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A Edward Scherer
Manager of Nuclear
Oversight and Regulatory Affairs

October 19, 2001

U. S. Nuclear Regulatory Commission
Attention: Document Control Desk
Washington, D.C. 20555

Subject: **Docket Nos. 50-361**
Surveillance Capsule Test Report
San Onofre Nuclear Generating Station, Unit 2

Reference: Letter from R. M. Rosenblum (SCE) to the Document Control Desk (NRC) dated May 8, 1991; Subject: Docket No. 50-361, Surveillance Capsule Test Report, San Onofre Nuclear Generating Station Unit 2

Gentlemen:

This letter provides as an enclosure Framatome ANP, Inc. report "Analysis of the 263 Degree Capsule, Southern California Edison Company, San Onofre Unit 2 Nuclear Generating Station - Reactor Vessel Material Surveillance Program," Framatome ANP Document No. 77-2408-00 dated October 2001. This report provides the test results of the second surveillance capsule which was removed from the San Onofre Unit 2 reactor vessel on October 22, 2000, as required by 10 CFR 50, Appendix H. No immediate revision of the reactor coolant system pressure-temperature (P-T) limits in existing Technical Specification (TS) 3.4.3 is necessary. The current Unit 2 TS P-T curves have been determined to be valid for at least the next four years. SCE will prepare an amendment request within three years to update the Unit 2 TS P-T curves as necessary, to ensure continued compliance.

A008

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The San Onofre Unit 2 reactor vessel surveillance capsule test report for the first surveillance capsule was submitted by the reference.

If you have any questions or need additional information regarding this matter, please feel free to contact me or Mr. Jack Rainsberry at (949) 368-7420.

Sincerely,

Enclosure

cc: E. W. Merschoff, Regional Administrator, NRC Region IV
M. L. Scott, NRC Project Manager, San Onofre Units 2, and 3
C. C. Osterholtz, NRC Senior Resident Inspector, San Onofre Units 2 & 3

ENCLOSURE

BAW-2408
October 2001

Analysis of the 263° Capsule
Southern California Edison Company
San Onofre Unit 2 Nuclear Generating Station

Reactor Vessel Material Surveillance Program

FRAMATOME ANP

BAW-2408
October 2001

Analysis of the 263° Capsule
Southern California Edison Company
San Onofre Unit 2 Nuclear Generating Station

-- Reactor Vessel Material Surveillance Program --

by

J. B. Hall
J. W. Newman, Jr.

Framatome ANP Document No. 77-2408-00
(See Section 9 for document signatures.)

Prepared for

Southern California Edison Company

Prepared by

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FRAMATOME ANP

Executive Summary

This report describes the results of the examination of the second capsule (the 263° capsule) of the Southern California Edison Company San Onofre Unit 2 Nuclear Generating Station as part of their reactor vessel surveillance program (RVSP). The objective of the program is to monitor the effects of neutron-irradiation on the mechanical properties of the reactor vessel materials by testing and evaluation of tensile and Charpy V-notch impact specimens. The San Onofre Unit 2 RVSP was designed and furnished by Combustion Engineering, Inc., based on ASTM Standard E 185-73.

The 263° capsule was removed from the San Onofre Unit 2 reactor vessel during the cycle eleven refueling shutdown for testing and evaluation. The capsule received an average fast fluence of 1.637×10^{19} n/cm^2 (E > 1.0 MeV). With the recent Appendix K power uprate to 3438 MWth from 3390 MWth, fluence values at the projected end-of-life (32 EFPY) were estimated using an artificially increased flux value for all future cycles. Based on this extrapolated flux, the projected peak fast fluence of the San Onofre Unit 2 reactor vessel beltline region clad/vessel interface is 4.355×10^{19} n/cm^2 (E > 1.0 MeV).

The results of the tension tests indicated that the San Onofre Unit 2 surveillance materials exhibited normal behavior for neutron-irradiation. The Charpy impact data for the San Onofre Unit 2 surveillance materials exhibited the characteristic behavior of an increase in ductile-to-brittle transition temperature and a decrease in upper-shelf energy as a result of neutron-irradiation.

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1. Introduction

This report presents the test and evaluation results of the second reactor vessel surveillance capsule (located at 263°) removed from the San Onofre Unit 2 reactor vessel. The capsule was removed from the San Onofre Unit 2 reactor on October 22, 2000 (The outage started on October 7, 2000). The contents were evaluated after being irradiated in the San Onofre Unit 2 reactor as part of the reactor vessel surveillance program (RVSP) as documented in S-NLM-002, Revision 2[1]. This report describes the testing and the post-irradiation results obtained from the 263° capsule removed from San Onofre Unit 2 after receiving an average fluence of 1.637 x 10^{19} n/cm^2 (E>1.0 MeV). These data are compared to the previous San Onofre Unit 2 RVSP results from the 97° capsule.[2] This report meets the reporting requirements of 10CFR50, Appendix H and American Society for Testing and Materials (ASTM) Standard E185-82.[3]

The objective of the program is to monitor the effects of neutron irradiation on the mechanical properties of reactor vessel materials under actual plant operating conditions. The program was planned to monitor the effects of neutron-irradiation on the reactor vessel materials for the 40-year design life of the reactor pressure vessel. The San Onofre Unit 2 RVSP was designed and furnished by Combustion Engineering, Inc., based on ASTM Standard E 185-70. However, the surveillance program was updated to the later 1973 version.

2. Background

The ability of the reactor vessel to resist fracture is a primary factor in ensuring the safety of the primary coolant system in light water reactors. The reactor vessel beltline region is the most critical region of the vessel since it is exposed to the highest level of neutron-irradiation. The general effects of fast neutron-irradiation on the mechanical properties of low-alloy ferritic steels used in the fabrication of reactor vessels are well characterized and documented. The low-alloy ferritic steels used in the beltline region of reactor vessels exhibit an increase in ultimate and yield strength properties with a corresponding decrease in ductility after irradiation. The most significant mechanical property change in reactor vessel steels is the increase in the ductile-to-brittle transition temperature accompanied by a reduction in Charpy upper-shelf energy (C_vUSE).

Code of Federal Regulation, Title 10, Part 50, (10 CFR 50) Appendix G, *"Fracture Toughness Requirements,"* [4] specifies minimum fracture toughness requirements for the ferritic materials of the pressure-retaining components of the reactor coolant pressure boundary (RCPB) of commercial light water reactors and provides specific guidelines for determining the pressure-temperature limitations for operation of the RCPB. The fracture toughness and operational requirements are specified to provide adequate safety margins during normal operation, anticipated transients and system hydrostatic tests, to which the pressure boundary may be subjected over its service lifetime. The requirements of 10 CFR 50, Appendix G, became effective on August 16, 1973. These requirements are applicable to all boiling and pressurized water nuclear power reactors, including those under construction or in operation on the effective date.

10 CFR 50, Appendix H, *"Reactor Vessel Material Surveillance Program Requirements,"*[5] defines the material surveillance program required to monitor changes in the fracture toughness properties of ferritic materials in the reactor vessel beltline region of light water reactors resulting from exposure to neutron-irradiation and the thermal environment. Fracture toughness test data are obtained from material specimens contained in capsules that are periodically withdrawn from the reactor vessel. These data permit determination of the conditions under which the vessel can be operated with adequate safety margins against non-ductile fracture throughout its service life.

A method for guarding against non-ductile fracture in reactor vessels is described in Appendix G to the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code, Section III, *"Nuclear Power Plant Components"*[6] and Section XI, *"Rules for Inservice Inspection"*[7]. This method uses fracture mechanics concepts and the reference nil-ductility temperature, RT_{NDT}, which is defined as the greater of the drop weight nil-ductility transition temperature (in accordance with ASTM E 208-81[8]) or the temperature that is 60°F below that at which the material exhibits 50 ft-lbs and 35 mils lateral expansion. The RT_{NDT} of a given material is used to index that material to a reference stress intensity factor curve (K_{IR} curve), which appears in Appendix G of ASME B&PV Code Section III and Section XI. The K_{IR} curve is a lower bound of dynamic and crack arrest fracture toughness data obtained from several heats of pressure vessel steel. When a given material is indexed to the K_{IR} curve, allowable stress intensity factors can be obtained for the material as a function of temperature. The operating limits can then be determined using these allowable stress intensity factors.

The RT_{NDT} and, in turn, the operating limits (pressure/temperature limits) of a nuclear power plant, are adjusted over the life of the plant to account for the effects of irradiation on the fracture toughness of the reactor vessel materials. Irradiation embrittlement and the resultant changes in mechanical properties of a given pressure vessel steel are monitored by each plant's surveillance program. The surveillance capsules, as part of the surveillance program, contain prepared specimens of the reactor vessel materials, which are irradiated in the reactor vessel. A surveillance capsule is periodically removed from the operating nuclear reactor and the specimens are tested to determine the changes in mechanical properties. The increase in the Charpy V-notch 30 ft-lb temperature is added to the original RT_{NDT} to adjust it for irradiation embrittlement. The adjusted RT_{NDT} is used to index the material to the K_{IR} curve which, in turn, is used to set operating limits for the nuclear power plant. These new limits take into account the effects of irradiation on the reactor vessel materials.

10 CFR 50, Appendix G, also requires a minimum initial C_vUSE of 75 ft-lbs for all beltline region materials unless it is demonstrated that lower values of upper-shelf fracture energy will provide an adequate margin of safety against fracture equivalent to those required by ASME Section XI, Appendix G. No action is required for a material that does not meet the initial 75 ft-lbs requirement if the irradiation embrittlement does not cause the C_vUSE to drop below 50 ft-lbs. The regulations specify that if the C_vUSE drops below 50 ft-lbs, it must be demonstrated, in a manner approved by the Office of Nuclear Reactor Regulation, that the lower values will provide adequate margins of safety.

3. Surveillance Program Description

The reactor vessel surveillance program for San Onofre Unit 2 includes six capsules designed to monitor the effects of neutron and thermal environment on the materials of the reactor pressure vessel core region. The capsules, which were inserted into the reactor vessel before initial plant startup, were positioned inside the reactor vessel between the core support barrel and the vessel wall at the locations shown in Figure 3-1. S-NLM-002[1] includes a full description of the capsule locations and design. The 263° capsule was irradiated in the 263° position in the reactor vessel from the start of cycle 1 to the end of cycle 10.

The 263° capsule was removed during the cycle 11 refueling shutdown of San Onofre Unit 2. The capsule contained Charpy V-notch (CVN) impact test specimens fabricated from one heat of base metal plate (SA-533, Grade B, Class 1), heat-affected-zone (HAZ) material, a weld metal representative of the San Onofre Unit 2 reactor vessel beltline region intermediate and lower shell longitudinal welds, and a Standard Reference Material (SRM). The SRM is a standard heat of SA-533, Grade B, Class 1 made available by the USAEC sponsored Heavy Section Steel Technology (HSST) program. The tensile test specimens were fabricated from the same base metal plate, HAZ, and weld metal. The number of specimens of each material contained in the 263° capsule is described in Table 3-1, and the location of the individual specimens within the capsule is shown in Table 3-2 and Figure 3-2.[9] The chemical compositions of the surveillance materials within the 263° capsule, obtained from the original surveillance program report,[1] are described in Table 3-3.

All base metal CVN and tensile specimens were machined from the ¼-thickness (¼T) location of the plate material. The base metal specimens were oriented such that the longitudinal axis of each specimen was perpendicular to the principal working direction of the plate (transverse orientation). The HAZ and weld metal specimens were oriented such that the longitudinal axis of each specimen was perpendicular to the weld seam. The CVN HAZ and weld metal specimens had the notch oriented parallel to the weld seam.

The 263° capsule contained dosimeter wires of copper, iron, nickel, titanium, aluminum-0.17 weight percent cobalt (cadmium-shielded and unshielded), sulfur pellet dosimeters, and uranium-238 (^{238}U) foil dosimeters. The location of these dosimeters within the 263° capsule is shown in Figure 3-2.

Thermal monitors fabricated from four low-melting alloys were included in the capsule. The thermal monitors were sealed in quartz tubes and inserted in spacers located in Figure 3-2. The eutectic alloys and their melting points are listed below:[1]

80% Ag, 20% Sn	Melting Point 536°F
5.0% Ag, 5.0% Sn, 90.0% Pb	Melting Point 558°F
2.5% Ag, 97.5% Pb	Melting Point 580°F
1.75% Ag, 0.75% Sn, 97.5% Pb	Melting Point 590°F

Table 3-1. Test Specimens Contained in the 263° San Onofre Unit 2 Capsule

Material Description	Number of Test Specimens: Tension	Number of Test Specimens: Charpy V-notch
Base Metal Plate C-6404-2 Transverse	3	12
HAZ Metal	3	12
Weld Metal C-6404-1/ C-6404-3 (9-203)	3	12
SRM*	--	12
Total	9	48

* Standard Reference Material: SA-533, Grade B, Class 1, HSST Plate 01

Table 3-2. Location of Test Specimens Contained in the 263° San Onofre Unit 2 Capsule

Compartment Position (from top)	Material	Specimen Type	Compartment ID
1	HAZ	Tensile	B414
2	HAZ	CVN	B424
3	SRM	CVN	B43A
4	BM-T	Tensile	B442
5	BM-T	CVN	B452
6	Weld	CVN	B463
7	Weld	Tensile	B473

BM-T = Base Metal – Transverse
CVN = Charpy V-notch
HAZ = Heat Affected Zone
SRM = Standard Reference Material

Table 3-3. Chemical Composition of the 263° San Onofre Unit 2 Capsule Surveillance Materials

Element	Chemical Composition, wt%	
	Base Metal Plate C-6404-2	Weld Metal C-6404-1/ C-6404-3 (9-203)
Si	0.26	0.21
S	0.009	0.009
P	0.005	0.003
Mn	1.43	1.34
C	0.23	0.17
Cr	0.18	0.09
Ni	0.60	0.12
Mo	0.58	0.52
V	0.003	0.005
Cb	< 0.01	< 0.01
B	< 0.001	< 0.001
Co	0.012	0.012
Cu	0.10	0.03
Al	0.034	0.012
W	<0.01	<0.01
Ti	<0.01	<0.01
As	0.001	<0.001
Sn	0.003	0.001
Zr	<0.001	<0.001
N_2	0.005	0.004
Sb	0.0025	0.0013
Pb	<0.001	<0.001

Figure 3-1. Reactor Vessel Cross Section and Elevation Views Showing the Locations of RVSP Capsules in San Onofre Unit 2 Reactor Vessel

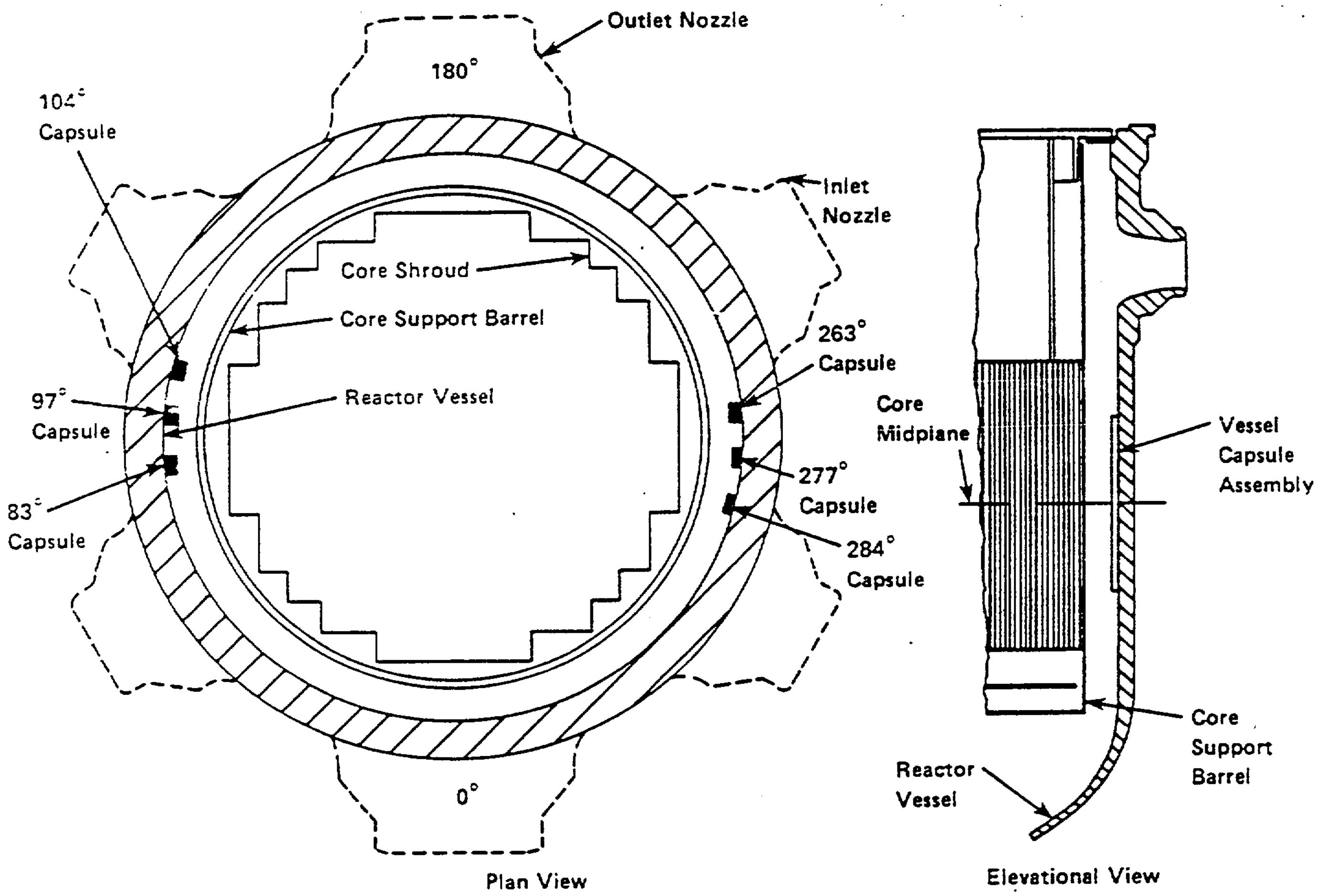
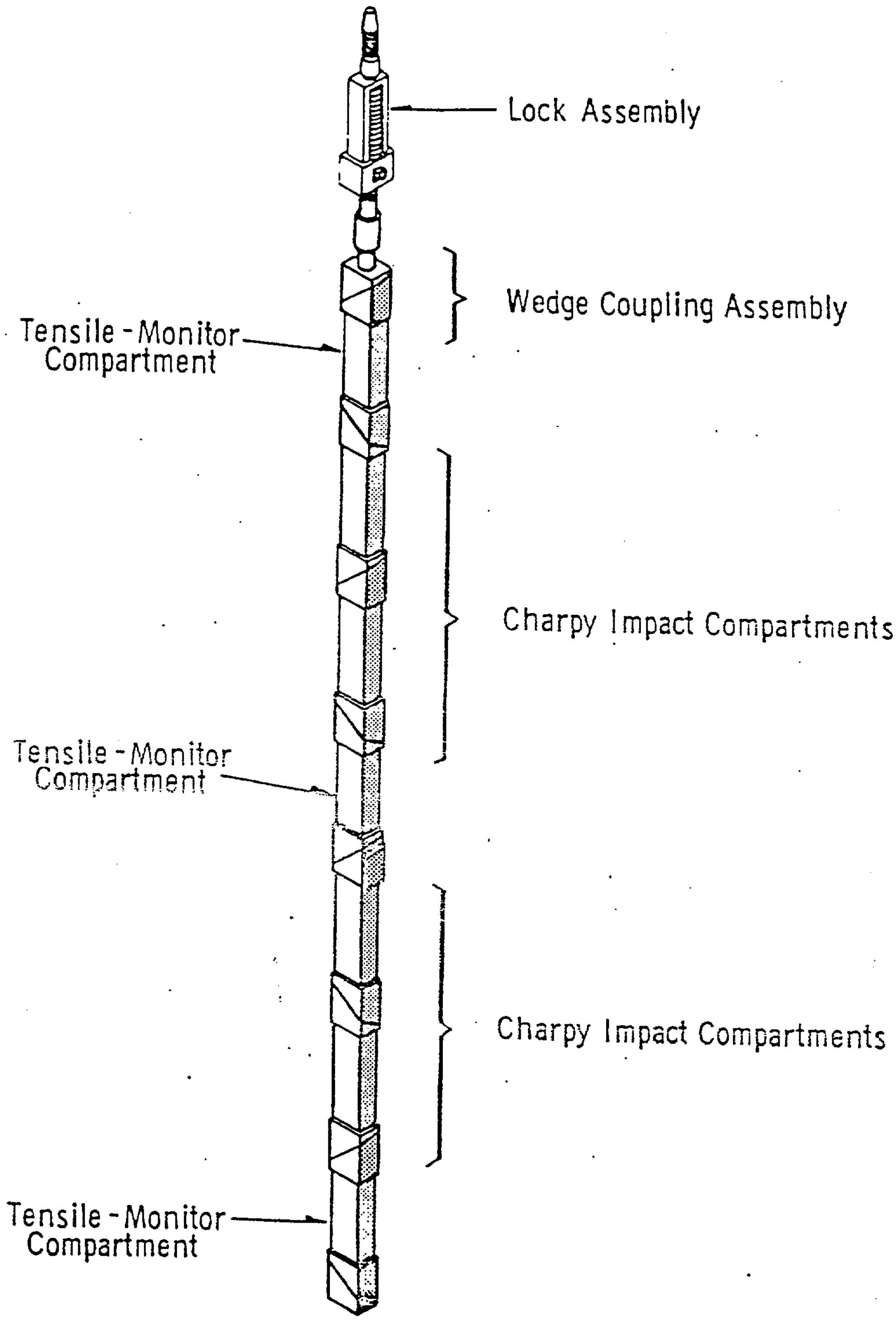


Figure 3-2. Surveillance Capsule Assembly Showing Locations of Specimens and Monitors for the 263° San Onofre Unit 2 Capsule



4. Tests of Unirradiated Material

Unirradiated material was evaluated for two purposes: (1) to establish baseline data to which irradiated properties data could be compared; and (2) to determine those material properties as required for compliance with 10 CFR 50, Appendices G and H.

Combustion Engineering, Inc., as part of the development of the San Onofre Unit 2 RVSP, performed the testing of the unirradiated surveillance material. The details of the testing procedures are described by Combustion Engineering, Inc.[10]. The unirradiated mechanical properties for the San Onofre Unit 2 RVSP materials are summarized in Appendices A and B of this report.

The original unirradiated Charpy V-notch impact data were evaluated based on hand-fit Charpy curves generated using engineering judgment[10]. The original irradiated Charpy impact data for the 97° Capsule were evaluated based on curves generated using SAM McFRAC code.[2] These data were re-evaluated herein using a hyperbolic tangent curve-fitting program, and the results of the re-evaluation are presented in Appendix B. In addition, Appendix C contains a comparison of the Charpy V-notch shift results for each surveillance material: SAM McFRAC fit versus current hyperbolic tangent curve-fit.

5. Post-Irradiation Testing

The post-irradiation testing of the tensile specimens, the CVN impact specimens, thermal monitors, and dosimeters for the 263° San Onofre Unit 2 capsule was performed at the BWX Technologies, Lynchburg Technology Center (LTC).[11]

5.1. Capsule Disassembly and Inventory

After capsule disassembly, the contents of the 263° capsule were inventoried and found to be consistent with the surveillance program report inventory.[9] The capsule contained a total of 48 standard Charpy V-notch specimens, nine (9) tensile specimens, six (6) dosimetry blocks, and three (3) sets of temperature monitors.

5.2. Thermal Monitors

The low-melting point (536°F, 558°F, 580°F and 590°F) eutectic alloys contained in the 263° capsule were encapsulated in quartz tubes. Each set of thermal monitors (capsule top, middle, and bottom) were photographed to reveal the shape of the monitors and examined for evidence of melting. In all cases the 536°F and 558°F temperature monitors showed evidence of partial melting, and the 580°F and 590°F monitors did not show any evidence of melting. Based on this examination, the maximum temperature that the capsule test specimens were exposed to was between 558°F and 580°F. Figures 5-1 through 5-3 contain photographs of the temperature monitors.

5.3. Tension Test Results

The capsule contained a total of nine (9) specimens, three (3) specimens made of base metal-transverse orientation, HAZ, and weld metal. The specimens were of standard round type with a gage length of 1.0 inch and a nominal gage diameter of 0.250 inch. The tensile tests for each material were performed at: 1). a temperature near the middle of the Charpy impact transition region, 2). 250°F, and 3). 550°F. The results of the post-irradiation tension tests are presented in Table 5-1, and the stress-strain curves are presented in Figures 5-4 through 5-12. The tests were performed using a MTS Model 312 servohydraulic test machine using stroke control with an initial actuator travel rate of 0.0075 inch per minute. Following specimen yielding, an actuator speed of 0.03 inch per minute was used. The tension testing was performed in accordance with the applicable requirements of ASTM Standard E 21-92.[12] Photographs of the tension test specimen fractured surfaces are shown in Figures 5-13 through 5-15.

5.4. Charpy V-Notch Impact Test Results

The Charpy V-notch impact testing was performed in accordance with the applicable requirements of ASTM Standard E 23-91.[13] Impact energy, lateral expansion, and percent shear fracture were measured at numerous test temperatures and recorded for each specimen. The impact energy was measured using a certified Satec S1-1K Impact tester (traceable to NIST Standard) with a striker velocity of 16.90 ft/sec and 240 ft-lb of available energy. The lateral expansion was measured using a certified dial indicator. The specimen percent shear was estimated by video examination and comparison with the visual standards presented in ASTM Standard E 23-91.

The results of the Charpy V-notch impact testing are shown in Tables 5-2 through 5-5. The curves in Figures 5-16 through 5-19 were generated using a hyperbolic tangent curve-fitting program to produce the best-fit curve through the data. The symmetric hyperbolic tangent (TANH) function (test response, i.e., absorbed energy, lateral expansion, and percent shear fracture, "R," as a function of test temperature, "T") used to evaluate the surveillance data is as follows:[14]

$$\boldsymbol{R = A + B * \tanh\left[\frac{(T - To)}{C}\right]}$$

The Charpy V-notch data was entered, and the coefficients *A, B, To,* and *C* are determined by the program minimizing the sum of the errors squared (least-squares fit) in "R" of the data points about the fitted curve. Using these coefficients and the above TANH function, a smooth curve is generated through the data for interpretation of the material transition region behavior. The coefficients determined for irradiated materials in 263° capsule are shown in Table 5-6. When performing the TANH fit for the absorbed energy, the lower shelf was fixed at 2.2 ft-lbs and the upper shelf was fixed at the upper shelf value defined by ASTM Standard E185-82[15]. In fitting the TANH function to the lateral expansion data, the lower shelf was fixed at 1 mil and the upper shelf was not fixed. For the percent shear fracture data, the lower shelf was fixed at 0% and the upper shelf at 100% shear in fitting the TANH function.

Photographs of the Charpy V-notch specimen fracture surfaces are presented in Figures 5-20 through 5-23.

All Charpy V-notch impact testing was performed using instrumentation to record a load-versus-time trace and energy-versus-time trace for each impact event. The instrumented data was recorded and is available upon request.

5.5. Hardness Testing

Rockwell hardness measurements were performed on three specimens from each of three material categories (base metal, reference material, and weld). Rockwell hardness measurements could not be performed on the HAZ specimens due to the small size of the heat affected zone, so Vickers microhardness measurements were alternatively conducted and the results converted to Rockwell B. Five measurements were performed on each specimen. The Rockwell tests were conducted in accordance with ASTM Standard E 18-97[16]. The Vickers microhardness measurements were conducted in accordance with ASTM Standard E 384-89[17] and ASTM Standard E 92-82[18]. The weld zones were verified using a macroetch, and the HAZ zones were verified by etching the polished metallographic samples. The results are tabulated in Tables 5-7 through 5-10.

5.6. Chemical Analysis

Inductively Coupled Plasma (ICP) Atomic Emission Spectroscopy was performed on samples of weld and base metal to determine the chemical composition. The samples were analyzed for manganese, molybdenum, phosphorous, sulfur, nickel, chromium, cobalt, vanadium, silicon, and copper. The results are tabulated in Table 5-11.

Table 5-1. Tensile Properties of the 263° San Onofre Unit 2 Capsule Reactor Vessel Surveillance Materials, Irradiated to 1.637 x 10^{19} n/cm^2 (E>1.0 MeV)[(a)]

Material	Specimen No.	Test Temp. (°F)	Strength		Fracture Properties			Elongation		Reduction in Area (%)
			Yield[(b)] (ksi)	Ultimate (ksi)	Load (lb)	Stress (ksi)	Strength (ksi)	Uniform (%)	Total (%)	
Base Metal Plate C-6404-2 Transverse	2J4	150	79.1	99.0	3413	181	69.5	9.5	21.4	61.6
	2JC	250	74.2	93.2	3230	178	65.8	9.0	20.2	63.0
	2L1	550	73.9	96.0	3638	171	74.1	8.7	17.8	56.7
Weld Metal C-6404-1/C-6404-3 (9-203)	3K4	0	88.0/83.2	99.1	2976	192	60.6	9.8	24.4	68.4
	3KL	250	81.2/76.3	87.4	2663	183	54.3	7.2	21.0	70.4
	3JM	550	72.2	88.8	2686	178	54.7	7.4	20.6	69.3
HAZ Metal C-6404-2	4J5	0	85.7	102.7	3152	208	64.2	8.7	23.8	69.1
	4K6	250	76.1	93.1	2760	183	56.2	7.8	21.9	69.3
	4KP	550	78.3	95.0	4571	293	93.1	6.5	(c)	68.2

(a). The fluence calculation is described in Section 6.0 of this report.
(b). 0.2% offset yield. If two numbers are listed, the first is the upper yield and the second is the 0.2% offset yield, which occurs near the lower yield for this data.
(c). Sample 4KP failed outside the gage length; therefore the total elongation is not available.

