponding to 30 ft-lb, 50 ft-lb and 35 mils lateral expansion. The upper shelf energy for the base metal was greater for the RW orientation (137.5 ft-lb) than for the WR orientation (121 ft-lb) as a result of the preferential orientation of inclusion stringers (as noted in Section IX.A). The HAZ metal had the lowest upper shelf energy (82 ft-lb), but all three materials (plate, weld and HAZ) had upper shelf energies in excess of the 75 ft-lb minimum requirement of 10 CFR 50, Appendix G, for unirradiated beltline materials. RT_{NDT} values ranged from -8° to +24°F, the lowest value being for base metal. It should be noted that the weld metal NDTT, which controls the lower bound value of RT_{NDT}, is typically -20°F or lower. Since no weld metal drop weight specimens were available for testing, the NDTT had to be conservatively estimated as 0°F using Branch Technical Position MTEB 5-2. The highest value of RT_{NDT} was for the HAZ material. RT_{NDT} determination for the HAZ was made difficult by the inherently large scatter in impact test results (see Figures VII - 14 through - 16). In the discussions of IC_V and PIC_V results, the HAZ is actually tougher than is indicated by the standard impact test results.

In addition to the standard Charpy impact data, instrumented impact test data were obtained to more fully characterize the surveillance material. T_b, T_N and T_D from the load vs temperature curves for each material are compared to the standard Charpy data in Figure IX-2. It is noteworthy that

*RT_{NDT} for longitudinally oriented base metal specimens is not strictly valid and provided for reference purposes only.

the T_B temperature is, in most cases, nearly the same as the highest temperature at which 100 percent cleavage fracture is experienced as shown on the fracture surfaces of the Charpy specimen. This indicates that the load behavior analysis can approximate the temperature at which the material fractures in a strictly brittle mode. Further comparison of the IC_v and standard C_v data shows that the T_N temperature closely represents the 50 ft-lb fix temperature for most materials tested. This comparison is difficult for HAZ material due to the large scatter normally found in the test results. For example, the T_N temperature for HAZ (-40°F) was 124°F less than the 50 ft-lb fix temperature (+84°F). However, the IC_v results for the HAZ (Figure VII - 13) exhibit considerably less scatter than the standard impact results (Figure VII - 14), indicating that instrumented test results more closely represent the true material toughness. Since the T_N temperature is also that point at which the material exhibits close to maximum load behavior and at the same time precedes the onset of ductile fracture, it may well be considered as a material property selection criterion in the near future. Similar to the T_B temperature, the T_D temperature defines a material property condition which can be substantiated by a fracture surface analysis of the broken C_v specimen. T_D is the temperature at which the material fails in a completely ductile manner. It is also characterized by the first 100 percent shear appearance of the specimen tested at elevated temperatures, which also defines the upper shelf energy. The close relation between T_D and 100 percent shear value is shown in Table IX-2.

The IC_v data demonstrate the same relative properties for each material as observed for the standard Charpy data with one exception. T_B and T_N are lower for the HAZ than any other material, which is not reflected in the RT_{NDT} values.

The rapid heating and quenching of the material adjacent to the weld fusion line (the HAZ) results in an inherently tougher material than the base metal. The crack seeks the path of least resistance, resulting in extensive crack branching preceding fracture which dissipates a considerable amount of energy. The resulting large scatter in standard data is not reflected in IC_v curves. The IC_v data in fact indicates much greater toughness in the HAZ than evident from standard results. Since IC_v results for all other materials support the standard data, it is assumed that for HAZ material the IC_v results more closely reflect true material toughness. This su :rior toughness is also demonstrated by the HAZ data from the PIC_v tests.

E. Precracked Charpy Tests

In addition to the already well defined material properties by standard tests, the use of precracked Charpy impact specimens provides valuable dynamic fracture toughness information. This is easily seen when the fracture toughness data are compared to the ASME "Lower Bound Reference Curve, K_{IR}" (ASME Boiler and Pressure Vessel Code, Section III, Appendix G). As evident from Figure VIII-33, all materials tested exceeded the lower bound K_{IR} curve. The highest of all material toughness was exhibited by the HAZ metal. This high toughness is most likely a reflection of considerable crack branching as the crack seeks out the weakest path.

The precracked Charpy data for the Fort Calhoun surveillance materials were analyzed using the best currently available techniques. Developmental programs, both planned and in progress, are being directed toward the refinement of analytical techniques for interpretation of test data at temperatures approaching the reactor vessel operating range. Recognizing the potential for this developmental effort, sufficient details have been reported in Section VIII to facilitate additional analyses of the Fort Calhoun precracked Charpy data if the need arises.

The fracture toughness data presented in this report should serve as a base for comparison of fracture toughness results from irradiated materials and aid in the adjustment of reactor pressure vessel operating parameters.

TABLE IX-1

SUMMARY OF MATERIAL DATA

Material and Code	30 ft-lb Fix[c] (°F)	50 ft-lb Fix[d] (°F)	35 Mils Lat. Exp.[d] (°F)	NDTT (°F)	RT_{NDT} (°F)	C_v Upper Shelf Energy (ft-lb)	RT Yield Strength (ksi) Static	RT Yield Strength (ksi) Dynamic
Base Metal Plate D-4802-2 (WR)	36	78	58	-20	18	121	69	99
Base Metal Plate D-4802-2 (RW)	26	52	34	-20	-8[a]	137.5	71	99
Weld Metal Plate D-4802-1/D-4802-3	-18	2	-12	0[b]	0[b]	97.5	78	98
HAZ Metal Plate D-4802-2	-70	34	58	0[b]	24[b]	82	67	106

a RT_{NDT} for the RW orientation is not valid per 10 CFR 50, Appendix G and is only reported for information.

b Estimated per Branch Technical Position MTEB 5-2, where NDTT is the higher of 0°F or the 30 ft-lb fix temperature, in the case where drop weight tests were not performed.

c Determined from average impact energy curve.

d Determined from lower bound curve.

TABLE IX-2

INSTRUMENTED VS STANDARD CHARPY IMPACT DATA

Material and Code	T_B Temp (°F)	Max. Temperature for 100% Cleavage Fracture (°F)	30 ft-lb Fix Temperature (°F)	T_N Temp (°F)	50 ft-lb Fix Temperature (°F)	RT_{NDT} Temp (°F)	NDTT (°F)	T_D Temp (°F)	Min. Temperature for 100% Shear Fracture (°F)
Base Metal (WR) D-4802-2	-40	-80	22	80	78	18	-20	160	190
Base Metal (RW) D-4802-2	-22	-80	[illegible]	52	52	-8	-20	120	160
Weld Metal D-4802-1/D-4802-3	-112	-120	-30	-30	2	0	0	80	80
HAZ Metal D-4802-2	-140	-160	-44	-40	84	24	0	160	160

APPENDIX A

DROP WEIGHT TESTS-DESCRIPTION AND EQUIPMENT

The drop weight specimens for this program were tested on the machine shown in Figure A-1.

Figure A-2 depicts the drop weight specimen used. Figures A-3 through A-5 are isometric drawings showing the orientation and location of the drop weight specimens in the base metal, weld metal and heat-affected-zone, respectively. A detailed description of specimen manufacturing is presented in Reference 1.

The drop weight tests were conducted in accordance with Standard Method ASTM E 208-69, "Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels." Specific procedures used are listed in Reference 2.

Heat tinting was conducted after the tests were completed as follows:

1. Heat at 600°F for 1 hour;
2. Air cooled to room temperature;
3. Cooled in liquid nitrogen until brittle;
4. Broken in half using the drop weight machine at low impact energies.

Padded support anvils were used when breaking the tinted specimen in half to preserve the fracture surface.

The constant temperature necessary for conducting the drop weight tests was obtained from a series of circulating liquid baths capable of maintaining stable temperatures throughout the range of -150°F to room temperature.

Any selected temperature in this range was maintained to an accuracy of 2°F. These constant temperature baths were composed of the following equipment.

One Neslab Constant Temperature Circulating Bath Model TEZ 10, with a Model CT 158 Thermoregulator and a Labline 11 inch diameter thermo cup. Designated Bath 2.

Medium: Isopropanol - room temperature -10°F
Neslab Bath Cooler, Model PCB-2, connected.

Two Low Temperature Stirred Baths, two 11 inch diameter thermo cups, two Honeywell Controllers and Solenoid control valves to liquid nitrogen bottle. Designated Baths 3 and 5.

Medium: Isopropanol - room temperature to -150°F

Coolant: Liquid nitrogen and Flexi-Cool unit.

All baths - copper constantan thermocouple.
Honeywell six-point temperature chart recorder.
Digitec thermocouple thermometer - 590 TF.
Standard mercury column thermometer.
Bimetallic-spring thermometer.

