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Arkansas Nuclear One, Unit 2
Reactor Vessel Radiation Surveillance Program"**

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Analysis of Capsule 284° from the Entergy Operations, Inc. Arkansas Nuclear One Unit 2 Reactor Vessel Radiation Surveillance Program

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EXECUTIVE SUMMARY

The purpose of this report is to document the testing results of surveillance Capsule 284° from Arkansas Nuclear One Unit 2 (ANO-2). Capsule 284° was removed at 29.24 effective full-power years (EFPY) and post-irradiation mechanical tests of the Charpy V-notch and tensile specimens were performed. A fluence evaluation utilizing the neutron transport and dosimetry cross-section libraries was derived from the Evaluated Nuclear Data File (ENDF) database (specifically, ENDF/B-VI). Capsule 284° received a fluence of 3.67 x 10^{19} n/cm^2 (E > 1.0 MeV) after irradiation to 29.24 EFPY. The peak clad/base metal interface vessel fluence after 32 EFPY (end-of-license) of plant operation is projected to be 3.02 x 10^{19} n/cm^2 (E > 1.0 MeV).

This evaluation led to the following conclusions: 1) The measured percent decreases in upper-shelf energy for the surveillance plate and weld materials contained in ANO-2 Capsule 284° are less than the Regulatory Guide 1.99, Revision 2 [Ref. 1] predictions. 2) The ANO-2 surveillance plate data and surveillance weld (Heat # 83650) are judged to be credible. This credibility evaluation can be found in Appendix D. 3) With consideration of surveillance data, all beltline materials exhibit adequate upper-shelf energy levels for continued safe plant operation and are predicted to maintain an upper-shelf energy greater than 50 ft-lb through end-of-license (32 EFPY) as required by 10 CFR 50, Appendix G [Ref. 2]. The upper-shelf energy evaluation is presented in Appendix E.

Lastly, a brief summary of the Charpy V-notch testing can be found in Section 1. All Charpy V-notch data was plotted using a symmetric hyperbolic tangent curve-fitting program.

1 SUMMARY OF RESULTS

The analysis of the reactor vessel materials contained in surveillance Capsule 284°, the third capsule removed and tested from the Arkansas Nuclear One Unit 2 (ANO-2) reactor pressure vessel, led to the following conclusions:

- Charpy V-notch test data were plotted using a symmetric hyperbolic tangent curve-fitting program. Appendix C presents the CVGRAPH, Version 6.02, Charpy V-notch plots for Capsule 284° and previous capsules, along with the program input data.

- Capsule 284° received an average fast neutron fluence (E > 1.0 MeV) of 3.67 x 10^{19} n/cm^2 after 29.24 effective full-power years (EFPY) of plant operation.

- Irradiation of the reactor vessel Intermediate Shell Plate C-8009-3 Charpy specimens, oriented with the longitudinal axis of the specimen parallel to the major rolling direction (longitudinal orientation), resulted in an irradiated 30 ft-lb transition temperature of 86.2°F and an irradiated 50 ft-lb transition temperature of 121.1°F. This results in a 30 ft-lb transition temperature increase of 85.7°F and a 50 ft-lb transition temperature increase of 98.9°F for the longitudinally oriented specimens.

- Irradiation of the reactor vessel Intermediate Shell Plate C-8009-3 Charpy specimens, oriented with the longitudinal axis of the specimen perpendicular to the major rolling direction (transverse orientation), resulted in an irradiated 30 ft-lb transition temperature of 100.5°F and an irradiated 50 ft-lb transition temperature of 138.5°F. This results in a 30 ft-lb transition temperature increase of 85.6°F and a 50 ft-lb transition temperature increase of 96.0°F for the transversely oriented specimens.

- Irradiation of the Surveillance Program Weld Material (Heat # 83650) Charpy specimens resulted in an irradiated 30 ft-lb transition temperature of 8.2°F and an irradiated 50 ft-lb transition temperature of 37.1°F. This results in a 30 ft-lb transition temperature increase of 12.0°F and a 50 ft-lb transition temperature increase of 26.3°F.

- Irradiation of the Heat-Affected Zone (HAZ) Material Charpy specimens resulted in an irradiated 30 ft-lb transition temperature of -56.4°F and an irradiated 50 ft-lb transition temperature of -17.8°F. This results in a 30 ft-lb transition temperature increase of 73.5°F and a 50 ft-lb transition temperature increase of 69.8°F.

- The average upper-shelf energy of Intermediate Shell Plate C-8009-3 (longitudinal orientation) resulted in an average energy decrease of 37 ft-lb after irradiation. This decrease results in an irradiated average upper-shelf energy of 122 ft-lb for the longitudinally oriented specimens.

- The average upper-shelf energy of Intermediate Shell Plate C-8009-3 (transverse orientation) resulted in an average energy decrease of 25 ft-lb after irradiation. This decrease results in an irradiated average upper-shelf energy of 109 ft-lb for the transversely oriented specimens.

- The average upper-shelf energy of the Surveillance Program Weld Material (Heat # 83650) Charpy specimens resulted in an average energy decrease of 19 ft-lb after irradiation. This decrease results in an irradiated average upper-shelf energy of 132 ft-lb for the weld metal specimens.

- The average upper-shelf energy of the HAZ Material Charpy specimens resulted in an average energy decrease of 19 ft-lb after irradiation. This decrease results in an irradiated average upper-shelf energy of 142 ft-lb for the HAZ Material.

- Comparisons of the measured 30 ft-lb shift in transition temperature values and upper-shelf energy decreases to those predicted by Regulatory Guide 1.99, Revision 2 [Ref. 1] for the ANO-2 reactor vessel surveillance materials are presented in Table 5-10.

  Standard Reference Material (SRM) Heavy-Section Steel Technology (HSST) 01 Charpy specimens were not included in the ANO-2 Capsule 284°. However, the SRM HSST 01 Charpy specimens were reanalyzed in this report. The SRM HSST 01 material was contained in Capsule 104°, which was irradiated to a neutron fluence of 2.15 x 10^{19} n/cm^2 (E > 1.0 MeV). The results of the SRM HSST 01 reanalysis are included in Table 5-10 and shown in Figures 5-13 through 5-15.

  - Irradiation of the SRM HSST 01 Charpy specimens resulted in an irradiated 30 ft-lb transition temperature of 163.8°F and an irradiated 50 ft-lb transition temperature of 205.3°F. This results in a 30 ft-lb transition temperature increase of 132.3°F and a 50 ft-lb transition temperature increase of 150.6°F.

  - The average upper-shelf energy of the SRM HSST 01 Charpy specimens resulted in an average energy decrease of 59 ft-lb after irradiation. This decrease results in an irradiated average upper-shelf energy of 87 ft-lb.

- Based on the credibility evaluation presented in Appendix D, the ANO-2 surveillance plate and the surveillance weld material (Heat # 83650) are both credible.

- Based on the upper-shelf energy evaluation in Appendix E, all beltline materials contained in the ANO-2 reactor vessel exhibit adequate upper-shelf energy levels for continued safe plant operation and are predicted to maintain an upper-shelf energy greater than 50 ft-lb through end-of-license (32 EFPY) as required by 10 CFR 50, Appendix G [Ref. 2].

- The maximum calculated 32 EFPY (end-of-license) neutron fluence (E > 1.0 MeV) for the ANO-2 reactor vessel beltline using the Regulatory Guide 1.99, Revision 2 [Ref. 1] attenuation formula (i.e., Equation # 3 in the Guide) is as follows:

  Calculated (32 EFPY): Vessel peak clad/base metal interface fluence* = 3.02 x 10^{19} n/cm^2
  Vessel peak quarter-thickness (1/4T) fluence = 1.88 x 10^{19} n/cm^2

  *This fluence value is documented in Table 6-4

2 INTRODUCTION

This report presents the results of the examination of Capsule 284°, the third capsule removed and tested in the continuing surveillance program, which monitors the effects of neutron irradiation on the Entergy Operations, Inc. (Entergy) ANO-2 reactor pressure vessel materials under actual operating conditions.

The surveillance program for the ANO-2 reactor pressure vessel materials was designed and recommended by Westinghouse Electric Company, LLC. A detailed description of the surveillance program is contained in A-NLM-005, Revision 1 [Ref. 3], "Program for Irradiation Surveillance of Arkansas Nuclear One Unit 2 Reactor Vessel Materials." The ANO-2 capsule contents are documented in CEN-15(A)-P [Ref. 4], "Summary Report on Manufacture of Test Specimens and Assembly of Capsules for Irradiation Surveillance of Arkansas Nuclear One – Unit 2 Reactor Vessel Materials." The pre-irradiation mechanical properties of the reactor vessel materials are presented in TR-MCD-002 [Ref. 5], "Arkansas Power & Light Arkansas Nuclear One – Unit 2 Evaluation of Baseline Specimens Reactor Vessel Materials Irradiation Surveillance Program." The surveillance program was originally planned to cover the 40-year design life of the reactor pressure vessel and was based on ASTM E185-73 [Ref. 6], "Standard Recommended Practice for Surveillance Tests for Nuclear Reactor Vessels." Capsule 284° was removed from the reactor after 29.24 EFPY of exposure and shipped to the Westinghouse Materials Center of Excellence Hot Cell Facility, where the post-irradiation mechanical testing of the Charpy V-notch impact and tensile surveillance specimens was performed.

This report summarizes the testing and post-irradiation data obtained from surveillance Capsule 284° removed from the ANO-2 reactor vessel and discusses the analysis of the data.

3 BACKGROUND

The ability of the large steel pressure vessel containing the reactor core and its primary coolant to resist fracture constitutes an important factor in ensuring safety in the nuclear industry. The beltline region of the reactor pressure vessel is the most critical region of the vessel because it is subjected to significant fast neutron bombardment. The overall effects of fast neutron irradiation on the mechanical properties of low-alloy, ferritic pressure vessel steels such as SA533 Grade B Class 1 (base material of the ANO-2 reactor pressure vessel beltline) are well documented in the literature. Generally, low-alloy ferritic materials show an increase in hardness and tensile properties and a decrease in ductility and toughness during high-energy irradiation.

A method for ensuring the integrity of reactor pressure vessels has been presented in "Fracture Toughness Criteria for Protection Against Failure," Appendix G to Section XI of the ASME Boiler and Pressure Vessel Code [Ref. 7]. The method uses fracture mechanics concepts and is based on the reference nil-ductility transition temperature (RT_{NDT}).