Table 5-2. Charpy V-Notch Impact Results for the 263° San Onofre Unit 2 Capsule Base Metal Plate C-6404-2, Irradiated to 1.637 x 10^{19} n/cm^2 (E>1.0 MeV) Transverse Orientation

Specimen ID	Test Temperature, °F	Impact Energy, ft-lbs	Lateral Expansion, mil	Shear Fracture, %
224	30	6.5	5	0
24D	70	11.5	14	5
25Y	90	25.5	24	10
243	110	32.5	36	25
25T	130	33	33	35
24M	150	43	44	60
26D	175	63.5	55	70
244	200	69.5	58	100
26J	225	76.5	47	75
267	250	91.5*	77	100
26C	300	89.5*	74	100
247	350	98.5*	85	100

* Value used to determine upper-shelf energy (USE) in accordance with ASTM Standard E 185-82.[15]

Table 5-3. Charpy V-Notch Impact Results for the 263° San Onofre Unit 2 Capsule Weld Metal, C-6404-1/C-6404-3 (9-203), Irradiated to 1.637 x 10^{19} n/cm^2 (E>1.0 MeV)

Specimen ID	Test Temperature, °F	Impact Energy, ft-lbs	Lateral Expansion, mil	Shear Fracture, %
31C	-100	6	7	5
31B	-50	16.5	14	30
33M	-30	37.5	32	45
33Y	-30	32.5	28	50
32L	-15	34.5	31	55
311	0	49.5	44	60
36J	15	72	56	70
34U	30	93.5	77	85
32C	70	112.5	85	95
314	150	128.5*	95	100
35D	200	131.5*	95	100
315	300	145*	95	100

* Value used to determine upper-shelf energy (USE) in accordance with ASTM Standard E 185-82.[15]

Table 5-4. Charpy V-Notch Impact Results for the 263° San Onofre Unit 2 Capsule Heat-Affected-Zone Material, Irradiated to 1.637 x 10^{19} n/cm^2 (E>1.0 MeV)

Specimen ID	Test Temperature, °F	Impact Energy, ft-lbs	Lateral Expansion, mil	Shear Fracture, %
474	-100	10.5	11	0
46J	-50	18.5	14	5
445	0	28.5	23	35
434	15	33.5	25	35
44T	30	52	39	45
43J	50	68	51	70
433	70	102.5	74	80
436	100	86.5	65	70
46T	110	62.5	51	65
446	150	117.5*	87	100
43M	200	130.5*	90	100
425	300	132.5*	80	100

* Value used to determine upper-shelf energy (USE) in accordance with ASTM Standard E 185-82.[15]

Table 5-5. Charpy V-Notch Impact Results for the 263° San Onofre Unit 2 Capsule Standard Reference Material, HSST Plate 01 Irradiated to 1.637 x 10^{19} n/cm^2 (E>1.0 MeV)

Specimen ID	Test Temperature, °F	Impact Energy, ft-lbs	Lateral Expansion, mil	Shear Fracture, %
A66	70	5.5	6	0
A5L	110	11	15	25
A61	150	13.5	23	45
A5T	150	17	18	50
A6A	175	20.5	21	60
A5Y	190	46.5	41	50
A6B	200	41.5	40	65
A5K	225	57.5	52	75
A5J	250	65	59	95
A65	300	82.5*	72	100
A67	350	79.5*	72	100
A6D	400	84.5*	71	100

* Value used to determine upper-shelf energy (USE) in accordance with ASTM Standard E 185-82.[15]

Table 5-6. Hyperbolic Tangent Curve Fit Coefficients for the 263° San Onofre Unit 2 Capsule Surveillance Materials

Material Description	Hyperbolic Tangent Curve Fit Coefficients		
	Absorbed Energy	Lateral Expansion	Percent Shear Fracture
Base Metal Plate C-6404-2 Transverse	A: 47.7 B: 45.5 C: 86.3 T0: 150.5	A: 42.9 B: 41.9 C: 128.0 T0: 154.9	A: 50.0 B: 50.0 C: 56.4 T0: 144.3
Weld Metal C-6404-1/C-6404-3 (9-203)	A: 68.6 B: 66.4 C: 64.2 T0: 12.7	A: 48.2 B: 47.2 C: 60.5 T0: 0.9	A: 50.0 B: 50.0 C: 69.2 T0: -21.6
HAZ Metal C-6404-2	A: 64.5 B: 62.3 C: 103.7 T0: 53.4	A: 43.3 B: 42.3 C: 92.2 T0: 39.2	A: 50.0 B: 50.0 C: 90.2 T0: 35.4
Standard Reference Material, HSST Plate 01	A: 42.2 B: 40.0 C: 64.6 T0: 199.0	A: 37.5 B: 36.5 C: 83.6 T0: 192.8	A: 50.0 B: 50.0 C: 89.1 T0: 165.2

Table 5-7. Rockwell Hardness B Measurements for the 263° San Onofre Unit 2 Capsule Base Metal Plate C-6404-2, Irradiated to 1.637 x 10^{19} n/cm^2 (E>1.0 MeV)

Specimen 25Y	Specimen 24D	Specimen 224
96.1	94.0	94.9
96.5	96.7	95.3
95.1	94.8	95.9
96.2	94.7	95.6
95.0	96.1	95.0
Average 95.8	Average 95.3	Average 95.3

Table 5-8. Rockwell Hardness B Measurements for the 263° San Onofre Unit 2 Capsule Weld Metal, C-6404-1/C-6404-3 (9-203), Irradiated to 1.637 x 10^{19} n/cm^2 (E>1.0 MeV)

Specimen 33Y	Specimen 31B	Specimen 31C
94.9	95.6	95.4
94.6	94.0	95.4
94.9	93.7	95.3
94.8	94.9	94.4
95.2	94.5	94.5
Average 94.9	Average 94.5	Average 95.0

Table 5-9. Rockwell Hardness B Values for the 263° San Onofre Unit 2 Capsule Heat-Affected-Zone Material, Irradiated to 1.637 x 10^{19} n/cm^2 (E>1.0 MeV) (Converted from Vickers)

Specimen 434	Specimen 474	Specimen 464
96.3	99.0	96.3
96.6	96.9	94.9
98.5	97.3	96.0
98.5	96.4	96.3
98.0	97.0	94.1
Average 97.6	Average 97.3	Average 95.5

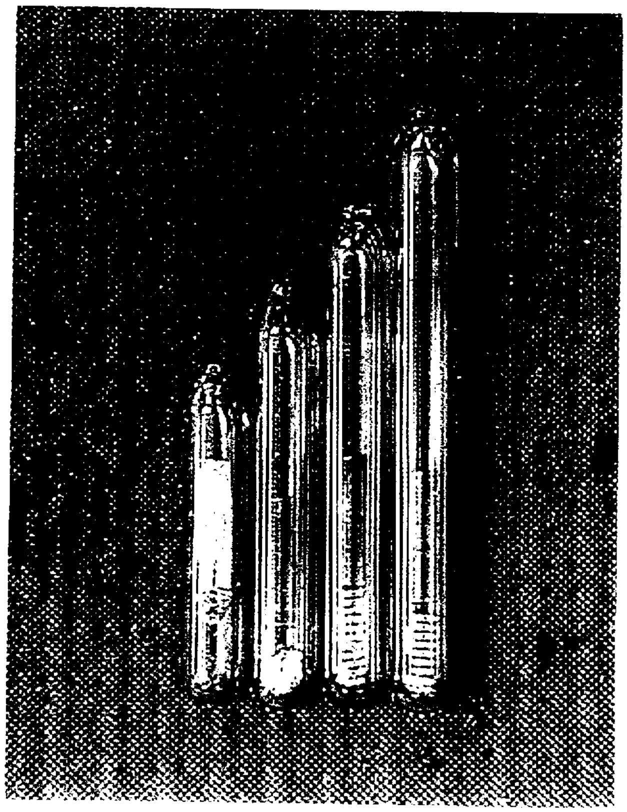
Table 5-10. Rockwell Hardness B Measurements for the 263° San Onofre Unit 2 Capsule Standard Reference Material, HSST Plate 01 Irradiated to 1.637 x 10^{19} n/cm^2 (E>1.0 MeV)

Specimen A61	Specimen A5L	Specimen A66
96.5	99.7	97.3
98.3	96.5	96.1
96.5	96.6	97.5
96.4	97.3	96.7
98.0	96.2	98.0
Average 97.1	Average 97.3	Average 97.1

Table 5-11. Chemical Analysis of the 263° San Onofre Unit 2 Capsule Base Metal Plate C-6404-2 and Weld Metal C-6404-1/C-6404-3 (9-203)

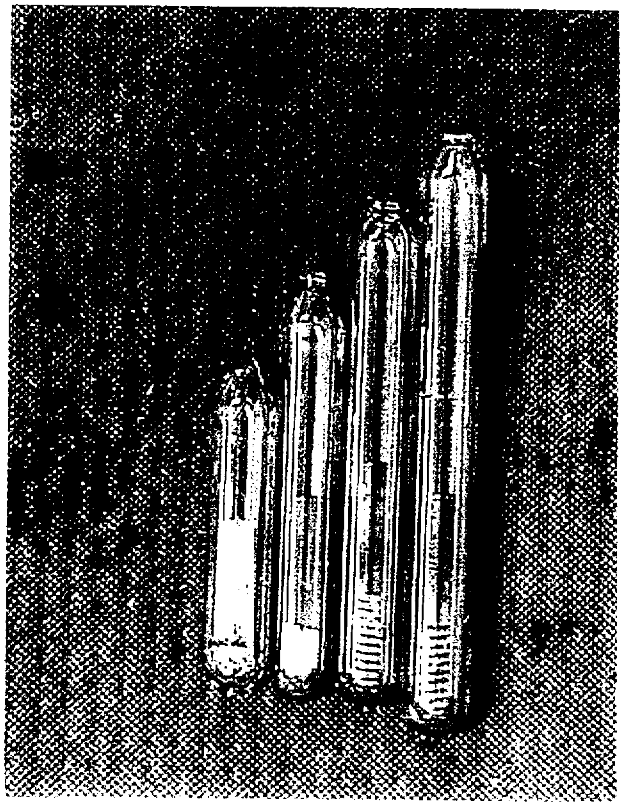
Element	Base Metal	Weld Material
Manganese	1.42	1.35
Molybdenum	0.61	0.60
Phosphorous	<0.02	<0.03
Sulfur	0.04	0.05
Nickel	0.60	0.15
Chromium	0.21	0.12
Cobalt	0.01	0.01
Vanadium	0.0035	0.01
Silicon	0.29	0.25
Copper	0.10	0.02

Figure 5-1. Photographs of Thermal Monitors Removed from the 263° San Onofre Unit 2 Capsule Top Compartment



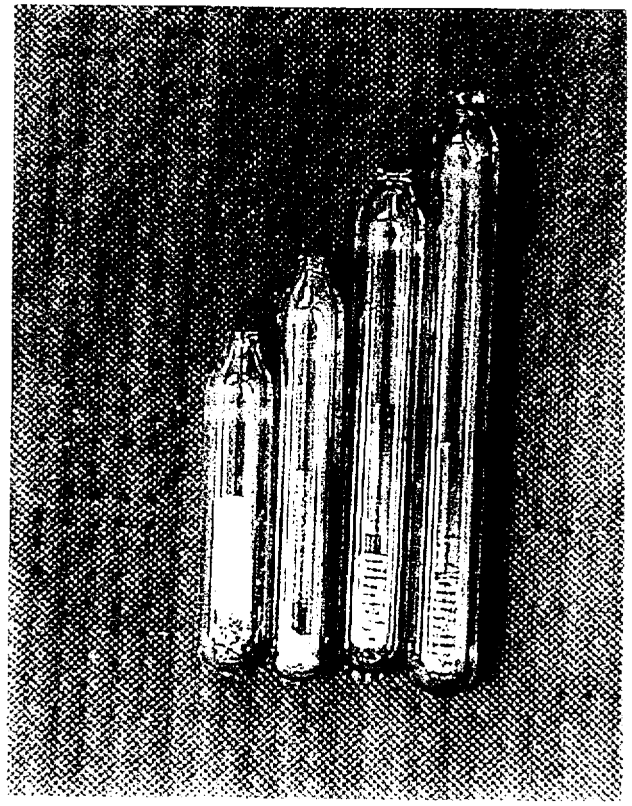
TEMPERATURE MONITORS IN TOP SEGMENT #1 (TEMPERATURES INCREASE WITH LENGTH)

Figure 5-2. Photographs of Thermal Monitors Removed from the 263° San Onofre Unit 2 Capsule Middle Compartment



TEMPERATURE MONITORS IN MIDDLE SEGMENT #4 (TEMPERATURES INCREASE WITH LENGTH)

Figure 5-3. Photographs of Thermal Monitors Removed from the 263° San Onofre Unit 2 Capsule Bottom Compartment



TEMPERATURE MONITORS IN BOTTOM SEGMENT #7 (TEMPERATURES INCREASE WITH LENGTH)

Figure 5-4. Tension Test Stress-Strain Curve for Base Metal Plate C-6404-2, Transverse Orientation, Specimen No. 2J4, Tested at 150°F

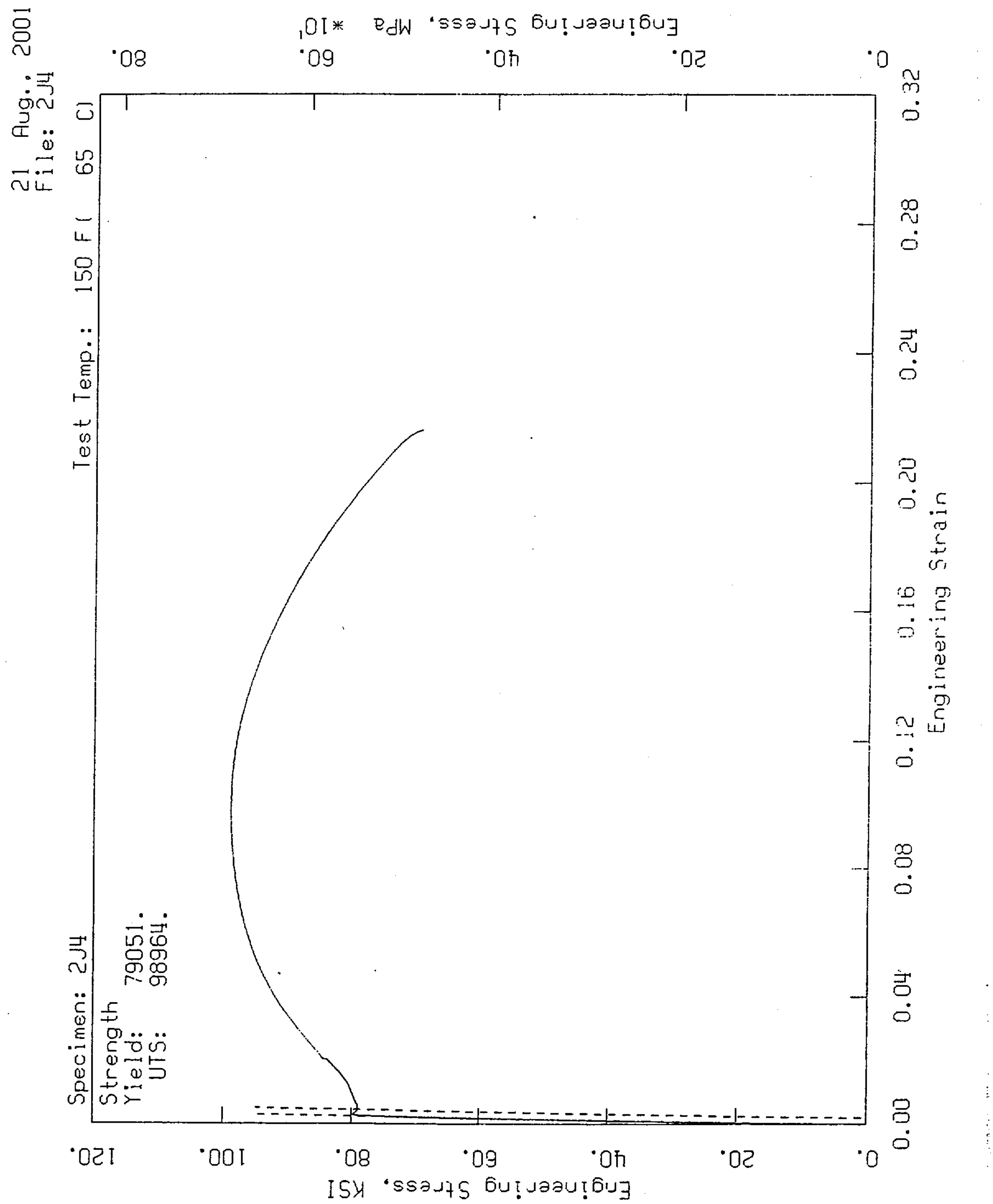


Figure 5-5. Tension Test Stress-Strain Curve for Base Metal Plate C-6404-2, Transverse Orientation, Specimen No. 2JC, Tested at 250°F

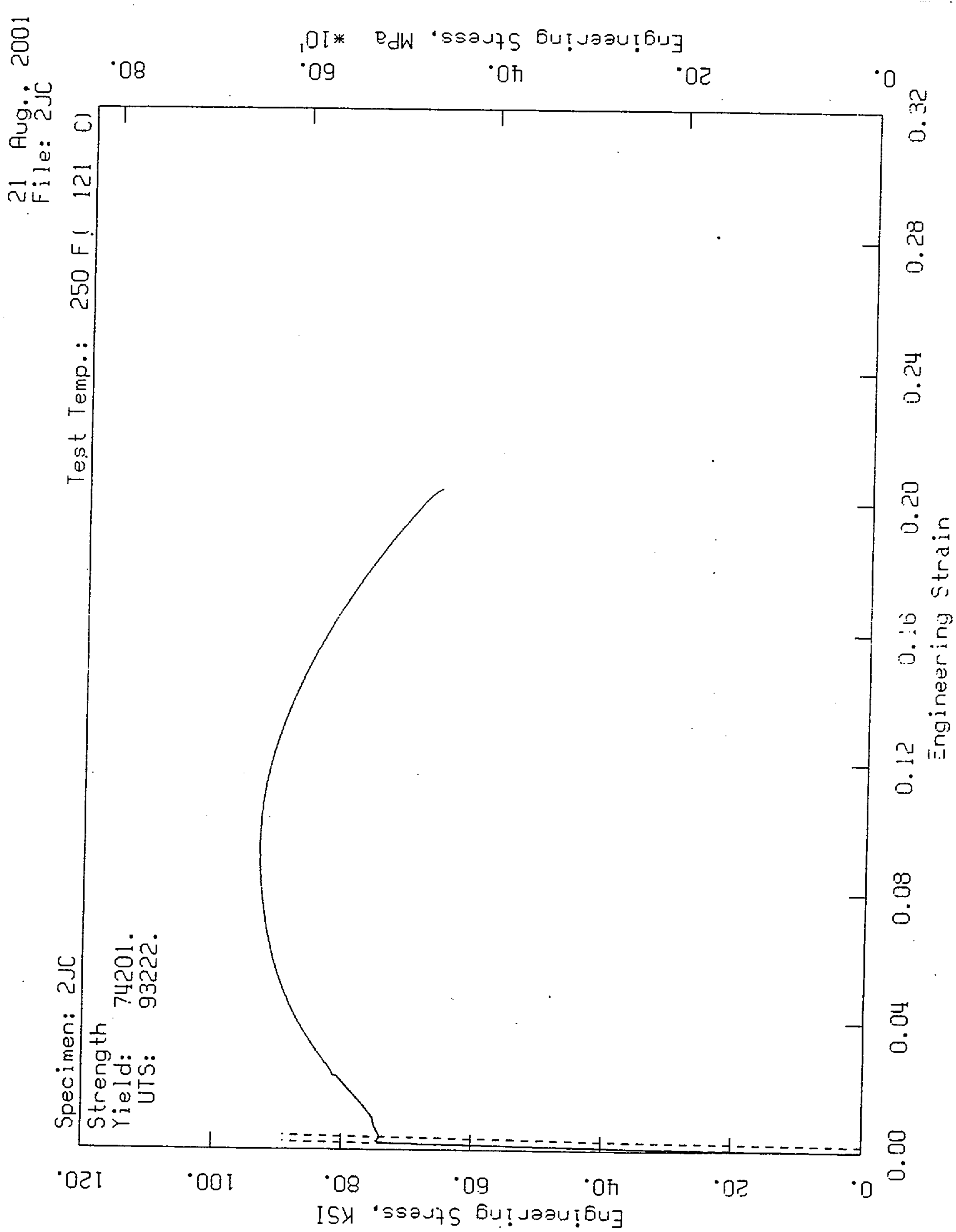


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Figure 5-6. Tension Test Stress-Strain Curve for Base Metal Plate C-6404-2, Transverse Orientation, Specimen No. 2L1, Tested at 550°F

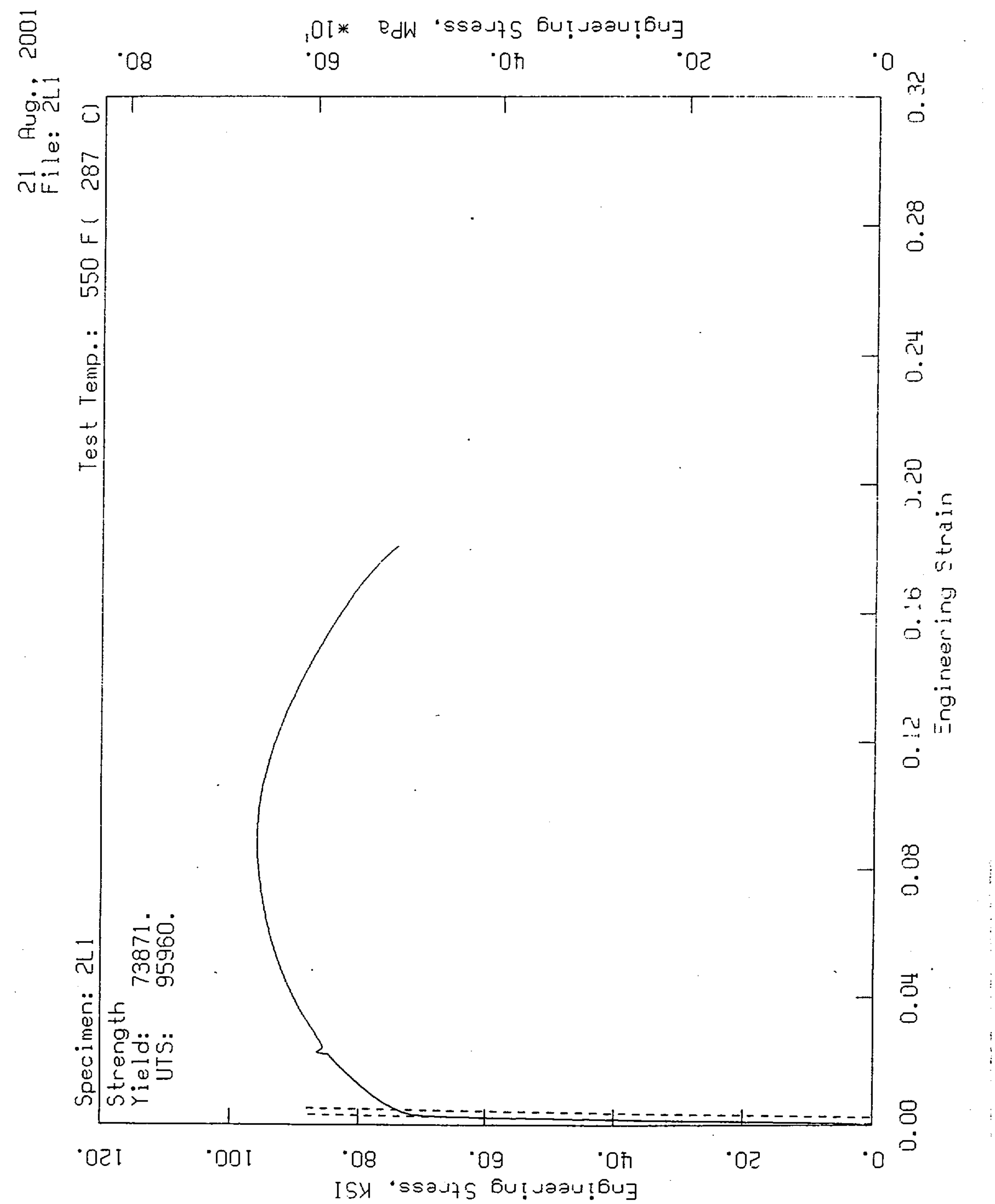

Figure 5-7. Tension Test Stress-Strain Curve for Weld Metal, C-6404-1/C-6404-3 (9-203), Specimen No. 3K4, Tested at 0°F

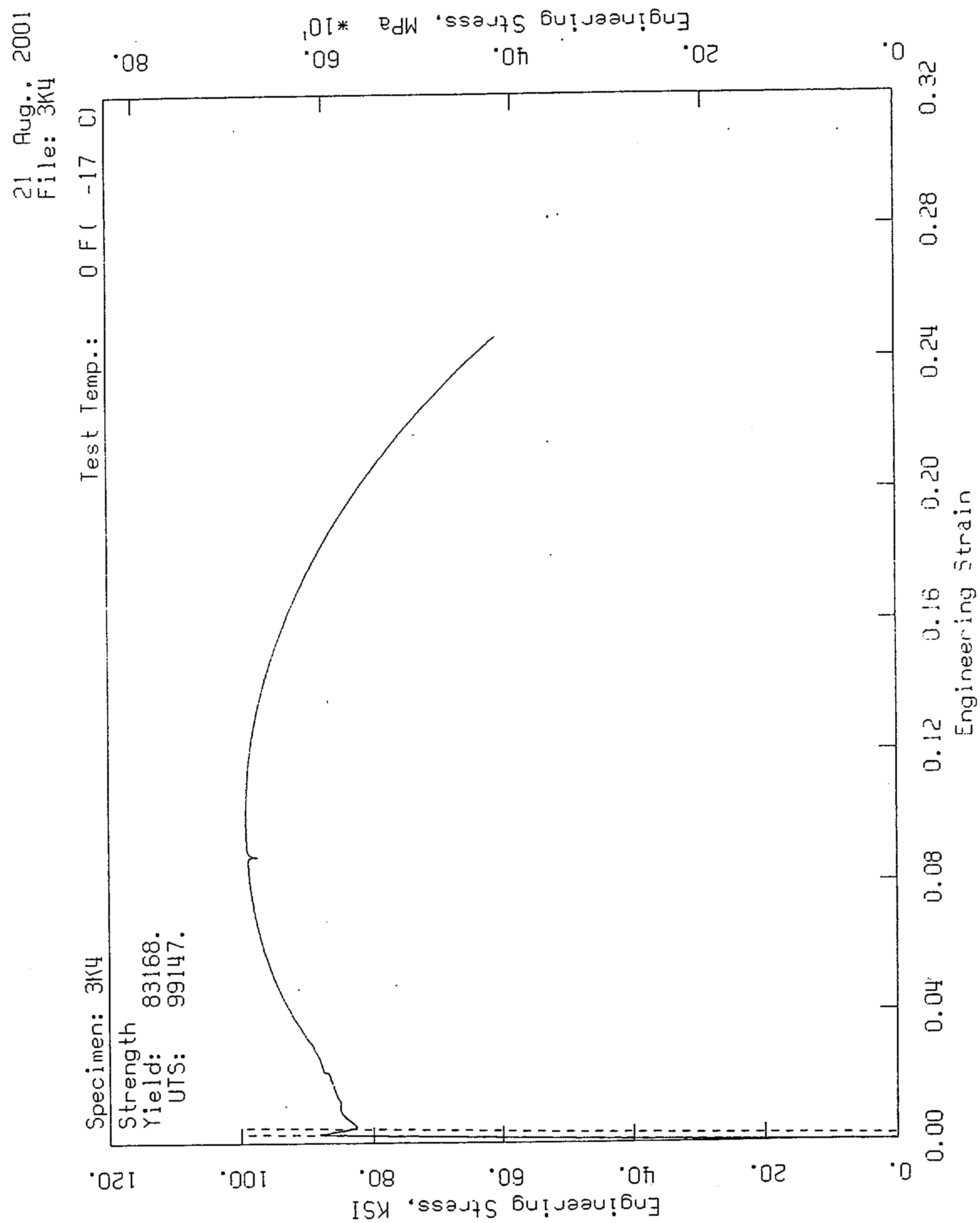

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Figure 5-8. Tension Test Stress-Strain Curve for Weld Metal, C-6404-1/C-6404-3 (9-203), Specimen No. 3KL, Tested at 250°F