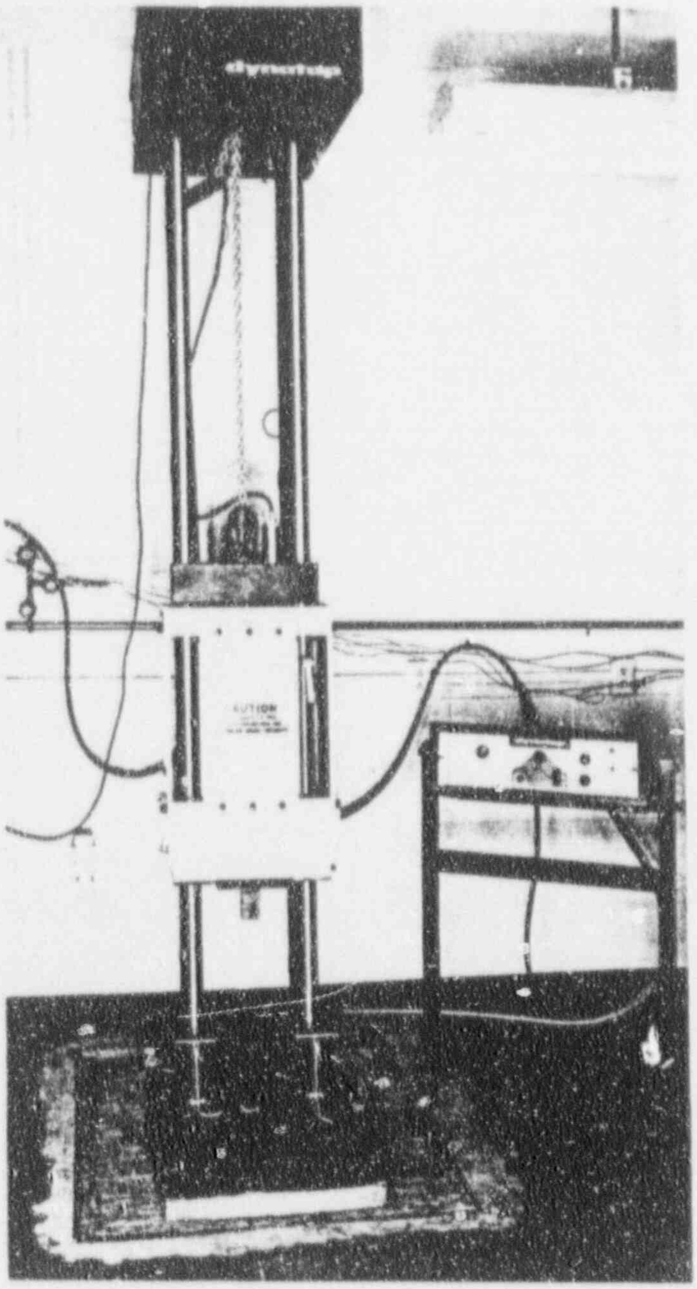

FIGURE: A-1. View of Drop Weight Testing Machine, Showing Details of Specimen Support, Lifting and Release Mechanism and Control Console.