RT_{NDT} is defined as the greater of either the drop-weight nil-ductility transition temperature (NDTT per ASTM E208-06 [Ref. 8]) or the temperature 60°F less than the 50 ft-lb (and 35-mil lateral expansion) temperature as determined from Charpy specimens oriented perpendicular (transverse) to the major rolling direction of the plate. The RT_{NDT} of a given material is used to index that material to a reference stress intensity factor curve (K_{Ic} curve) which appears in Appendix G to Section XI of the ASME Code [Ref. 7]. The K_{Ic} curve is a lower bound of static fracture toughness results obtained from several heats of pressure vessel steel. When a given material is indexed to the K_{Ic} curve, allowable stress intensity factors can be obtained for this material as a function of temperature. Allowable operating limits can then be determined using these allowable stress intensity factors.

RT_{NDT} and, in turn, the operating limits of nuclear power plants can be adjusted to account for the effects of radiation on the reactor vessel material properties. The changes in mechanical properties of a given reactor pressure vessel steel, due to irradiation, can be monitored by a reactor vessel surveillance program, such as the ANO-2 reactor vessel radiation surveillance program, in which a surveillance capsule is periodically removed from the operating nuclear reactor and the encapsulated specimens are tested. The increase in the average Charpy V-notch 30 ft-lb temperature (ΔRT_{NDT}) due to irradiation is added to the initial RT_{NDT}, along with a margin (M) to cover uncertainties, to adjust the RT_{NDT} (ART) for radiation embrittlement. This ART (initial RT_{NDT} + M + ΔRT_{NDT}) is used to index the material to the K_{Ic} curve and, in turn, to set operating limits for the nuclear power plant that take into account the effects of irradiation on the reactor vessel materials.

4 DESCRIPTION OF PROGRAM

Six surveillance capsules for monitoring the effects of neutron exposure on the ANO-2 reactor pressure vessel core region (beltline) materials were inserted in the reactor vessel prior to initial plant startup. The six capsules were positioned in the reactor vessel, as shown in Figure 4-1, between the core barrel and the vessel wall, at various azimuthal locations. The vertical center of the capsules is opposite the vertical center of the core. The capsules contain specimens made from the following:

- Intermediate Shell Plate C-8009-3 (longitudinal orientation)
- Intermediate Shell Plate C-8009-3 (transverse orientation)
- Weld metal fabricated with weld wire Heat Number 83650, Linde Type 0091 flux, Lot Number 1122 which is equivalent to the heat number, Flux Type, and Flux Lot number used in the actual fabrication of the intermediate shell to lower shell circumferential weld seam
- Weld heat-affected zone (HAZ) material of Intermediate Shell Plate C-8009-3
- Standard Reference Material (SRM) Heavy-Section Steel Technology (HSST)-01MY Plate

Test material obtained from the Intermediate Shell Plate C-8009-3 (after thermal heat treatment and forming of the plate) was taken at least one plate thickness from the quenched edges of the plate. All test specimens were machined from the ¼ thickness location of the plate after performing a simulated post-weld stress-relieving treatment on the test material. Test specimens were also removed from the weld and heat-affected zone metal of stress-relieved weldments joining Intermediate Shell Plate C-8009-1 and adjacent Intermediate Shell Plate C-8009-2 for the weld and Intermediate Shell Plate C-8009-2 and Intermediate Shell Plate C-8009-3 for the heat-affected zone. All heat-affected zone specimens were obtained from the weld heat-affected zone of Intermediate Shell Plate C-8009-3.

Charpy V-notch impact specimens from Intermediate Shell Plate C-8009-3 were machined in the longitudinal orientation (longitudinal axis of the specimen parallel to the major rolling direction) and also in the transverse orientation (longitudinal axis of the specimen perpendicular to the major rolling direction). The core-region weld Charpy impact specimens were machined from the weldment such that the long dimension of each Charpy specimen was perpendicular (normal) to the weld direction. The notch of the weld metal Charpy specimens was machined such that the direction of crack propagation in the specimen was in the welding direction.

Tensile specimens from Intermediate Shell Plate C-8009-3 were machined in the transverse orientation only. Tensile specimens from the weld metal were oriented perpendicular to the welding direction.

Some of the ANO-2 capsules, specifically the previously tested Capsule 104° and also Capsule 263°, which is still in the reactor vessel, contain SRM, which was supplied by the Oak Ridge National Laboratory, from plate materials used in the HSST Program. The material for the ANO-2 Capsules was obtained from an A533, Grade B Class 1 plate labeled HSST 01. The plate was produced by the Lukens Steel Company and heat treated by Combustion Engineering, Inc. (CE).

All six capsules contain flux monitor assemblies that include sulfur pellets, iron wire, titanium wire, nickel wire *(cadmium-shielded)*, aluminum-cobalt wire *(cadmium-shielded and unshielded)*, copper wire *(cadmium-shielded)* and uranium foil *(cadmium-shielded and unshielded)*.

The capsules contain (12 total) thermal monitors made from four low-melting-point eutectic alloys, which were sealed in quartz tubes. These thermal monitors were located in three different positions in the capsule. These thermal monitors are used to define the maximum temperature attained by the test specimens during irradiation. The composition of the four eutectic alloys and their melting points are as follows:

80.0% Au, 20.0% Sn	Melting Point: 536°F (280°C)
5.0% Ag, 5.0% Sn, 90.0% Pb	Melting Point: 558°F (292°C)
2.5% Ag, 97.5% Pb	Melting Point: 580°F (304°C)
1.75% Ag, 0.75% Sn, 97.5% Pb	Melting Point: 590°F (310°C)

The chemical composition and the arrangement of the various mechanical specimens in Capsule 284° are presented in Tables 4-1 and 4-2, respectively. The data in Tables 4-1 and 4-2 was obtained from the original specimen manufacture and capsule assembly report, CEN-15(A)-P [Ref. 4], as well as NUREG/CR-6413 [Ref. 9].

Capsule 284° was removed after 29.24 EFPY of plant operation. This capsule contained Charpy V-notch specimens, tensile specimens, dosimeters, and thermal monitors. Figures 4-1 through 4-4 detail the arrangement of the surveillance capsules, an example of an original program surveillance capsule, a close-up of the Charpy impact specimen compartment, and the tensile and flux-monitor compartment assembly in the ANO-2 reactor vessel. Capsules 83°, 97°, 263° and 277° are radiologically equivalent to the 7° azimuth, while Capsules 104° and 284° are radiologically equivalent to the 14° azimuth.

Table 4-1 Chemical Composition (wt. %) of the ANO-2 Reactor Vessel Surveillance Materials (Unirradiated)[(a)]

Element	Intermediate Shell Plate C-8009-3		Standard Reference Material HSST 01MY Plate[(c)]	Surveillance Weld Metal[(d)]	
	Original CE Analysis[(a)]	Best-Estimate Analysis[(b)]		Original CE Analysis[(a)]	Best-Estimate Analysis[(b)]
C	0.22	---	---	0.13	---
Mn	1.40	---	---	1.33	---
P	0.009	---	---	0.004	---
S	0.011	---	---	0.009	---
Si	0.21	---	---	0.14	---
Ni	**0.60**	**0.580**	**0.66**	**0.08**	**0.083**
Mo	0.63	---	---	0.62	---
Cr	0.15	---	---	0.02	---
Cu	**0.08**	**0.096**	**0.18**	**0.04**	**0.045**
Al	0.034	---	---	0.001	---
Co	0.012	---	---	0.003	---
W	<0.01	---	---	<0.01	---
Ti	<0.01	---	---	<0.01	---
Zr	0.001	---	---	0.001	---
V	0.006	---	---	0.006	---
Sn	0.005	---	---	0.001	---
As	0.010	---	---	0.006	---
Cb	<0.01	---	---	<0.01	---
N_2	0.008	---	---	0.005	---
B	<0.001	---	---	<0.001	---

Notes:

(a) Data obtained from CEN-15(A)-P, Table III [Ref. 4], unless otherwise noted.

(b) Chemistry values are the average of all available data from unirradiated and capsule chemistry test results. Nine measurements in total were averaged for the plate, while six measurements in total were averaged for the weld.

(c) Data obtained from NUREG/CR-6413 [Ref. 9].

(d) The surveillance weld was fabricated with the same wire, flux type, and flux lot as that used in the intermediate to lower shell circumferential weld seam 9-203. The surveillance and reactor vessel welds were fabricated using weld wire heat number 83650, with a Linde 0091 flux, Lot Number 1122.

Table 4-2 Arrangement of Encapsulated Test Specimens within ANO-2 Capsule 284°

Compartment Position[(a)]	Compartment Number (Specimen Type and Material)[(a)]	Specimen Numbers[(a)]
1	D614 (Tensile HAZ Specimens)	4KT, 4KE, 4JL
2	D624 (Charpy Impact HAZ Specimens)	42B, 47T, 454, 42A, 46J, 43B, 412, 433, 47M, 423, 411, 41P
3	D631 (Charpy Impact Longitudinal Plate Specimens)	11B, 11P, 13E, 12K, 13J, 12E, 111, 14P, 136, 15J, 11M, 125
4	D642 (Tensile Transverse Plate Specimens)	2KE, 2KY, 2KU
5	D652 (Charpy Impact Transverse Plate Specimens)	22C, 235, 233, 21T, 265, 237, 267, 23P, 23M, 21M, 21J, 221
6	D663 (Charpy Impact Weld Specimens)	33M, 313, 37U, 367, 311, 352, 37E, 32L, 341, 33T, 365, 35C
7	D673 (Tensile Weld Specimens)	3JU, 3JB, 3KD

Note:

(a) Data obtained from CEN-15(A)-P, Table XIX and/or Table XX [Ref. 4].