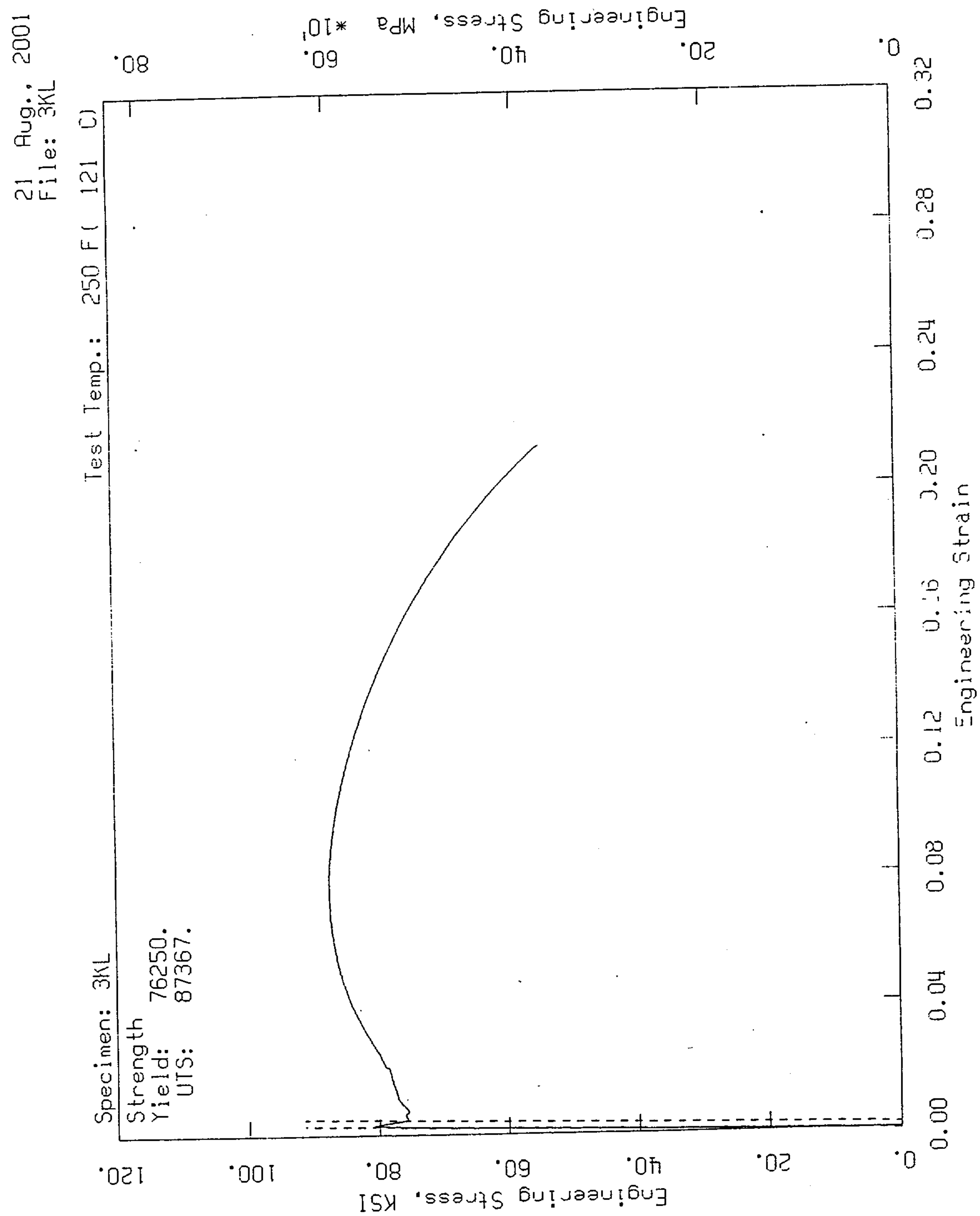

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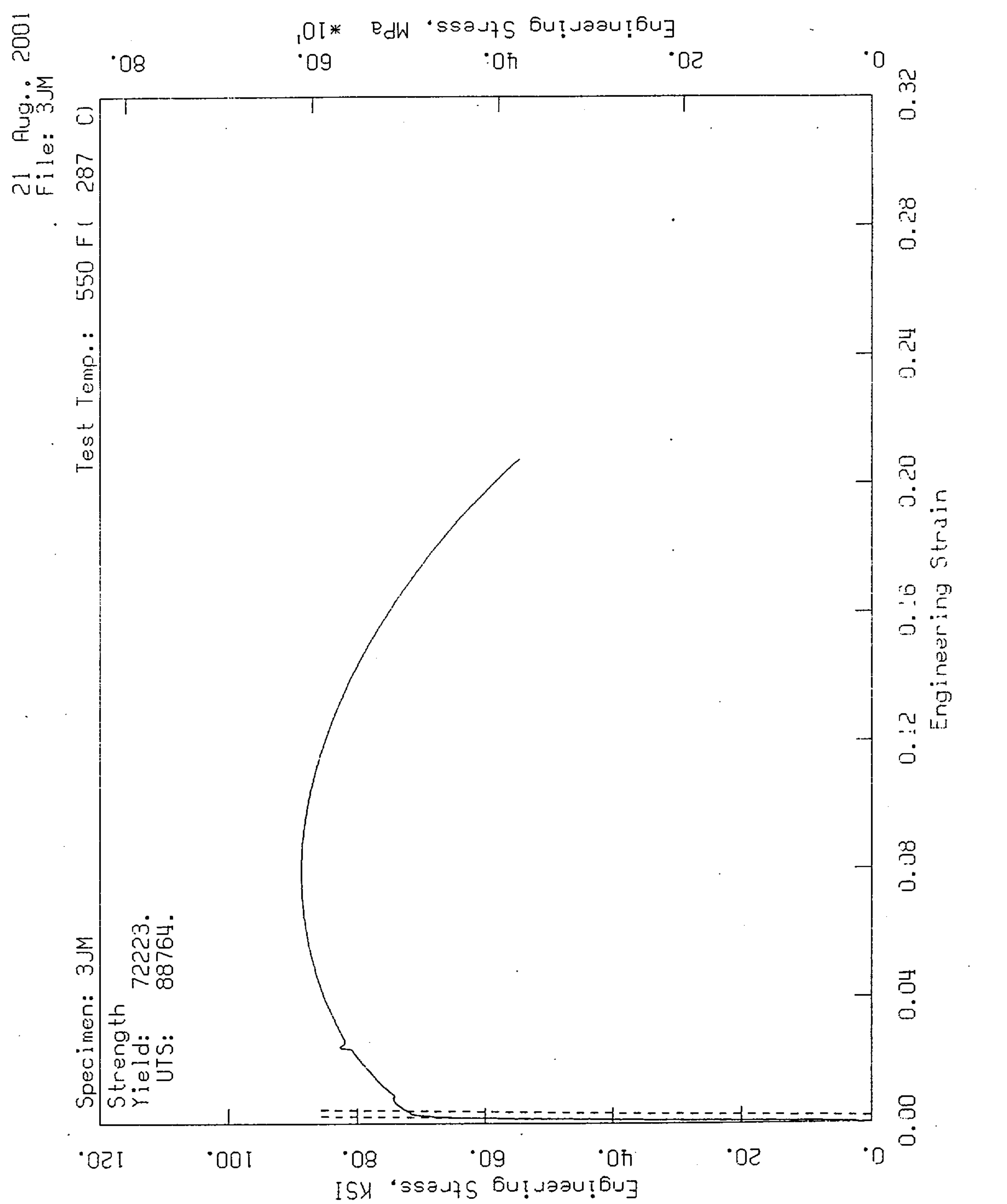
Figure 5-9. Tension Test Stress-Strain Curve for Weld Metal, C-6404-1/C-6404-3 (9-203), Specimen No. 3JM, Tested at 550°F



FRAMATOME ANP

Figure 5-10. Tension Test Stress-Strain Curve for Heat-Affected-Zone Material, Specimen No. 4J5, Tested at 0°F

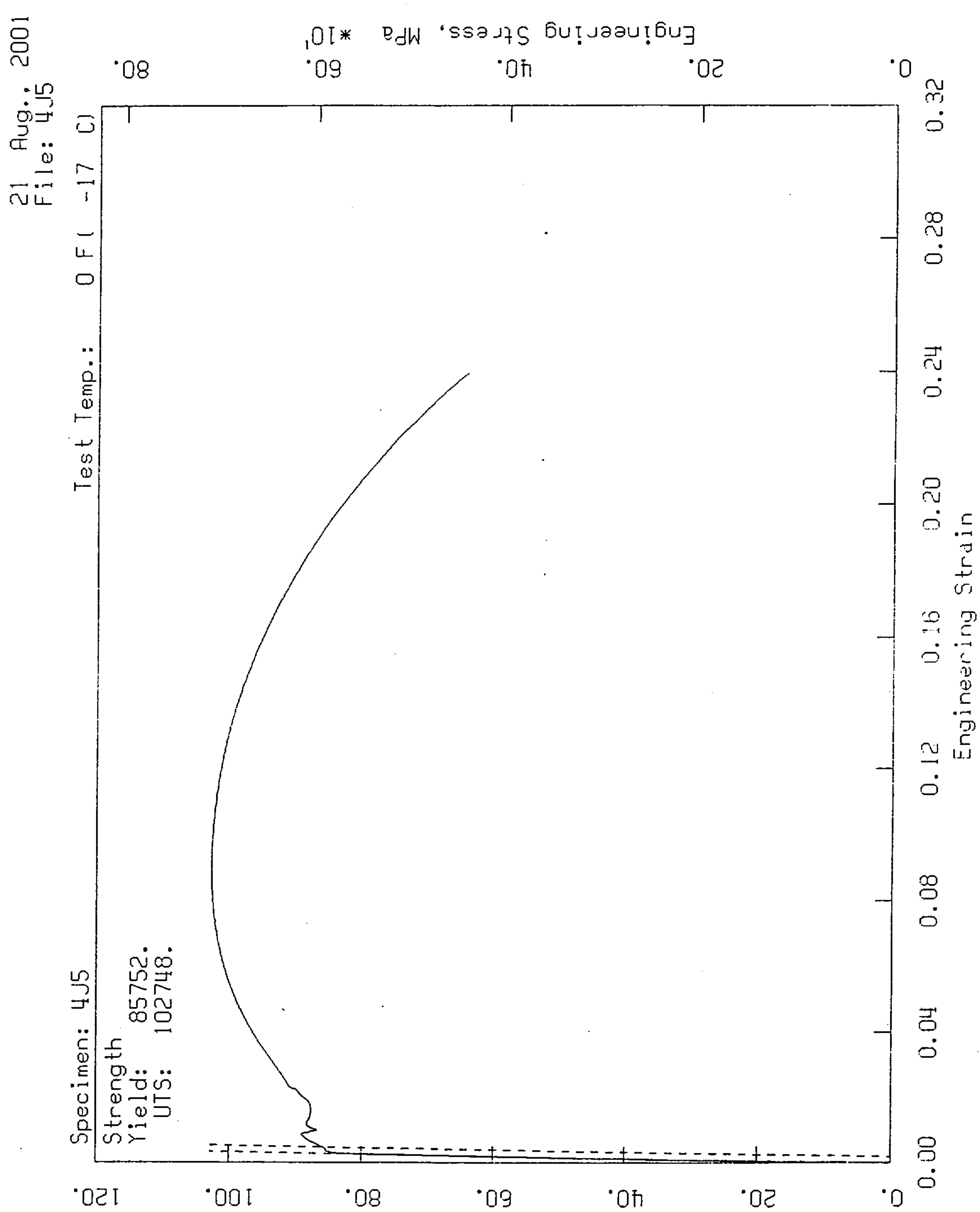
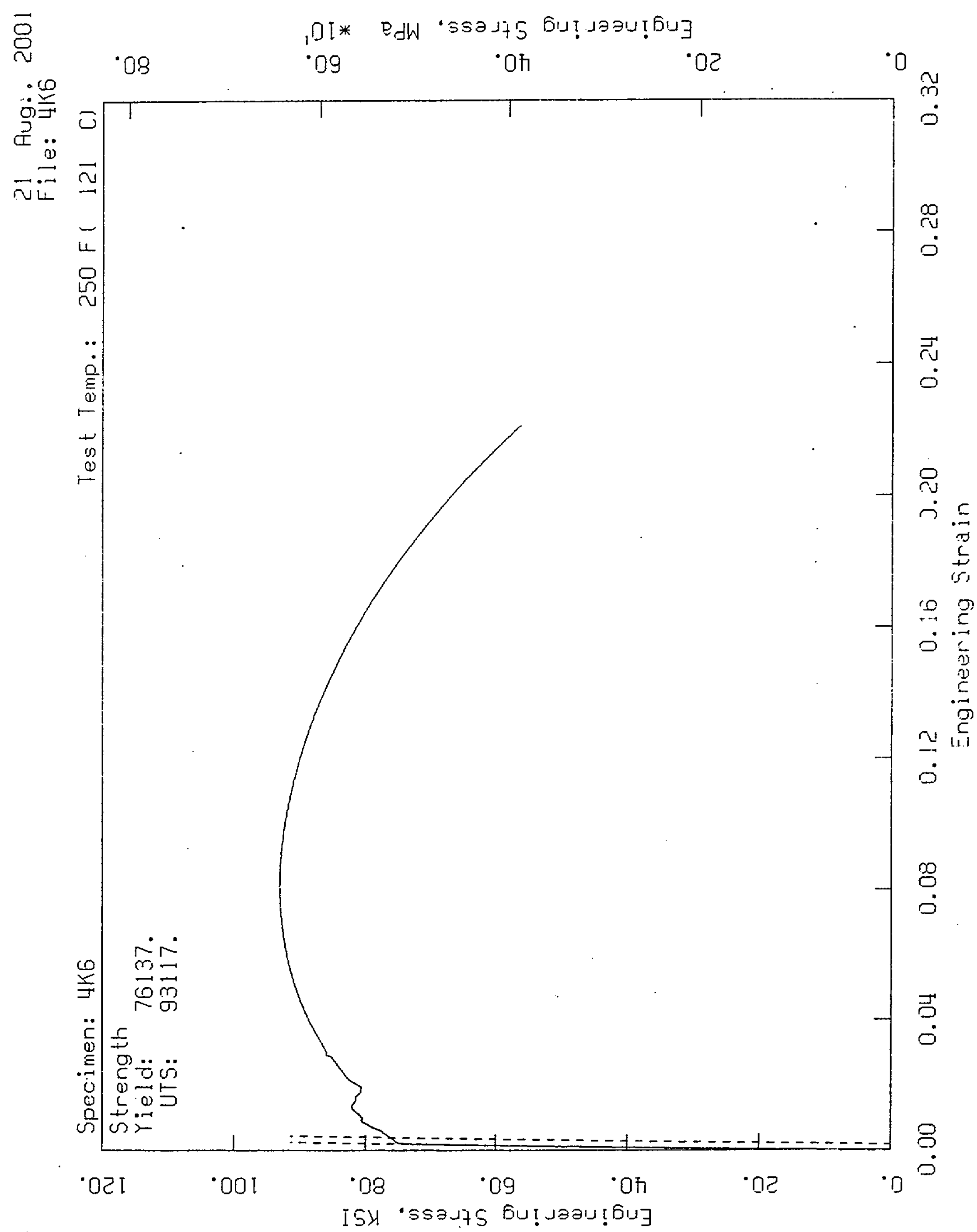
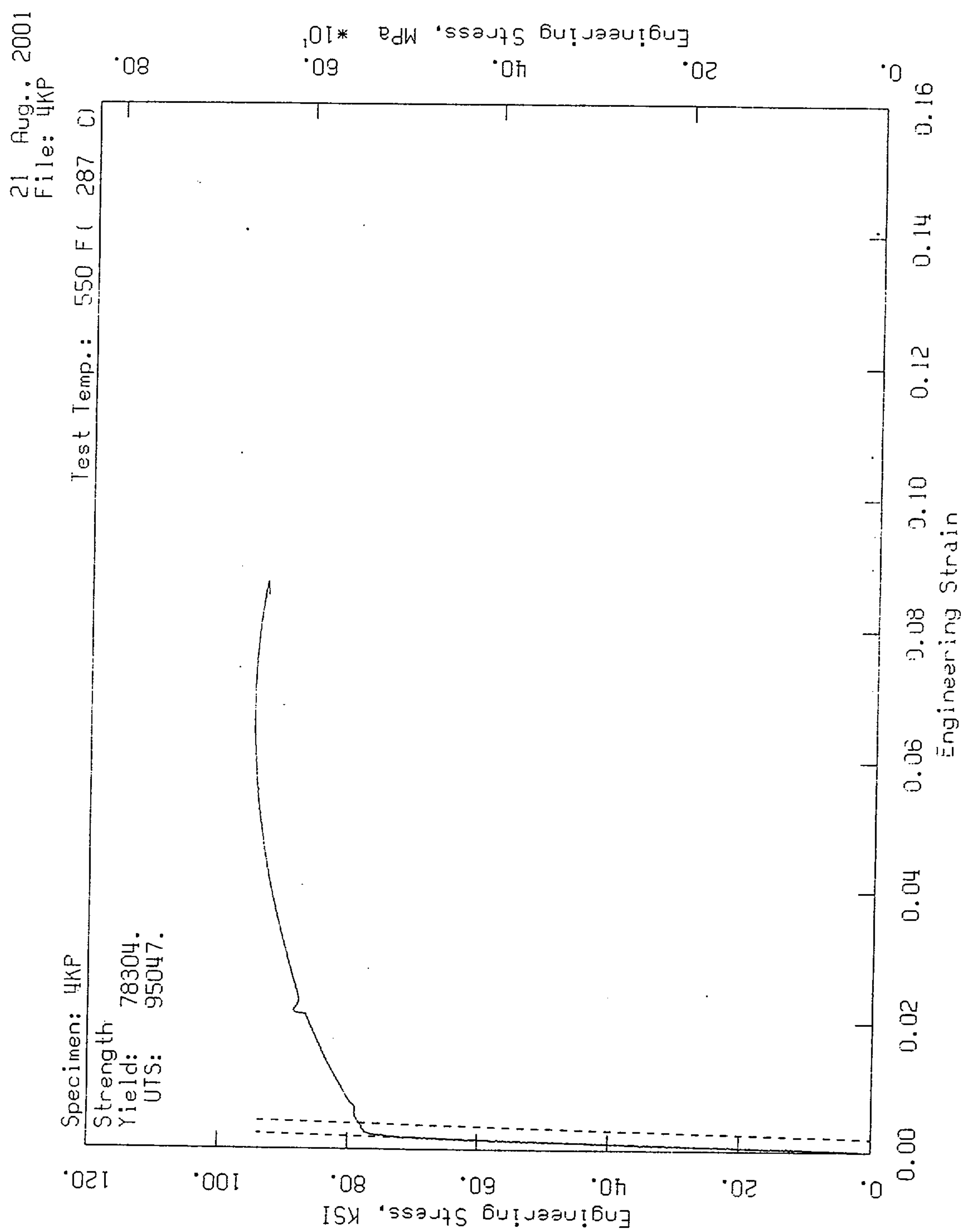


Figure 5-11. Tension Test Stress-Strain Curve Heat-Affected-Zone Material, Specimen No. 4K6, Tested at 250°F



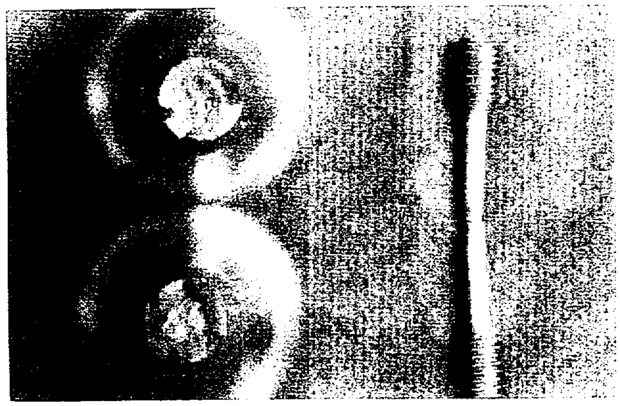
FRAMATOME ANP

Figure 5-12. Tension Test Stress-Strain Curve for Heat-Affected-Zone Material, Specimen No. 4KP, Tested at 550°F

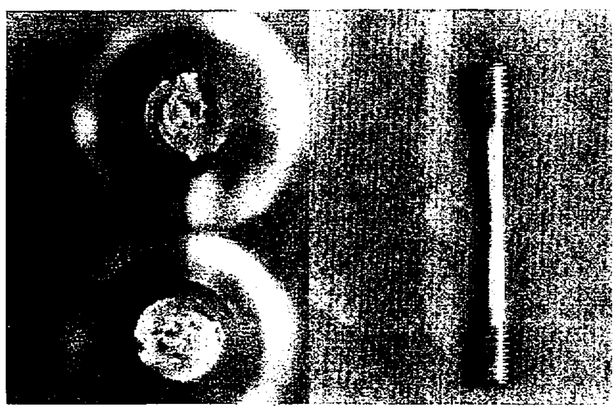


FRAMATOME ANP

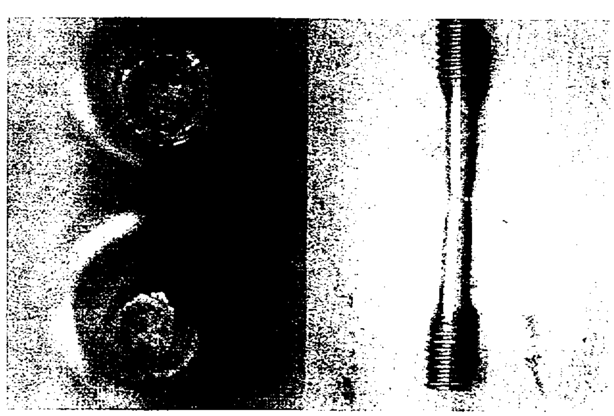
Figure 5-13. Photographs of Tested Tension Test Specimens and Corresponding Fracture Surfaces – Base Metal Plate C-6404-2, Transverse Orientation



2J4 150F

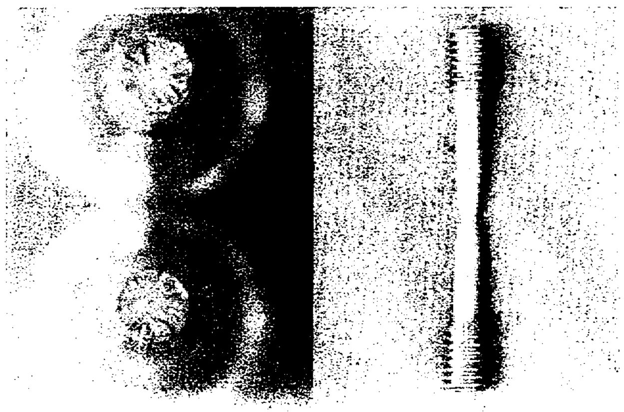


2JC 250F

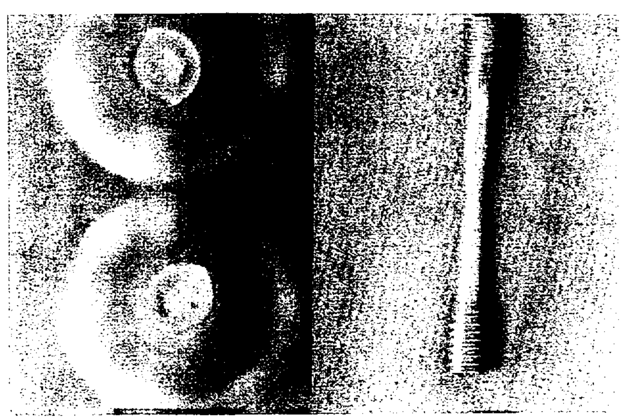


2L1 550F

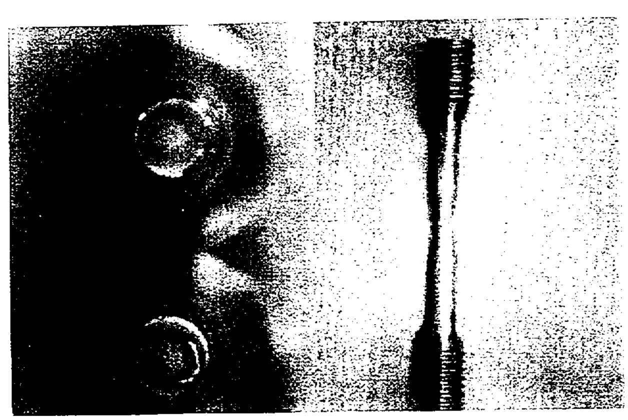
Figure 5-14. Photographs of Tested Tension Test Specimens and Corresponding Fracture Surfaces – Weld Metal, C-6404-1/C-6404-3 (9-203)



3K4 0F

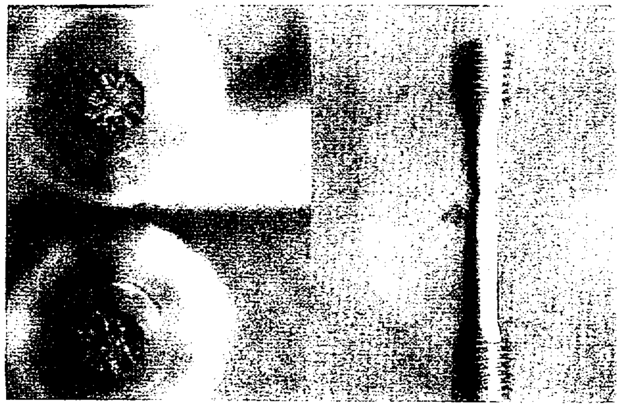


3KL 250F

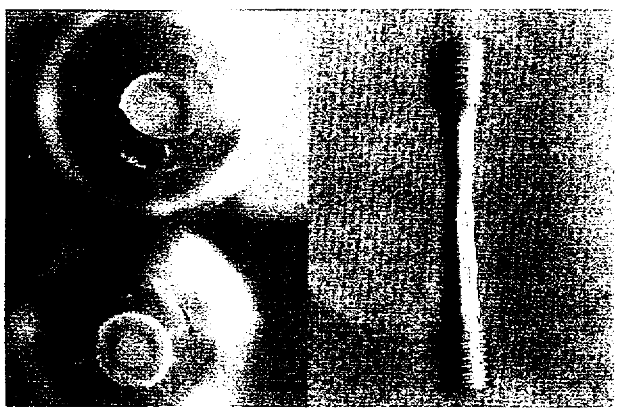


3JM 550F

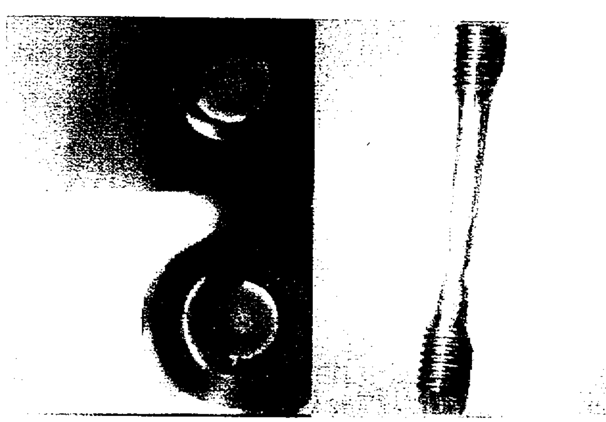
Figure 5-15. Photographs of Tested Tension Test Specimens and Corresponding Fracture Surfaces – Heat-Affected-Zone Material



4J5 0F



4K6 250F



4KP 550F

Figure 5-16. Charpy Impact Data for Irradiated Base Metal Plate C-6404-2, Transverse Orientation

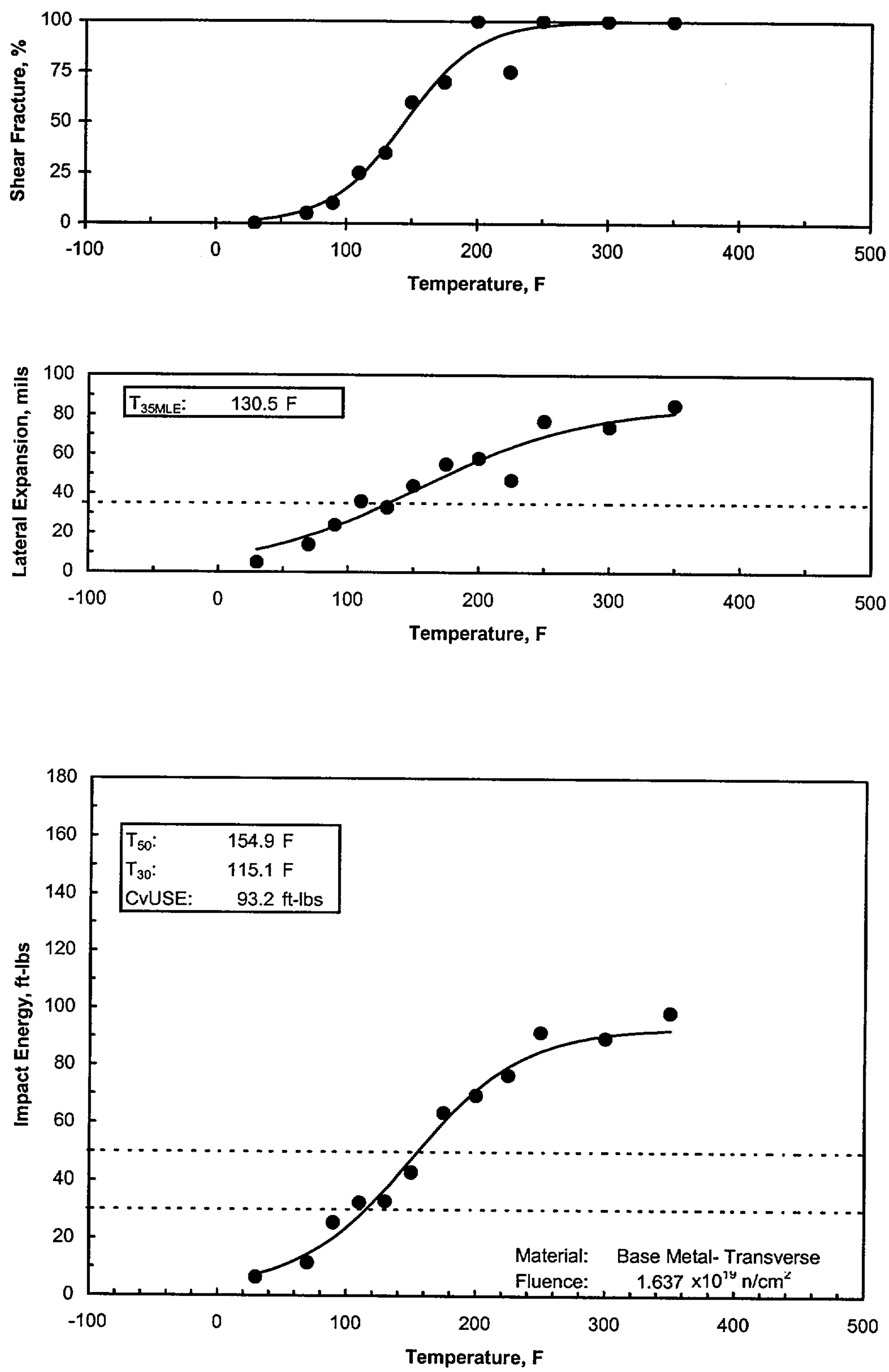


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Figure 5-17. Charpy Impact Data for Irradiated Weld Metal, C-6404-1/C-6404-3 (9-203)