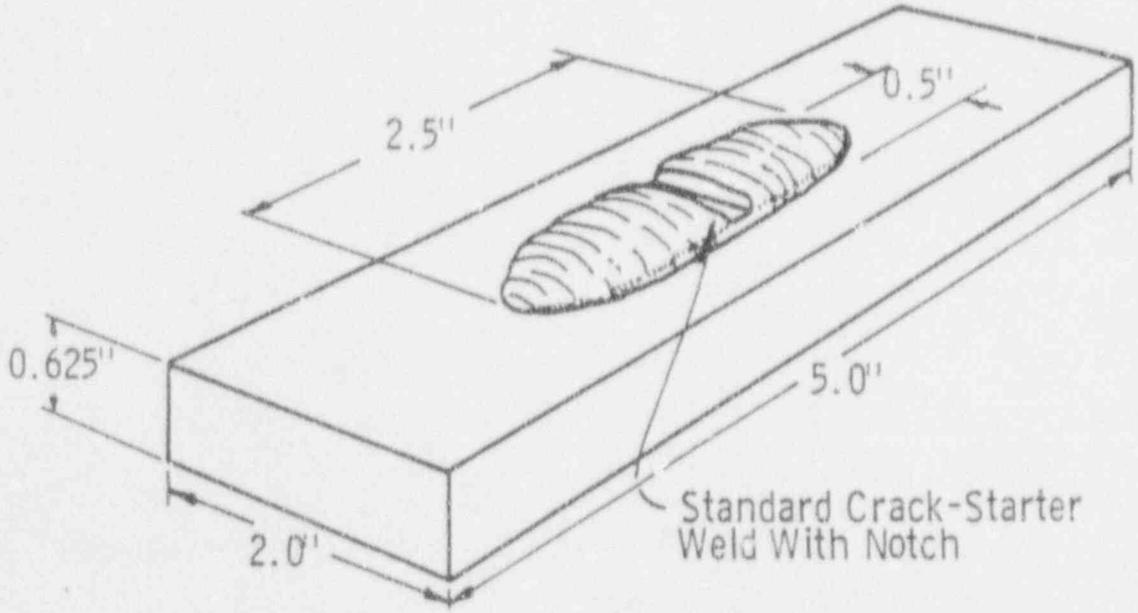

FIGURE: A-2. Typical Drop Weight Specimen

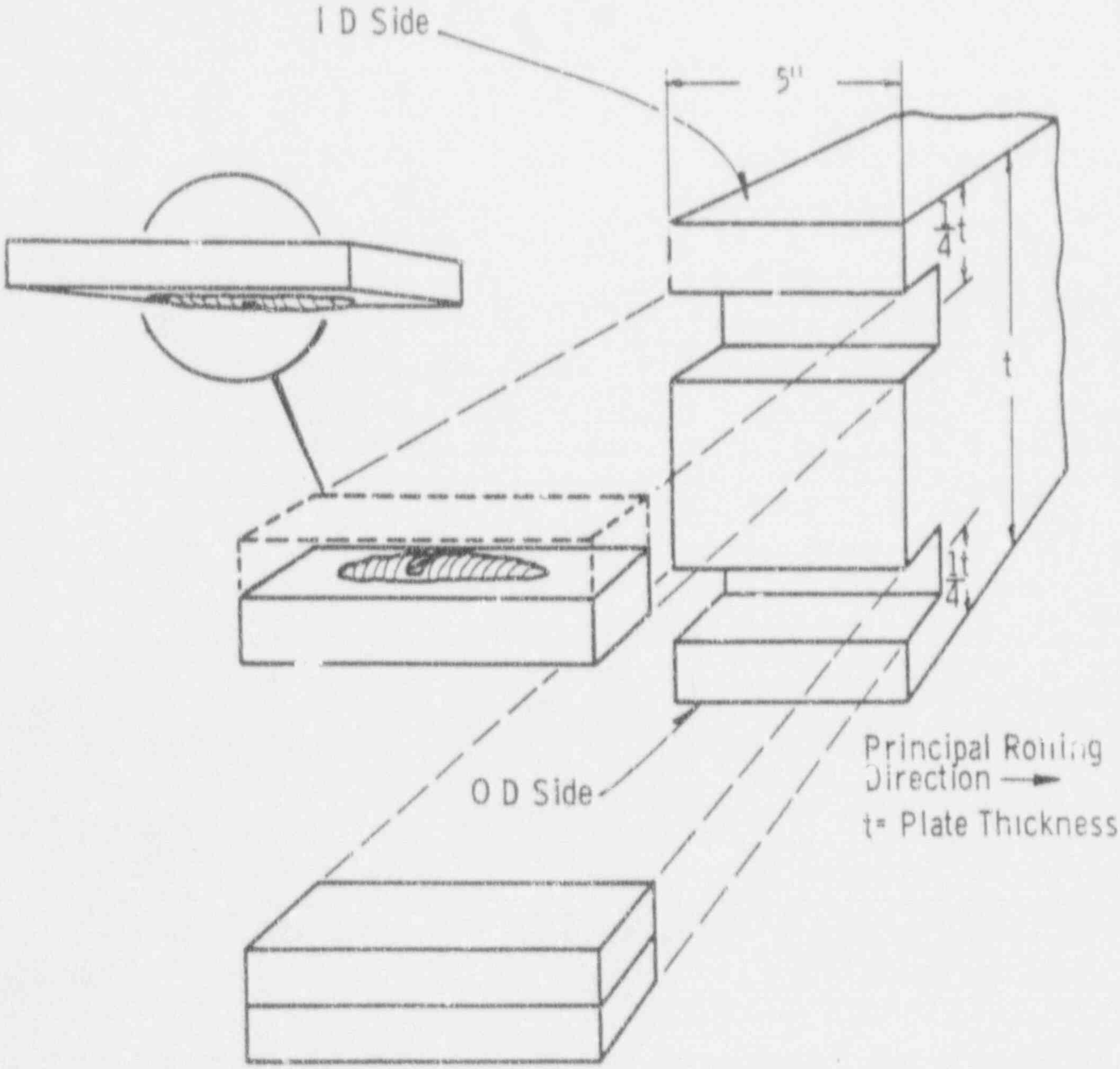

FIGURE: A-3. Location of Drop Weight Specimens Within Base Metal Test Material

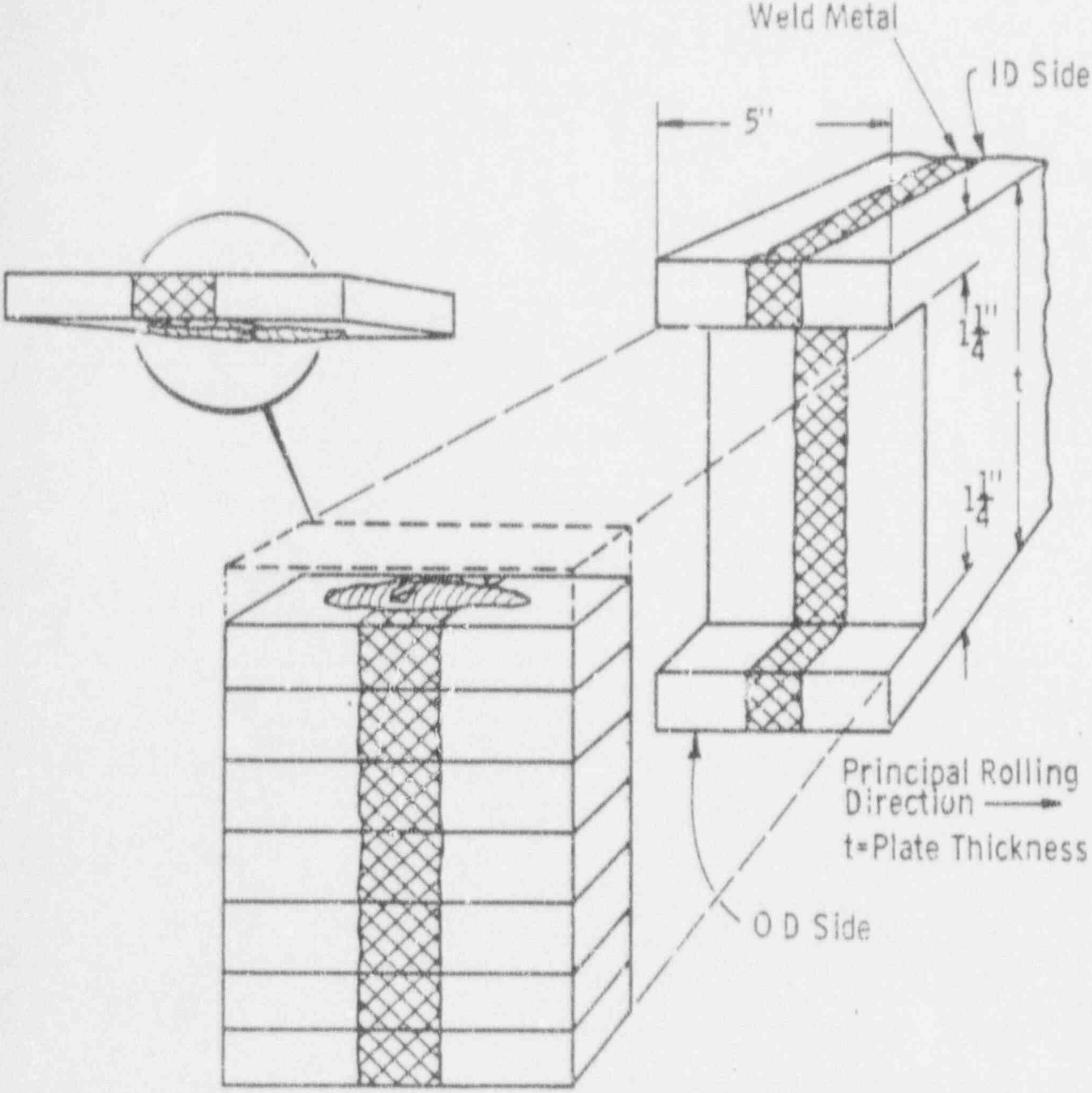

FIGURE: A-4. Location of Drop Weight Specimens Within Weld Metal Test Material

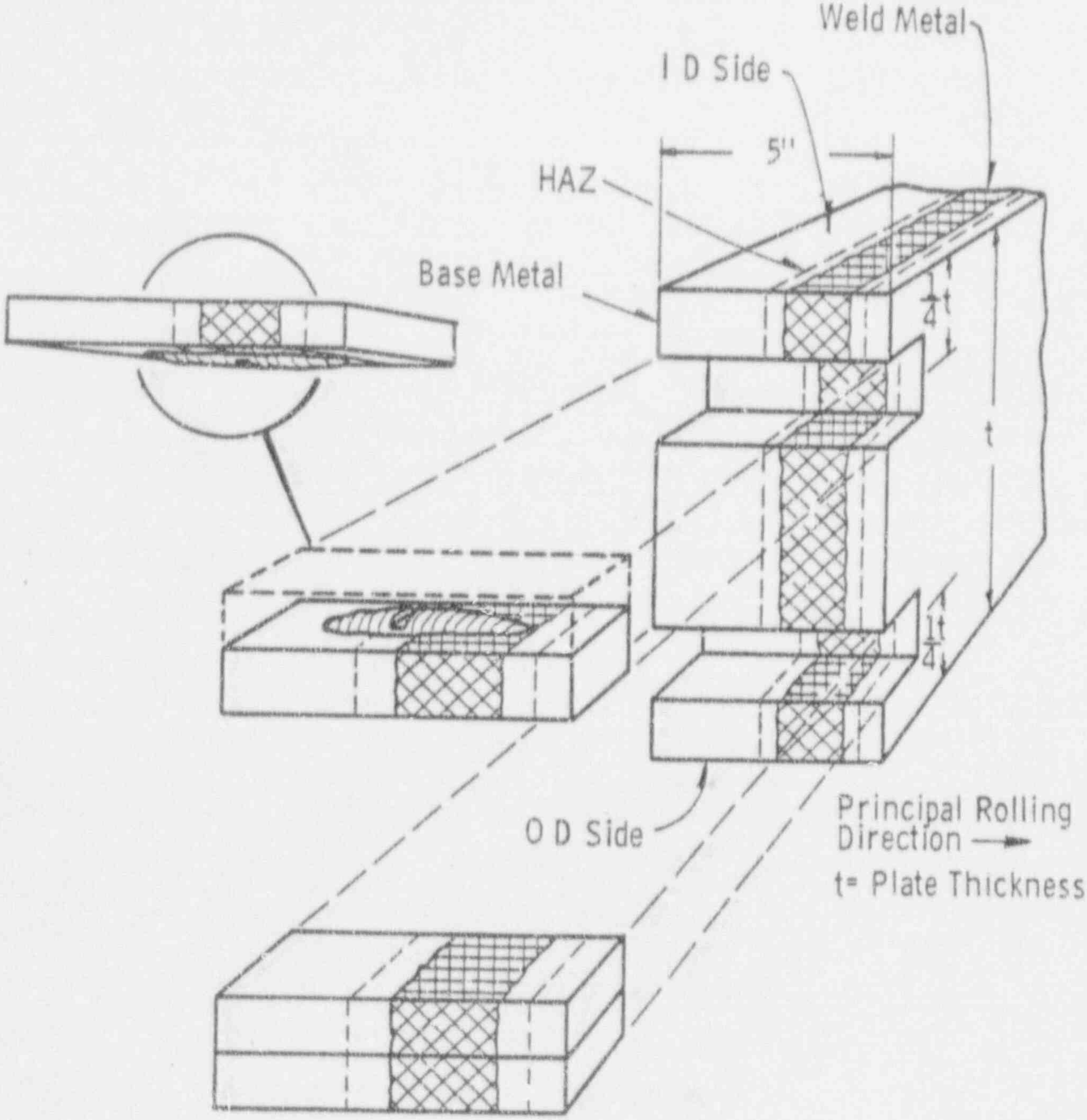

FIGURE: A-5. Location of Drop Weight Specimens Within Heat-Affected-Zone Test Material

APPENDIX A

REFERENCES

1. "Summary Report on Manufacture of Test Specimens and Assembly of Capsules for Irradiation Surveillance of Fort Calhoun Reactor Vessel Materials", C-E Document CENPD-33 Proprietary Information, dated November 15, 1971.

2. "Test Plan for Omaha Public Power District, Fort Calhoun Station Unit No. 1 Evaluation of Baseline Specimens - Reactor Vessel Materials Irradiation Surveillance Program", Test Plan No. 23866-TP-MCD-002, dated April 1976.

APPENDIX B

TENSILE TESTS DESCRIPTION AND EQUIPMENT

The tensile tests were performed using a Riehle universal screw testing machine with a maximum capacity of 30,000 lb and separate scale ranges between 50 lb and 30,000 lb. The machine, shown in Figure B-1, is capable of constant cross head rate or constant strain rate operation. The tensile testing was covered by the certificate of calibration which is included at the end of the Appendix B.

Elevated temperature tests were performed in a 2-1/2" ID x 18" long high temperature tensile testing furnace with a temperature limit of 1800°F. A Riehle high temperature, dual range extensometer was used for monitoring specimen elongation.

The tensile specimen is depicted in Figure B-2. Figures B-3 through B-5 are isometric drawings showing the orientation and location of the tensile specimens in the base metal, weld metal and heat-affected-zone, respectively. A detailed explanation of specimen manufacturing is presented in Reference 1.

Tensile testing was conducted in accordance with ASTM Method E-8, "Tension Tests of Metallic Materials: and/or Recommended Practice E-21, "Short-Time Elevated Temperature Tension Tests of Materials," except as modified by Section 6.1 of Recommended Practice E-184, "Effects of High-Energy Radiation on the Mechanical Properties of Mettalic Materials." Specific procedures used are listed in Reference 2.