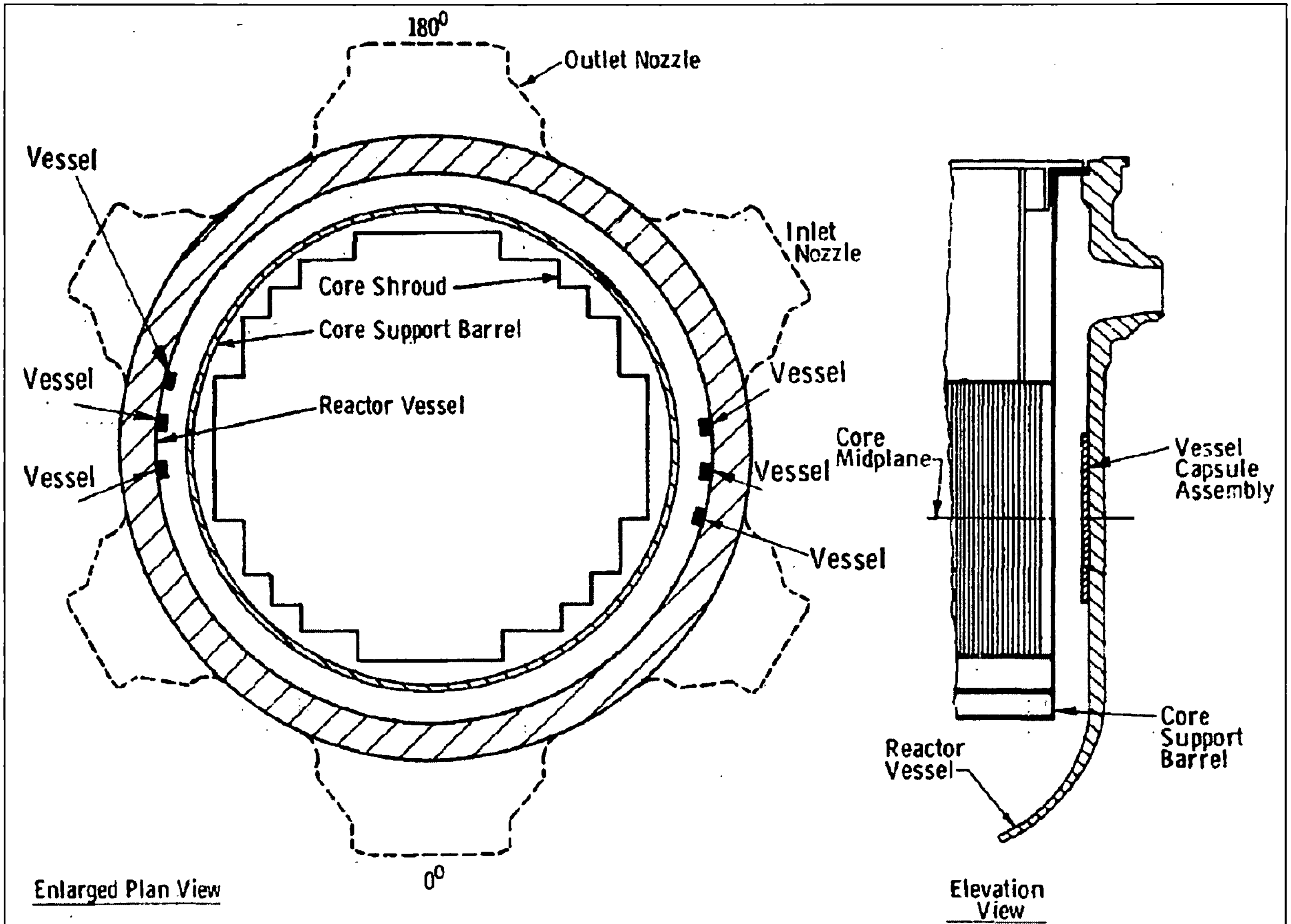


Figure 4-1 Arrangement of Surveillance Capsules in the ANO-2 Reactor Vessel

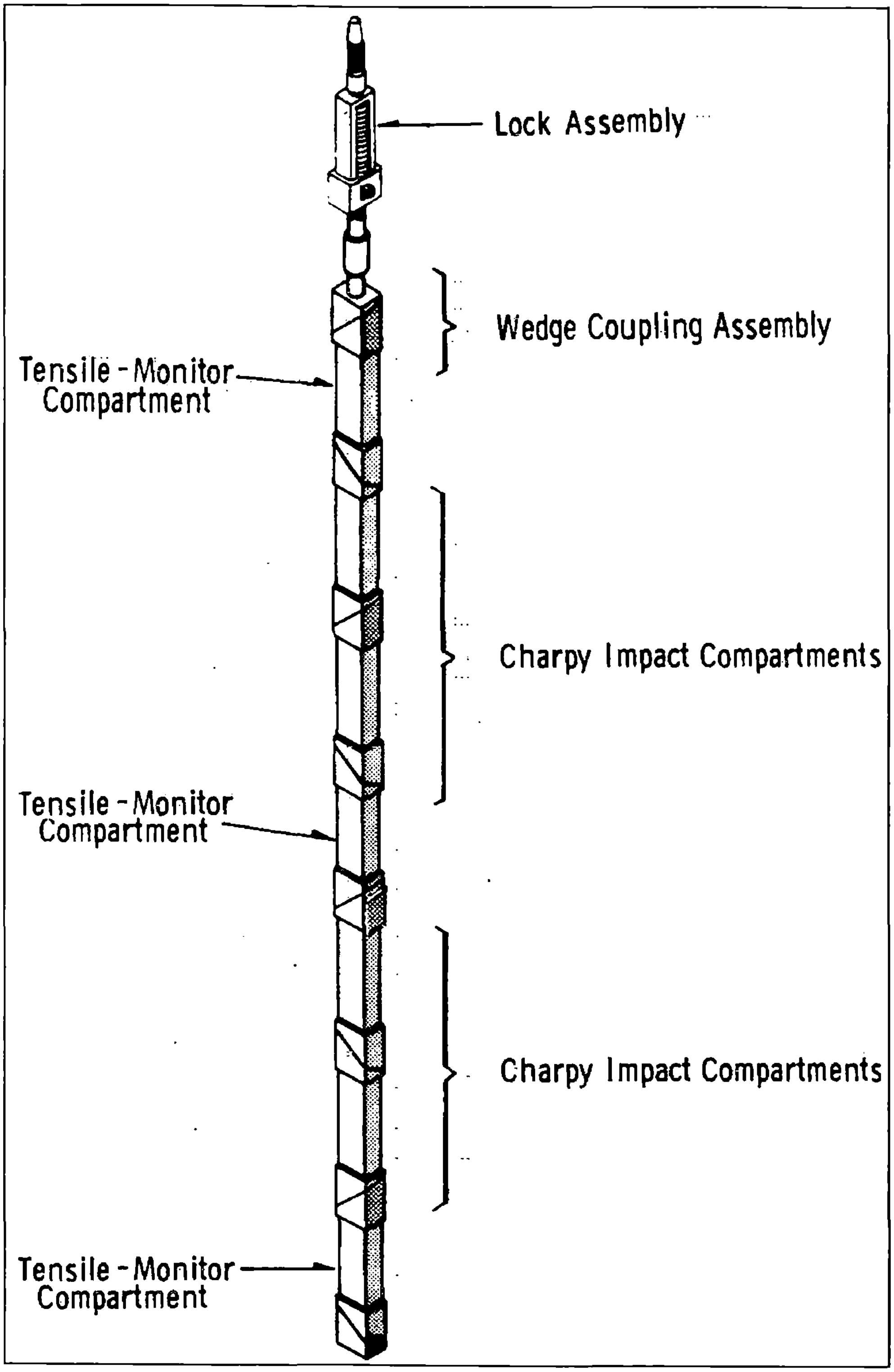


Figure 4-2 Original Surveillance Program Capsule in the ANO-2 Reactor Vessel

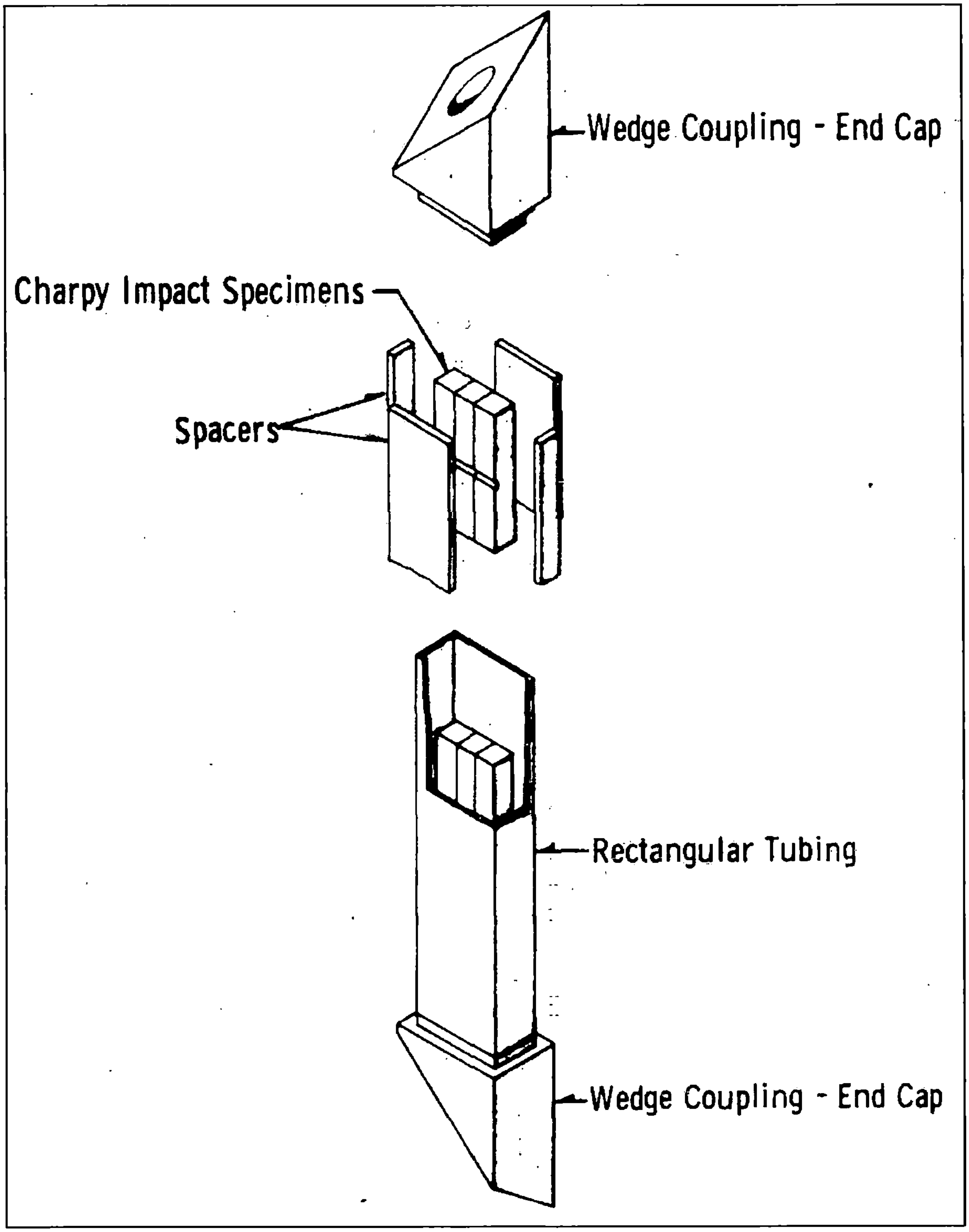


Figure 4-3 Surveillance Capsule Charpy Impact Specimen Compartment Assembly in the ANO-2 Reactor Vessel