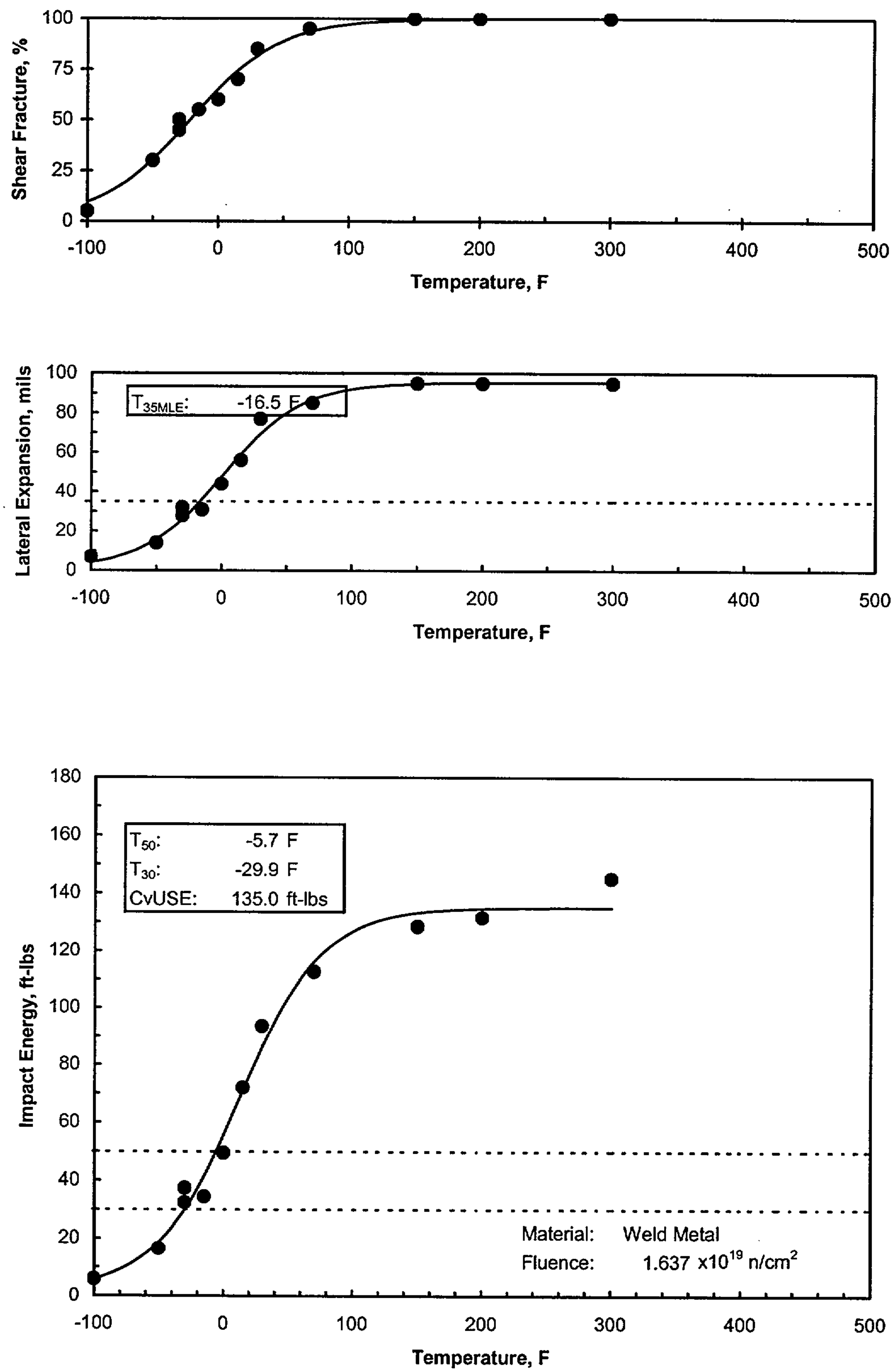

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Figure 5-18. Charpy Impact Data for Irradiated Heat-Affected-Zone Material

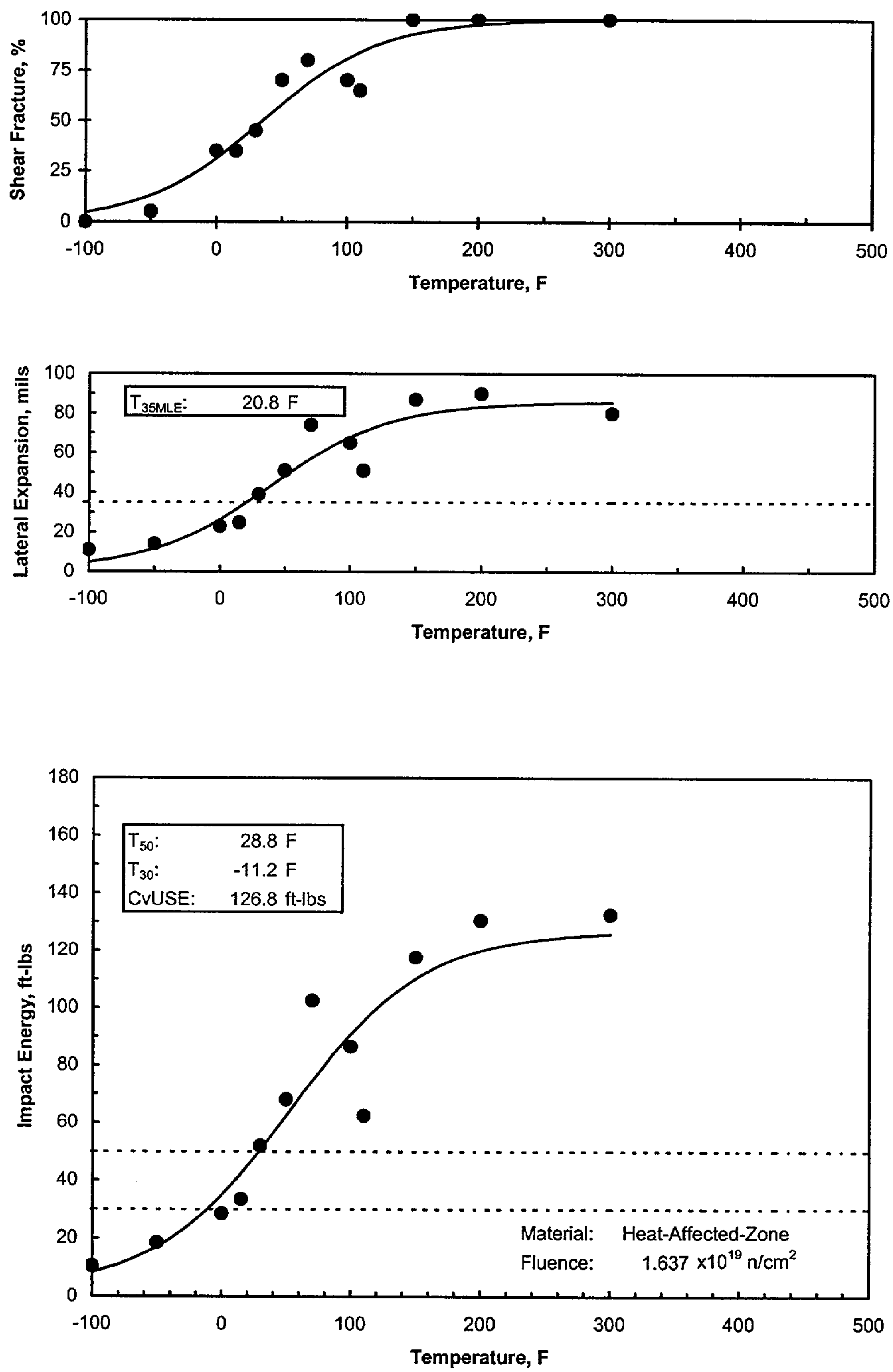

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Figure 5-19. Charpy Impact Data for Irradiated Standard Reference Material, HSST Plate 01

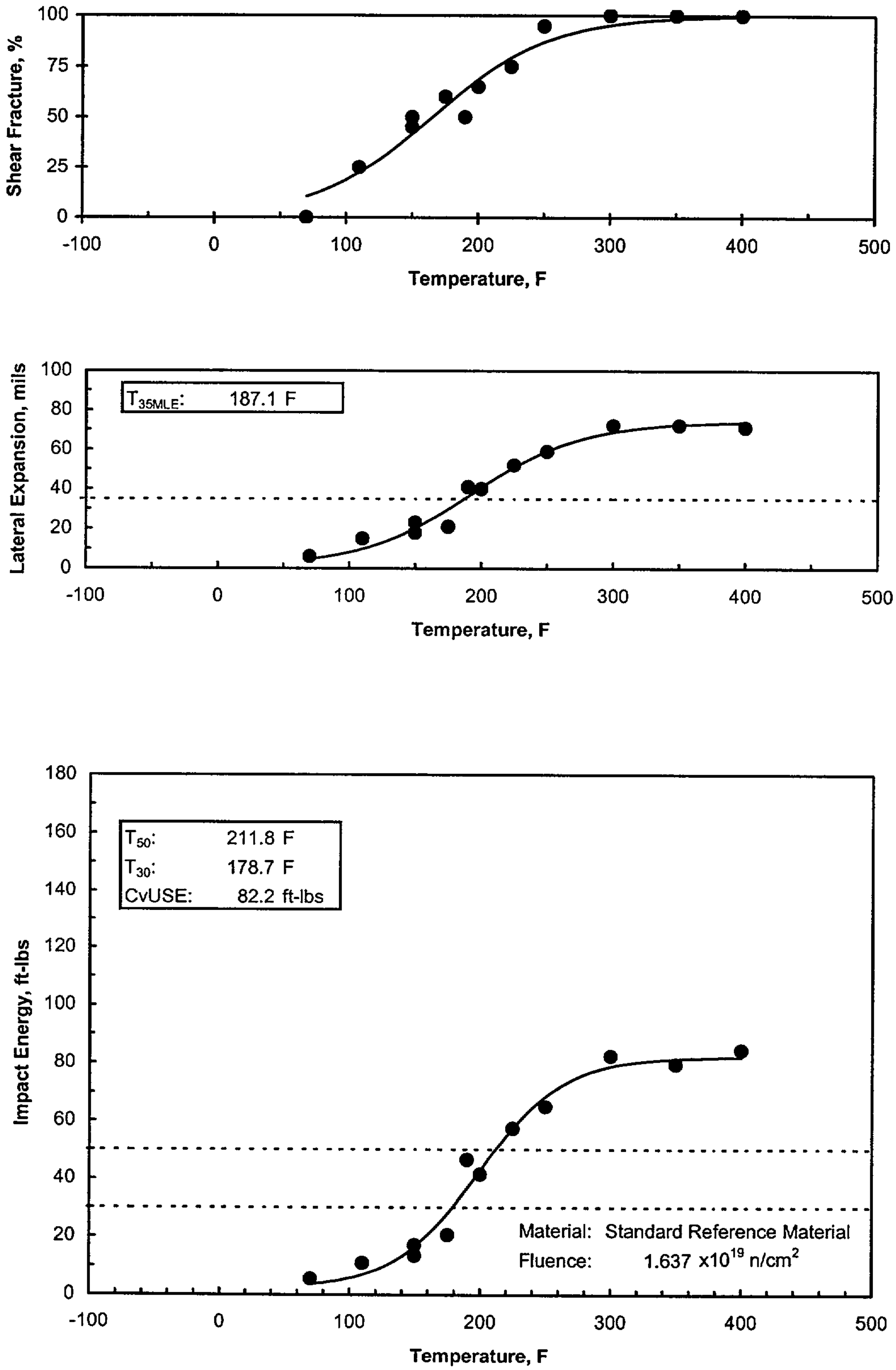
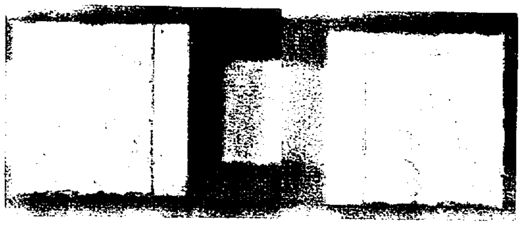
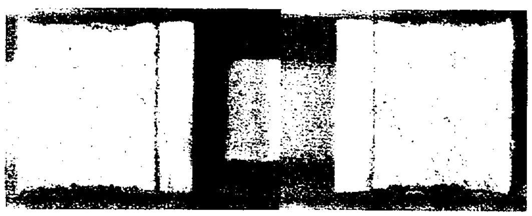


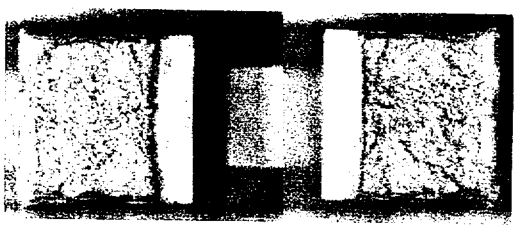
Figure 5-20. Photographs of Charpy Impact Specimen Fracture Surfaces, Base Metal Plate C-6404-2, Transverse Orientation



Specimen No. 224, Test Temperature 30F

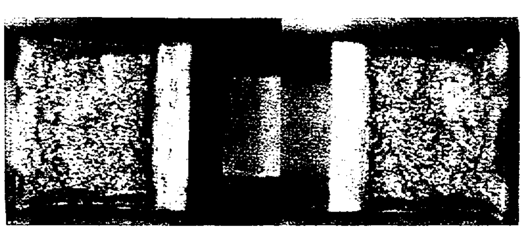


Specimen No. 24D, Test Temperature 70F

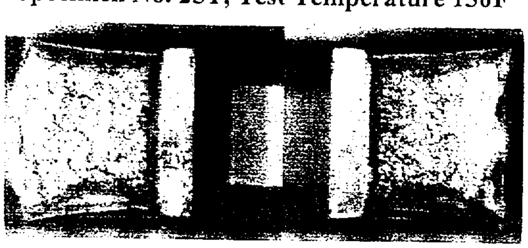


Specimen No. 25Y, Test Temperature 90F

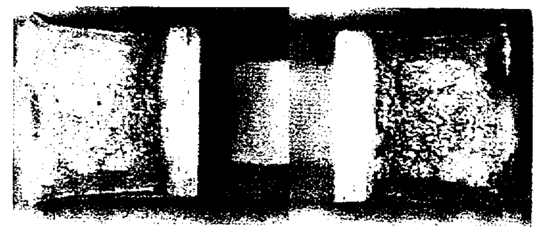
Specimen No. 243, Test Temperature 110F



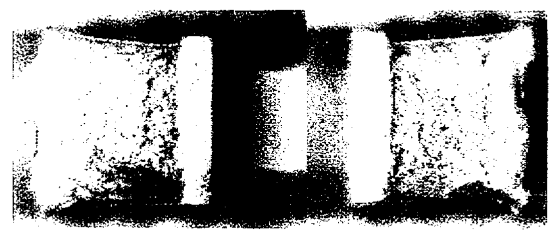
Specimen No. 25T, Test Temperature 130F



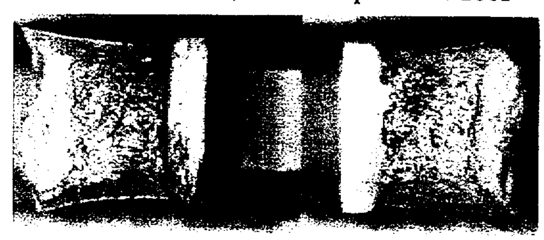
Specimen No. 24M, Test Temperature 150F



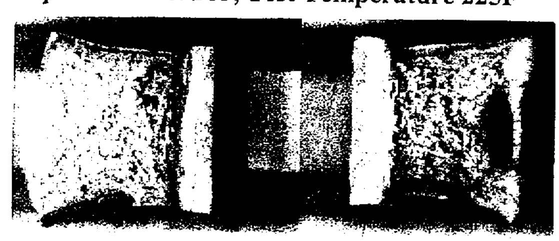
Specimen No. 26D, Test Temperature 175F



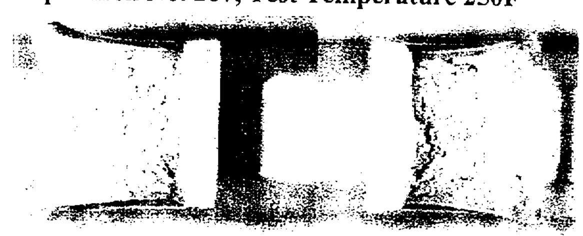
Specimen No. 244, Test Temperature 200F



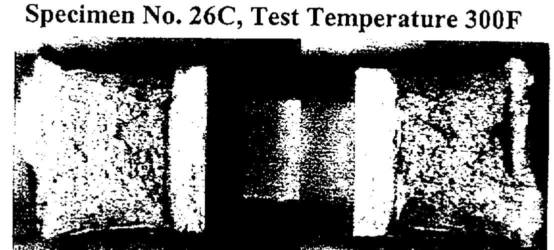
Specimen No. 26J, Test Temperature 225F



Specimen No. 267, Test Temperature 250F

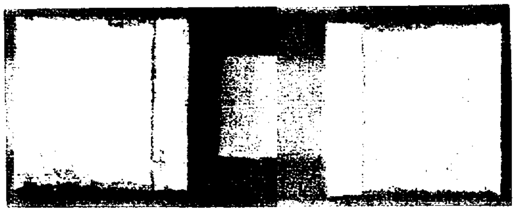


Specimen No. 26C, Test Temperature 300F

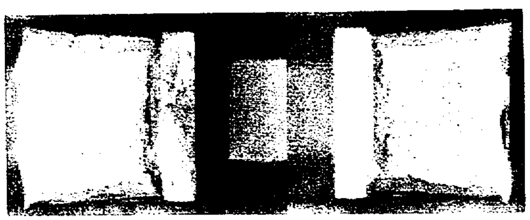


Specimen No. 247, Test Temperature 350F

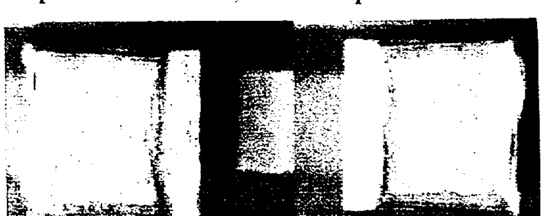
Figure 5-21. Photographs of Charpy Impact Specimen Fracture Surfaces, Weld Metal, C-6404-1/C-6404-3 (9-203)

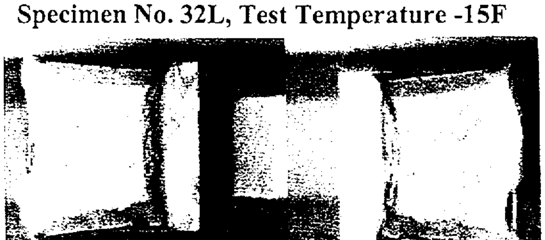

Specimen No. 31C, Test Temperature -100F

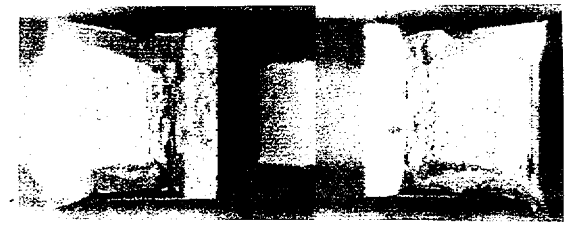

Specimen No. 31B, Test Temperature -50F


Specimen No. 33M, Test Temperature -30F

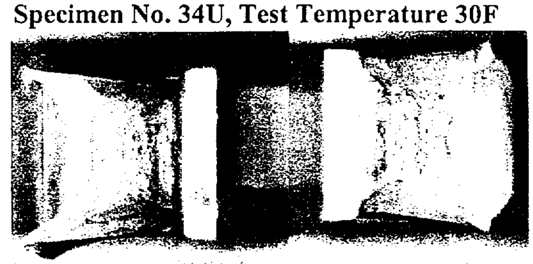

Specimen No. 33Y, Test Temperature -30F


Specimen No. 32L, Test Temperature -15F

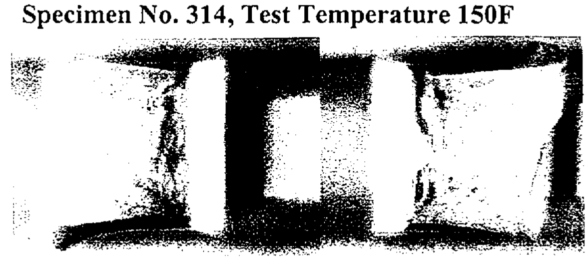

Specimen No. 311, Test Temperature 0F


Specimen No. 36J, Test Temperature 15F


Specimen No. 34U, Test Temperature 30F


Specimen No. 32C, Test Temperature 70F


Specimen No. 314, Test Temperature 150F


Specimen No. 35D, Test Temperature 200F

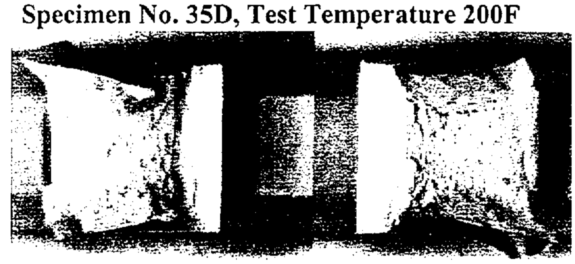
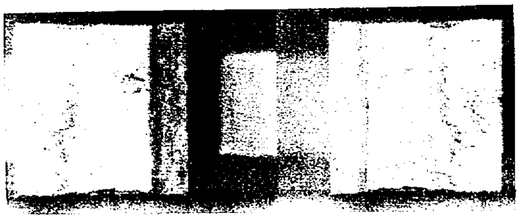
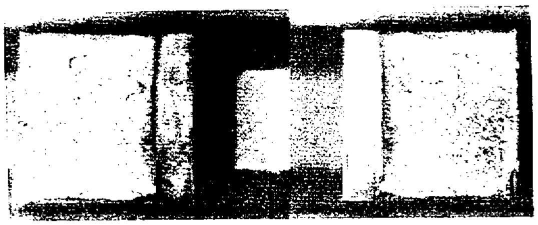

Specimen No. 315, Test Temperature 300F

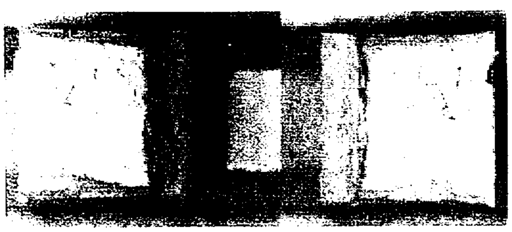
Figure 5-22. Photographs of Charpy Impact Specimen Fracture Surfaces, Heat-Affected-Zone Material



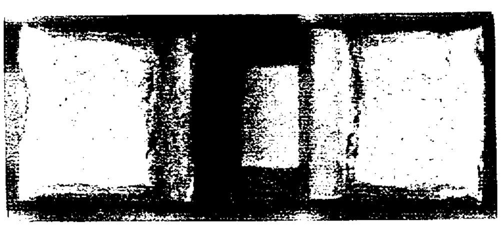
Specimen No. 474, Test Temperature -100F



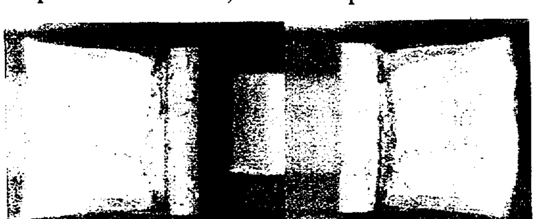
Specimen No. 46J, Test Temperature -50F



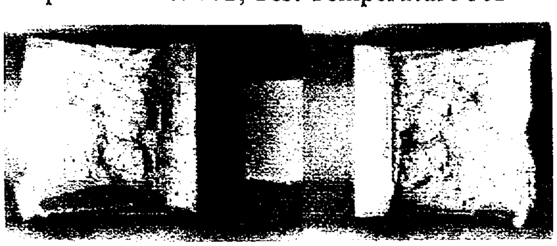
Specimen No. 445, Test Temperature 0F



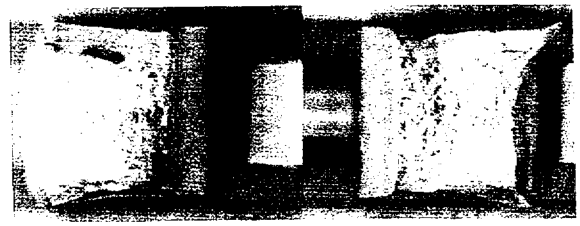
Specimen No. 434, Test Temperature 15F



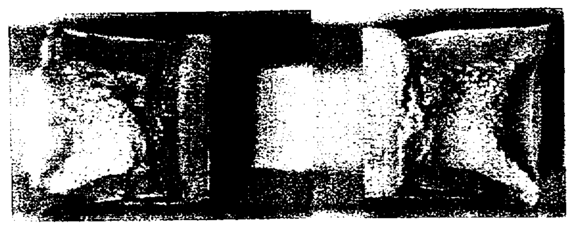
Specimen No. 44T, Test Temperature 30F



Specimen No. 43J, Test Temperature 50F

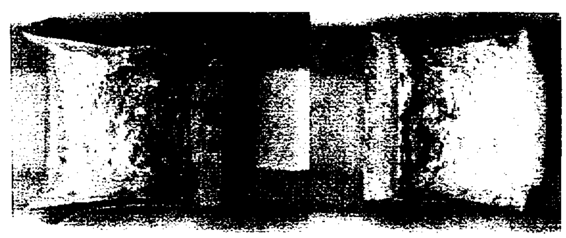


Specimen No. 433, Test Temperature 70F

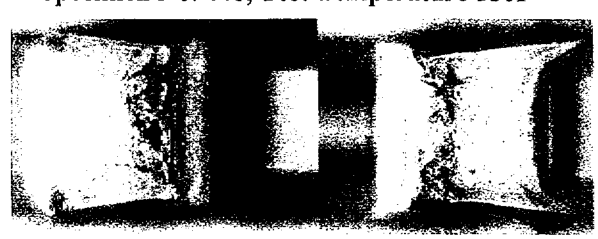


Specimen No. 436, Test Temperature 100F

Specimen No. 46T, Test Temperature 110F



Specimen No. 446, Test Temperature 150F



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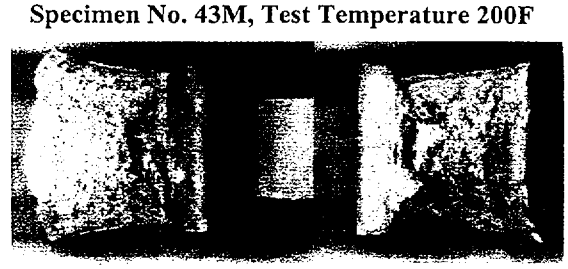
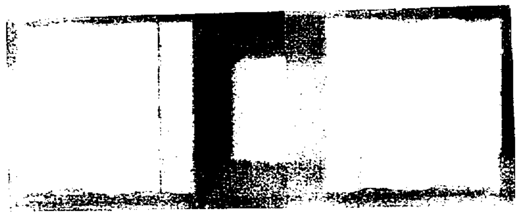


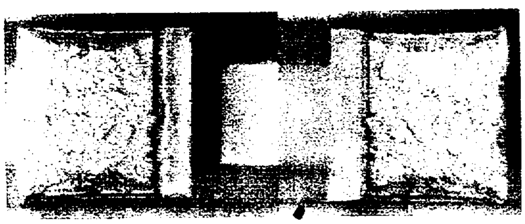
Specimen No. 425, Test Temperature 300F

Figure 5-23. Photographs of Charpy Impact Specimen Fracture Surfaces, Standard Reference Material, HSST Plate 01

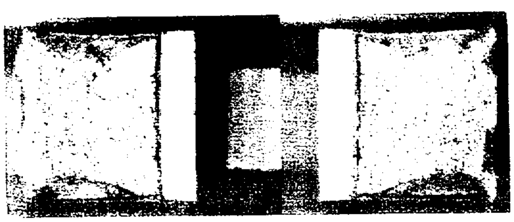


Specimen No. A66, Test Temperature 70F

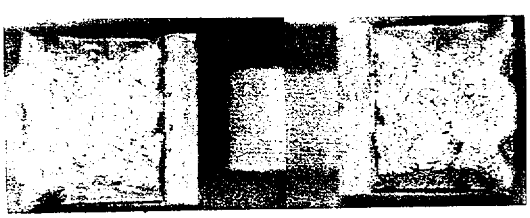
Specimen No. A5L, Test Temperature 110F



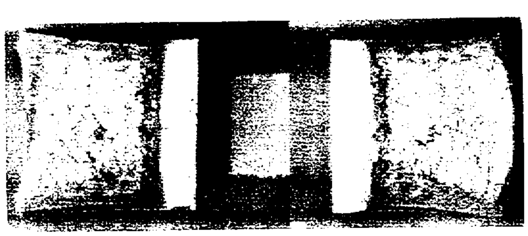
Specimen No. A5T, Test Temperature 150F



Specimen No. A61, Test Temperature 150F

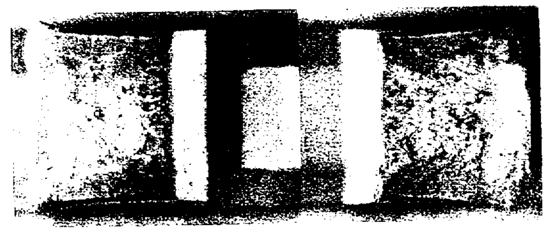


Specimen No. A6A, Test Temperature 175F

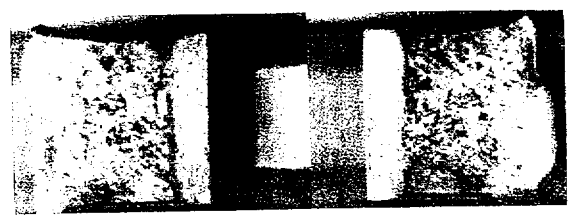


Specimen No. A5Y, Test Temperature 190F

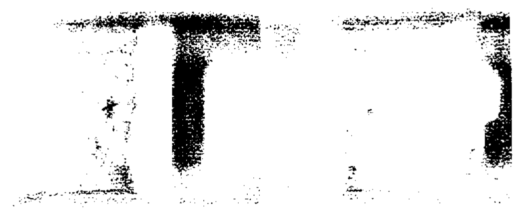
Specimen No. A6B, Test Temperature 200F



Specimen No. A5K, Test Temperature 225F



Specimen No. A5J, Test Temperature 250F



Specimen No. A65, Test Temperature 300F

Specimen No. A67, Test Temperature 350F

Specimen No. A6D, Test Temperature 400F

6. Neutron Fluence

6.1. Introduction

Over the last fifteen years, Framatome ANP has developed a calculational based fluence analysis methodology,[19] that can be used to accurately predict the fast neutron fluence in the reactor vessel using surveillance capsule dosimetry or cavity dosimetry (or both) to verify the fluence predictions. This methodology was developed through a full-scale benchmark experiment that was performed at the Davis-Besse Unit 1 reactor,[19] and the methodology is described in detail in Appendix D. The results of the benchmark experiment demonstrated that the accuracy of a fluence analysis that employs the Framatome ANP methodology would be unbiased and have a precision well within the U.S Nuclear Regulatory Guide 1.190 limit of 20%.[20]

The Framatome ANP methodology was used to calculate the neutron fluence exposure to the 263° capsule of the San Onofre Unit 2 nuclear reactor. The methodology was also used to estimate fluences on the inner surface of the reactor vessel, as well as at specified locations in the pressure vessel. The fast neutron fluence ($E > 1.0$ MeV) at each location was calculated in accordance with the requirements of U.S. Nuclear Regulatory Guide 1.190.