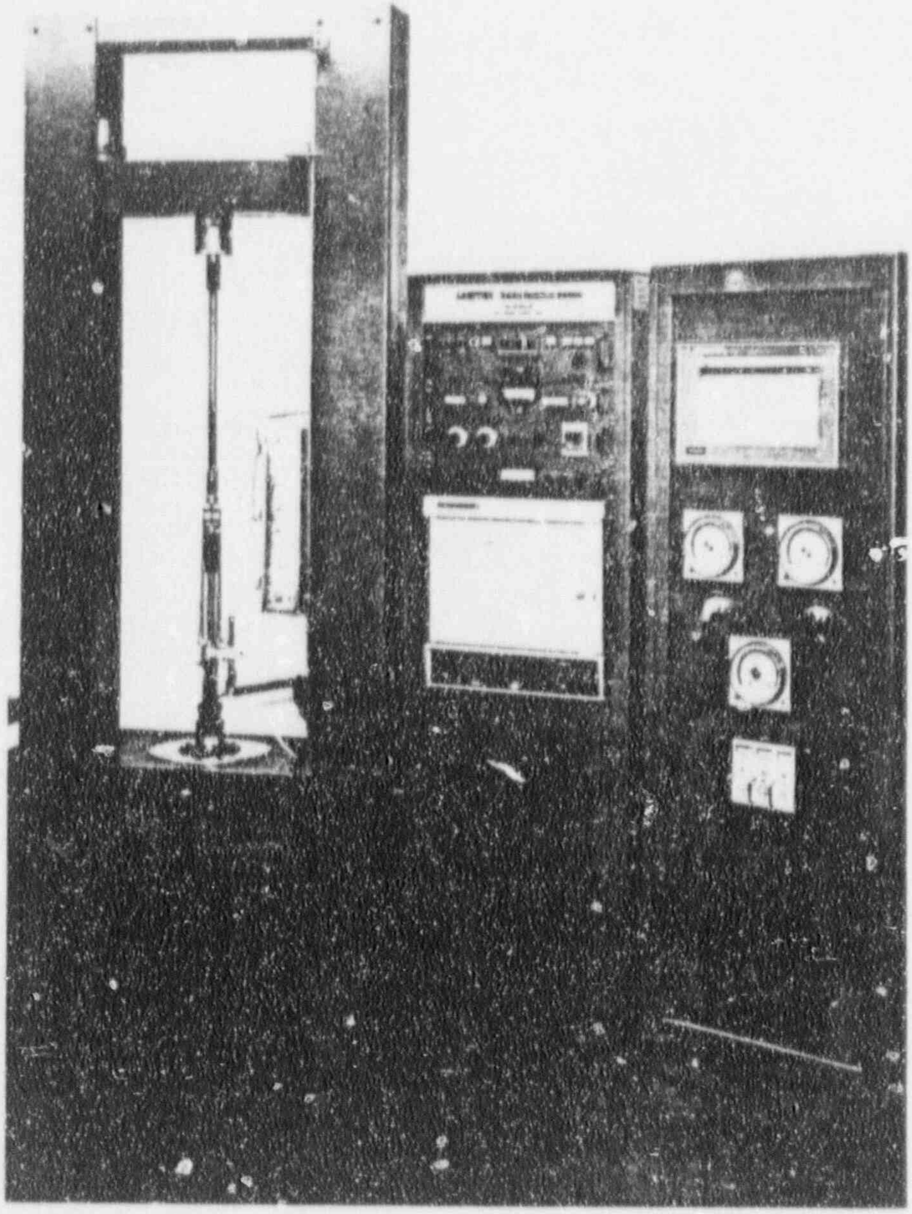

Figure: B-1. Tensile Test System with Control Console and Elevated Temperature Testing Equipment