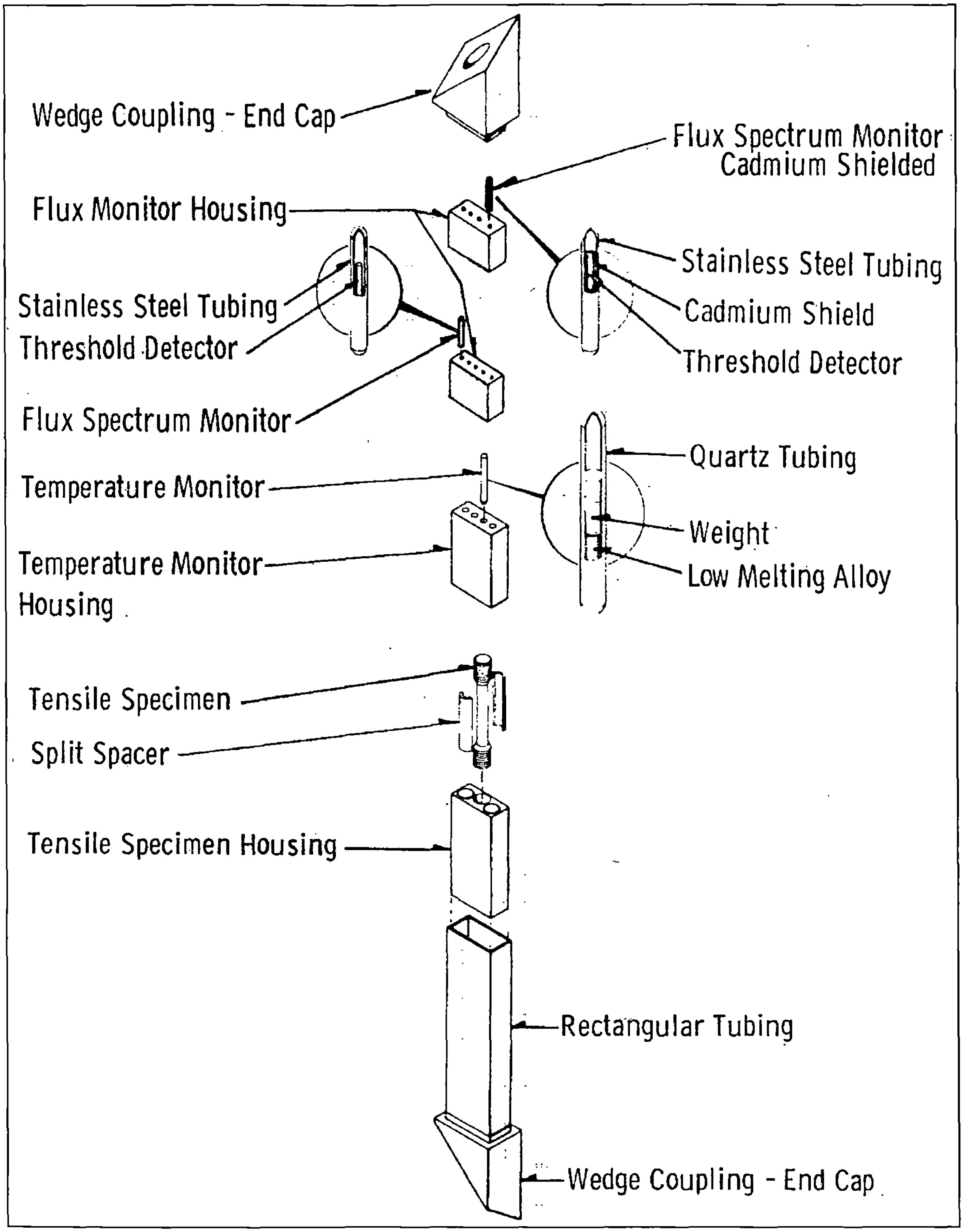


Figure 4-4 Surveillance Capsule Tensile and Flux-Monitor Compartment Assembly in the ANO-2 Reactor Vessel

5 TESTING OF SPECIMENS FROM CAPSULE 284°

5.1 OVERVIEW

The post-irradiation mechanical testing of the Charpy V-notch impact specimens and tensile specimens was performed at the Westinghouse Materials Center of Excellence Hot Cell Facility. Testing was performed in accordance with 10 CFR 50, Appendix H [Ref. 2] and ASTM Specification E185-82 [Ref. 10].

Capsule 284° was opened upon receipt at the hot cell laboratory. The specimens and spacer blocks were carefully removed, inspected for identification number, and checked against the master list in CEN-15(A)-P [Ref. 4]. All of the items were in their proper locations.

Examination of the thermal monitors indicated that the 536°F and 558°F temperature monitors had melted at all three axial locations. None of the 580°F or 590°F temperature monitors had melted. Based on this examination, the maximum temperature to which the specimens were exposed was less than 580°F (304°C) and greater than 558°F (292°C), assuming a uniform temperature throughout the capsule.

The Charpy impact tests were performed per ASTM Specification E185-82 [Ref. 10] and E23-07a [Ref. 11] on a Tinius-Olsen Model 74, 358J machine. The Charpy machine striker was instrumented with an Instron®[1] Impulse system. Instrumented testing and calibration were performed to ASTM E2298-15 [Ref. 12].

The instrumented striker load signal data acquisition rate was 819 kHz with data acquired for 10 ms. From the load-time curve, the load of general yielding (F_{gy}), the maximum load (F_m) and the time to maximum load were determined. Under some test conditions, a sharp drop in load indicative of fast fracture was observed. The load at which fast fracture was initiated is identified as the brittle fracture initiation/load at initiation of unstable crack propagation (F_{bf}). The termination load after the fast load drop is identified as the arrest load/load at end of unstable crack propagation (F_a). F_{gy}, F_m, F_{bf}, and F_a were determined per the guidance in ASTM Standard E2298-15 [Ref. 12].

The pre-maximum load energy (W_m) was determined by integrating the load-time record to the maximum load point via the instrumented Charpy software. The pre-maximum load energy is approximately equivalent to the energy required to initiate a crack in the specimen. Therefore, the propagation energy for the crack (W_p) is the difference between the total impact energy (W_t) and the pre-maximum load energy (W_m). W_t is compared to the absorbed energy measured from the dial energy (KV).

Percent shear was determined from post-fracture photographs using the ratio-of-areas method in compliance with ASTM E23-07a [Ref. 11] and A370-16 [Ref. 13]. The lateral expansion was measured using a dial gage rig similar to that shown in the same ASTM Standards.

[1]Instron is a registered trademark of Instron Corporation.

Tensile tests were performed on a 250 kN Instron® screw driven tensile machine (Model 5985) per ASTM E185-82 [Ref. 10]. Testing met ASTM Specifications E8/E8M-15a [Ref. 14] for room temperature or E21-09 [Ref. 15] for elevated temperatures.

The tensile specimens were, nominally, 3.00 inches long with a 1.00 inch gage section and a reduced section 1.50 inches long with a 0.250 inch diameter, per CEN-15(A)-P [Ref. 4]. Load was applied through a threaded connection. Strain measurements were made using an extensometer, which was attached to the 1.00 inch gage section of the tensile specimen. The strain rate obtained met the requirements of ASTM E8/E8M-15a [Ref. 14] and ASTM E21-09 [Ref. 15].

Elevated test temperatures were obtained with a three-zone electric resistance split-tube Instron SF-16 furnace with an 11-inch hot zone. For the elevated tests, temperature was measured by two Type N thermocouples in contact with the gage section of the specimen per ASTM E21-09 [Ref. 15]. Tensile specimens were soaked at temperature (± 5°F) for a minimum of 20 minutes before testing. All tests were conducted in air.

The yield load, ultimate load, fracture load, uniform elongation, and elongation at fracture were determined directly from the load-extension curve. The yield strength (0.2% offset method), ultimate tensile strength, and fracture strength were calculated using the original cross-sectional area. Yield point elongation (YPE) was calculated as the difference in strain between the upper yield strength and the onset of uniform strain hardening using the methodology described in ASTM E8/E8M-15a [Ref. 14]. The final diameter and final gage length were determined from post-fracture photographs. This final diameter measurement was used to calculate the fracture stress (fracture true stress) and the percent reduction in area. The final and original gage lengths were used to calculate total elongation after fracture.

5.2 CHARPY V-NOTCH IMPACT TEST RESULTS

The results of the Charpy V-notch impact tests performed on the various materials contained in Capsule 284°, which received a fluence of 3.67 x 10^{19} n/cm^2 (E > 1.0 MeV) in 29.24 EFPY of operation, are presented in Tables 5-1 through 5-8 and are compared with the unirradiated and previously withdrawn capsule results as shown in Figures 5-1 through 5-12. The unirradiated and previously withdrawn capsule results were taken from TR-MCD-002 [Ref. 5], BMI-0584 [Ref. 16], and BAW-2399, Revision 1 [Ref. 17]. The previous capsules, along with the original program unirradiated material input data, were updated using CVGRAPH, Version 6.02.

The transition temperature increases and decreases in upper-shelf energies for the Capsule 284° materials are summarized in Table 5-9 and led to the following results:

- Irradiation of the reactor vessel Intermediate Shell Plate C-8009-3 Charpy specimens, oriented with the longitudinal axis of the specimen parallel to the major rolling direction (longitudinal orientation), resulted in an irradiated 30 ft-lb transition temperature of 86.2°F and an irradiated 50 ft-lb transition temperature of 121.1°F. This results in a 30 ft-lb transition temperature increase of 85.7°F and a 50 ft-lb transition temperature increase of 98.9°F for the longitudinally oriented specimens.

- Irradiation of the reactor vessel Intermediate Shell Plate C-8009-3 Charpy specimens, oriented with the longitudinal axis of the specimen perpendicular to the major rolling direction (transverse

orientation), resulted in an irradiated 30 ft-lb transition temperature of 100.5°F and an irradiated 50 ft-lb transition temperature of 138.5°F. This results in a 30 ft-lb transition temperature increase of 85.6°F and a 50 ft-lb transition temperature increase of 96.0°F for the transversely oriented specimens.

- Irradiation of the Surveillance Program Weld Material (Heat # 83650) Charpy specimens resulted in an irradiated 30 ft-lb transition temperature of 8.2°F and an irradiated 50 ft-lb transition temperature of 37.1°F. This results in a 30 ft-lb transition temperature increase of 12.0°F and a 50 ft-lb transition temperature increase of 26.3°F.