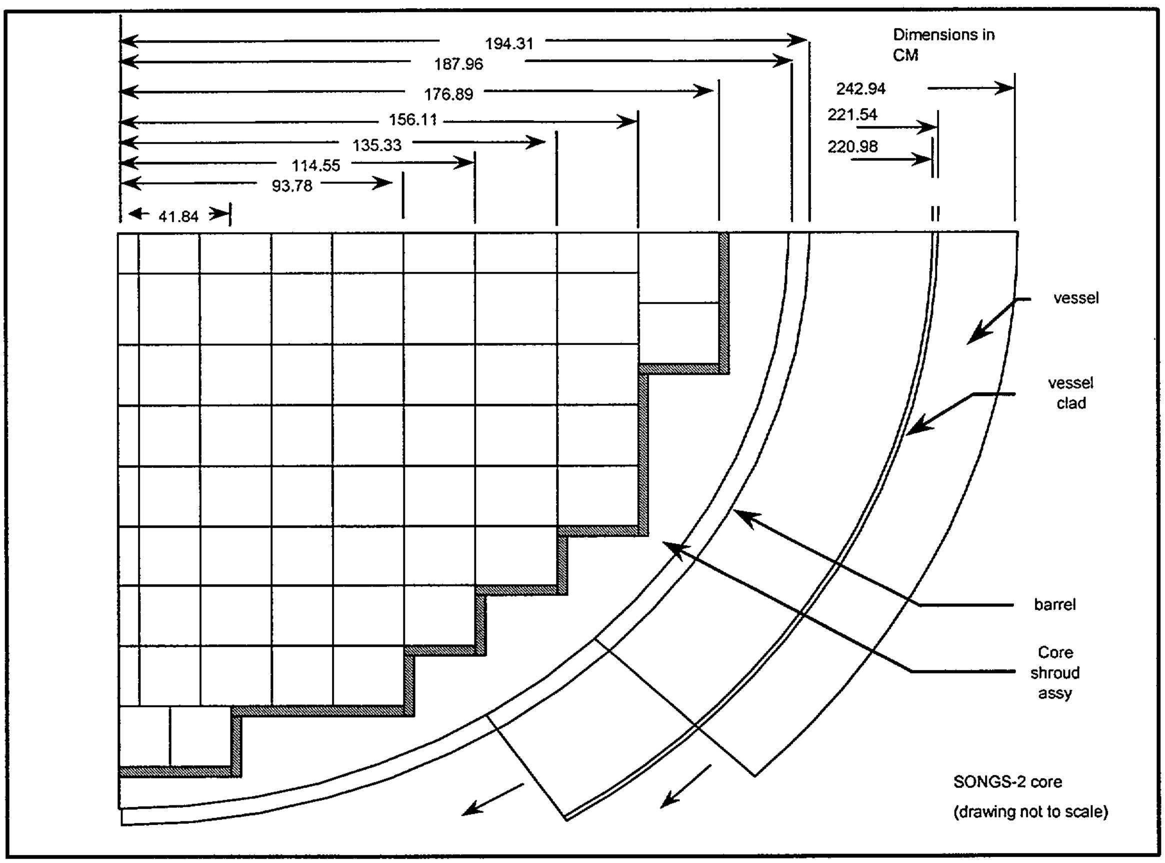
The energy-dependent flux on the capsule was used to determine the calculated activity of each dosimeter. Neutron transport calculations in two-dimensional geometry were used to obtain energy dependent flux distributions throughout the core. Reactor conditions were representative of an average over the cycles 1-9a, 9b and cycle 10 irradiation periods. These periods were separated to adequately represent water temperature variations that occurred between cycles 9 and 10. Specifically, RCS operating temperatures were lowered in two phases (during the last half of cycle 9 and then at the start of cycle 10) to reduce S/G tube failures due to stress corrosion cracking. Geometric detail was selected to explicitly represent the dosimeter holder and the reactor vessel. A more detailed discussion of the calculational procedure is given in Appendix D. The calculated activities were adjusted for known biases (photofission, short half-life, U-235 impurity, and non-saturation), and compared to measured activities directly. It is noted that these measurements are not used in any way to determine the magnitude of the flux or the fluence. The measurements are used only to show that the calculational results are reasonable, and to show that the results for San Onofre Unit 2 cycles 1-10 are consistent with the Framatome ANP benchmark database of uncertainties.

6.2. Fluence Results

The San Onofre Unit 2 dosimeter holder is located in the downcomer region of the reactor, 7° off the major axis. The dosimetry of the 263° capsule was located in the reactor for a total irradiation time of 4849 effective full power days (EFPDs) for cycles 1-10. The rated thermal power for the ten cycles was 3390 MWth.

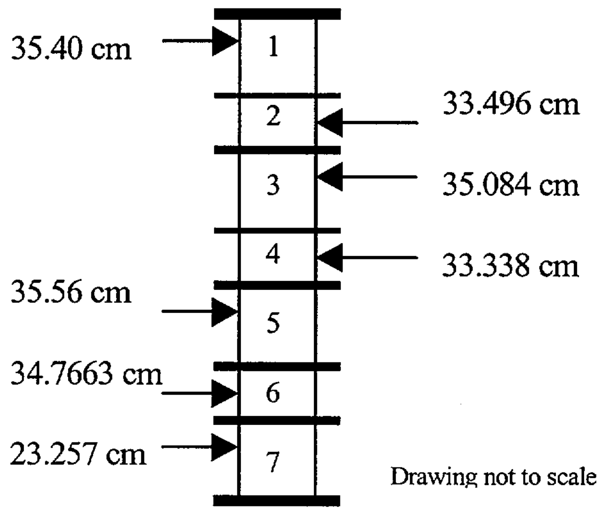
The incident fast fluence (E > 1.0 MeV) was calculated on the inner surface of the reactor vessel. The layout of the reactor vessel is shown in Figure 6-1.

Figure 6-1. San Onofre Unit 2 Core Overview



The capsule is located between the core barrel and pressure vessel cladding, and is mounted on the pressure vessel wall, with the centerline of the capsule at 217.756 cm. The capsule is divided into 7 compartments, 3 of which contain dosimetry. The dimensions and compartment identification numbers are shown in Figure 6-2.

Figure 6-2. San Onofre Unit 2 263° Dosimetry Locations



The three dosimeter compartments (1, 4, and 7) are labeled in accordance with their position in the holder, and dosimeters are labeled according to their holder relative position. For example, a Fe-54 dosimeter in compartment 1 would be designated as Top Fe-54. The dosimeters, which measure the fast fluence (E>1 MeV) inside of the San Onofre Unit 2 reactor, are listed in Table 6-1. The axial positions of each dosimeter are also listed relative to the bottom of the DORT model.

Table 6-1. San Onofre Unit 2 Fast Fluence Dosimetry

Dosimeter	Can	Axial position (cm)
Fe-54	Top	351.72
Fe-54	Mid	247.745
Fe-54	Bot	144.08
Cu-63	Top	354.26
Cu-63	Mid	250.28
Cu-63	Bot	146.62
Ni–58	Top	354.26
Ni–58	Mid	250.28
Ni–58	Bot	146.62
U-238	Top	354.26
U-238	Mid	250.28
U-238	Bot	146.62

The fluence on the center of the capsule must be estimated for the center of the dosimetry capsule in order to allow for analysis of the Charpy and Tensile specimens. Doing this calculation for the cycle 1-10 analysis results in a maximum capsule fluence of 1.637E+19 n/cm^2.

Flux estimates were also made on the inner surface of the reactor vessel and the vessel/clad interface. These estimates are of particular importance in determining the effect of neutron fluence on the properties of the vessel surface. The points of interest, and their respective three-dimensional coordinates, relative to the DORT origin, are shown in Table 6-2, with the inner surface radius given first.

Table 6-2. 3D Coordinates for San Onofre Unit 2 Points of Interest

Point of Interest	R position (cm)	θ coordinate (°)	Z coordinate (cm)
Intermediate Shell	220.98/221.036	0 to 45	212.169 to 451
Lower Shell	220.98/221.036	0 to 45	0 to 212.169
I.S. Max	220.98/221.036	0 to 45	0 to 451
¼ T	223.19	max	max
¾ T	227.51	max	max

The three-dimensionally synthesized fluxes at the inside surface of the vessel and vessel/clad interface are given in Table 6-3 for each point of interest over the cycle 1-9a, 9b, and 10 irradiation periods. The azimuthal angles for the upper and lower shells shown in Table 6-3 were determined from the maximum fluxes of Table 6-3.

Table 6-3. 3D Synthesized Fluxes

Vessel/Clad Interface				
Cycles 1-9a,				
	R	**Theta**	**Z**	**3D Flux**
Intermediate Shell Max	221.0356	0.74111	213.277	4.2247E+10
Lower Shell Max	221.0356	0.74111	143.794	4.2617E+10
inside surface max	221.0356	0.74111	143.794	4.2617E+10
Cycle 9b				
	R	**Theta**	**Z**	**3D Flux**
Intermediate Shell Max	221.0356	0.74111	213.277	4.0980E+10
Lower Shell Max	221.0356	0.74111	134.6145	4.2669E+10
Inside Surface Max	221.0356	0.74111	134.6145	4.2669E+10
Cycle 10				
	R	**Theta**	**Z**	**3D Flux**
Intermediate Shell Max	221.0356	1.037556	213.277	4.1597E+10
Lower Shell Max	221.0356	1.037556	143.794	4.2250E+10
Inside Surface Max	221.0356	1.037556	143.794	4.2250E+10

Wetted Surface				
Cycles 1-9a,				
	R	**Theta**	**Z**	**3D Flux**
Intermediate Shell Max	220.98	0.74111	204.943	4.2516E+10
Lower Shell Max	220.98	0.74111	143.794	4.2888E+10
Inside Surface Max	220.98	0.74111	143.794	4.2888E+10
Cycle 9b				
	R	**Theta**	**Z**	**3D Flux**
Intermediate Shell Max	220.98	0.74111	213.277	4.1113E+10
Lower Shell Max	220.98	0.74111	137.18	4.2908E+10
Inside Surface Max	220.98	0.74111	137.18	4.2908E+10
Cycle 10				
	R	**Theta**	**Z**	**3D Flux**
Intermediate Shell Max	220.98	0.444666	213.277	4.1855E+10
Lower Shell Max	220.98	0.444666	137.18	4.2336E+10
inside surface max	220.98	0.444666	137.18	4.2336E+10

Fluences for the vessel can also be extrapolated to longer time periods in order to estimate total fluences on the points of interest. This extrapolation is performed by assuming that the average fluence on the vessel for the extrapolated time is at equilibrium at the cycle 10 average fluence. This assumption is acceptable since each cycle shows a declining maximum fluence on the vessel surface, which is expected to continue throughout the lifetime of the plant, and the utility is expected to continue the use of a low leakage core design. End of life fluences are determined by taking the cumulative fluence and then extrapolating forward. The cumulative fluence values for cycles 1-9a, 9b, and 10 are shown in Table 6-4, along with the extrapolated EOL fluence, for the vessel wetted surface and Table 6-5 for the vessel/clad interface position. The end of life (32 EFPY) fluences are calculated using the following formula:

$$F(EOL) = F(EOC10) + \left(\phi_{10} * (t_{EOL}(s) - t_{EOC10}(s))\right),$$

where F(EOL) is the fluence estimate at the end of life (32 EFPY), F(EOC10) is the fluence at the end of cycle 10, ϕ_{10} is the flux for cycle 10, $t_{EOL}(s)$ is the total number of EFPS at the 32 EFPY end of life (1.0098E9 s), and $t_{EOC10}(s)$ is the total number of EFPS accumulated through the end of cycle 10 (4.189E8 s).

Table 6-4. Cumulative Fluence Estimates at the Wetted Surface

Flux Location	Cumulative Fluence (n/cm^2)			Extrapolated Fluence (n/cm^2)
	EOC 9a	EOC 9b	EOC 10	
EFPY's	10.687	11.67	13.275	32 EFPY
Intermediate Shell Max	1.4339E+19	1.5614E+19	1.7734E+19	4.2467E+19
Lower Shell Max	1.4465E+19	1.5795E+19	1.7940E+19	4.2957E+19
Inside Surface Max	1.4465E+19	1.5795E+19	1.7940E+19	4.2957E+19

Table 6-5. Cumulative Fluence Estimates at the Vessel/Clad Interface

Flux Location	Cumulative Fluence (n/cm^2)			Extrapolated Fluence (n/cm^2)
	EOC 9a	EOC 9b	EOC 10	
EFPY's	10.687	11.67	13.275	32 EFPY
Intermediate Shell Max	1.4248E+19	1.5519E+19	1.7626E+19	4.2206E+19
Lower Shell Max	1.4373E+19	1.5696E+19	1.7836E+19	4.2802E+19
Inside Surface Max	1.4373E+19	1.5696E+19	1.7836E+19	4.2802E+19

Lead factors between the vessel and capsule can be determined from the cumulative fluence values at EOC 10. This factor is determined by taking the cumulative fluence on the capsule at EOC 10, 1.637E+19 n/cm^2 and dividing that value by the EOC 10 maximum inner surface fluence, 1.784E+19 n/cm^2. Performing this calculation results in a lead factor for the capsule to vessel clad surface of 0.9177. Lead factors can also be determined for the ¼ T and ¾ T vessel positions using the methodology outlined in Reg Guide 1.99.[21] The equation given for determining the attenuated fluence (E> 1.0 MeV, 10^{19} n/cm^2) is given in the Reg Guide as:

$$f = f_{surf}\left(e^{-0.24x}\right), \text{ where}$$

f is the fluence at the point desired, f_{surf} is the fluence on the wetted surface of the vessel, and x is the distance, in inches, of the desired position, as measured from the wetted surface. The thickness of the reactor vessel wall is 21.9075 cm (8.625 inches). The cladding thickness is 0.555625 cm (.21875 inches). Therefore, x for the ¼ T position is 2.375 inches, and for the ¾ T position, x is 6.6875 inches. Using the maximum fluence on the clad surface, 1.794E+19 n/cm^2, the ¼ T fluence is calculated to be 1.0145E+19 n/cm^2, and the ¾ T fluence is calculated to be 3.6039E+18 n/cm^2. Using these fluence values with the fluence on the capsule, the lead factor between the capsule and ¼ T position is found to be 1.6135, while for the ¾ T position, the lead factor is found to be 4.5421.

With the recent Appendix K power uprate to 3438 MWth for the San Onofre Unit 2 reactor, fluence values at 32 EFPY can be estimated using an artificially increased flux value for all future cycles. Tables 6-6 and 6-7 show the fluence values based on a hypothetical increase in flux for all future cycles, in which the cycle 10 flux used for future cycles is increased by 3% to provide a conservative estimate of the increased flux for future cycles.

Table 6-6. Estimated Power Uprate Fluences on the Wetted Surface

Flux Location	Cumulative Fluence (n/cm^2)			Extrapolated Fluence (n/cm^2)
	EOC 9a	EOC 9b	EOC 10	
EFPY's	**10.687**	**11.67**	**13.275**	**32 EFPY**
Intermediate Shell Max	1.4339E+19	1.5614E+19	1.7734E+19	4.3209E+19
Lower Shell Max	1.4465E+19	1.5795E+19	1.7940E+19	4.3707E+19
Inside Surface Max	1.4465E+19	1.5795E+19	1.7940E+19	4.3707E+19

Table 6-7. Estimated Power Uprate Fluences on the Vessel/Clad Interface

Flux Location	Cumulative Fluence (n/cm^2)			Extrapolated Fluence (n/cm^2)
	EOC 9a	EOC 9b	EOC 10	
EFPY's	10.687	11.67	13.275	32 EFPY
Intermediate Shell Max	1.4248E+19	1.5519E+19	1.7626E+19	4.2944E+19
Lower Shell Max	1.4373E+19	1.5696E+19	1.7837E+19	4.3551E+19
Inside Surface Max	1.4373E+19	1.5696E+19	1.7837E+19	4.3551E+19

6.3. Dosimetry Activity

The ratio of the specified activities to the measured specific activities (C/M) is presented in Table 6-8 for cycles 1-10. In this table, overall average is the average C/M for the entire capsule.

Table 6-8. C/M ratios

Cycles 1-10			
Dosimeter	**Calculated**	**Measured**	**Capsule Average**
Top Fe	1672.880	1792.000	0.99187
Middle Fe	1701.856	1727.000	
Bottom Fe	1787.568	1688.000	
Top Ni	1983.603	2255.000	
Middle Ni	2019.928	1931.000	
Bottom Ni	2206.762	2108.000	
Top Cu	12.139	12.960	
Middle Cu	12.544	12.780	
Bottom Cu	12.740	13.130	
Top Sh U238	20.320	19.520	
Middle Sh U238	21.049	20.490	
Bottom Sh U238	22.719	22.830	

7. Discussion of Capsule Results

7.1. Chemical Composition Data

In addition to the 263° capsule weld and base metal chemical analysis of broken Charpy specimens, chemical analyses results were reported in the San Onofre Unit 2 RVSP baseline and 97° capsule reports. These analyses were performed on the unirradiated surveillance materials and broken Charpy specimens tested as part of the 97° San Onofre Unit 2 capsule analysis. The chemical compositions of the base and weld metals are presented in Tables 7-1 and 7-2, respectively. The similarity of the chemical contents provides evidence that the specimens are of the same heat of material. The mean copper and nickel contents for the San Onofre Unit 2 RVSP base metal plate and weld metal represent the best-estimate chemical contents for these surveillance materials.

7.2. Unirradiated Material Property Data

The base metal and weld metal were selected for inclusion in the San Onofre Unit 2 surveillance program in accordance with the regulations in effect at the time the program was designed. The applicable selection criterion was based on the unirradiated properties of the San Onofre Unit 2 reactor vessel beltline region materials only.

The unirradiated mechanical properties for the San Onofre Unit 2 RVSP materials are summarized in Appendices A and B of this report. The original unirradiated Charpy impact data were evaluated based on hand-fit Charpy curves generated using engineering judgement.[10] These data were re-plotted and re-evaluated herein using a hyperbolic tangent curve-fitting program in order to be consistent with the 263° capsule Charpy curves. Appendix C contains a comparison of the Charpy V-notch shift results for each surveillance material: original-fit versus current hyperbolic tangent curve-fit for the unirradiated and 97° capsule data. The hyperbolic tangent curve fitting procedure used herein is consistent with current industry practice for fitting Charpy impact data.[21]

7.3. Irradiated Property Data

In addition to the 263° capsule mechanical test data, surveillance data are also available from the 97° San Onofre Unit 2 RVSP capsule. Battelle Columbus Laboratories performed the testing and evaluation for the 97° capsule.[2]

7.3.1. Tensile Properties

Table 7-3 compares the irradiated and unirradiated tensile properties. Review of the surveillance tensile test data indicates that the ultimate strength and yield strength changes in the base metal plate as a result of irradiation and the corresponding changes in ductility are within the ranges observed for similar irradiated materials. The changes in tensile properties for the surveillance weld metal, as a result of irradiation, are also within the observed ranges for similar irradiated materials. The general behavior of the tensile properties as a function of neutron irradiation is an increase in both ultimate and yield strength and a decrease in ductility as measured by both total elongation and reduction in area.

7.3.2. Impact Properties

Tables 7-4 and 7-5 compare the measured changes in irradiated Charpy V-notch impact properties from the 263° capsule with the predicted changes in accordance with Regulatory Guide 1.99, Revision 2.[22]

The measured 30 ft-lb transition temperature shift for all the materials in the 263° capsule is within one standard deviation of the shift predicted using Regulatory Guide 1.99, Revision 2, Position 1.1 (See Table 7-4).

The measured upper-shelf energies for the San Onofre Unit 2 the 263° capsule surveillance materials do not fall below the required 50 ft-lb limit. The measured percent decrease in C_vUSE for the surveillance base metal plate, weld metal, HAZ, and SRM are within reasonable agreement with the values predicted using Regulatory Guide 1.99, Revision 2 (see Table 7-5).

The radiation-induced changes in toughness of the San Onofre Unit 2 surveillance materials are summarized in Table 7-6. The original irradiated Charpy impact data for the 97° capsule were evaluated based on curves generated using SAM McFRAC code.[2] These data were re-plotted and re-evaluated herein using a hyperbolic tangent curve-fitting program to be consistent with the 263° capsule Charpy curves. The results of the re-evaluation are presented in Appendix B. In addition, Appendix C contains a comparison of the Charpy V-notch shift results for each surveillance material: SAM McFRAC fit versus current hyperbolic tangent curve-fit.

7.3.3. Hardness

No baseline hardness readings are available. Hardness values were reported in the 97° capsule report for the base, weld and HAZ samples. The hardness readings were reported as Rockwell, but the 97° capsule report did not state the scale. It was presumed that they were of the Rockwell C scale. The values were converted to Rockwell B scale for comparison to the 263° capsule hardness test results (See Table 7-7). It is felt that the change in hardness as listed in Table 7-7 is not representative of the material for the following reasons:

- many of the values reported in the 97° capsule are below the normal Rockwell C range,
- the conversion from Rockwell C to Rockwell B is approximate,
- irradiation is expected to harden the materials, not soften,
- the increase in material yield strength (Table 7-2) was not accompanied by an increase in the hardness values.

Since the 97° capsule hardness reading were taken outside the normal Rockwell C range, it is felt that the Rockwell B measurements taken on the 263° capsule specimens are more representative of the material. It is recommended that future hardness measurements be compared the 263° capsule hardness results.

7.4. Extrapolated Adjusted Reference Temperature at Peak Fluence Location

The extrapolated 32 EFPY adjusted reference temperature (ART) at the peak fluence location for San Onofre Unit 2 reactor vessel beltline region is presented in Table 7-8. The peak fluence location was determined to be in the lower shell from the fluence analysis (Section 6.2). A description of the San Onofre Unit 2 reactor vessel beltline materials is contained in Appendix E.

Table 7-1.
Chemical Composition Data for San Onofre
Unit 2 Reactor Vessel Surveillance Base Metal Plate C-6404-2

Element	Composition (% Weight)			
	Baseline	97°	263°	Average[(a)]
Copper	0.10	0.100	0.10	0.10
Nickel	0.60	0.593	0.60	0.60
Phosphorous	0.005	0.0115	<0.02	0.008
Chromium	0.18	0.204	0.21	0.20
Molybdenum	0.58	0.548	0.61	0.58
Vanadium	0.003	<0.025	0.0035	0.003
Manganese	1.43	1.417	1.42	1.42
Cobalt	0.012	0.008	0.01	0.01
Sulfur	0.009	(b)	0.04	0.02
Silicon	0.26	(b)	0.29	0.28

(a). Measurements below the detection limit were not included in the average.
(b). Not measured.

Table 7-2.
Chemical Composition Data for San Onofre
Unit 2 Reactor Vessel Surveillance Weld Metal C-6404-1/C-6404-3 (9-203)

Element	Composition (% Weight)			
	Baseline	97°	263°	Average[(a)]
Copper	0.03	0.027	0.02	0.03
Nickel	0.12	0.145	0.15	0.14
Phosphorous	0.003	<0.005	<0.03	---
Chromium	0.09	0.125	0.12	0.11
Molybdenum	0.52	0.507	0.60	0.54
Vanadium	0.005	<0.025	0.01	0.01
Manganese	1.34	1.459	1.35	1.38
Cobalt	0.012	0.014	0.01	0.01
Sulphur	0.009	(b)	0.05	0.03
Silicon	0.21	(b)	0.25	0.23

(a). Measurements below the detection limit were not included in the average.
(b). Not measured.

Table 7-3. Summary of San Onofre Unit 2 Reactor Vessel Surveillance Capsules Tensile Test Results

Material	Fluence, 10^{19} n/cm^2	Test Temp., F	Strength, ksi				Ductility, %			
			Yield	%(a)	Ultimate	%(a)	Total Elong.	%(a)	Reduction of Area	%(a)
Base Metal Plate C-6404-2 (Transverse Orientation)	0.00	71	72.2(b)	---	93.2(b)	---	25.3(b)	---	67.5(b)	---
		250	65.9(b)	---	84.6(b)	---	22.7(b)	---	67.0(b)	---
		550	65.5(b)	---	86.6(b)	---	19.7(b)	---	60.9(b)	---
	0.507(c)	100	74.4	3.1	95.2	2.1	21.8	-13.9	62.2	-7.9
		200	75.3	14.3	94.0	11.1	22.3	-1.6	62.7	-6.4
		550	68.3	4.3	90.3	4.3	20.6	4.7	57.6	-5.4
	1.637	150	79.1	9.6	99.0	6.2	21.4	-15.5	61.6	-8.7
		250	74.2	12.7	93.2	10.1	20.2	-10.9	63.0	-6.0
		550	73.9	12.8	96.0	10.9	17.8	-9.5	56.7	-6.8
Weld Metal C-6404-1/C-6404-3 (9-203)	0.00	71	69.3(b)	---	90.6(b)	---	25.3(b)	---	67.8(b)	---
		250	71.9(b)	---	83.7(b)	---	23.3(b)	---	71.8(b)	---
		550	64.7(b)	---	84.9(b)	---	23.3(b)	---	70.1(b)	---
	0.507(c)	79	76.9	11.0	88.6	-2.2	22.8	-10.0	72.2	6.5
		250	63.7	-11.4	83.7	0.0	21.6	-7.4	71.7	-0.1
		550	66.0	2.0	85.6	0.8	21.6	-7.4	69.1	-1.4
	1.637	0	83.2	20.1	99.1	9.4	24.4	-3.7	68.4	0.9
		250	76.3	6.1	87.4	4.4	21.0	-10.0	70.4	-1.9
		550	72.2	11.6	88.8	4.6	20.6	-11.7	69.3	-1.1

(a) Change relative to unirradiated material property.

(b) Mean value of available test data.

(c) Average 97° capsule fluence

Table 7-4. Measured vs. Predicted 30 ft-lb Transition Temperature Changes for 263° San Onofre Unit 2 Capsule Surveillance Materials – 1.637 x 10^{19} n/cm^2

Material	Measured 30 ft-lb Transition Temperature, F			30 ft-lb Transition Temperature Shift Predicted in Accordance With Regulatory Guide 1.99, Revision 2				
	Unirradiated	Irradiated	Difference	Chemistry Factor	ΔRT_{NDT}[c], F	σ_Δ, F	$\Delta RT_{NDT} - \sigma_\Delta$, F	$\Delta RT_{NDT} + \sigma_\Delta$, F
Base Metal Plate C-6404-2 (Transverse Orientation)	27.5	115.1	87.6	65.0[a]	73.8	17	56.8	90.8
Weld Metal, C-6404-1/C-6404-3 (9-203)	-53.2	-29.9	23.3	31.1[a]	35.3	28	7.3	63.3
Heat-Affect-Zone Material C-6404-2	-62.7	-11.2	51.5	65.0[a]	73.8	17	56.8	90.8
Standard Reference Material, HSST Plate 01	27.1	178.7	151.6	131.7[b]	149.6	17	132.6	166.6

(a) Chemistry factor based on mean copper and nickel contents as shown in Tables 7-1 and 7-2.

(b) Chemistry factor based on copper and nickel contents as shown in NUREG/CR-6551.[21]

(c) ΔRT_{NDT} = Chemistry Factor * fluence factor (using the 263° capsule fluence).