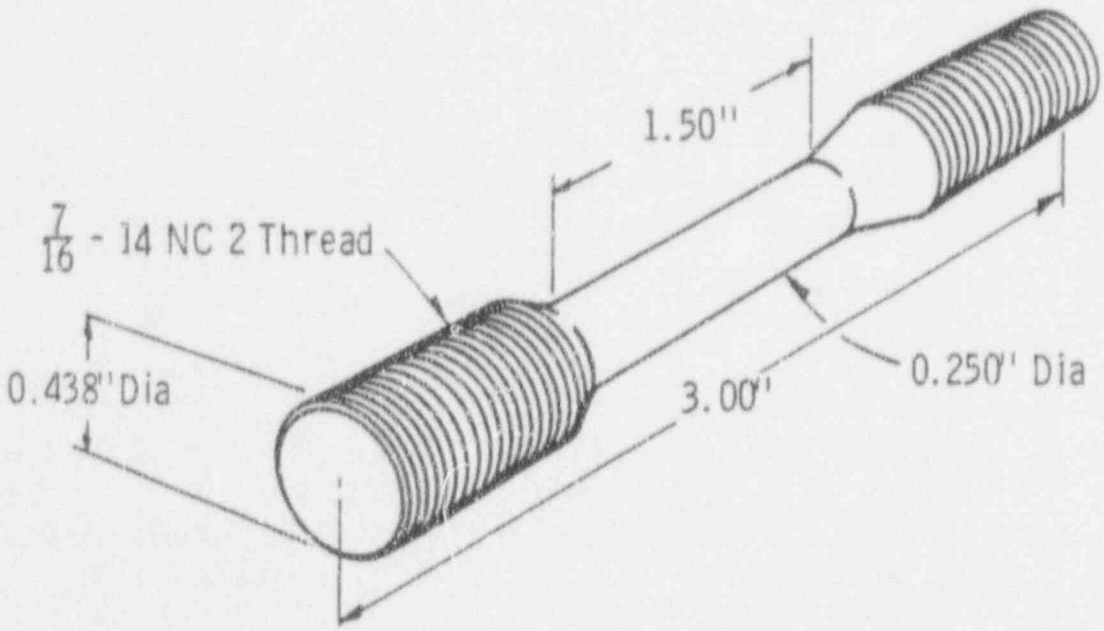

FIGURE: B-2. Typical Tensile Specimen

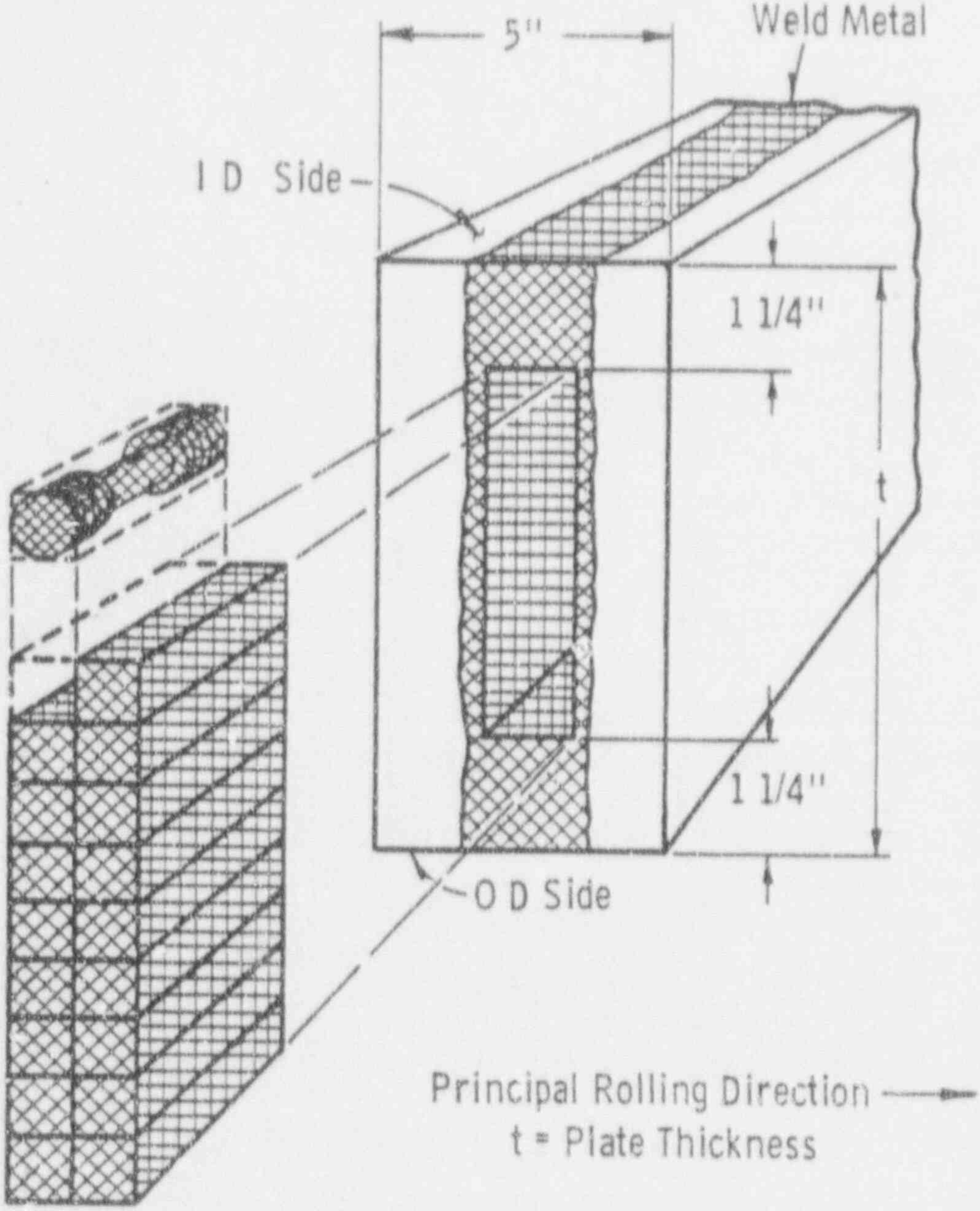

FIGURE: B-4. Location of Tensile Specimens Within Weld Metal Test Material

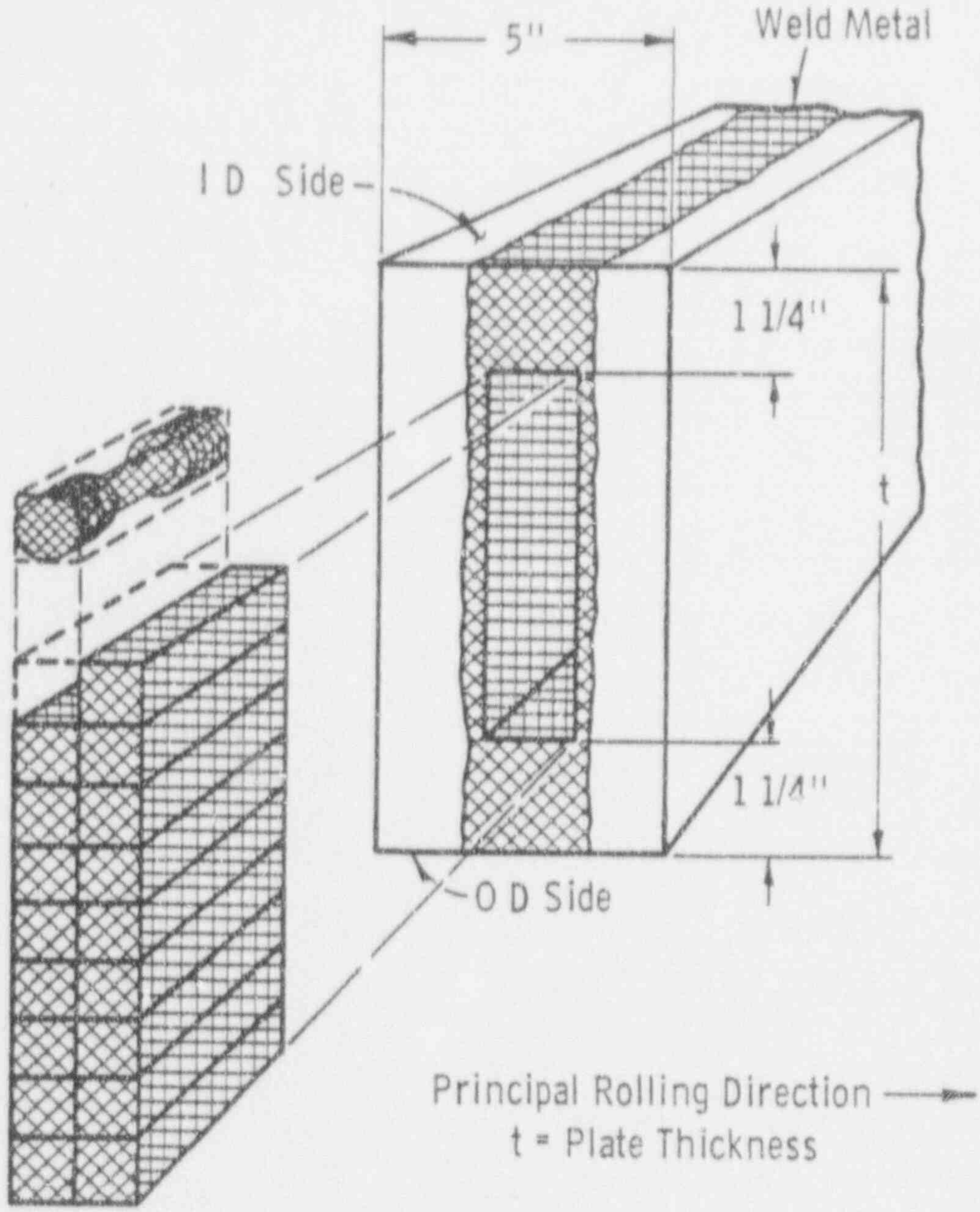

FIGURE: B-4. Location of Tensile Specimens Within Weld Metal Test Material

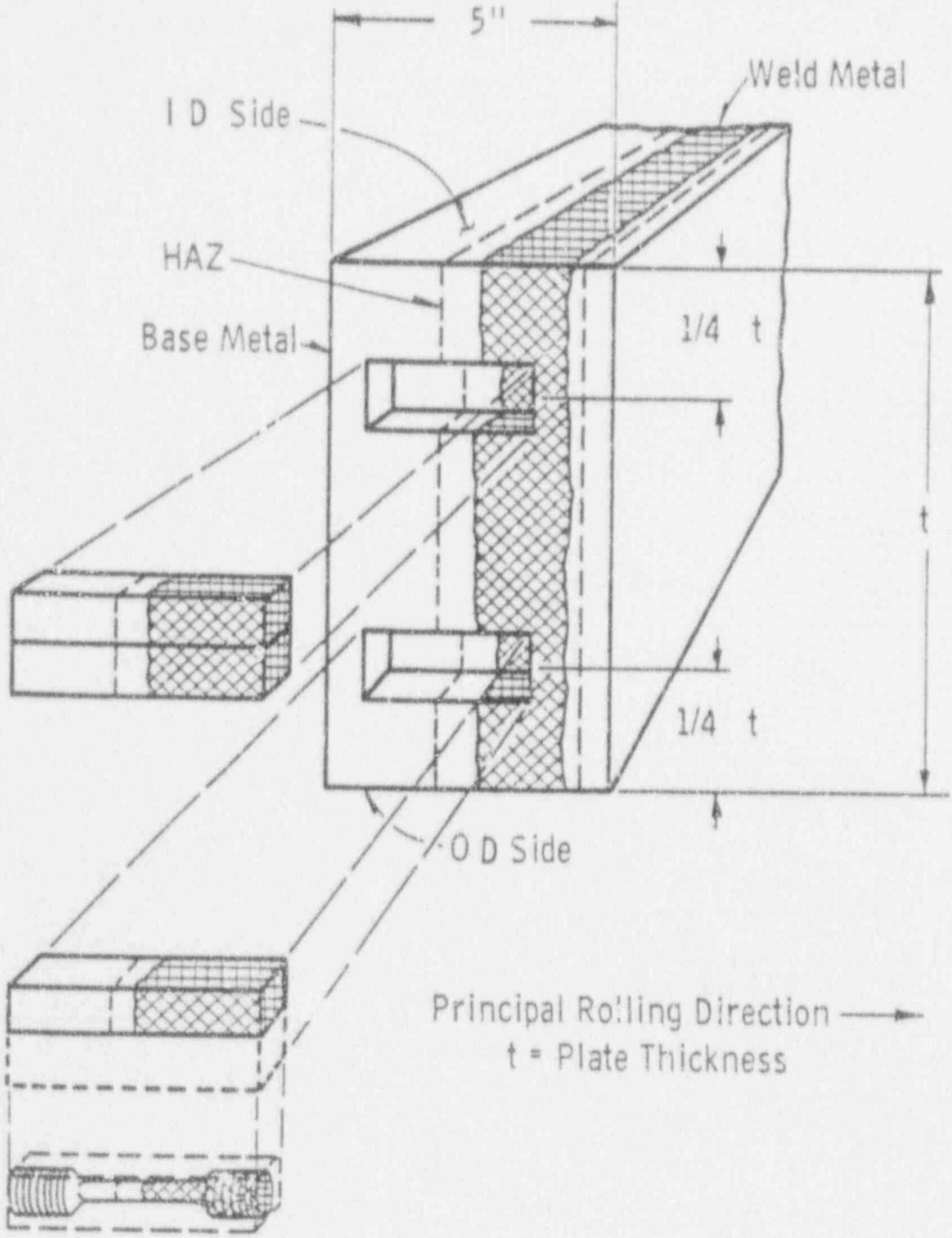

FIGURE: B-5. Location of Tensile Specimens Within Heat-Affected-Zone Test Material

ACCO

Wilson Instrument Division
929 CONNECTICUT AVENUE, BRIDGEPORT, CONNECTICUT 06602 • (203) 335-2511
AMERICAN CHAIN & CABLE COMPANY, INC.

Certificate of Calibration

Calibration Date October 28,1975

Machine Description Riehle DS-30

Customer Combustion Engineering
Windsor Locks, Conn.

Serial No. RA-44372

Wilson Instrument Division of Acco certifies that the machine described above has been calibrated to ASTM designation E4 using calibrated weights and/or proving rings calibrated to National Bureau of Standards Specification.

TENSION

Machine Range 3,000

Machine reading	% Error
500	-.130
1000	-.197
1500	-.198
2000	-.216
2500	-.173
3000	+.072

Machine Range 30,000

Machine reading	% Error
5000	+.130
10000	-.564
15000	-.188
20000	-.293
25000	-.056
30000	0

Machine Range 6,000

Machine reading	% Error
2000	0
3000	+.216
4000	+.054
5000	+.173
6000	+.180

Machine Range

Machine reading	% Error

Machine Range 15,000

Machine reading	% Error
3000	+.072
6000	-.036
9000	0
12000	+.054

Machine Range

Machine reading	% Error

Calibrating apparatus used

Capacity	Serial no	Cal. date	Lab. no
2,000	1809	2-26-75	SJT.01/100773
20,000	4127	3-25-74	SJT.01/100640
100,000	1815	2-27-75	SJT.01/100773

C. E. McMartin
Calibrating Engineer

Standards Manager

ACCO

Wilson Instrument Division
929 CONNECTICUT AVENUE, BRIDGEPORT, CONNECTICUT 06602 • (203) 335-2511
AMERICAN CHAIN & CABLE COMPANY, INC.

RIEHLE
Testing Machines

Certificate of Calibration

Calibration Date October 28,1975

Instrument Description Riehle Extensometer
Riehle Recorder

Customer Combustion Engineering
Windsor Locks, Conn.

Serial No. Model DH1-10
R-67338

Wilson Instrument Division of Acco verifies that the attached graph is certification of calibration of the instrument described above. This instrument was calibrated to ASTM designation E83.

Recorder Extensometer Calibrator
Equipment used in calibration EM 528864

C. E. McMartin
Calibration Engineer

Andrew R. Lee
Standards Manager

APPENDIX B

REFERENCES

1. "Summary Report on Manufacture of Test Specimens and Assembly of Capsules for Irradiation Surveillance of Fort Calhoun Reactor Vessel Materials", C-E Document CENPD-33 Proprietary Information, dated November 15, 1971.

2. "Test Plan for Omaha Public Power District, Fort Calhoun Station Unit No. 1 Evaluation of Baseline Specimens - Reactor Vessel Materials Irradiation Surveillance Program", Test Plan No. 23866-TP-MCD-002, dated April 1976.

APPENDIX C

CHARPY IMPACT TESTS - DESCRIPTION AND EQUIPMENT

The standard impact tests and instrumented tests were performed on a calibrated instrumented impact testing system, shown in Figure C-1. C-E's instrumented impact test equipment provides for signal retention and the subsequent data analysis. The output signal from the instrumented tup is recorded simultaneously by an oscilloscope and a transient recorder. A permanent visual record was made of the load signal, as it was displayed on the oscilloscope screen, with a polaroid camera. Another permanent recording of the impact load signal was made by a paper punch, which received a digitized signal from the transient recorder. An electronic interface unit was used to make these units compatible. The evaluation of all collected signals was made using the punched paper tape as input to a computer program for the data analysis.