- Irradiation of the HAZ Material Charpy specimens resulted in an irradiated 30 ft-lb transition temperature of -56.4°F and an irradiated 50 ft-lb transition temperature of -17.8°F. This results in a 30 ft-lb transition temperature increase of 73.5°F and a 50 ft-lb transition temperature increase of 69.8°F.

- The average upper-shelf energy of Intermediate Shell Plate C-8009-3 (longitudinal orientation) resulted in an average energy decrease of 37 ft-lb after irradiation. This decrease results in an irradiated average upper-shelf energy of 122 ft-lb for the longitudinally oriented specimens.

- The average upper-shelf energy of Intermediate Shell Plate C-8009-3 (transverse orientation) resulted in an average energy decrease of 25 ft-lb after irradiation. This decrease results in an irradiated average upper-shelf energy of 109 ft-lb for the transversely oriented specimens.

- The average upper-shelf energy of the Surveillance Program Weld Material (Heat # 83650) Charpy specimens resulted in an average energy decrease of 19 ft-lb after irradiation. This decrease results in an irradiated average upper-shelf energy of 132 ft-lb for the weld metal specimens.

- The average upper-shelf energy of the HAZ Material Charpy specimens resulted in an average energy decrease of 19 ft-lb after irradiation. This decrease results in an irradiated average upper-shelf energy of 142 ft-lb for the HAZ Material.

- Comparisons of the measured 30 ft-lb shift in transition temperature values and upper-shelf energy decreases to those predicted by Regulatory Guide 1.99, Revision 2 [Ref. 1] for the ANO-2 reactor vessel surveillance materials are presented in Table 5-10.

  Standard Reference Material (SRM) HSST 01 Charpy specimens were not included in the ANO-2 Capsule 284°. However, the SRM HSST 01 Charpy specimens were reanalyzed in this report. The SRM HSST 01 material was contained in Capsule 104°, which was irradiated to a neutron fluence of 2.15×10^{19} n/cm^2 (E > 1.0 MeV). The results of the SRM HSST 01 reanalysis are included in Table 5-10 and shown in Figures 5-13 through 5-15.

  - Irradiation of the SRM HSST 01 Charpy specimens resulted in an irradiated 30 ft-lb transition temperature of 163.8°F and an irradiated 50 ft-lb transition temperature of 205.3°F. This results in a 30 ft-lb transition temperature increase of 132.3°F and a 50 ft-lb transition temperature increase of 150.6°F.

- The average upper-shelf energy of the SRM HSST 01 Charpy specimens resulted in an average energy decrease of 59 ft-lb after irradiation. This decrease results in an irradiated average upper-shelf energy of 87 ft-lb.

The fracture appearance of each irradiated Charpy specimen from the various materials is shown in Figures 5-16 through 5-19. The fractures show an increasingly ductile or tougher appearance with increasing test temperature. Load-time records for the individual instrumented Charpy specimens are contained in Appendix B.

With consideration of the surveillance data, all beltline materials exhibit adequate upper-shelf energy levels for continued safe plant operation and are predicted to maintain an upper-shelf energy greater than 50 ft-lb through end-of-license (32 EFPY) as required by 10 CFR 50, Appendix G [Ref. 2]. This evaluation is contained in Appendix E.

5.3 TENSILE TEST RESULTS

The results of the tensile tests performed on the various materials contained in Capsule 284° irradiated to 3.67 x 10^{19} n/cm^2 (E > 1.0 MeV) are presented in Table 5-11 and are compared with unirradiated results as shown in Figures 5-20 through 5-22.

The results of the tensile tests performed on the Intermediate Shell Plate C-8009-3 (transverse orientation) indicated that irradiation to 3.67 x 10^{19} n/cm^2 (E > 1.0 MeV) caused increases in the 0.2 percent offset yield strength and the ultimate tensile strength when compared to unirradiated data [Ref. 5]. See Figure 5-20 and Table 5-11.

The results of the tensile tests performed on the Surveillance Program Weld Material (Heat # 83650) indicated that irradiation to 3.67 x 10^{19} n/cm^2 (E > 1.0 MeV) caused increases in the 0.2 percent offset yield strength and the ultimate tensile strength when compared to unirradiated data [Ref. 5]. See Figure 5-21 and Table 5-11.

The results of the tensile tests performed on the Heat-Affected Zone Material indicated that irradiation to 3.67 x 10^{19} n/cm^2 (E > 1.0 MeV) caused increases in the 0.2 percent offset yield strength and the ultimate tensile strength when compared to unirradiated data [Ref. 5]. See Figure 5-22 and Table 5-11.

The fractured tensile specimens for the Intermediate Shell Plate C-8009-3 (transverse orientation) material are shown in Figure 5-23, the fracture tensile specimens for the Surveillance Program Weld Material (Heat # 83650) are shown in Figure 5-24, and the fracture tensile specimens for the Heat-Affected Zone Material are shown in Figure 5-25. The engineering stress-strain curves for the tensile tests are shown in Figures 5-26 through 5-31.

Table 5-1 Charpy V-notch Data for the ANO-2 Intermediate Shell Plate C-8009-3 Irradiated to a Fluence of 3.67×10^{19} n/cm^2 (E > 1.0 MeV) (Longitudinal Orientation)

Sample Number	Temperature		Impact Energy		Lateral Expansion		Shear
	°F	°C	ft-lbs	Joules	mils	mm	%
14P	25	-4	16.5	22	18	0.46	15
111	60	16	28.5	39	25.5	0.65	20
12K	72	22	29	39	24	0.61	25
15J	80	27	35	47	30.5	0.77	30
11P	100	38	36.5	49	30	0.76	30
125	120	49	35	47	33	0.84	30
136	130	54	54	73	42.5	1.08	40
13E	165	74	67	91	57	1.45	55
13J	200	93	111	150	86	2.18	85
11B	250	121	123	167	92	2.34	100
12E	275	135	126	171	94.5	2.40	100
11M	300	149	117	159	89	2.26	100

Table 5-2 Charpy V-notch Data for the ANO-2 Intermediate Shell Plate C-8009-3 Irradiated to a Fluence of 3.67 x 10^{19} n/cm^2 (E > 1.0 MeV) (Transverse Orientation)

Sample Number	Temperature		Impact Energy		Lateral Expansion		Shear
	°F	°C	ft-lbs	Joules	mils	mm	%
267	25	-4	6	8	10.5	0.27	10
237	60	16	16	22	19	0.48	20
221	72	22	28.5	39	28	0.71	25
21J	80	27	28	38	24	0.61	25
233	100	38	33	45	30	0.76	30
235	130	54	45	61	39.5	1.00	40
23M	150	66	45	61	44	1.12	40
21T	175	79	58	79	48	1.22	50
23P	200	93	94	127	74.5	1.89	80
21M	250	121	105	142	85	2.16	100
22C	275	135	113.5	154	86	2.18	100
265	300	149	109	148	90	2.29	100

Table 5-3 Charpy V-notch Data for the ANO-2 Surveillance Program Weld Material (Heat # 83650) Irradiated to a Fluence of 3.67 x 10^{19} n/cm^2 (E > 1.0 MeV)

Sample Number	Temperature		Impact Energy		Lateral Expansion		Shear
	°F	°C	ft-lbs	Joules	mils	mm	%
37E	-25	-32	8.5	12	13	0.33	15
367	0	-18	18	24	22.5	0.57	35
352	15	-9	62.5	85	50	1.27	50
33M	15	-9	68	92	55	1.40	50
341	25	-4	34	46	33.5	0.85	45
32L	40	4	31	42	32	0.81	55
313	60	16	29	39	33.5	0.85	50
365	72	22	93	126	70	1.78	75
33T	110	43	125	169	96	2.44	95
35C	150	66	121	164	95	2.41	95
311	200	93	144	195	98	2.49	100
37U	250	121	139	188	96	2.44	100

Table 5-4 Charpy V-notch Data for the ANO-2 Heat-Affected Zone (HAZ) Material Irradiated to a Fluence of 3.67 x 10^{19} n/cm^2 (E > 1.0 MeV)

Sample Number	Temperature		Impact Energy		Lateral Expansion		Shear
	°F	°C	ft-lbs	Joules	mils	mm	%
412	-75	-59	6.5	9	11	0.28	15
43B	-50	-46	24	33	18	0.46	20
47T	-40	-40	29.5	40	20.5	0.52	20
433	-30	-34	47	64	35.5	0.90	45
46J	-25	-32	51.5	70	35.5	0.90	50
454	15	-9	88	119	59	1.50	75
423	40	4	101	137	93	2.36	75
42A	100	38	86	117	56.5	1.44	70
47M	130	54	136	184	91	2.31	100
411	165	74	123	167	80	2.03	80
41P	200	93	138	187	85.5	2.17	100
42B	250	121	150.5	203	92.5	2.35	100

Table 5-5 Instrumented Charpy Impact Test Results for the ANO-2 Intermediate Shell Plate C-8009-3 Irradiated to a Fluence of 3.67 x 10^{19} n/cm^2 (E > 1.0 MeV) (Longitudinal Orientation)

Sample Number	Test Temp (°F)	Total Dial Energy, KV (ft-lb)	Total Instrumented Energy, W_t (ft-lb)	Difference, $(KV-W_t)/KV$ (%)	Energy to Max Load, W_m (ft-lb)	Maximum Load, F_m (lb)	Time to F_m (msec)	General Yield Load, F_{gy} (lb)	Fracture Load, F_{bf} (lb)	Arrest Load, F_a (lb)
14P	25	16.5	15.5	6.1	12.92	3887	0.26	3234	3763	0
111	60	28.5	25.9	9.1	22.91	3902	0.43	2952	3837	0
12K	72	29	25.2	13.1	22.49	3832	0.43	3047	3832	0
15J	80	35	30.2	13.7	25.25	3864	0.48	2904	3737	0
11P	100	36.5	31.9	12.6	25.37	3887	0.48	2778	3752	639
125	120	35	30.2	13.7	24.79	3796	0.48	2824	3796	847
136	130	54	47.9	11.3	32.32	3964	0.61	2770	3854	1180
13E	165	67	59.4	11.3	30.80	3960	0.60	2737	3818	1935
13J	200	111	99.6	10.3	32.06	3984	0.60	2633	2933	1880
11B	250	123	110.3	10.3	30.73	3823	0.60	2528	0	0
12E	275	126	114.1	9.4	30.93	3832	0.60	2518	0	0
11M	300	117	106.4	9.1	31.39	3723	0.63	2512	0	0

Table 5-6 Instrumented Charpy Impact Test Results for the ANO-2 Intermediate Shell Plate C-8009-3 Irradiated to a Fluence of 3.67 x 10^{19} n/cm^2 (E > 1.0 MeV) (Transverse Orientation)