Table 7-5. Measured vs. Predicted Upper-Shelf Energy Decreases for the 263° San Onofre Unit 2 Capsule Surveillance Materials – 1.637 x 10^{19} n/cm^2

Material	Measured Upper-Shelf Energy, ft-lb			% Decrease Predicted In Accordance With Regulatory Guide 1.99, Rev. 2 Figure 2[(a)]
	Unirradiated	Irradiated	% Decrease	
Base Metal Plate C-6404-2 (Transverse Orientation)	126.7	93.2	26.4	21.4[(b)]
Weld Metal, C-6404-1/C-6404-3 (9-203)	146.1	135.0	7.6	19.1[(c)]
Heat-Affect-Zone Material C-6404-2	145.0	126.8	12.6	21.4[(b)]
Standard Reference Material, HSST Plate 01	132.5	82.2	38.0	29.7[(d)]

(a) Calculated using equation reported in NUREG/CR-5799.[23]

(b) Based on mean copper content as shown in Table 7-1.

(c) Based on mean copper content as shown in Table 7-2.

(d) Based on mean copper content as shown in NUREG/CR-6551.[21]

Table 7-6. Summary of San Onofre Unit 2 Reactor Vessel Surveillance Capsules Charpy Impact Test Results (Based on Tanh Reevaluation)

Material	Capsule	Fluence, 10^{19} n/cm^2	Measured Transition Temperature		Measured Upper-Shelf	
			ΔCv30, F	ΔCv50, F	Energy, ft-lb	% Decrease
Base Metal Plate C-6404-2 (Transverse Orientation)	Baseline	---	---	---	127	---
	97	0.507	41	46	99	22
	263	1.637	88	100	93	26
Weld Metal, C-6404-1/C-6404-3 (9-203)	Baseline	---	---	---	146	---
	97	0.507	4	5	142	3
	263	1.637	23	26	135	8
Heat-Affected Zone Material C-6404-2	Baseline	---	---	---	145	---
	97	0.507	28	29	135	7
	263	1.637	52	64	127	13
Standard Reference Material, HSST Plate 01	Baseline	---	---	---	133	---
	263	1.637	152	155	82	38

Table 7-7. Hardness Data for San Onofre Unit 2 Reactor Vessel Surveillance Materials

Element	Average Rockwell Hardness			
	97°		263°	Change relative to 97°
	C Scale[a]	**B Scale[b]**	**B Scale**	**B Scale**
Base Metal Plate C-6404-2	17.0	95.9	95.5	-0.4
Weld Metal, C-6404-1/C-6404-3 (9-203)	16.1	95.3	94.8	-0.4
Heat-Affected Zone Material, C-6404-2	20.6	98.5	96.8	-1.7
Standard Reference Material, HSST Plate 01	---	---	97.2	---

(a). The Rockwell hardness scale used was not reported in the 97° capsule report[2]; Rockwell Scale C was presumed.
(b). Converted using tables in the ASM Metals Handbook[24]

Table 7-8. Extrapolated Adjusted Reference Temperature at 32 EFPY for the Uprated Peak Fluence Location in San Onofre Unit 2 Reactor Vessel Beltline Region

Material Description				Initial RT_{NDT}[25]	Chemistry Factor[25]	ΔRT_{NDT}, F at 32 EFPY(a)			ART_{NDT}, F at 32 EFPY(f)		
Reactor Vessel Beltline Location	Matl. Ident.	Base Metal Type	Heat Number			Vessel/ Clad Interface	T/4 Location	3/4T Location	Vessel/ Clad Interface	T/4 Location	3/4T Location
Lower Shell	C-6404-4	A 533B-1	A6735-1	+20	65	89.3	80.8	62.7	143.3	134.8	116.7
Lower Shell	C-6404-5	A 533B-1	C7585-1	+10	75	103.1	93.2	72.3	147.1	137.2	116.3
Lower Shell	C-6404-6	A 533B-1	C7596-2	-10	65	89.3	80.8	62.7	113.3	104.8	86.7

(a) ΔRT_{NDT} = Chemistry Factor * Fluence Factor listed in the following table.

Peak Fluence Location (Lower Shell)	Extrapolated Uprated 32 EFPY Fluence, $x10^{19}$ n/cm^2	Fluence Factor(e)
Inside Wetted Surface	4.371(b)	1.375
Vessel/Clad Interface	4.355(c)	1.374
1/4T Location	2.472(d)	1.243
3/4T Location	0.878(d)	0.964

(b.) from Table 6-6

(c.) from Table 6-7

(d.) Attenuation calculated per RG 1.99 Rev. 2;[22] see Section 6.2 for equation and dimensions used.

(e.) Fluence Factor calculated per RG 1.99 Rev. 2 equation (2).[22]

(f.) ART_{NDT} = Initial RT_{NDT} + ΔRT_{NDT} + Margin. Margin = 34°F. Margin calculated per RG 1.99 Rev. 2 equation (4)[22] with $\sigma_I = 0$ (measured initial RT_{NDT}) and σ_Δ = 17°F (base metal).

8. Summary of Results

The analysis of the reactor vessel material contained in the second surveillance capsule, the 263° capsule, removed for evaluation as part of the San Onofre Unit 2 Reactor Vessel Surveillance Program, led to the following conclusions:

1. The capsule received an average fast neutron fluence of 1.637×10^{19} n/cm^2 (E > 1.0 MeV).

2. With the recent Appendix K power uprate to 3438 MWth, fluence values at the projected end-of-life (32 EFPY) were estimated using an artificially increased flux value for all future cycles. Based on this extrapolated flux, the projected peak fast fluence of the San Onofre Unit 2 reactor vessel beltline region clad/vessel interface is 4.355×10^{19} n/cm^2 (E > 1.0 MeV).

3. The 30 ft-lb transition temperature for the Base Metal Plate C-6404-2, in the transverse orientation, increased 88°F after irradiation to 1.637×10^{19} n/cm^2 (E > 1.0 MeV). In addition, the C_vUSE for this material decreased 26%.

4. The 30 ft-lb transition temperature for the Weld Metal, C-6404-1/C-6404-3 (9-203), increased 23°F after irradiation to 1.637×10^{19} n/cm^2 (E > 1.0 MeV). In addition, the C_vUSE for this material decreased 8%.

5. The 30 ft-lb transition temperature for the heat affected zone increased 52°F after irradiation to 1.637×10^{19} n/cm^2 (E > 1.0 MeV). In addition, the C_vUSE for this material decreased 13%.

6. The 30 ft-lb transition temperature for the Standard Reference Material, HSST Plate 01, increased 152°F after irradiation to 1.637×10^{19} n/cm^2 (E > 1.0 MeV). In addition, the C_vUSE for this material decreased 38%.

7. The measured upper-shelf energies for the San Onofre Unit 2 263° capsule surveillance materials do not fall below the required 50 ft-lbs limit after the irradiation to 1.637×10^{19} n/cm^2 (E > 1.0 MeV).

9. Certification

The specimens obtained from the Southern California Edison Company's San Onofre Unit 2 reactor vessel surveillance capsule (the 263° capsule) were tested and evaluated using accepted techniques and established standard methods and procedures in accordance with the requirements of 10 CFR 50, Appendices G and H.

J. B. Hall (Material Analysis) Materials & Structural Analysis Unit	10-15-01 Date
J. W. Newman, Jr. (Fluence Analysis) Performance Analysis Unit	10/15/01 Date

This report has been reviewed for technical content and accuracy.

for BR Grambau B. R. Grambau (Material Analysis) Materials & Structural Analysis Unit	10/15/01 Date
E. Giavedoni (Fluence Analysis) Performance Analysis Unit	10/15/2001 Date

Verification of independent review.

D. R. Cofflin, Acting Manager Materials & Structural Analysis Unit	10/15/2001 Date

This report is approved for release.

E. Giavedoni Program Manager	10/15/2001 Date

10. References

1. *"Program for Irradiation Surveillance of San Onofre Reactor Vessel Materials, San Onofre Nuclear Generating Station, Units 2 and 3,"* S-NLM-002, Revision 2, Combustion Engineering, Inc., Windsor, Connecticut, October 1974.

2. M. P. Manahan, L. M. Lowry, and E. O. Fromm, *"Examination, Testing, and Evaluation of Irradiated Pressure Vessel Surveillance Specimens from the San Onofre Nuclear Generating Station Unit 2,"* Battelle Columbus Laboratories, Columbus, Ohio, December 1988.

3. ASTM Standard E 185, *"Standard Recommended Practice for Surveillance Tests for Nuclear Reactor Vessels,"* American Society for Testing and Materials, Philadelphia, Pennsylvania.

4. Code of Federal Regulation, Title 10, Part 50, *"Domestic Licensing of Production and Utilization Facilities,"* Appendix G, Fracture Toughness Requirements.

5. Code of Federal Regulation, Title 10, Part 50, *"Domestic Licensing of Production and Utilization Facilities,"* Appendix H, Reactor Vessel Material Surveillance Program Requirements.

6. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, *"Nuclear Power Plant Components,"* Appendix G, Protection Against Nonductile Failure, 1989 Edition.

7. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section XI, *"Rules for Inservice Inspection of Nuclear Power Plant Components,"* Appendix G, Fracture Toughness Criteria for Protection Against Failure, 1989 Edition.

8. ASTM Standard E 208-81, *"Method for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels,"* American Society for Testing and Materials, Philadelphia, Pennsylvania.

9. "*Summary Report on Manufacture of Test Specimens and Assembly of Capsules for Irradiation Surveillance of San Onofre Unit 2 Reactor Vessel Materials*," TR-S-MCM-001-P, Combustion Engineering, Inc., Windsor, Connecticut, May 1978.

10. A. Ragl, *"Southern California Edison San Onofre Unit 2 Evaluation of Baseline Specimens Reactor Vessel Materials Irradiation Surveillance Program,"* S-TR-MCS-002, Combustion Engineering, Inc., Windsor, Connecticut, May 1978.

* - Available from Framatome ANP, Lynchburg, Virginia.

11. S. M. Jensen, *"Evaluation of SONGS Unit 2 Reactor Vessel Surveillance Capsule 263,"* 00:1150-019-00-53:01 (Framatome ANP Document No. 31-1182320-00), BWX Technologies, Inc., Lynchburg, Virginia, August 2001.*

12. ASTM Standard E 21-92, *"Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials,"* American Society for Testing and Materials, Philadelphia, Pennsylvania.

13. ASTM Standard E 23-91, *"Standard Test Methods for Notched Bar Impact Testing of Metallic Materials,"* American Society for Testing and Materials, Philadelphia, Pennsylvania.

14. W. Oldfield, *"Curve Fitting Impact Test Data: A Statistical Procedure,"* ASTM Standardization News, November 1975.

15. ASTM Standard E 185-82, *"Standard Practice for Conducting Surveillance Tests for Light-Water Cooled Nuclear Power Reactor Vessels, E 706 (IF),"* American Society for Testing and Materials, Philadelphia, Pennsylvania.

16. ASTM Standard E 18-97, *"Standard Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials,"* American Society for Testing and Materials, Philadelphia, Pennsylvania.

17. ASTM Standard E 384-89, *"Standard Test Method for Microhardness of Materials,"* American Society for Testing and Materials, Philadelphia, Pennsylvania.

18. ASTM Standard E 92-82, *"Standard Test Method for Vickers Hardness of Metallic Materials,"* American Society for Testing and Materials, Philadelphia, Pennsylvania.

19. J.R. Worsham, et al., *"Fluence and Uncertainty Methodologies,"* BAW-2241P-A, Revision 1, Framatome ANP, Lynchburg, Virginia, April 1999.

20. U.S. Nuclear Regulatory Commission, *"Calculational and Dosimetry Methods for Determining Pressure Vessel Neutron Fluence,"* Regulatory Guide 1.190, March 2001.

21. E. D. Eason, J. E. Wright, and G. R. Odette, *"Improved Embrittlement Correlations for Reactor Vessel Steels,"* NUREG/CR-6551, November 1998.

22. U.S. Nuclear Regulatory Commission, *"Radiation Embrittlement of Reactor Vessel Materials,"* Regulatory Guide 1.99, Revision 2, May 1988.

23. R. D. Cheverton, T. L. Dickson, J. G. Merkle, and R. K. Nanstad, *"Review of Reactor Pressure Vessel Evaluation Report for Yankee Row Nuclear Power Station,"* NUREG/CR-5799, March 1992.

FRAMATOME ANP

* - Available from Framatome ANP, Lynchburg, Virginia.

24. "*Metals Handbook Ninth Edition,*" Volume 8, Mechanical Testing, American Society for Metals, Metals Park, Ohio, 1985.

25. "*San Onofre Nuclear Generating Station, Unit 2, Response to Generic Letter 92-01,*" Revision 1, ATI Consulting, San Ramon, California, January 22, 1993.

FRAMATOME ANP

* - Available from Framatome ANP, Lynchburg, Virginia.

APPENDIX A

Unirradiated and Irradiated Tensile Data for the San Onofre Unit 2 RVSP Materials

Table A-1. Tensile Properties of Unirradiated Base Metal Plate C-6404-2, Transverse Orientation

Specimen No.	Test Temp. (F)	Strength, Ksi		Elongation, %		Reduction of Area, %
		0.2% Yield or Upper/Lower	Ultimate	Uniform	Total	
2JU	71	72.2	93.2	9.8	25	67.4
2K2	71	73.4	93.9	8.8	23	68.5
2L2	71	72.2/70.9	92.6	10.5	28	66.6
2JE	250	65.5/64.9	83.8	8.8	22	65.7
2K6	250	65.5	84.0	8.3	22	67.9
2KK	250	67.2	86.1	7.8	24	67.4
2J5	550	65.5	88.4	7.7	21	63.8
2JD	550	65.5	85.3	8.2	20	59.4
2KU	550	65.5	86.0	8.3	18	59.4

Table A-2. Tensile Properties of Unirradiated Weld Metal C-6404-1/C-6404-3 (9-203)

Specimen No.	Test Temp. (F)	Strength, Ksi		Elongation, %		Reduction of Area, %
		0.2% Yield or Upper/Lower	Ultimate	Uniform	Total	
3K5	71	71.5	91.2	9.7	26	66.9
3KD	71	69.1/67.9	90.4	8.8	26	67.1
3KY	71	69.1/68.5	90.2	9.3	24	69.3
3JB	250	75.2/71.5	83.6	7.5	24	71.9
3JP	250	75.2/71.5	83.7	6.8	22	69.8
3J6	250	76.4/72.8	83.9	6.8	24	73.6
3K6	550	66.7/64.3	84.8	8.2	22	70.7
3KE	550	67.9/65.5	85.3	7.7	24	68.0
3L2	550	66.1/64.3	84.6	8.0	24	71.5

Table A-3. Tensile Properties of Unirradiated Heat Affected Zone Metal

Specimen No.	Test Temp. (F)	Strength, Ksi		Elongation, %		Reduction of Area, %
		0.2% Yield or Upper/Lower	Ultimate	Uniform	Total	
4JM	71	71.5	91.8	8.7	22	66.9
4JL	71	69.1/67.9	91.3	8.3	23	67.1
4JU	71	69.1/68.5	91.4	8.7	22	69.3
4K4	250	67.9	85.2	6.2	21	69.3
4JE	250	67.9	84.5	6.8	22	68.9
4KA	250	70.3	85.7	7.1	22	69.8
4J7	550	60.9/59.7	87.4	9.2	21	69.4
4JA	550	61.5/60.9	87.0	8.3	23	69.5
4K3	550	62.5/61.8	86.6	6.8	20	65.7

Table A-4. Tensile Properties of Base Metal Plate C-6404-2, Irradiated to 5.07 x 10^{18} n/cm^2 (E>1.0 MeV) Transverse Orientation

Specimen No.	Test Temp. (F)	Strength, Ksi		Elongation, %		Reduction of Area, %
		0.2% Yield	Ultimate	Uniform	Total	
2KT	100	74.4	95.2	11.5	21.8	62.2
2K4	200	75.3	94.0	10.0	22.3	62.7
2JJ	550	68.3	90.3	11.3	20.6	57.6

Table A-5. Tensile Properties of Weld Metal C-6404-1/C-6404-3 (9-203) Irradiated to 5.07 x 10^{18} n/cm^2 (E>1.0 MeV)

Specimen No.	Test Temp. (F)	Strength, Ksi		Elongation, %		Reduction of Area, %
		0.2% Yield	Ultimate	Uniform	Total	
3KT	79	79.1/76.9	88.6	9.1	22.8	72.2
3J5	250	77.7/63.7	83.7	7.5	21.6	71.7
3L1	550	68.9/66.0	85.6	11.2	21.6	69.1

Table A-6. Tensile Properties of Heat Affected Zone Metal Irradiated to 5.07 x 10^{18} n/cm^2 (E>1.0 MeV)

Specimen No.	Test Temp. (F)	Strength, Ksi		Elongation, %		Reduction of Area, %
		0.2% Yield	Ultimate	Uniform	Total	
4J6	100	76.3	93.5	8.7	24.3	72.7
4J1	250	71.2	89.1	11.0	22.5	70.4
4KB	550	68.4	92.9	11.9	20.7	62.9

APPENDIX B

Unirradiated and Irradiated
Charpy V-Notch Impact Surveillance Data for the
San Onofre Unit 2 RVSP Materials
Using Hyperbolic Tangent Curve-Fitting Method

Table B-1. Unirradiated Surveillance Charpy V-Notch Impact Data for San Onofre Unit 2, Base Metal Plate C-6404-2, Transverse Orientation

Specimen No.	Test Temp. (F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
264	-80	4.5	2	0
25A	-40	8	8	0
23D	-40	8	9	0
21T	0	12	15	10
21Y	0	24.5	24	10
262	40	33	32	20
22B	40	40	35	25
24J	80	68.5	58	30
24E	80	78.5	62	40
21E	120	87	66	75
24A	120	107	72	80
245	160	111.5	78	85
24T	160	127.5	84	90
216	190	116	80	100
24U	210	126.5	87	100
231	210	137.5	91	100

Table B-2. San Onofre Unit 2 97° Capsule Surveillance Charpy Impact Data for Base Metal Plate C-6404-2, Irradiated to 5.07×10^{18} n/cm^2 (E>1.0 MeV) Transverse Orientation

Specimen No.	Test Temp. (F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
214	0	4.0	10.0	4
23J	0	11.0	11.0	6
223	40	22.0	19.6	11
22K	72	27.9	32.8	15
22T	62	32.1	31.8	15
25U	100	44.1	42.8	42
23P	100	50.0	44.0	49
21B	160	82.0	68.4	85
221	200	93.0	71.0	100
25L	200	98.0	68.6	100
256	260	101.9	83.4	100
211	260	103.0	83.8	100

Table B-3. Hyperbolic Tangent Curve Fit Coefficients for San Onofre Unit 2, Base Metal Plate C-6404-2, Transverse Orientation

	Hyperbolic Tangent Curve Fit Coefficients		
	Absorbed Energy	Lateral Expansion	Percent Shear Fracture
Unirradiated	A: 64.4 B: 62.2 C: 71.7 T0: 72.1	A: 44.5 B: 43.5 C: 83.9 T0: 57.4	A: 50.0 B: 50.0 C: 64.5 T0: 89.4
97° Capsule	A: 50.6 B: 48.4 C: 73.3 T0: 101.9	A: 43.0 B: 42.0 C: 105.0 T0: 99.2	A: 50.0 B: 50.0 C: 52.7 T0: 106.7

Table B-4. Unirradiated Surveillance Charpy V-Notch Impact Data for San Onofre Unit 2, Base Metal Plate C-6404-2, Longitudinal Orientation

Specimen No.	Test Temp. (F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
154	-80	4.5	2	0
136	-80	8.5	10	0
122	-40	5	6	0
132	-40	6.5	6	0
143	0	11	13	15
147	0	16.5	18	15
114	40	41	38	25
11A	40	56.5	48	25
12K	80	93.5	72	65
14A	80	124.5	83	75
156	120	118	78	80
11E	120	141.5	96	90
13T	160	146.5	90	100
11T	160	157.5	95	90
157	210	148	96	100
14L	210	155	94	100

Table B-5. San Onofre Unit 2 97° Capsule Surveillance Charpy Impact Data for Base Metal Plate C-6404-2, Irradiated to 5.07 x 10^{18} n/cm^2 (E>1.0 MeV) Longitudinal Orientation

Specimen No.	Test Temp. (F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
141	0	6.0	6.8	4
111	0	8.1	6.4	5
15M	40	12.5	7.8	11
14T	72	23.5	23.6	9
13M	72	27.4	26.6	13
123	100	59.5	53.6	18
13E	100	74.2	58.8	20
11M	160	113.4	83.0	77
15E	160	138.5	99.4	100
11U	200	127.3	93.4	100
124	200	136.2	105.8	100
137	260	137.3	95.4	100

Table B-6. Hyperbolic Tangent Curve Fit Coefficients for San Onofre Unit 2, Base Metal Plate C-6404-2, Longitudinal Orientation

	Hyperbolic Tangent Curve Fit Coefficients		
	Absorbed Energy	Lateral Expansion	Percent Shear Fracture
Unirradiated	A: 77.0 B: 74.8 C: 52.5 T0: 59.9	A: 47.5 B: 46.5 C: 52.9 T0: 43.8	A: 50.0 B: 50.0 C: 56.1 T0: 62.9
97° Capsule	A: 68.5 B: 66.3 C: 42.6 T0: 102.0	A: 49.4 B: 48.4 C: 44.3 T0: 94.9	A: 50.0 B: 50.0 C: 37.7 T0: 123.8

Table B-7. Unirradiated Surveillance Charpy V-Notch Impact Data for San Onofre Unit 2, Weld Metal C-6404-1/C-6404-3 (9-203)

Specimen No.	Test Temp. (F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
34A	-150	3.5	1	0
31M	-120	7	6	15
333	-120	14	12	15
346	-80	16	15	25
37A	-80	29.5	25	30
31K	-40	43.5	37	35
35T	0	63.5	53	65
34T	0	90	68	75
33B	40	132	90	90
324	40	146	97	100
35L	80	135.5	95	100
326	80	140	96	100
331	120	145.5	95	100
34J	120	153	98	100
35J	160	151	96	100
335	160	152	100	100

Table B-8. San Onofre Unit 2 97° Capsule Surveillance Charpy Impact Data for Weld Metal C-6404-1/C-6404-3 (9-203) Irradiated to 5.07 x 10^{18} n/cm^2 (E>1.0 MeV)

Specimen No.	Test Temp. (F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
37M	-79	15.0	14.4	18
37L	-79	18.4	20.0	13
3A3	-40	25.0	23.6	36
36M	-40	45.4	36.6	40
36P	0	78.0	65.2	68
36K	0	82.4	64.6	70
31E	72	126.9	95.0	92
33P	72	138.2	102.2	100
342	160	134.0	99.8	100
36E	160	142.5	97.8	100
32P	260	147.9	97.6	100
341	260	149.0	100.4	100

Table B-9. Hyperbolic Tangent Curve Fit Coefficients for San Onofre Unit 2 Weld Metal C-6404-1/C-6404-3 (9-203)

	Hyperbolic Tangent Curve Fit Coefficients		
	Absorbed Energy	Lateral Expansion	Percent Shear Fracture
Unirradiated	A: 74.2 B: 72.0 C: 58.6 T0: -11.3	A: 50.6 B: 49.6 C: 70.3 T0: -22.4	A: 50.0 B: 50.0 C: 74.2 T0: -35.8
97° Capsule	A: 72.3 B: 70.1 C: 61.4 T0: -6.3	A: 50.7 B: 49.7 C: 60.9 T0: -17.6	A: 50.0 B: 50.0 C: 62.6 T0: -25.0

Table B-10. Unirradiated Surveillance Charpy V-Notch Impact Data for San Onofre Unit 2, Heat-Affected-Zone Material

Specimen No.	Test Temp. (F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
45J	-150	5	3	0
43C	-120	9.5	6	0
41M	-80	23.5	19	25
415	-80	35	28	30
466	-40	30	24	30
46K	-40	40	34	30
47B	0	82	56	50
41Y	0	101	70	70
44C	40	104.5	71	90
432	40	115.5	88	100
461	80	135.5	86	90
42B	80	153	92	100
43K	120	108	79	90
421	120	144.5	88	100
451	160	139	85	100
442	160	151.5	86	100

Table B-11. San Onofre Unit 2 97° Capsule Surveillance Charpy Impact Data for Heat-Affected-Zone Material, Irradiated to 5.07 x 10^{18} n/cm^2 (E>1.0 MeV)

Specimen No.	Test Temp. (F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
476	-79	12.0	9.8	17
41A	-79	14.1	10.2	13
41C	-40	20.0	14.0	27
413	-40	28.2	26.8	38
43U	0	38.3	30.4	46
42J	0	77.5	54.8	54
42Y	72	103.8	81.2	89
42C	72	114.2	84.4	93
444	160	130.0	87.0	100
412	160	132.6	85.6	100
44P	260	133.7	82.2	100
424	260	145.3	89.8	100

Table B-12. Hyperbolic Tangent Curve Fit Coefficients for San Onofre Unit 2 Heat-Affected-Zone Material

Weld Metal	Hyperbolic Tangent Curve Fit Coefficients		
	Absorbed Energy	Lateral Expansion	Percent Shear Fracture
Unirradiated	A: 73.6 B: 71.4 C: 74.0 T0: -10.2	A: 44.5 B: 43.5 C: 67.0 T0: -27.2	A: 50.0 B: 50.0 C: 69.5 T0: -20.9
97° Capsule	A: 68.8 B: 66.6 C: 76.7 T0: 16.0	A: 44.2 B: 43.2 C: 62.2 T0: -0.5	A: 50.0 B: 50.0 C: 79.9 T0: -6.4

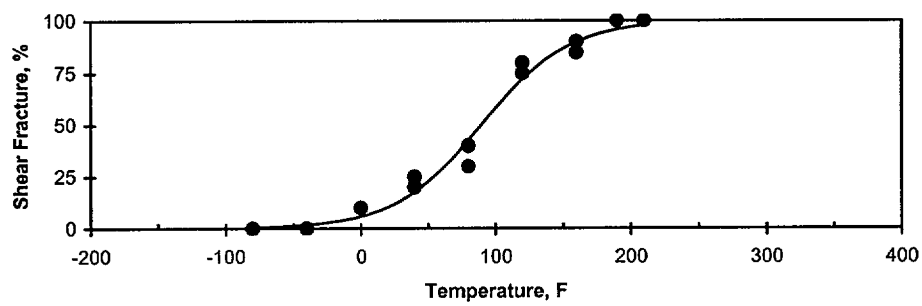
Table B-13. Unirradiated Surveillance Charpy V-Notch Impact Data for San Onofre Unit 2, Standard Reference Material

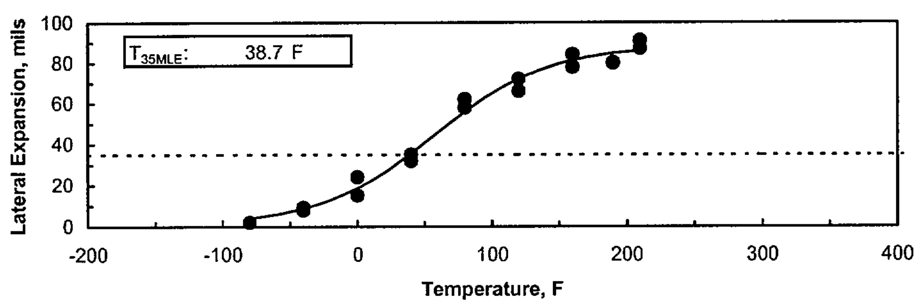
Specimen No.	Test Temp. (F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
A6Y	-80	2.5	0	0
A6P	-40	7.5	6	0
A6M	0	11.5	12	15
A6L	0	12.5	13	15
A6U	40	34.5	31	25
A6T	40	49.5	42	25
A74	80	63.5	50	40
A71	80	78.5	61	70
A7A	120	103	75	55
A77	120	88.5	71	80
A76	160	114.5	78	100
A72	160	119.5	84	90
A73	210	129	88	100
A75	210	136	90	100

Table B-14. Hyperbolic Tangent Curve Fit Coefficients for San Onofre Unit 2 Standard Reference Material

Weld Metal	Hyperbolic Tangent Curve Fit Coefficients		
	Absorbed Energy	Lateral Expansion	Percent Shear Fracture
Unirradiated	A: 67.4 B: 65.2 C: 78.0 T0: 78.0	A: 44.7 B: 43.7 C: 74.4 T0: 60.2	A: 50.0 B: 50.0 C: 76.7 T0: 78.1

Figure B-1. Unirradiated Surveillance Charpy V-Notch Impact Data for San Onofre Unit 2, Base Metal Plate C-6404-2, Transverse Orientation – Refitted Using Hyperbolic Tangent Curve-Fitting Method –





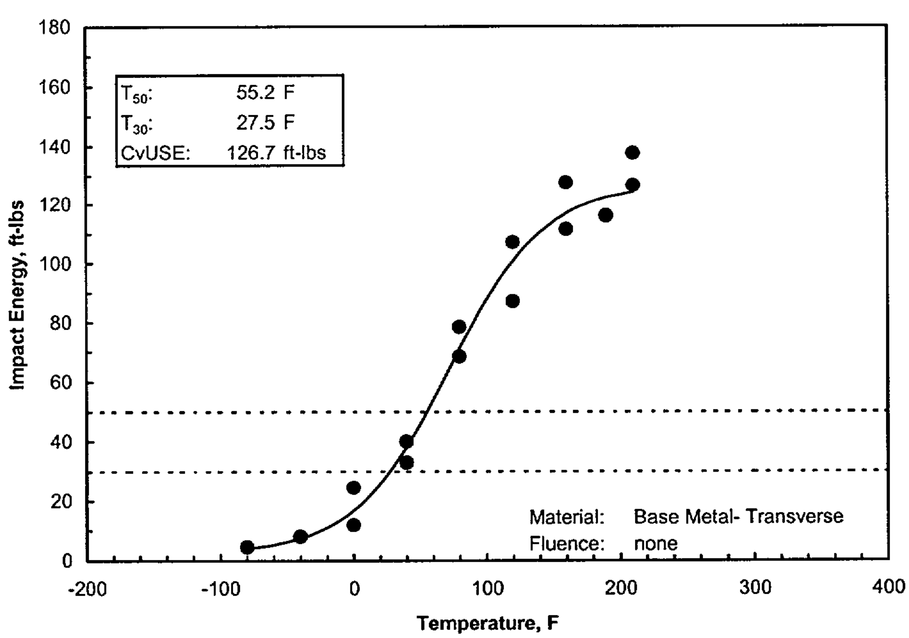


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Figure B-2. San Onofre Unit 2 97° Capsule Surveillance Charpy Impact Data for Base Metal Plate C-6404-2, Irradiated to 5.07 x 10^{18} n/cm^2 (E>1.0 MeV) Transverse Orientation – Refitted Using Hyperbolic Tangent Curve-Fitting Method –