The system consists of the following elements:

a. A Model SI-1 BLH Sonntag Universal Impact Machine with a specifically machined pendulum tup, instrumented with four resistance strain gages in full bridge circuit. This tup "load cell" is calibrated statically and dynamically to provide a given pounds/volt sensitivity for known settings of the balance and gain on the dynamic response system. The instrumented machine meets all impact test machine requirements of ASTM and is certified by AMMRC, the U.S. Army Materials and Mechanics Research Center (Watertown Arsenal). A copy of the certification papers is included in this Appendix.

b. A Model 500 Dynatup dynamic response system which supplies regulated and constant dc excitation to strain gages on the pendulum tup, provides balancing, variable load sensitivity and calibration functions, and amplifies load-time signal to a ±10 volt, ±100 milliampere level while preserving kHz frequency response and 0.05 percent accuracy while simultaneously recording the area beneath the load-time trace.

c. A photoelectric triggering device and velocometer composed of a high intensity light directed through a grid mounted on the pendulum of the impact tester, and passed to a photosensor through fiber optics. A special circuit ensures accurate, reliable and fail safe triggering of the oscilloscope recorder plus an accurate display of the average velocity of the pendulum during impact.

d. A 5103N Dual Beam Tektronix Storage Oscilloscope with a No. 5A18N dual-trace amplifier plug-in unit and a No. 5B12N dual time base plug-in unit. Also included is a C-58 camera with mounting adapter. This device gives a display of each test trace for visual analysis of the load-time impulse recorded by the instrument.

e. A model 802 Biomation transient recorder. This unit receives the load-time signal from the instrumented tup and stores it for play back to the oscilloscope. Its internal analog to digital converter also provides a signal output in digital form to an electronic interface.

f. A model B-204 Datacap electronic interface with a model D-101 index interface. This unit is the link between the transient recorder and the paper punch. It also allows the precise numerical identification of each test signal.

g. A model 4070 Facit Addo paper tape punch with a writing speed of 75 characters per second on standard 8 track paper tape. The digital signal from the transient recorder and test signal identification from the interface are permanently recorded on paper tape. This paper tape is used as the input to a computer.

h. A PDP-11A computer. This unit is capable of accepting punched paper tape as data input into a program designed to analyze all Charpy impact signals and to produce the required fracture toughness data output.

The standard Charpy specimen is described in Figure C-2. For a detailed discussion concerning specimen manufacturing see Reference 1.

Figures C-3 through C-5 are isometric drawings showing the orientation and location of the Charpy impact specimens in the base metal, weld metal and heat-affected-zone, respectively.

All standard Charpy impact tests were conducted in accordance with ASTM Method E-23, "Notched Bar Impact Testing of Metallic Materials." Specific procedures used are listed in Reference 2.

The precracking for and precracked tests of Charpy specimens were performed according to Electric Power Research Institute (EPRI) methods as reported in Reference 3 of this Appendix C. The proper stress intensity factor range (K_f) for precracking is currently being studied by ASTM Committee E24.03.03. For these tests, precracking was conducted at a K_f of 12 Ksi-in.$^{1/2}$.

The data analysis techniques for instrumented precracked Charpy impact test data were based on the procedure developed in the EPRI Fracture Toughness Program.[3] A precracked Charpy V-notch specimen is impact tested at a preselected impact velocity. The test record, consisting of load as a function of time, is stored in a transient recorder and is transferred to paper tape in a digital form. The paper tape is fed into a PDP-11A computer which is programmed to output two test records. They are:

1) load versus time;
2) energy versus time.

The PDP-11A computer then provides enlarged load/time plots. From these expanded plots, the following information is obtained:

- t_{GY} - time to cause general yielding
- P_{GY} - general yield load
- P_M - maximum load
- E_{af} - uncorrected value of energy to cause fracture.

The dynamic stress intensity factor (K_{Id}) is calculated using the following test parameters in addition to the above values:

- a - notch plus crack depth
- w - C_v specimen width
- a/w - crack depth ratio
- C_s^* - non-dimensional specimen compliance, f(a/w)
- T - test temperature
- V_o - test velocity
- E_o - available impact energy

For linear elastic fracture (case where fracture occurs before general yielding), a value of K_{Id} is calculated using the procedure given in the EPRI Fracture Toughness Program.[3]

This states that:

$$K_{Id} = \frac{6Ya^{1/2}P_M}{BW}$$

where,

$$Y = 1.93-3.07\ (a/w) + 14.53\ (a/w)^2 - 25.11\ (a/w)^3 + 25.8\ (a/w)^4$$

B = specimen thickness = 0.394 inches
W = specimen width = 0.394 inches

For elastic-plastic fracture (when general yielding occurs before maximum load), the equivalent energy method for calculation of the stress intensity factor is used.(3)

In this case:

$$K_{Bd} = \frac{6y_a \, 1/2 \, P^*}{BW}$$

where,

$$P^* = \left(\frac{2E_I}{C_s}\right)^{1/2}$$

$$E_I = E_{af}\left(1 - \frac{E_{af}}{4E_o}\right) - E_M$$

$$E_M = 1/2 \, P_M^{\;2} \, C_M$$

$$C_M = \frac{V_o \, t_{GY}}{P_{GY}} - \frac{C_s^*}{E}$$

$$C_s = \frac{C_s^*}{EB}$$

E = elastic modulus, $f(T) = 30.20 \times 10^6 - 0.46 \times 10^4 T$

The constant temperature necessary for conducting the Charpy impact tests was obtained from a series of circulating liquid baths capable of maintaining stable temperature throughout the range of -150°F to +250°F. Any selected temperature in this range was maintained to an accuracy of 2°F. These constant temperature baths were composed of the following equipment:

One Neslab Constant Temperature Circulating Bath - Model TEZ 10, with a Model CT 150 Thermoregulator and a Labline 11 inch diameter thermo cup. Designated Bath 1.

Medium: Ethylene Glycol - room temperature to 250°F.

One Neslab Constant Temperature Circulating Bath - Model TEZ 10, with a Model CT 150 Thermoregulator and a Labline 11 inch diameter thermo cup. Designated Bath 4.

Medium: Ethylene Glycol - room temperature to 250°F.

One Neslab Constant Temperature Circulating Bath - Model TEZ 10 with a Model CT 59 Thermoregulator and a Labline 11 inch diameter thermo cup. Designated Bath 2.

Medium: Isopranol - room temperature to -10°F.
Neslab Portable Bath Cooler, Model PCB-2 connected.

Two Low Temperature Stirred Baths, two 11 inch diameter thermo cups, two Honeywell Controllers and Solenoid control valves to liquid nitrogen bottle. Designated Baths 3 and 5.

Medium: Isopranol - room temperature to -150°F.
Coolant: Liquid nitrogen and Flexi-Cool unit.

All baths - Copper Constantan Thermocouple
Honeywell Six Point Temperature Chart Recorder
Digitec Thermocouple Thermometer - Model 590 TF
Standard Mercury Column Thermometer
Bimetallic-spring Thermometer

The temperature instruments were calibrated in accordance with the ASME Boiler and Pressure Vessel Code, Section III, Paragraph 2360. Copies of the applicable calibration certificates are provided at the end of this appendix.

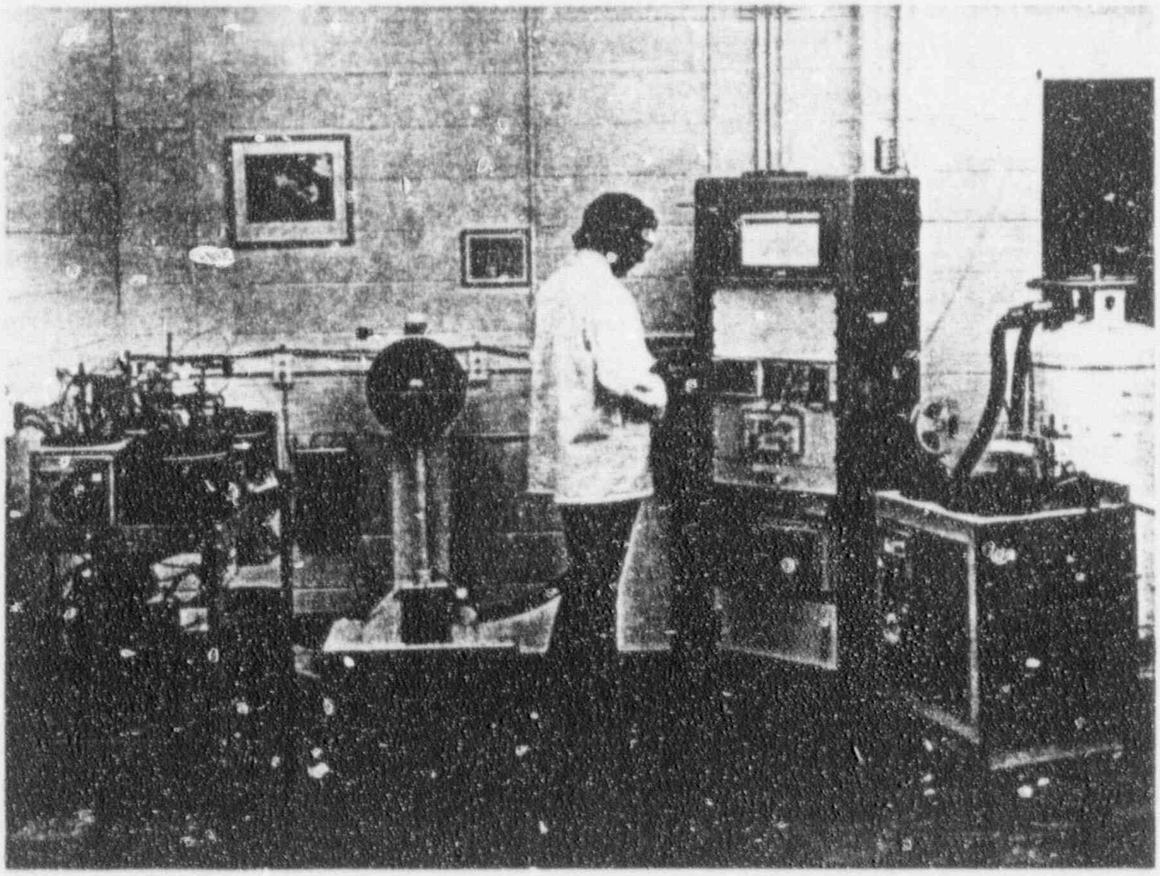

Figure: C-1. Charpy Impact Test System, Associated Constant Temperature Baths and Instrumented Charpy Impact Data Processing Equipment.