Sample Number	Test Temp (°F)	Total Dial Energy, KV (ft-lb)	Total Instrumented Energy, W_t (ft-lb)	Difference, $(KV-W_t)/KV$ (%)	Energy to Max Load, W_m (ft-lb)	Maximum Load, F_m (lb)	Time to F_m (msec)	General Yield Load, F_{gy} (lb)	Fracture Load, F_{bf} (lb)	Arrest Load, F_a (lb)
267	25	6	5.4	10.0	3.17	3683	0.09	3165	3366	0
237	60	16	13.8	13.8	3.12	3713	0.09	3034	3668	0
221	72	28.5	25.2	11.6	22.26	3927	0.43	2980	3927	0
21J	80	28	25.0	10.7	22.67	3820	0.43	2901	3820	0
233	100	33	28.5	13.6	25.11	3850	0.48	2858	3826	350
235	130	45	39.6	12.0	32.35	3894	0.60	2803	3883	1294
23M	150	45	39.6	12.0	32.23	3901	0.60	2824	3901	1605
21T	175	58	49.4	14.8	31.15	3814	0.60	2782	3559	2081
23P	200	94	85.2	9.4	32.78	4000	0.60	2810	3702	2807
21M	250	105	94.9	9.6	31.66	3883	0.61	2565	0	0
22C	275	113.5	102.0	10.1	27.86	3998	0.57	2708	0	0
265	300	109	100.3	8.0	30.81	3792	0.60	2491	0	0

Table 5-7 Instrumented Charpy Impact Test Results for the ANO-2 Surveillance Program Weld Material (Heat # 83650) Irradiated to a Fluence of 3.67 x 10^{19} n/cm^2 (E > 1.0 MeV)

Sample Number	Test Temp (°F)	Total Dial Energy, KV (ft-lb)	Total Instrumented Energy, W_t (ft-lb)	Difference, $(KV-W_t)/KV$ (%)	Energy to Max Load, W_m (ft-lb)	Maximum Load, F_m (lb)	Time to F_m (msec)	General Yield Load, F_{gy} (lb)	Fracture Load, F_{bf} (lb)	Arrest Load, F_a (lb)
37E	-25	8.5	7.4	12.9	3.34	3907	0.09	3252	3379	0
367	0	18	15.9	11.7	3.88	4403	0.11	3181	3360	832
352	15	62.5	54.0	13.6	32.94	3884	0.61	3095	3639	994
33M	15	68	60.3	11.3	33.56	3995	0.60	3137	3759	761
341	25	34	29.1	14.4	18.42	3820	0.36	3081	3681	1191
32L	40	31	26.4	14.8	3.08	3797	0.09	3023	3521	1579
313	60	29	25.7	11.4	3.10	3732	0.09	3108	3386	1532
365	72	93	84.6	9.0	31.49	3750	0.60	2929	3391	2708
33T	110	125	111.8	10.6	41.63	3760	0.79	2797	2693	2544
35C	150	121	108.7	10.2	30.74	3720	0.60	2686	2575	2284
311	200	144	130.7	9.2	29.73	3680	0.60	2380	0	0
37U	250	139	124.8	10.2	28.78	3543	0.60	2428	0	0

Table 5-8 Instrumented Charpy Impact Test Results for the ANO-2 Heat-Affected Zone (HAZ) Material Irradiated to a Fluence of 3.67 x 10^{19} n/cm^2 (E > 1.0 MeV)

Sample Number	Test Temp (°F)	Total Dial Energy, KV (ft-lb)	Total Instrumented Energy, W_t (ft-lb)	Difference, (KV-W_t)/KV (%)	Energy to Max Load, W_m (ft-lb)	Maximum Load, F_m (lb)	Time to F_m (msec)	General Yield Load, F_{gy} (lb)	Fracture Load, F_{bf} (lb)	Arrest Load, F_a (lb)
412	-75	6.5	5.9	9.2	3.50	4343	0.09	3263	4156	0
43B	-50	24	22.5	6.3	3.61	4271	0.09	3384	4236	0
47T	-40	29.5	26.5	10.2	3.53	4183	0.09	3257	4142	0
433	-30	47	42.5	9.6	36.65	4267	0.61	3383	4267	791
46J	-25	51.5	46.6	9.5	4.43	4313	0.12	3460	4009	1143
454	15	88	77.2	12.3	35.39	4217	0.61	3320	3666	1838
423	40	101	90.0	10.9	34.65	4191	0.60	3220	3238	1817
42A	100	86	76.4	11.2	33.87	4107	0.60	3052	3326	2320
47M	130	136	120.7	11.3	32.06	3895	0.60	2888	0	0
411	165	123	109.5	11.0	32.72	4026	0.60	2860	2355	1349
41P	200	138	123.9	10.2	43.61	4297	0.82	2429	0	0
42B	250	150.5	134.9	10.4	47.23	4042	0.91	3035	0	0

Table 5-9 Effect of Irradiation to 3.67 x 10^{19} n/cm^2 (E > 1.0 MeV) on the Charpy V-Notch Toughness Properties of the ANO-2 Reactor Vessel Surveillance Capsule 284° Materials

Material	Average 30 ft-lb Transition Temperature[a] (°F)			Average 35 mil Lateral Expansion Temperature[a] (°F)			Average 50 ft-lb Transition Temperature[a] (°F)			Average Energy Absorption ≥ 95% Shear[b] (ft-lb)		
	Unirradiated	Irradiated	ΔT	Unirradiated	Irradiated	ΔT	Unirradiated	Irradiated	ΔT	Unirradiated	Irradiated	ΔE
Intermediate Shell Plate C-8009-3 (Longitudinal)	0.5	86.2	85.7	15.0	103.9	88.9	22.2	121.1	98.9	159	122	-37
Intermediate Shell Plate C-8009-3 (Transverse)	14.9	100.5	85.6	28.7	114.0	85.3	42.5	138.5	96.0	134	109	-25
Surveillance Weld Material (Heat # 83650)	-3.8	8.2	12.0	6.0	17.8	11.8	10.8	37.1	26.3	151	132	-19
Heat-Affected Zone (HAZ) Material	-129.9	-56.4	73.5	-77.1	-26.2	50.9	-87.6	-17.8	69.8	161[c]	142	-19

Notes:

(a) Average value is determined by CVGRAPH, Version 6.02 (see Appendix C).

(b) Upper-shelf Energy (USE) values are a calculated average from unirradiated and Capsule 284° Charpy test results for specimens that achieved greater than or equal to 95% shear, unless otherwise noted.

(c) Consistent with the previous evaluation, one 95% shear point was deemed "out of family" and was excluded from the USE determination for the unirradiated HAZ material.

Table 5-10 Comparison of the ANO-2 Surveillance Material 30 ft-lb Transition Temperature Shifts and Upper-Shelf Energy Decreases with Regulatory Guide 1.99, Revision 2, Predictions

Material	Capsule	Capsule Fluence (x 10^{19} n/cm^2, E > 1.0 MeV)	30 ft-lb Transition Temperature Shift		Upper-Shelf Energy Decrease	
			Predicted[(a)] (°F)	Measured[(b)] (°F)	Predicted[(a)] (%)	Measured[(b)] (%)
Intermediate Shell Plate C-8009-3 (Longitudinal)	97°	0.303	41.9	23.5	14.5	12
	284°	3.67	83.2	85.7	26	23
Intermediate Shell Plate C-8009-3 (Transverse)	97°	0.303	41.9	33.4	14.5	10
	104°	2.15	75.1	52.9	23.0	31
	284°	3.67	83.2	85.6	26.0	19
Surveillance Weld Material (Heat # 83650)	97°	0.303	22.7	13.2	14.5	3
	104°	2.15	40.7	16.1	23.0	17
	284°	3.67	45.1	12.0	26.0	13
Heat-Affected Zone Material	97°	0.303	---	50.9	---	14
	104°	2.15	---	113.1	---	19
	284°	3.67	---	73.5	---	12
Standard Reference Material	104°	2.15	---	132.3	---	40

Notes:

(a) Based on Regulatory Guide 1.99, Revision 2 [Ref. 1], methodology using the capsule fluence and best-estimate weight percent values of copper and nickel of the surveillance material.

(b) Calculated by CVGRAPH, Version 6.02 using measured Charpy data (See Appendix C).

Table 5-11 Tensile Properties of the ANO-2 Capsule 284° Reactor Vessel Surveillance Materials Irradiated to 3.67×10^{19} n/cm^2 (E > 1.0 MeV)

Material	Sample Number	Test Temp. (°F)	0.2% Yield Strength (ksi)	Ultimate Strength (ksi)	Fracture Load (kip)	Fracture Strength (ksi)	Fracture True Stress (ksi)	Uniform Elongation (%)	Total Elongation (%)	Reduction in Area (%)
Intermediate Shell Plate C-8009-3 (Transverse)	2KE	72	81.7	102.5	3.38	70.1	166	10.8	23.3	58
	2KY	250	77.0	96.0	3.18	65.2	171	9.8	21.4	62
	2KU	550	72.4	96.3	3.40	70.3	178	9.1	19.3	60
Surveillance Weld Material (Heat # 83650)	3JU(a)	72	80.5	94.9	2.82	57.9	81	8.8	14.1	29
	3JB	250	75.5	88.3	2.64	54.2	205	8.3	22.6	74
	3KD	550	73.2	89.4	2.81	58.1	175	8.2	20.8	67
Heat-Affected Zone Material	4KT	72	74.1	91.3	2.64	54.1	182	7.5	21.8	70
	4KE	250	71.9	86.0	2.53	52.3	188	6.5	20.0	72
	4JL	550	72.7	91.1	2.88	59.1	195	7.6	20.1	70