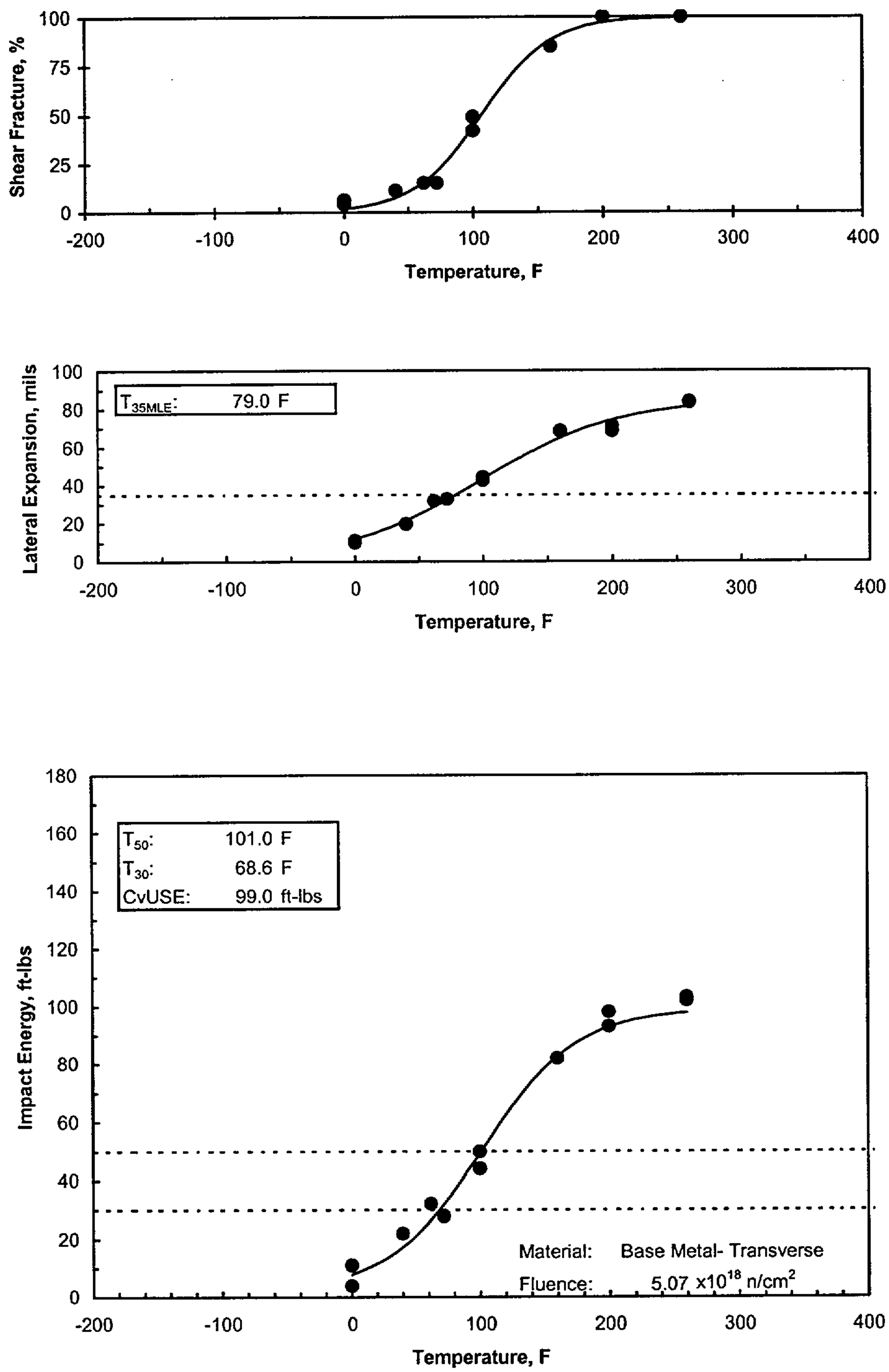

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Figure B-3. Unirradiated Surveillance Charpy V-Notch Impact Data for San Onofre Unit 2, Base Metal Plate C-6404-2, Longitudinal Orientation – Refitted Using Hyperbolic Tangent Curve-Fitting Method –

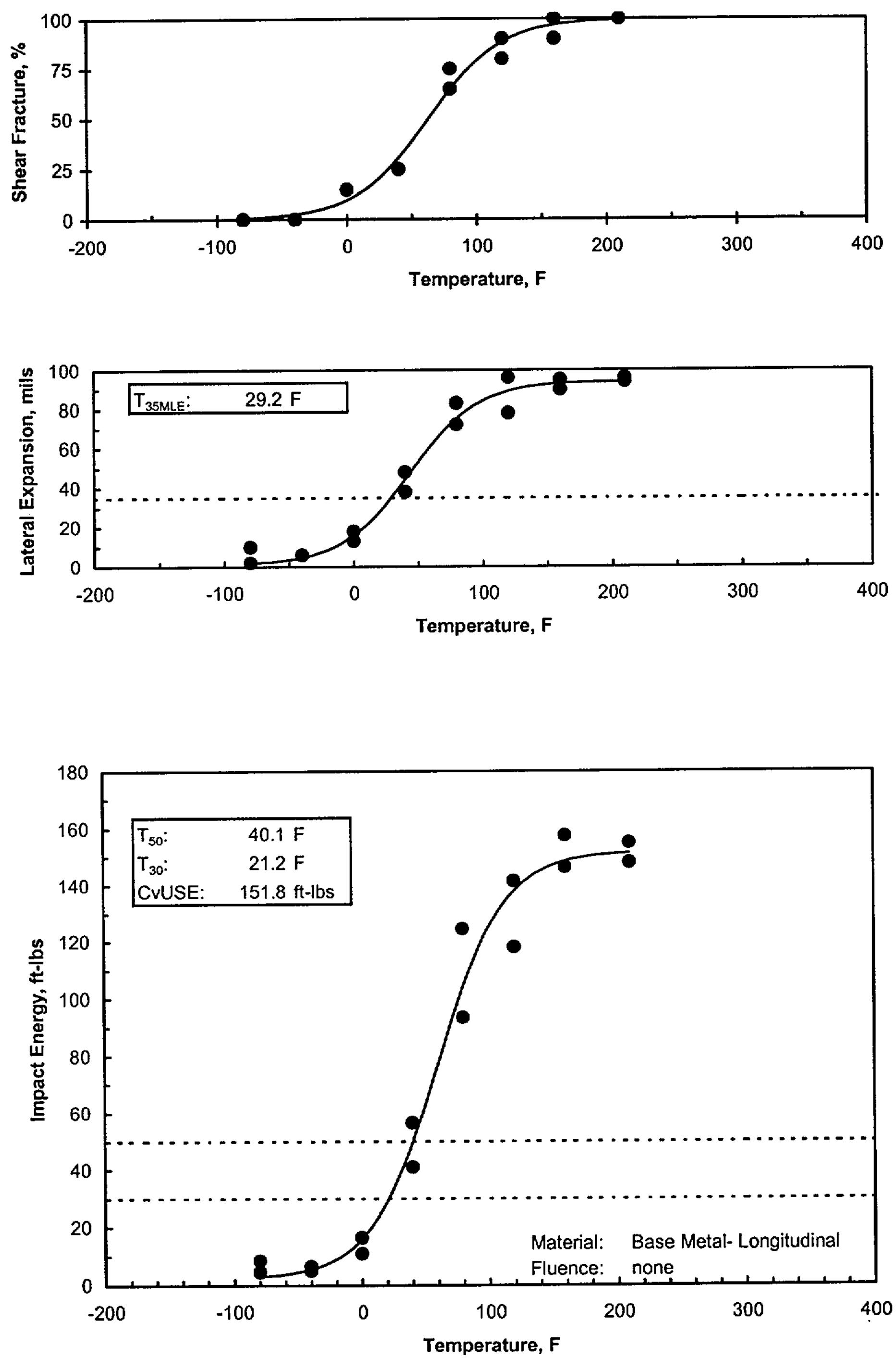

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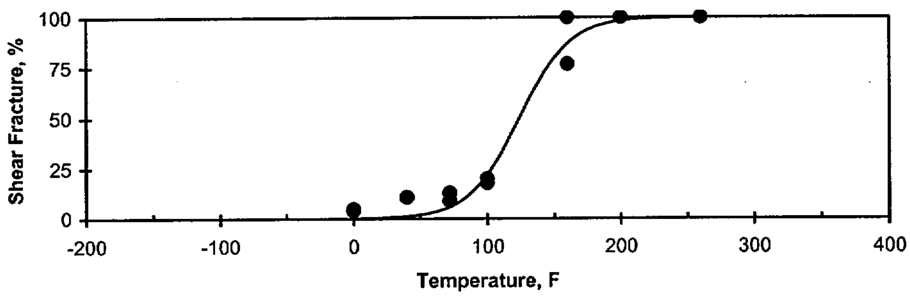
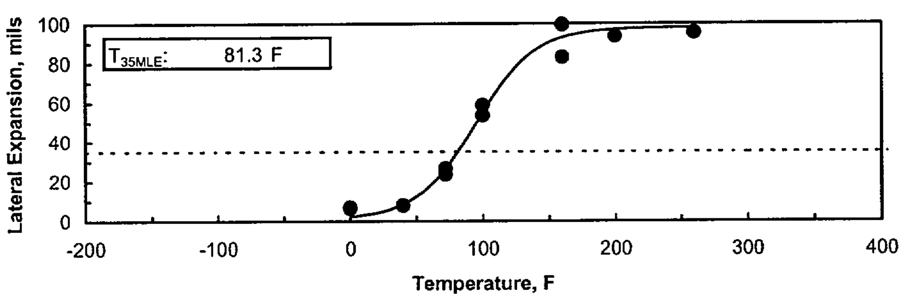
Figure B-4. San Onofre Unit 2 97° Capsule Surveillance Charpy Impact Data for Base Metal Plate C-6404-2, Irradiated to 5.07×10^{18} n/cm^2 (E>1.0 MeV) Longitudinal Orientation – Refitted Using Hyperbolic Tangent Curve-Fitting Method –





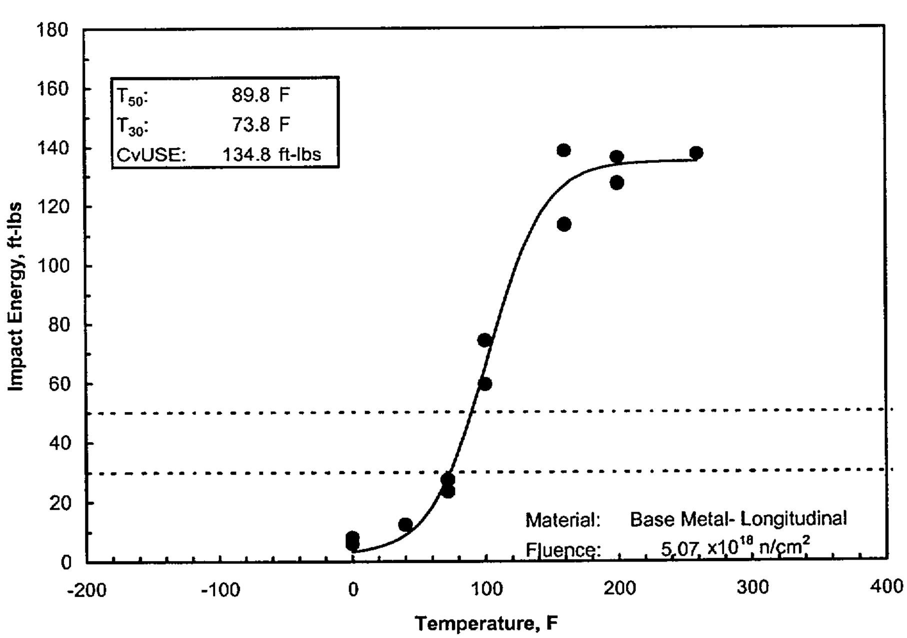


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Figure B-5. Unirradiated Surveillance Charpy V-Notch Impact Data for San Onofre Unit 2, Weld Metal C-6404-1/C-6404-3 (9-203) – Refitted Using Hyperbolic Tangent Curve-Fitting Method –

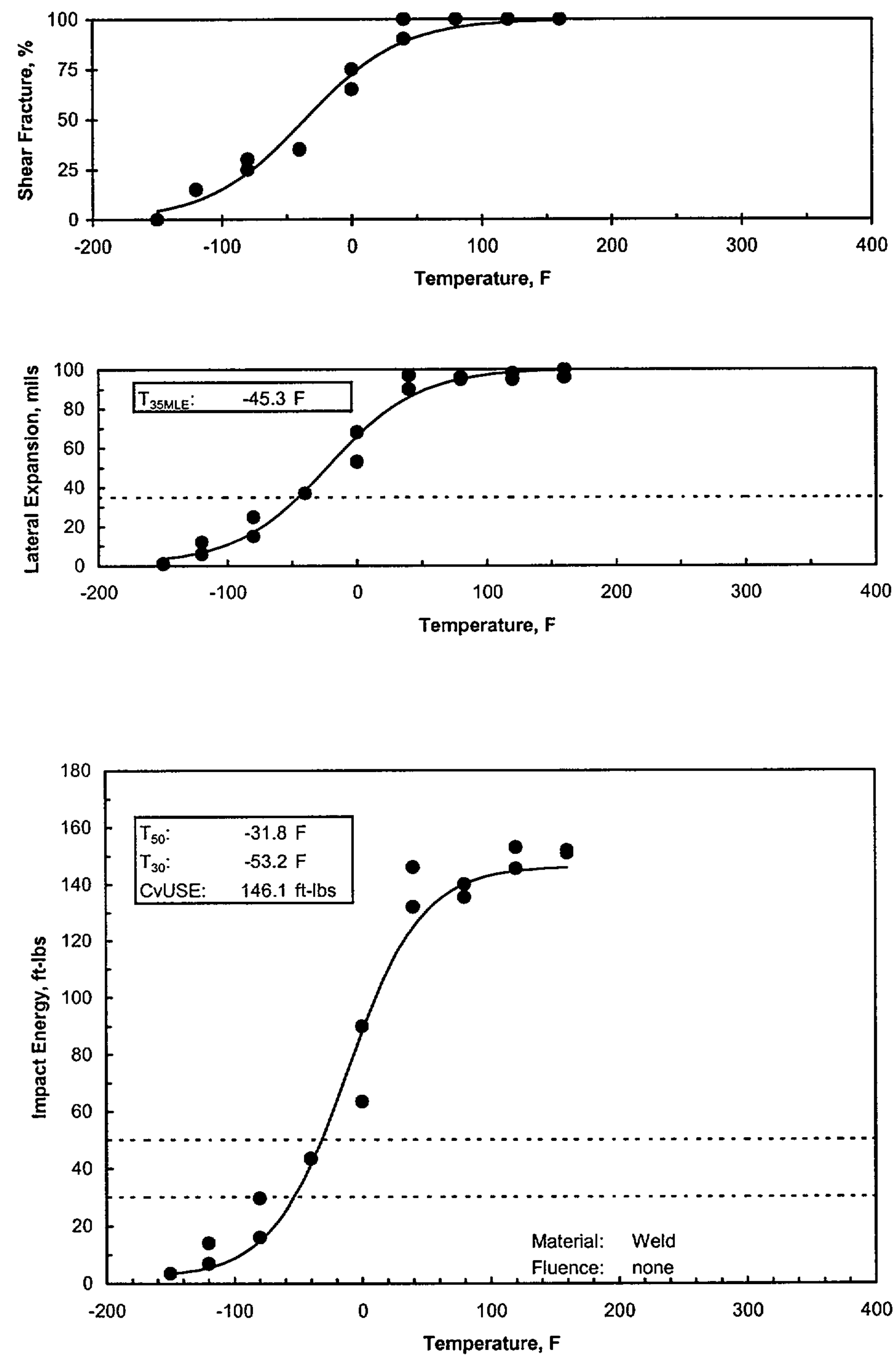

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Figure B-6. San Onofre Unit 2 97° Capsule Surveillance Charpy Impact Data for Weld Metal C-6404-1/C-6404-3 (9-203) Irradiated to 5.07 x 10^{18} n/cm^2 (E>1.0 MeV) – Refitted Using Hyperbolic Tangent Curve-Fitting Method –

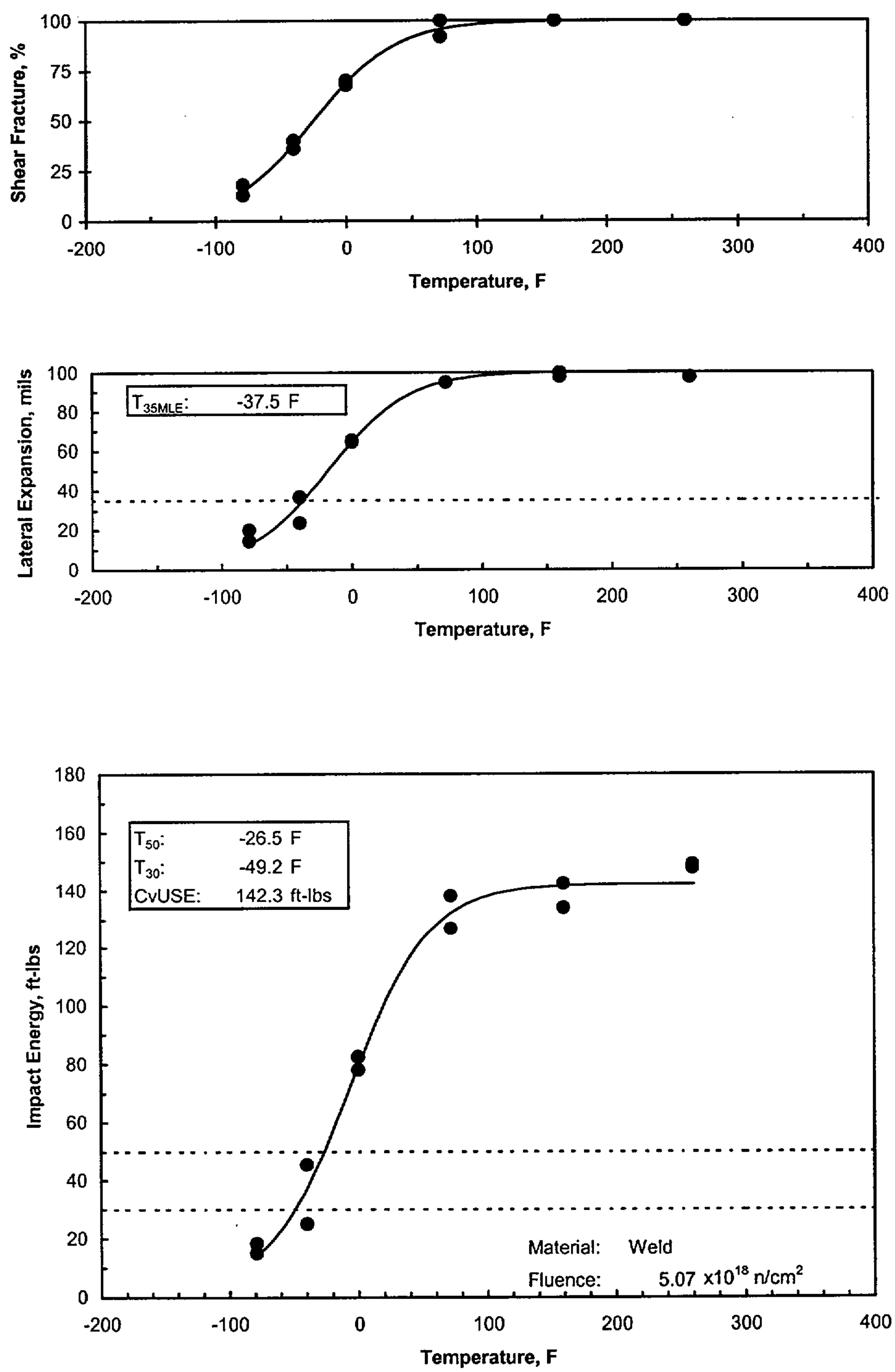

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Figure B-7. Unirradiated Surveillance Charpy V-Notch Impact Data for San Onofre Unit 2, Heat-Affected-Zone Material – Refitted Using Hyperbolic Tangent Curve-Fitting Method –

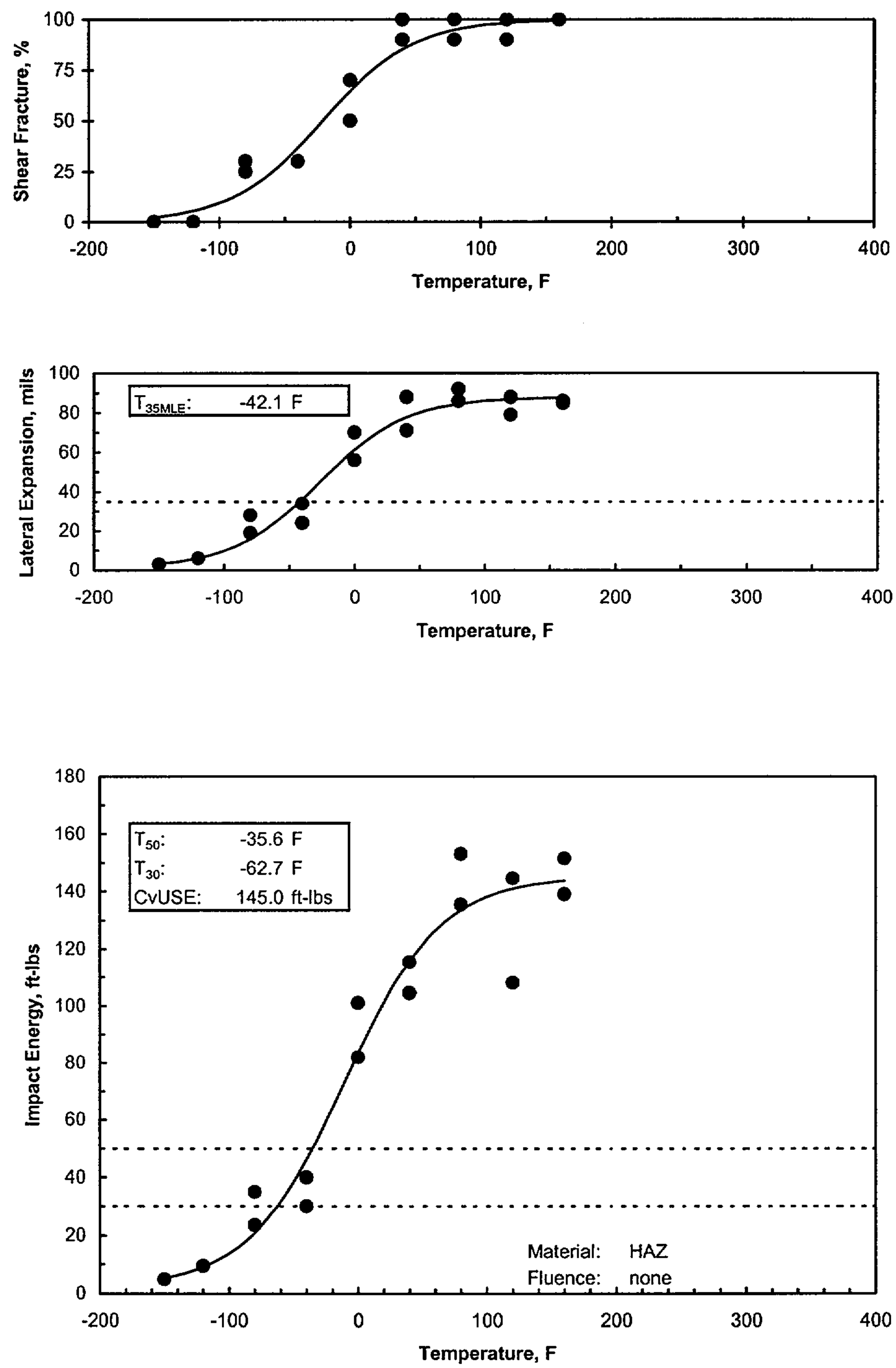

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Figure B-8. San Onofre Unit 2 97° Capsule Surveillance Charpy Impact Data for Heat-Affected-Zone Material, Irradiated to 5.07 x 10^{18} n/cm^2 (E>1.0 MeV) – Refitted Using Hyperbolic Tangent Curve-Fitting Method –

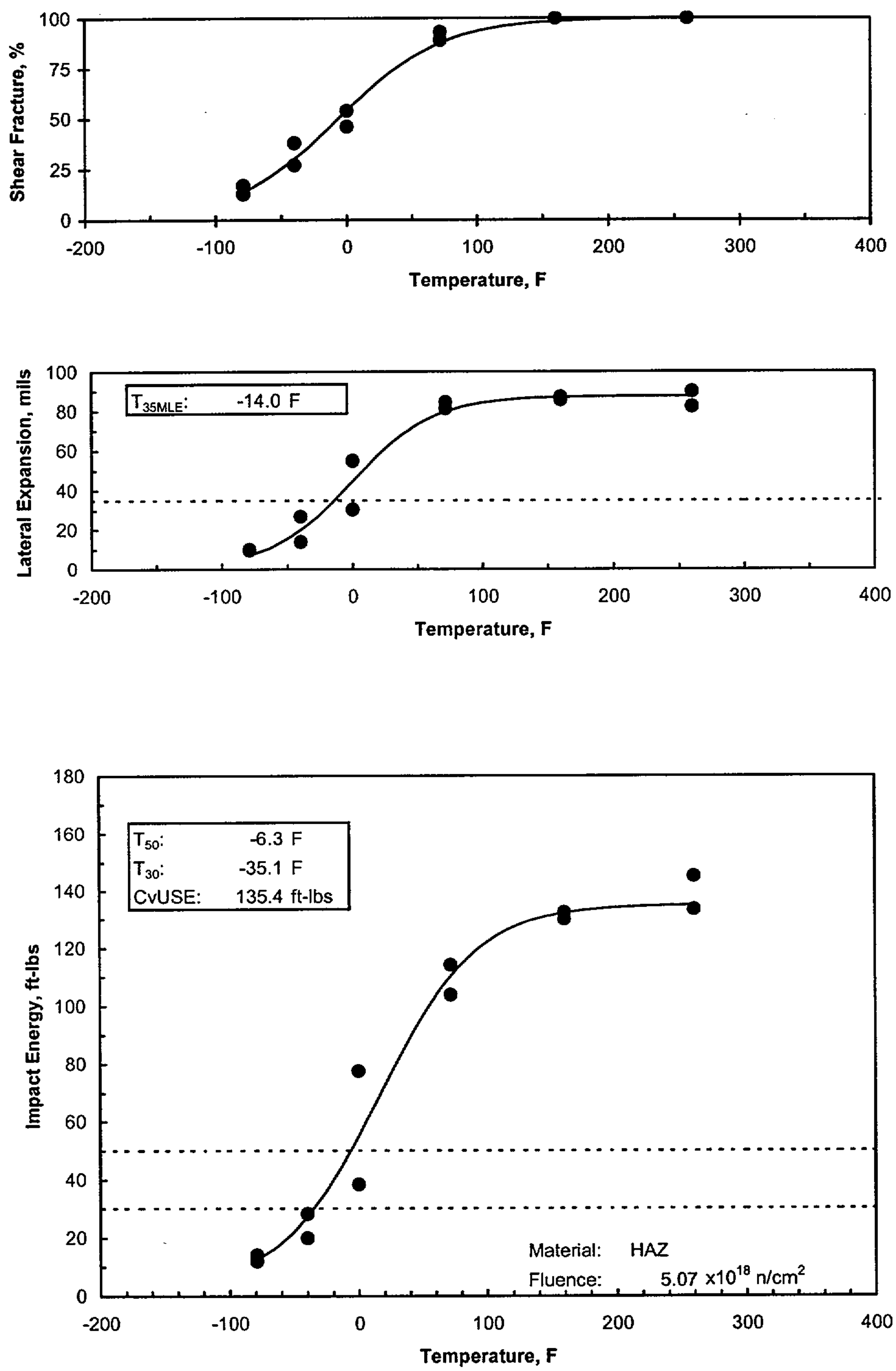

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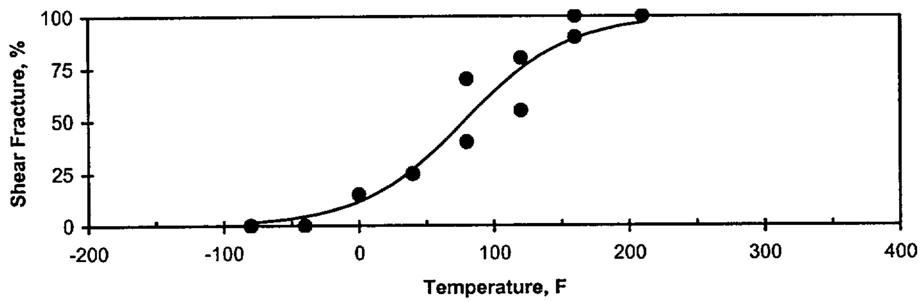
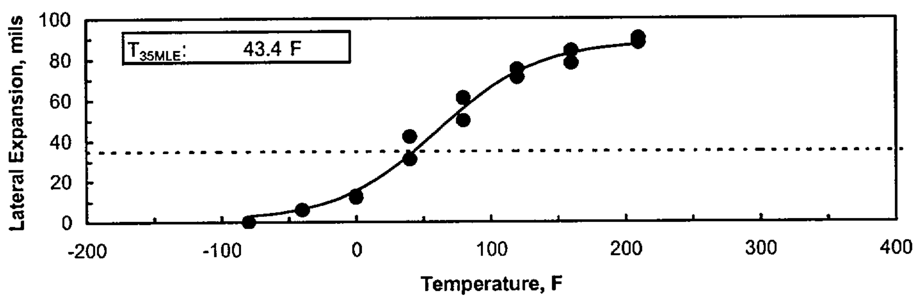
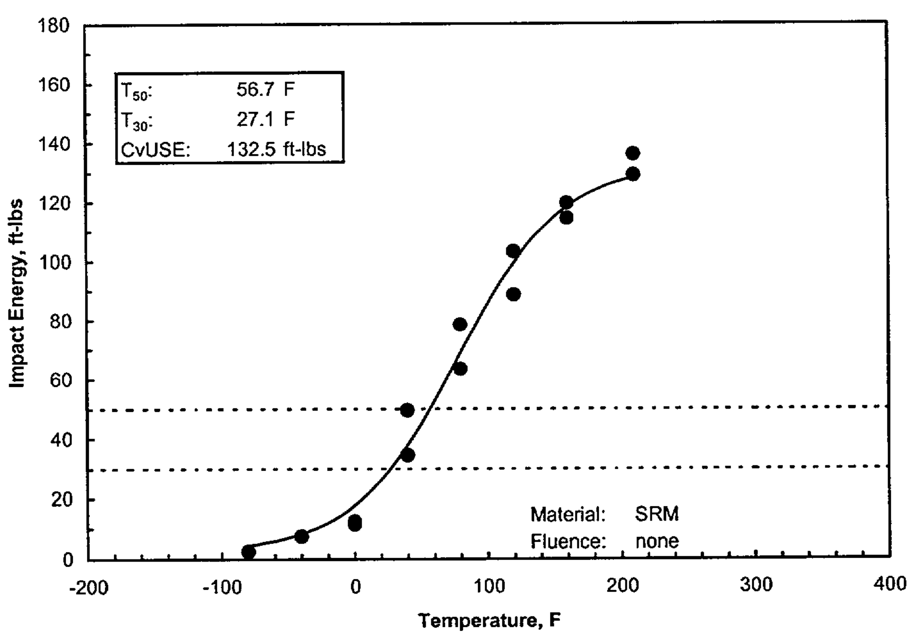
Figure B-9. Unirradiated Surveillance Charpy V-Notch Impact Data for San Onofre Unit 2, Standard Reference Material – Refitted Using Hyperbolic Tangent Curve-Fitting Method –