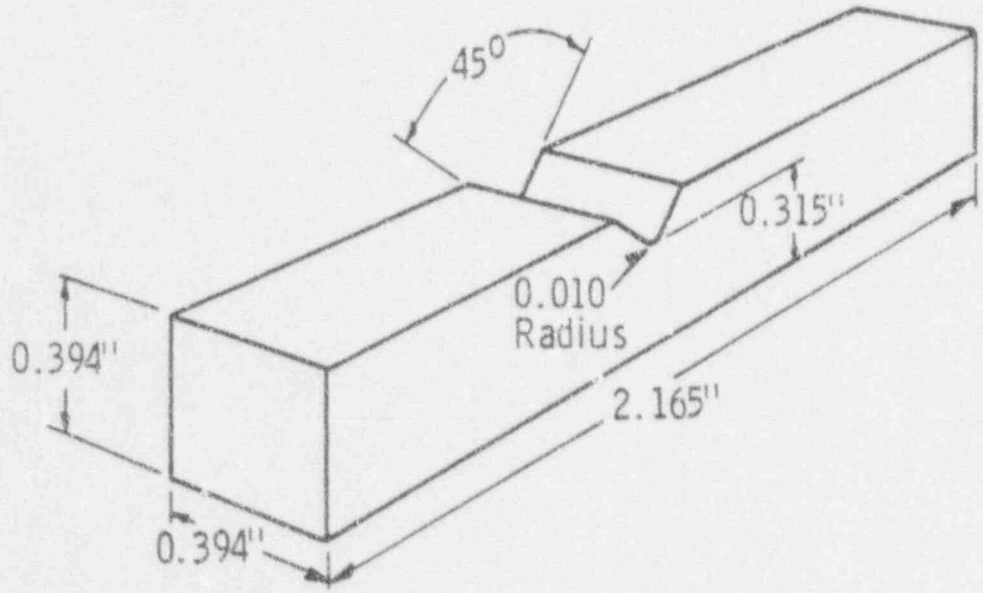

FIGURE: C-2. Typical Charpy V-Notch Impact Specimen

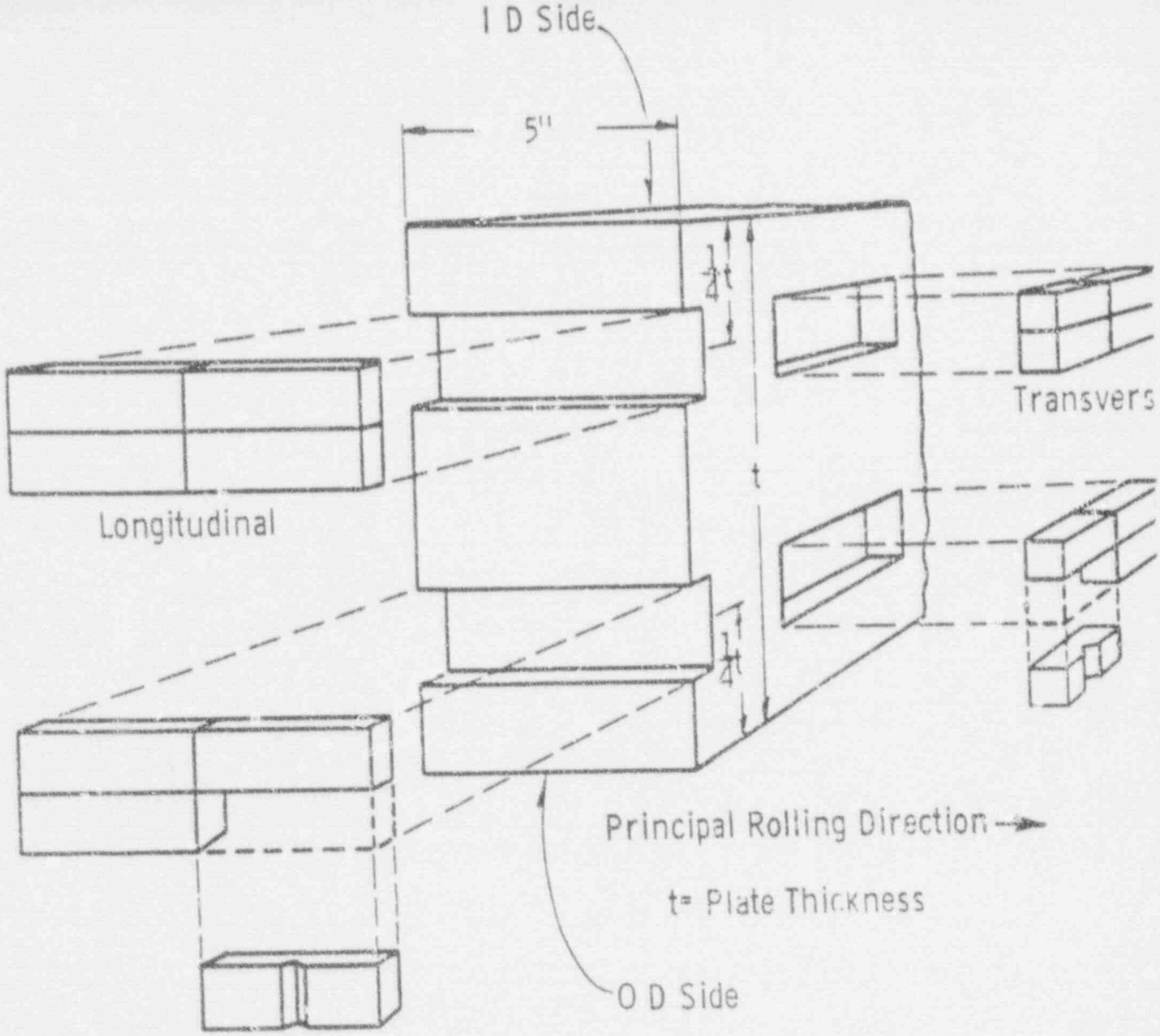

FIGURE: C-3. Location of Charpy Impact Specimens Within Base Metal Test Material

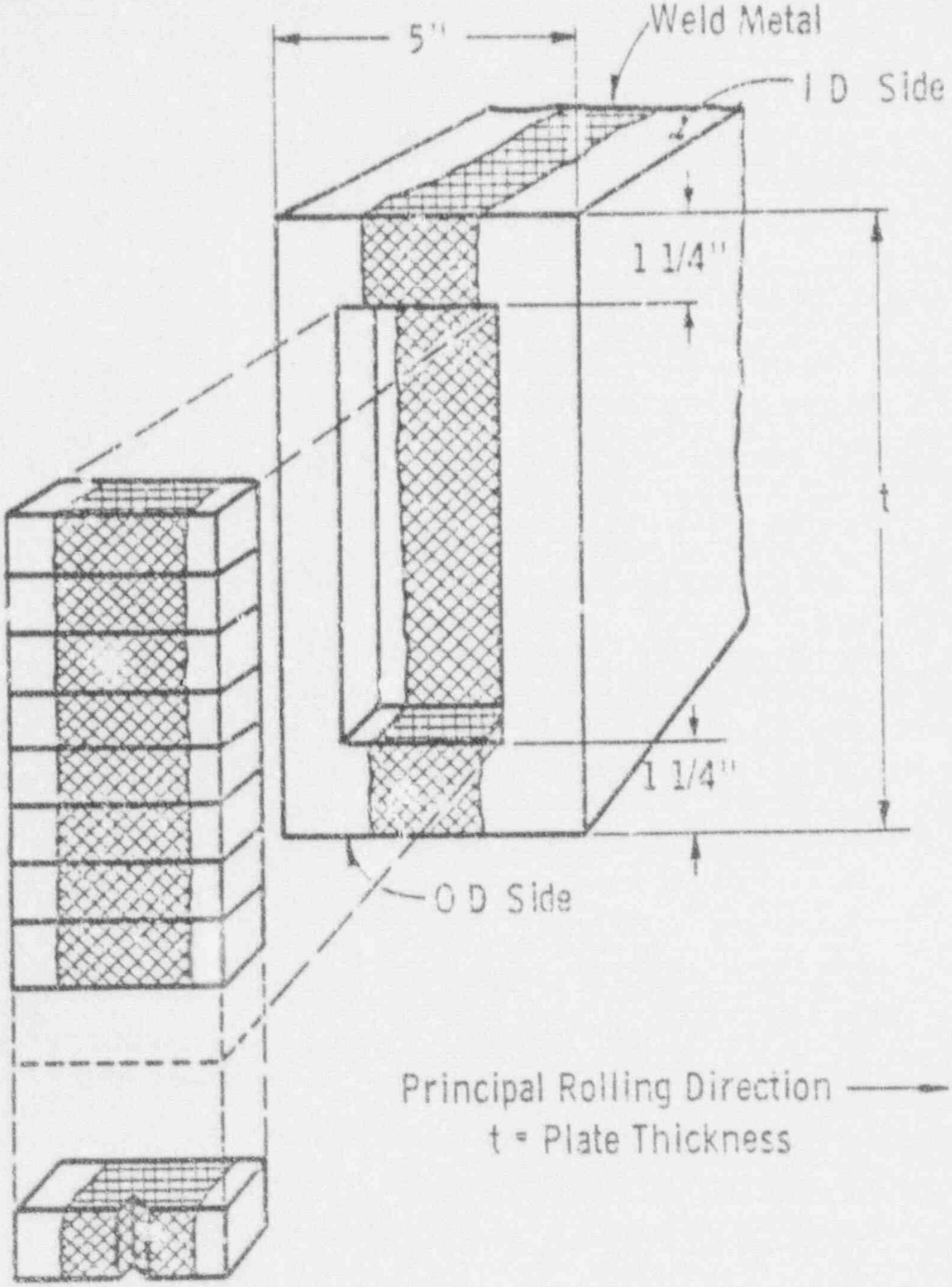

FIGURE: C-4. Location of Charpy Impact Specimens Within Weld Metal Test Material

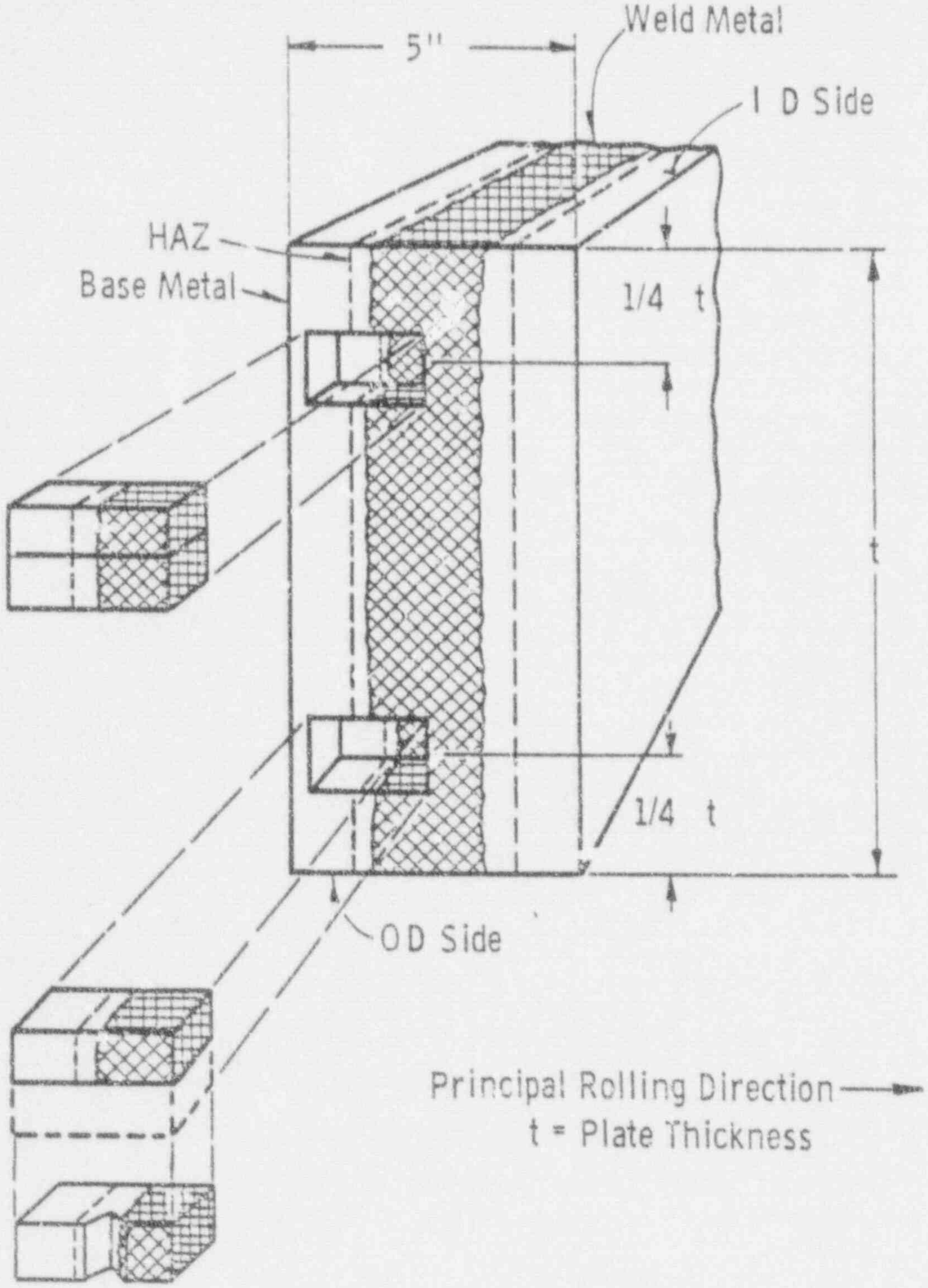

FIGURE: C-5. Location of Charpy Impact Specimens Within Heat-Affected-Zone Test Material

DEPARTMENT OF THE ARMY
ARMY MATERIALS AND MECHANICS RESEARCH CENTER
WATERTOWN, MASSACHUSETTS 02172

DRXMR-MQ

17 August 1976

Combustion Engineering, Inc.
ATTN: Mr. E. Dombkowski
1000 Prospect Hill Road
Windsor, CT 06095

Dear Mr. Dombkowski:

A set of Charpy specimens broken on the 240 ft-lb capacity Sonntag machine has been received for evaluation along with the completed questionnaire.

The results of the tests indicate the machine to be producing acceptable energy values at both energy levels (see inclosed table).

This machine satisfies the proof-test requirements of ASTM Standard E-23.

If this machine is moved or undergoes major repairs or adjustments, this certification becomes invalid and the machine must be rechecked. Removal of the pendulum, replacement of anvils or adjusting the height of drop are examples of such major repairs or adjustments. It should be noted that if a specimen requires over 80% of the machine capacity to fracture, the machine should be checked to insure that the pendulum is straight, the anvils or striker have not been damaged and that all bolts are still tight. This certification is valid for one year from the date of the test.

Sincerely yours,

Paul W. Rolston
Chief
Quality Engineering Branch

1 Incl
Table

AMERICAN REVOLUTION BICENTENNIAL 1776-1976

COMBUSTION ENGINEERING, INC.
Nuclear Laboratories
INSTRUMENT CALIBRATION REQUIREMENT SHEET

DATE: July 13, 1976

EQUIPMENT Honeywell Temperature Controller EL-120 AREA Room 235-5

INSTRUMENT		READABILITY		CALIBRATION		CHECKED
FUNCTION	TYPE	RANGE	MIN READABILITY	ACCURACY	FREQUENCY	BY
Temperature Control	Dial	-350° to 250°F	2°F	± 2°F	3 months	[signature]

PREPARED BY [signature]

APPROVED BY [signature] APPROVED BY [signature]

CE 0090193 (8/73)

COMBUSTION ENGINEERING, INC.
Nuclear Laboratories
INSTRUMENT CALIBRATION REQUIREMENT SHEET

DATE: July 13, 1976