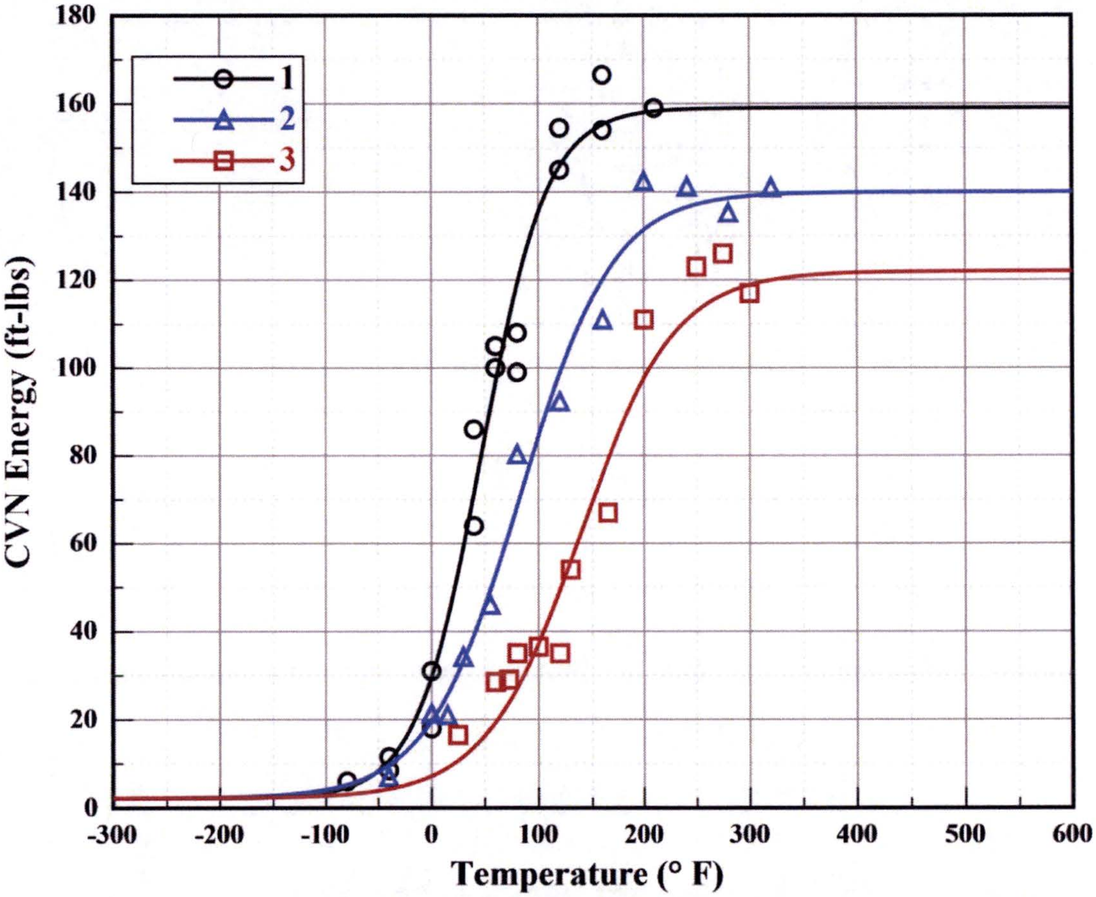
Note:

(a) Specimen 3JU failed at the extensometer knife edge

Intermediate Shell Plate C-8009-3 (Longitudinal)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 2:44 PM

Curve	Plant	Capsule	Material	Ori.	Heat #
1	Arkansas 2	UNIRR	SA533B CL1	LT	C8182-2
2	Arkansas 2	97°	SA533B CL1	LT	C8182-2
3	Arkansas 2	284°	SA533B CL1	LT	C8182-2



Curve	Fluence	LSE	USE	d-USE	T @30	d-T @30	T @50	d-T @50
1	---	2.2	159	0	0.5	0	22.2	0
2	---	2.2	140	-19	24	23.5	56	33.8
3	---	2.2	122	-37	86.2	85.7	121.1	98.9

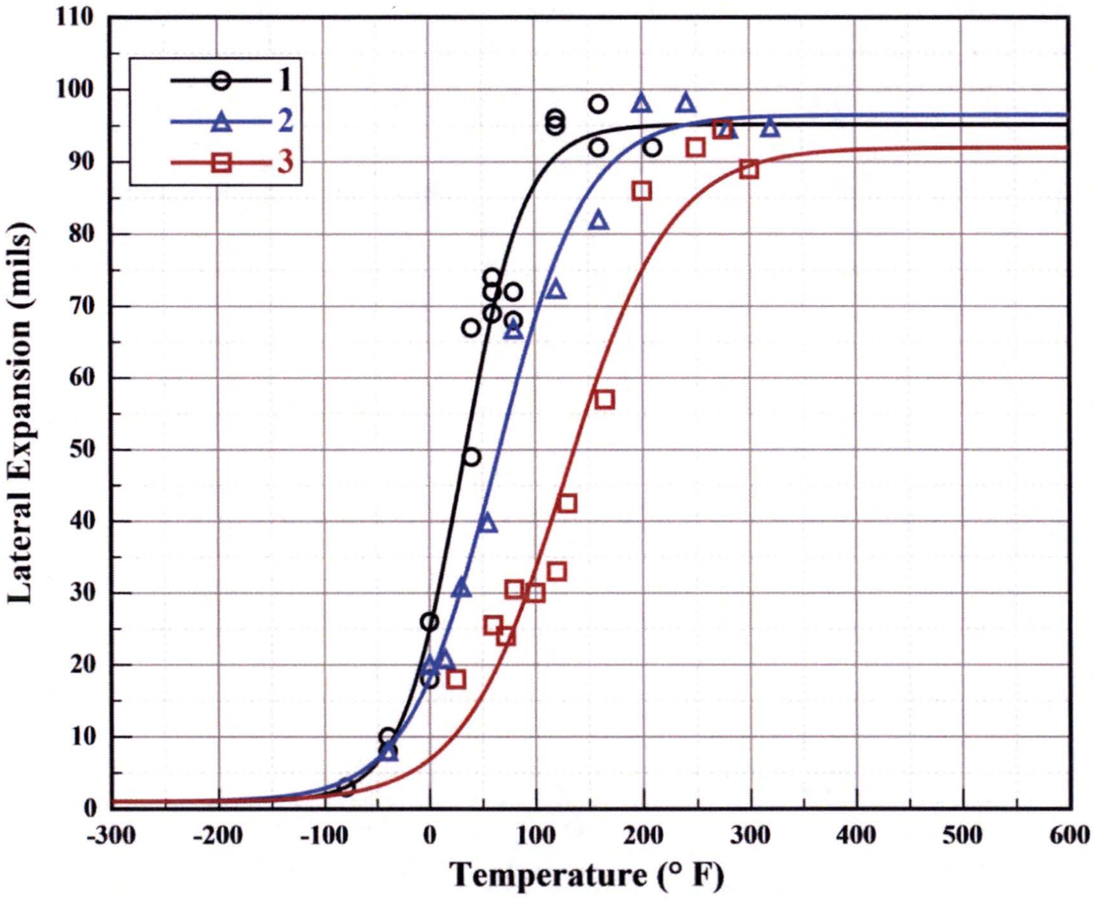
Figure 5-1 Charpy V-Notch Impact Energy vs. Temperature for ANO-2 Reactor Vessel Intermediate Shell Plate C-8009-3 (Longitudinal Orientation)

Note: Data for Capsule 284° was taken from Table 5-1.

Intermediate Shell Plate C-8009-3 (Longitudinal)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 2:45 PM

Curve	Plant	Capsule	Material	Ori.	Heat #
1	Arkansas 2	UNIRR	SA533B CL1	LT	C8182-2
2	Arkansas 2	97°	SA533B CL1	LT	C8182-2
3	Arkansas 2	284°	SA533B CL1	LT	C8182-2



Curve	Fluence	LSE	USE	d-USE	T @35	d-T @35
1	---	1	95.17	0	15	0
2	---	1	96.51	1.34	39	24
3	---	1	92*	-3.17	103.9	88.9

* The upper-shelf LE value for Capsule 284° was fixed based on the average of three data points that achieved greater than or equal to 95% shear.

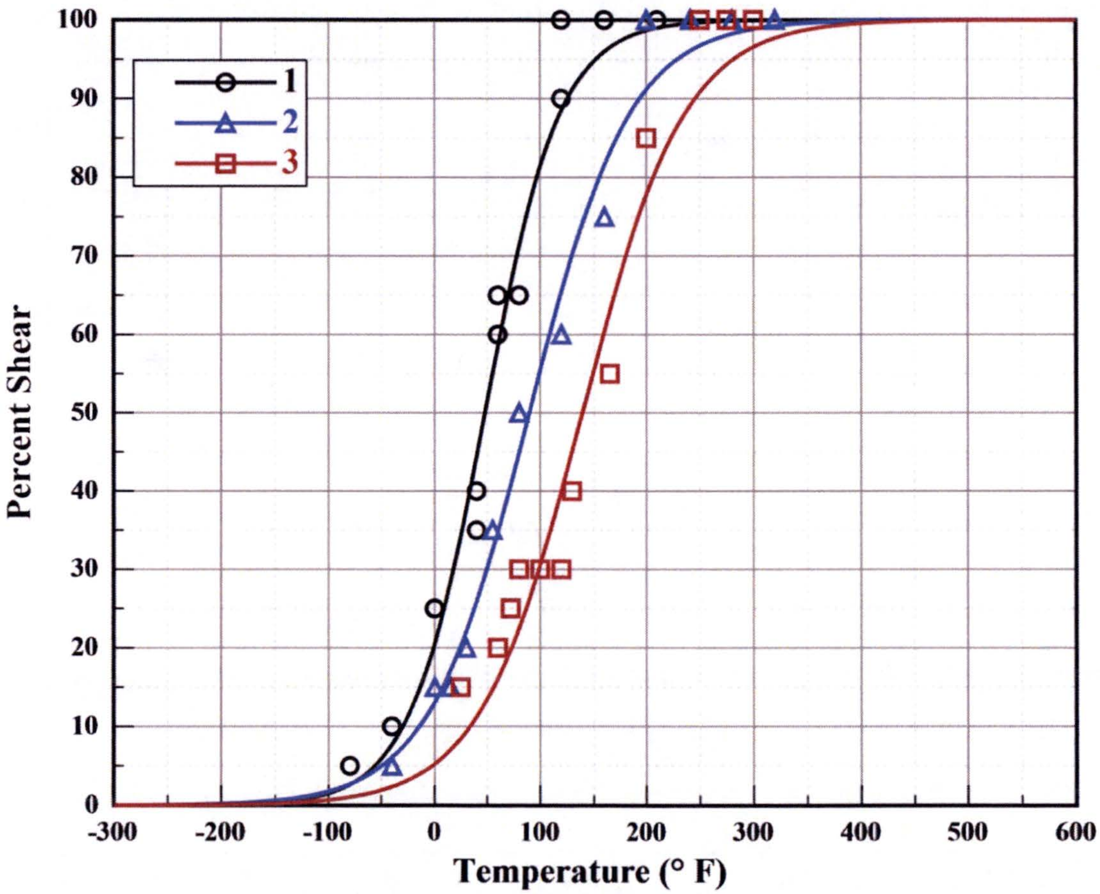
Figure 5-2 Charpy V-Notch Lateral Expansion vs. Temperature for ANO-2 Reactor Vessel Intermediate Shell Plate C-8009-3 (Longitudinal Orientation)

Note: Data for Capsule 284° was taken from Table 5-1.