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APPENDIX C

Charpy V-Notch Shift Comparison:
SAM McFRAC Curve Fitting vs. Hyperbolic Tangent Curve Fitting

Table C-1. Comparison of Curve Fit Transition Temperature Shifts for San Onofre Unit 2 Surveillance Material, Base Metal Plate C-6404-2, Transverse Orientation

Capsule	Fluence ($x10^{19}$ n/cm^2) (E>1.0 MeV)	30 ft-lb Transition Temperature			
		SAM McFRAC Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	20.5	---	27.5	---
97°	0.507	65.0	44.5	68.6	41.1

Capsule	Fluence ($x10^{19}$ n/cm^2) (E>1.0 MeV)	50 ft-lb Transition Temperature			
		SAM McFRAC Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	53.4	---	55.2	---
97°	0.507	103.1	49.7	101.0	45.8

Capsule	Fluence ($x10^{19}$ n/cm^2) (E>1.0 MeV)	35 MLE Transition Temperature			
		SAM McFRAC Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	48	---	38.7	---
97°	0.507	77.1	29.1	79.0	40.3

Table C-2. Comparison of Curve Fit Transition Temperature Shifts for San Onofre Unit 2 Surveillance Material, Base Metal Plate C-6404-2, Longitudinal Orientation

Capsule	Fluence ($x10^{19}$ n/cm^2) (E>1.0 MeV)	30 ft-lb Transition Temperature			
		SAM McFRAC Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	14.7	---	21.2	---
97°	0.507	65.8	51.1	73.8	52.6

Capsule	Fluence ($x10^{19}$ n/cm^2) (E>1.0 MeV)	50 ft-lb Transition Temperature			
		SAM McFRAC Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	43.7	---	40.1	---
97°	0.507	91.9	48.2	89.8	49.7

Capsule	Fluence ($x10^{19}$ n/cm^2) (E>1.0 MeV)	35 MLE Transition Temperature			
		SAM McFRAC Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	40.0	---	29.2	---
97°	0.507	75.4	35.4	81.3	52.1

Table C-3. Comparison of Curve Fit Transition Temperature Shifts for San Onofre Unit 2 Surveillance Material, Weld Metal, C-6404-1/C-6404-3 (9-203)

Capsule	Fluence ($x10^{19}$ n/cm^2) (E>1.0 MeV)	30 ft-lb Transition Temperature			
		SAM McFRAC Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	-61.1	---	-53.2	---
97°	0.507	-53.9	7.2	-49.2	4.0

Capsule	Fluence ($x10^{19}$ n/cm^2) (E>1.0 MeV)	50 ft-lb Transition Temperature			
		SAM McFRAC Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	-29.1	---	-31.8	---
97°	0.507	-29.0	0.1	-26.5	5.3

Capsule	Fluence ($x10^{19}$ n/cm^2) (E>1.0 MeV)	35 MLE Transition Temperature			
		SAM McFRAC Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	-32	---	-45.3	---
97°	0.507	-42.6	-10.6	-37.5	7.8

Table C-4. Comparison of Curve Fit Transition Temperature Shifts for San Onofre Unit 2 Surveillance Material, Heat-Affected-Zone Material

Capsule	Fluence ($x10^{19}$ n/cm^2) (E>1.0 MeV)	30 ft-lb Transition Temperature			
		SAM McFRAC Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	-61.1	---	-62.7	---
97°	0.507	-32.4	28.7	-35.1	27.6

Capsule	Fluence ($x10^{19}$ n/cm^2) (E>1.0 MeV)	50 ft-lb Transition Temperature			
		SAM McFRAC Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	-28.1	---	-35.6	---
97°	0.507	-1.8	26.3	-6.3	29.3

Capsule	Fluence ($x10^{19}$ n/cm^2) (E>1.0 MeV)	35 MLE Transition Temperature			
		SAM McFRAC Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	-20	---	-42.1	---
97°	0.507	-12.0	8.0	-14.0	28.1

APPENDIX D

Fluence Analysis Methodology

The primary tool used in the determination of the flux and fluence exposure to the surveillance capsule dosimeters is the two-dimensional discrete ordinates transport code DORT.[D-3]

The San Onofre Unit 2 capsule was located at 7.0 degrees (off of the major axis) for cycles 1 through 10. The power distributions in the 10 irradiation cycles were symmetric both in θ and Z. That is, the axial power shape is roughly the same for any angle and, conversely, that the azimuthal power shape is the same for any height. This means that the neutron flux at some point (R, θ, Z) can be considered to be a separable function of (R, θ) and (R, Z). Therefore, the cycle 1-10 irradiations can be modeled using the standard Framatome ANP synthesis procedures.[D-1]

Figure D–1 depicts the analytical procedure that is used to determine the fluence accumulated over each irradiation period. As shown in the figure, the analysis is divided into seven tasks: (1) generation of the neutron source, (2) development of the DORT geometry models, (3) calculation of the macroscopic material cross sections, (4) synthesis of the results, and (5-7) estimation of the calculational bias, the calculational uncertainty, and the final fluence. Each of these tasks is discussed in greater detail in the following sections.

D.1. Generation of the Neutron Source

The time-averaged space and energy-dependent neutron sources for cycles 1-10 were calculated using the SORREL[D-4] code. The effects of burnup on the spatial distribution of the neutron source were accounted for by calculating the cycle average fission spectrum for each fissile isotope on an assembly-by-assembly basis, and by determining the cycle-average specific neutron emission rate. This data was then used with the normalized time weighted average pin-by-pin relative power density (RPD) distribution to determine the space and energy-dependent neutron source. The azimuthally averaged, time averaged axial power shape in the peripheral assemblies was used with the fission spectrum of the peripheral assemblies to determine the neutron source for the axial DORT run. These two neutron source distributions were input to DORT as indicated in Figure D–1. Three separate sources (1-9a, 9b and 10) were developed in order to account for two changes in T_{ave} that occurred between cycles 9 and 10.

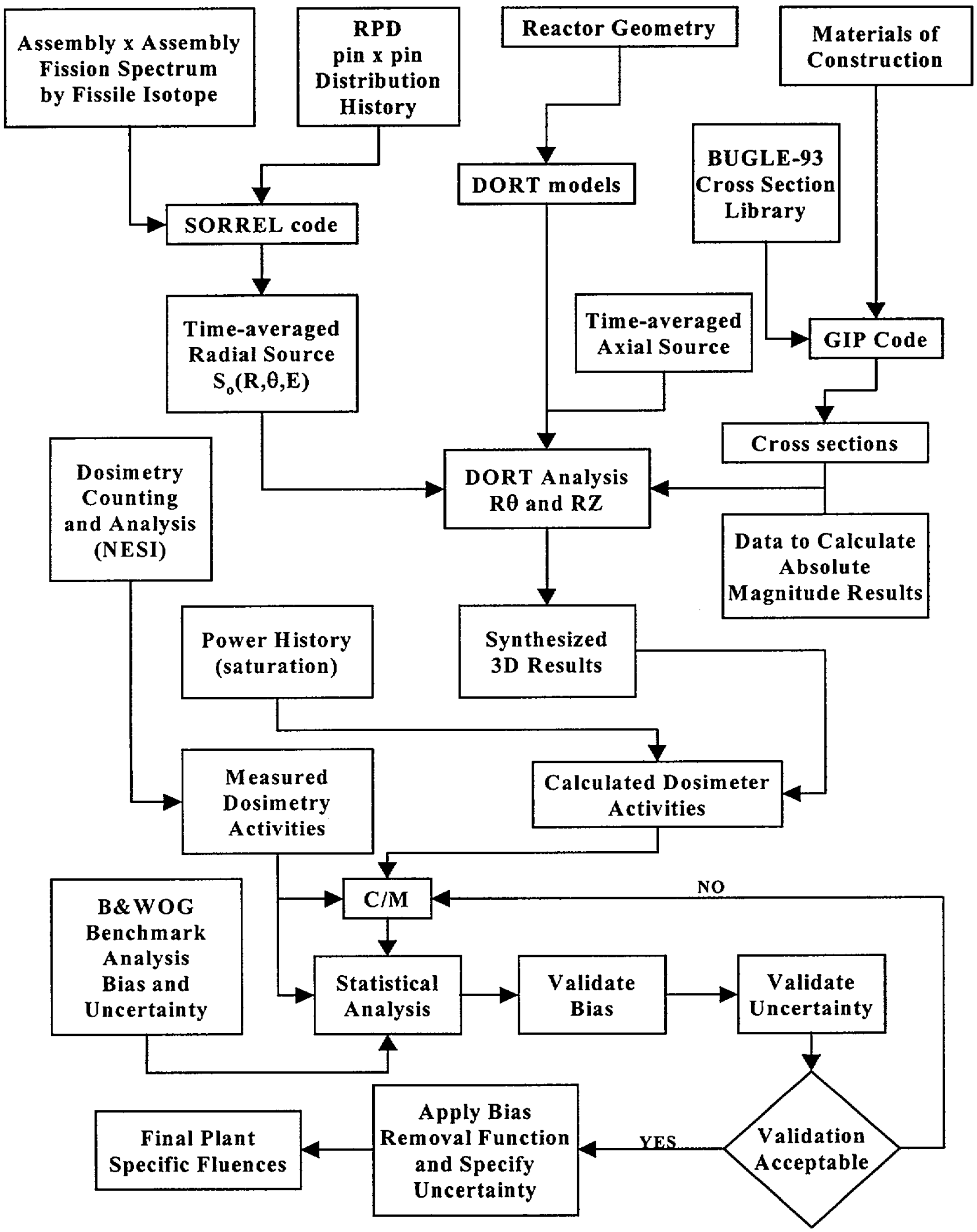
D.2. Development of the Geometrical Models

The system geometry models for the mid-plane (R, θ) DORT were developed using standard FRA-ANP interval size and configuration guidelines. The Rθ model for the cycles 1-9a, 9b, and 10 analysis extended radially from the center of the core to the outer surface of the pressure vessel, and azimuthally from the major axis to 45°. The axial model extended from 35 cm below the active core region to 35 cm above the active core region. The geometrical models either met or exceeded all guidance criteria concerning interval size that are provided in US Regulatory Guide 1.190.[D-2] In all cases, cold dimensions were used. The geometry models were input to the DORT code as indicated in Figure D–1. These models will be used in all subsequent fluence analyses that may be performed by Framatome ANP for San Onofre Unit 2.

D.3. Calculation of Macroscopic Material Cross Sections

In accordance with Regulatory Guide 1.190, the BUGLE-93[D-5] cross section library was used. The GIP code[D-6] was used to calculate the macroscopic energy-dependent cross sections for all materials used in the analysis – from the core out through the pressure vessel and from core plate to core plate. The ENDF/B-VI dosimeter reaction cross sections were used to generate the response functions that were used to calculate the DORT-calculated "saturated" specific activities.

Figure D-1. Fluence Analysis Methodology for San Onofre Unit 2 Surveillance Capsule



D.4. DORT Analyses

The cross sections, geometry, and appropriate source were combined to create a set of DORT models (Rθ and RZ) for the cycles 1-9a, 9b and 10 analyses. Each Rθ DORT run utilized a cross section Legendre expansion of three (P_3), seventy directions (S_{10}), with the appropriate boundary conditions. The RZ models used a cross section Legendre expansion of three (P_3), forty-eight directions (S_8), with the appropriate boundary conditions. A theta-weighted flux extrapolation model was used, and all other requirements of Regulatory Guide 1.190 that relate to the various DORT parameters were either met or exceeded for all DORT runs.

D.5. Synthesized Three Dimensional Results

The DORT analyses produce two sets of two-dimensional flux distributions, one for a vertical cylinder and one for the radial plane for each set of dosimetry. The vertical cylinder, which will be referred to as the RZ plane, is defined as the plane bounded 35 cm above and below the active core region and radially by the center of the core the outside surface of the reactor pressure vessel. The horizontal plane, referred to as the Rθ plane, is defined as the plane bounded radially by the center of the core and the outside surface of the pressure vessel, and azimuthally by the major axis and the adjacent 45 degree radius. The vessel flux, however, varies significantly in all three cylindrical-coordinate directions (R, θ, Z). This means that if a point of interest is outside the boundaries of both the R-Z DORT and the R-θ DORT, the true flux cannot be determined from either DORT run. Under the assumption that the three-dimensional flux is a separable function,[D-1] both two-dimensional data sets were mathematically combined to estimate the flux at all three-dimensional points (R, θ, Z) of interest. The synthesis procedure outlined in Regulatory Guide 1.190 is identical to the basis used for the Framatome ANP flux-synthesis process.

D.6. Calculated Activities and Measured Activities

The calculated activities for each dosimeter type "d" for each irradiation period were determined using the following equation:

$$C_d = \sum_{g=1}^{G} \phi_g(\bar{r}_d) \times RF_g^d \times B_d \times NSF \qquad (1)$$

where

C_d ... calculated specific activity for dosimeter "d" in μCi of product isotope per gram of target isotope

$\phi_g(\vec{r}_d)$	...	three dimensional flux for dosimeter "d" at position $\vec{r}_d$ for energy group "g"
RF_g^d	...	dosimeter response function for dosimeter "d" and energy group "g"
B_d	...	bias correction factors for dosimeter "d"
NSF	...	non-saturation correction factor (NSF).

For this analysis, three separate sets of activities will be calculated, therefore a combination of the calculated activities must be performed. The EOC 10 total calculated activity, $C^{10}{}_{I}$, will be accomplished using the equation, for dosimeter "i",

$$\left(C_{d(\text{cycles 1-10})}\right)_i = \left(C_{d(\text{cycles 1-9a})}\right)_i + \left(C_{d(\text{cycle 9b})}\right)_i + \left(C_{d(\text{cycle 10})}\right)_i . \qquad \textbf{(2)}$$

Each calculated activity in equation 2, $C_{d(cycle)}$, is calculated using equation 1, however each set of data, i.e. 1-9a, 9b and 10, will be calculated using a cycle specific $NSF_{(cycle)}$ factor.

The bias correction factors (B_d) in the specific activity calculation above are listed in Table D–1.

Table D-1. Bias Correction Factors

Dosimeter Type	Bias
Activation	Short Half Life
Fission	Photofission
	Impurities

A photofission factor was applied to correct for the fact that some of the ^{137}Cs atoms present in the dosimeter were produced by (γ, f) reactions and were not accounted for in DORT analysis. Likewise, an impurity factor was included to account for U-235 content in the U-238 dosimetry. The short half life was insignificant and therefore was not applied.

D.7. C/M Ratios

The following explanations will define the meanings of the terms "measurements" (M) and "calculations" (C) as used in this analysis: [D-1]

- Measurements: The meaning of the term "measurements" as used by Framatome ANP is the measurement of the physical quantity of the dosimeter (specific activity) that responded to the neutron fluence, not to the "measured fluence." For the example of an iron dosimeter, a reference to the measurements means the specific activity of ^{54}Mn in μCi /g, which is the product isotope of the dosimeter reaction:

$$^{54}\mathrm{Fe} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{54}\mathrm{Mn} + \mathrm{p}^{+}$$

- Calculations: The calculational methodology produces two primary results – the calculated dosimeter activities and the neutron flux at all points of interest. The meaning of the term "calculations" as used by Framatome ANP is the calculated dosimeter activity. The calculated activities are determined in such a way that they are directly comparable to the measurement values, but without recourse to the measurements. That is, the calculated values are determined by the DORT calculation and are directly comparable to the measurement values. ENDF/B-VI based dosimeter reaction cross sections[D-7] and response functions were used in determining the calculated values for each individual dosimeter. In summary, it should be stressed that the calculation values in the Framatome ANP approach[D-1] are independent of the measurement values.

D.8. Uncertainty

The San Onofre Unit 2 cycles 1 through 10 fluence predictions are based on the methodology described in the Framatome ANP "Fluence and Uncertainty Methodologies" topical report, BAW-2241P-A. The time-averaged fluxes, and thereby the fluences throughout the reactor and vessel, are calculated with the DORT discrete ordinates computer code using three-dimensional synthesis methods. The basic theory for synthesis is described in Section 3.0 of the topical and the DORT three-dimensional synthesis results are the bases for the fluence predictions using the Framatome ANP "Semi-Analytical" (calculational) methodology.

The uncertainties in the San Onofre Unit 2 fluence values have been evaluated to ensure that the greater than 1.0 MeV calculated fluence values are accurate (with no discernible bias) and have a mean standard deviation that is consistent with the Framatome ANP benchmark database of uncertainties. Consistency between the fluence uncertainties in the updated calculations for San Onofre Unit 2 cycles 1-10 and those in the Framatome ANP benchmark database ensures that the vessel fluence predictions are consistent with the 10 CFR 50.61, Pressurized Thermal Shock (PTS) screening criteria and the Regulatory Guide 1.99[D-8] embrittlement evaluations.

The verification of the fluence uncertainty for the San Onofre Unit 2 reactor includes:

- estimating the uncertainties in the cycles 1 through 10 dosimetry measurements,
- estimating the uncertainties in the cycles 1 through 10 benchmark comparison of calculations to measurements,
- estimating the uncertainties in the cycles 1 through 10 pressure vessel fluence, and
- determining if the specific measurement and benchmark uncertainties for cycles 1–10 are consistent with the Framatome ANP database of generic uncertainties in the measurements and calculations.

The embrittlement evaluations in Regulatory Guide 1.99 and those in 10 CFR 50.61 for the PTS screening criteria apply a margin term to the reference temperatures. The margin term includes the product of a confidence factor of 2.0 and the mean embrittlement standard deviation. The factor of 2.0 implies a very high level of confidence in the fluence uncertainty as well as the uncertainty in the other variables contributing to the embrittlement. The dosimeter measurements from the San Onofre Unit 2 analysis would not directly support this high level of confidence. However, the dosimeter measurement uncertainties are consistent with the Framatome ANP database. Therefore, the calculational uncertainties in the updated fluence predictions for San Onofre Unit 2 are supported by 728 additional dosimeter measurements and thirty-nine benchmark comparisons of calculations to measurements as shown in Appendix A of the topical. The calculational uncertainties are also supported by the fluence sensitivity evaluation of the uncertainties in the physical and operational parameters, which are included in the vessel fluence uncertainty.[D-1] The dosimetry measurements and benchmarks, as well as the fluence sensitivity analyses in the topical are sufficient to support a 95 percent confidence level, with a confidence factor of ±2.0, in the fluence results from the "Semi-Analytical" methodology.

The Framatome ANP generic uncertainty in the dosimetry measurements has been determined to be unbiased and has an estimated standard deviation of 7.0 percent for the qualified set of dosimeters. The San Onofre Unit 2 cycles 1-10 dosimetry measurement uncertainties were evaluated to determine if any biases were evident and to estimate the standard deviation. The dosimetry measurements were found to be appropriately calibrated to standards traceable to the National Institute of Standards and Technology and are thereby unbiased by definition. The mean measurement uncertainties associated with cycles 1-10 are as follows:

$$\sigma_M = 6.27\% .$$

This value was determined from Equation 7.6 in the topical[1] and indicates that there is consistency with the Framatome ANP database. Consequently, when the Framatome ANP database is updated, the San Onofre Unit 2 cycles 1-10 dosimetry measurement uncertainties may be combined with the other 728 dosimeters. Since the cycles 1-10 measurements are consistent with the Framatome ANP database, it is estimated that the San Onofre Unit 2 dosimeter measurement uncertainty may be represented by the Framatome ANP database standard deviation of 7.0 percent. Based on the Framatome ANP database, there appears to be a 95 percent level of confidence that 95 percent of the San Onofre Unit 2 dosimetry measurements, for fluence reactions above 1.0 MeV, are within ±14.2 percent of the true values.

The Framatome ANP generic uncertainty for benchmark comparisons of dosimetry calculations relative to the measurements indicates that any benchmark bias in the greater than 1.0 MeV results is too small to be uniquely identified. The estimated standard deviation between the calculations and measurements is 9.9 percent. This implies that the root mean square deviation between the Framatome ANP calculations of the San Onofre Unit 2 dosimetry and the measurements should be approximately 9.9 percent in general and bounded by ±20.04 percent for a 95 percent confidence interval with thirty-nine independent benchmarks.

The weighted mean values of the ratio of calculated dosimeter activities to measurements (C/M) for cycles 1-10 have been statistically evaluated using Equation 7.15 from the topical. The standard deviation in the benchmark comparisons is as follows:

$$\sigma_{C/M} = 0.8133\% .$$

This standard deviation indicates that the benchmark comparisons are consistent with the Framatome ANP database. Consequently, when the Framatome ANP database is updated, the cycles 1-10 benchmark uncertainties may be included with the other thirty-nine benchmark uncertainties in the topical. The consistency between the cycles 1-10 benchmark uncertainties and those in the Framatome ANP database indicates that the San Onofre Unit 2 fluence calculations for cycles 1-10 have no discernible bias in the greater than 1.0 MeV fluence values. In addition, the consistency indicates that the fluence values can be represented by the Framatome ANP reference set which includes a calculational standard deviation of 7.0 percent at dosimetry locations. That is:

Table D-2. Calculational Fluence Uncertainties

Type of Calculation	**Uncertainty (%)**	
	Standard Deviation (σ)	**95% / 95% Confidence ($\approx \pm 2\sigma$)**
Capsule	7.0	14.2
Pressure Vessel (maximum location)	10.0	20.0
Pressure Vessel (extrapolation)	11.4	22.8

D.9. References

D-1. Worsham, J.R., et al., "*Fluence and Uncertainty Methodologies*," BAW-2241P-A, Revision 1, Framatome ANP, Lynchburg, Virginia, April 1999.*

D-2. U.S. Nuclear Regulatory Commission Regulatory Guide 1.190, "*Calculational and Dosimetry Methods for Determining Pressure Vessel Neutron Fluence*," March 2001.

D-3. Rutherford, M. A., N. M. Hassan, et. al., Eds., "*DORT, Two Dimensional Discrete Ordinates Transport Cod,.*" BWNT-TM-107, Framatome Technologies, Inc., Lynchburg, Virginia, May 1995.*

D-4. Hassler, L. A., and N. M. Hassan, "*SORREL, DOT Input Generation Code User's Manual*," NPGD-TM-427, Revision 10, Framatome ANP, Lynchburg, Virginia, May 2001.

D-5. Ingersoll, D. T., et. al., "*BUGLE-93, Production and Testing of the VITAMIN-B6 Fine Group and the BUGLE-93 Broad Group Neutron/photon Cross-Section Libraries Derived from ENDF/B-VI Nuclear Data*," ORNL-DLC-175, Radiation Safety Information Computational Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, April 1994.

D-6. Hassler, L. A. and N. M. Hassan, "*GIP User's Manual for B&W Version, Group Organized Cross Section Input Program*," NPGD-TM-456, Revision 11, Framatome ANP, Lynchburg, Virginia, August 1994.

D-7. Worsham, J. R., "*BUGLE-93 Response Functions*," FRA-ANP Document Number 32-1232719-00, Revision 0, Framatome ANP, Lynchburg, Virginia, June 1995.

D-8. U.S. Nuclear Regulatory Commission, "*Radiation Embrittlement of Reactor Vessel Materials*," Regulatory Guide 1.99, Revision 2, May 1998.

*- Available from Framatome ANP, Inc., Lynchburg, Virginia

APPENDIX E

Reactor Vessel Surveillance Program
Background Data and Information

E.1. San Onofre Unit 2 Reactor Pressure Vessel

The San Onofre Unit 2 reactor vessel was fabricated by Combustion Engineering, Inc. (CE). The San Onofre Unit 2 reactor vessel beltline region consists of two shells (intermediate and lower), containing three base metal plates each with associated longitudinal welds and two circumferential weld seams. Table E-1 presents a description of the San Onofre Unit 2 reactor vessel beltline materials including their copper and nickel chemical contents and their unirradiated RT_{NDT} values.[25] The locations of the materials within the reactor vessel beltline region are shown in Figure E-1.[25]

The heat treatment for the plate materials consisted of austenitization at 1575 ± 50°F for 4 hours; water quenched and tempered at 1225 ± 25°F for 4 hours. For ASME Code qualification, the plates were stress relieved at 1150 ± 25°F for 40 hours and then were furnace cooled to 600°F at a rate of 100°F/hour. The actual time at temperature for a specific weld or plate in the vessel depended upon the sequence of vessel fabrication; intermediate and final stress relief times were selected such that the total did not exceed 40 hours for any particular portion of the vessel. Longitudinal weld seams would see stress relief times near the 40 hour maximum, while the closing girth weld in the beltline region would see not more than approximately half this amount. All of the testing of plate materials was performed on pieces with essentially an identical heat treatment as the actual reactor vessel. The surveillance weldment received a final 42-hour and 15-minute stress relief at 1100°F to 1150°F.[25]

E.2. Surveillance Material Selection Data

The plate material that was selected for the surveillance program was selected based on an estimate of the highest end of life RT_{NDT}, in accordance with ASTM Standard E 185-70. However, the surveillance program was updated to the later 1973 version. The San Onofre Unit 2 RVSP capsules include the predicted limiting reactor vessel beltline plate C-6404-2, heat no. C7595-2 at the time of the development of the surveillance program.[9] The surveillance weld used in the San Onofre Unit 2 RVSP was fabricated using the wire heat 90130 which is the same wire heat used for the lower to intermediate shell girth weld in the San Onofre Unit 2 reactor vessel.[25]

Table E-1. Description of the San Onofre Unit 2 Reactor Vessel Beltline Region Materials

Beltline Region Location	Material Identification	Material Type	Material Heat No.	Chemical Composition		Initial Toughness Properties		
				Cu, wt%	Ni, wt%	NDT, F	RT_{NDT}, F	USE, ft-lbs
Inter. Shell Long. Welds	2-203A	Subarc Weld	E8018	0.03	0.90	-60	-60	126
Inter. Shell Long. Welds	2-203B	Subarc Weld	E8018	0.03	0.91	-60	-60	106
Inter. Shell Long. Welds	2-203C	Subarc Weld	E8018	0.03	0.95	-60	-60	106
Lower Shell Long. Welds	3-203A	Subarc Weld	83637	0.05	0.12	-50	-50	136
Lower Shell Long. Welds	3-203B	Subarc Weld	83637	0.04	0.06	-50	-50	136
Lower Shell Long. Welds	3-203C	Subarc Weld	83637	0.06	0.11	-50	-50	136
Lower/Inter. Shell Girth Weld	9-203	Subarc Weld	90130	0.07	0.29	-60	-60	144
Intermediate Shell	C-6404-1	A 533B-1	C7596-1	0.10	0.56	-30	+20	119
Intermediate Shell	C-6404-2	A 533B-1	C7595-2	0.10	0.59	+10	+20	113
Intermediate Shell	C-6404-3	A 533B-1	C7595-1	0.10	0.56	-20	+20	99
Lower Shell	C-6404-4	A 533B-1	A6735-1	0.10	0.62	-10	+20	104
Lower Shell	C-6404-5	A 533B-1	C7585-1	0.11	0.64	-20	+10	118
Lower Shell	C-6404-6	A 533B-1	C7596-2	0.10	0.58	-10	-10	124

Figure E-1. Location and Identification of Materials used in the Fabrication of the San Onofre Unit 2 Reactor Pressure Vessel