EQUIPMENT Honeywell Temperature Controller EL-80 AREA Room 235-5

INSTRUMENT		READABILITY		CALIBRATION		CHECKED
FUNCTION	TYPE	RANGE	MIN READABILITY	ACCURACY	FREQUENCY	BY
Temperature Control	Dial	-350° to 250°F	2°F	± 2°F	3 months	[signature]

PREPARED BY [signature]

APPROVED BY [signature] APPROVED BY [signature]

CE 0090193 (8/73)

COMBUSTION ENGINEERING, INC.
Nuclear Laboratories
INSTRUMENT CALIBRATION REQUIREMENT SHEET

DATE: July 13, 1976

EQUIPMENT Honeywell 6 Point Recorder EL-78 AREA Room 235-5

INSTRUMENT		READABILITY		CALIBRATION		CHECKED
FUNCTION	TYPE	RANGE	MIN READABILITY	ACCURACY	FREQUENCY	BY
Temperature Recorder	6-Point	-350° to 250°F	1°F	± 1°F	3 months	[illegible]

PREPARED BY [signature]

APPROVED BY [signature] APPROVED BY [signature]

CE 0090193 (8/73)

COMBUSTION ENGINEERING, INC.
Nuclear Laboratories
INSTRUMENT CALIBRATION REQUIREMENT SHEET

DATE: June 16, 1976

EQUIPMENT Digital Thermocouple Thermometer EL-96 AREA Room 235-5

INSTRUMENT		READABILITY		CALIBRATION		CHECKED
FUNCTION	TYPE	RANGE	MIN READABILITY	ACCURACY	FREQUENCY	BY
Thermometer	Digital	-313° to +752°F	.1°F	± 1°F	3 months	

PREPARED BY Edward P [illegible]

APPROVED BY [illegible] APPROVED BY [illegible]

CE 0090193 (8/73)

COMBUSTION ENGINEERING, INC.
Nuclear Laboratories
INSTRUMENT CALIBRATION REQUIREMENT SHEET

DATE: June 16, 1976

EQUIPMENT Digital Thermocouple Thermometer EL-81 AREA Room 235-5

INSTRUMENT		READABILITY		CALIBRATION		CHECKED
FUNCTION	TYPE	RANGE	MIN READABILITY	ACCURACY	FREQUENCY	BY
Thermometer	Digital	-350° to +1000°F	.2°F	± 2°F	3 months	[signature]

PREPARED BY [signature: Edward P. Ornbkowski]

APPROVED BY [signature] APPROVED BY [signature]

CE 0090193 (8/73)

APPENDIX C

REFERENCES

1. "Summary Report on Manufacture of Test Specimens and Assembly of Capsules for Irradiation Surveillance of Fort Calhoun Reactor Vessel Materials", C-E Document CENPD-33 Proprietary Information, dated November 15, 1971.

2. "Test Plan for Omaha Public Power District, Fort Calhoun Station Unit No. 1 Evaluation of Baseline Specimens - Reactor Vessel Materials Irradiation Surveillance Program", Test Plan No. 23866-TP-MCD-002, dated April 1976.

3. D. R. Ireland, W. L. Server and R. A. Wullaert, "Procedure for Testing and Data Analysis", ETI Technical Report 75-43, October 1975, Effects Technology, Inc., Santa Barbara, California.

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