Intermediate Shell Plate C-8009-3 (Longitudinal)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 2:46 PM

Curve	Plant	Capsule	Material	Ori.	Heat #
1	Arkansas 2	UNIRR	SA533B CL1	LT	C8182-2
2	Arkansas 2	97°	SA533B CL1	LT	C8182-2
3	Arkansas 2	284°	SA533B CL1	LT	C8182-2



Curve	Fluence	LSE	USE	d-USE	T @50	d-T @50
1	- - -	0	100	0	48.1	0
2	- - -	0	100	0	89.7	41.6
3	- - -	0	100	0	139.6	91.5

Figure 5-3 Charpy V-Notch Percent Shear vs. Temperature for ANO-2 Reactor Vessel Intermediate Shell Plate C-8009-3 (Longitudinal Orientation)

Note: Data for Capsule 284° was taken from Table 5-1.

Intermediate Shell Plate C-8009-3 (Transverse)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 2:47 PM

Curve	Plant	Capsule	Material	Ori.	Heat #
1	Arkansas 2	UNIRR	SA533B CL1	TL	C8182-2
2	Arkansas 2	97°	SA533B CL1	TL	C8182-2
3	Arkansas 2	104°	SA533BCL1	TL	C8182-2
4	Arkansas 2	284°	SA533B CL1	TL	C8182-2

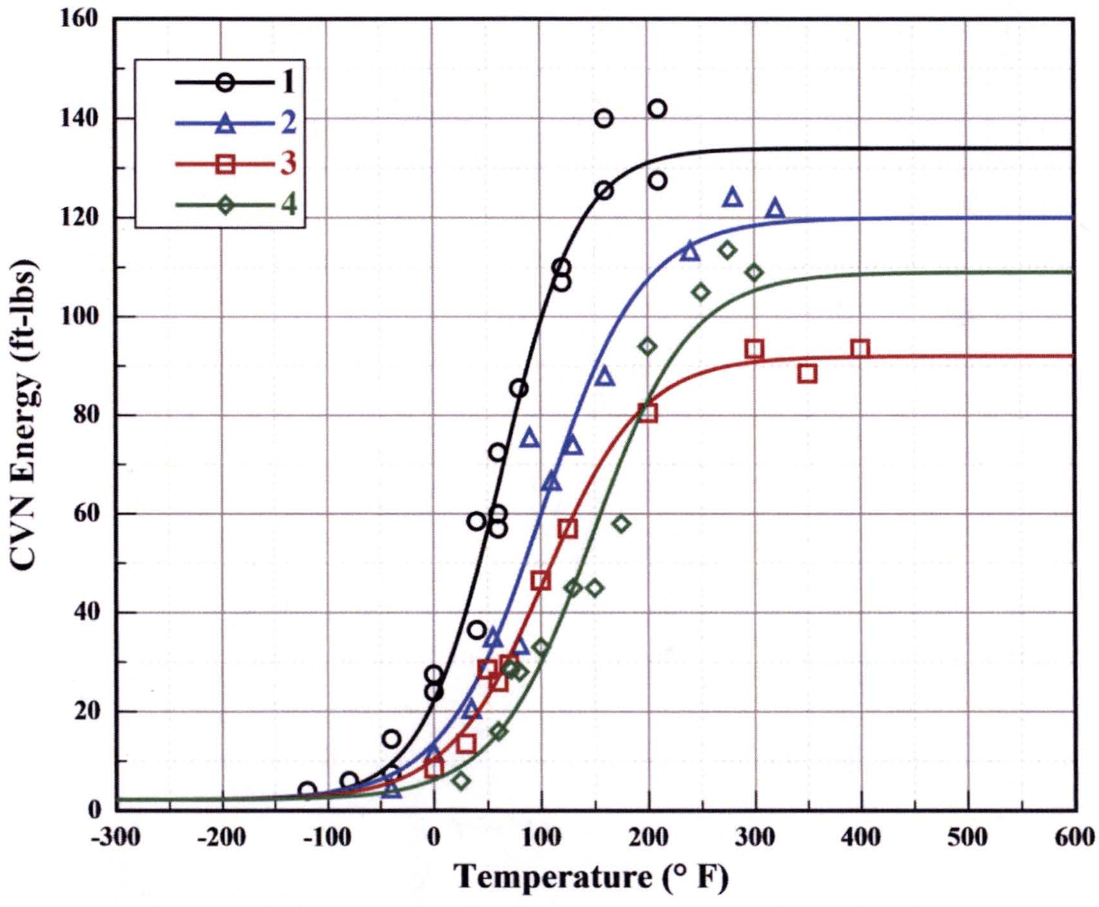


Figure 5-4 Charpy V-Notch Impact Energy vs. Temperature for ANO-2 Reactor Vessel Intermediate Shell Plate C-8009-3 (Transverse Orientation)

Note: Data for Capsule 284° was taken from Table 5-2.

Intermediate Shell Plate C-8009-3 (Transverse)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 2:47 PM

Curve	Fluence	LSE	USE	d-USE	T @30	d-T @30	T @50	d-T @50
1	---	2.2	134	0	14.9	0	42.5	0
2	---	2.2	120	-14	48.3	33.4	84.8	42.3
3	---	2.2	92	-42	67.8	52.9	110	67.5
4	---	2.2	109	-25	100.5	85.6	138.5	96

Figure 5-4 Charpy V-Notch Impact Energy vs. Temperature for ANO-2 Reactor Vessel Intermediate Shell Plate C-8009-3 (Transverse Orientation) – Continued

Intermediate Shell Plate C-8009-3 (Transverse)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 2:48 PM

Curve	Plant	Capsule	Material	Ori.	Heat #
1	Arkansas 2	UNIRR	SA533B CL1	TL	C8182-2
2	Arkansas 2	97°	SA533B CL1	TL	C8182-2
3	Arkansas 2	104°	SA533BCL1	TL	C8182-2
4	Arkansas 2	284°	SA533B CL1	TL	C8182-2

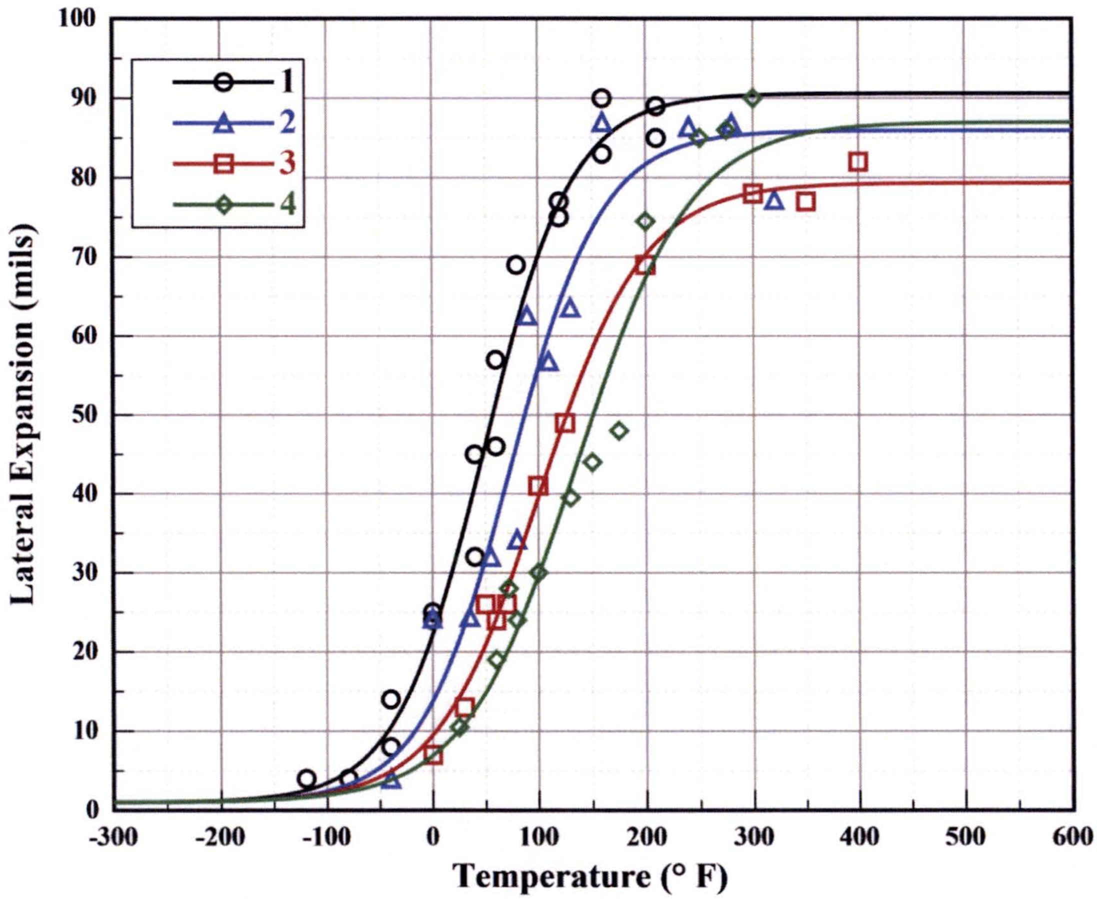


Figure 5-5 Charpy V-Notch Lateral Expansion vs. Temperature for ANO-2 Reactor Vessel Intermediate Shell Plate C-8009-3 (Transverse Orientation)

Note: Data for Capsule 284° was taken from Table 5-2.

Intermediate Shell Plate C-8009-3 (Transverse)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 2:48 PM

Curve	Fluence	LSE	USE	d-USE	T @35	d-T @35
1	- - -	1	90.61	0	28.7	0
2	- - -	1	85.94	-4.67	56.9	28.2
3	- - -	1	79.35	-11.26	88.9	60.2
4	- - -	1	87*	-3.61	114	85.3

* The upper-shelf LE value for Capsule 284° was fixed based on the average of three data points that achieved greater than or equal to 95% shear.

Figure 5-5 Charpy V-Notch Lateral Expansion vs. Temperature for ANO-2 Reactor Vessel Intermediate Shell Plate C-8009-3 (Transverse Orientation) – Continued

Intermediate Shell Plate C-8009-3 (Transverse)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 2:49 PM

Curve	Plant	Capsule	Material	Ori.	Heat #
1	Arkansas 2	UNIRR	SA533B CL1	TL	C8182-2
2	Arkansas 2	97°	SA533B CL1	TL	C8182-2
3	Arkansas 2	104°	SA533BCL1	TL	C8182-2
4	Arkansas 2	284°	SA533B CL1	TL	C8182-2

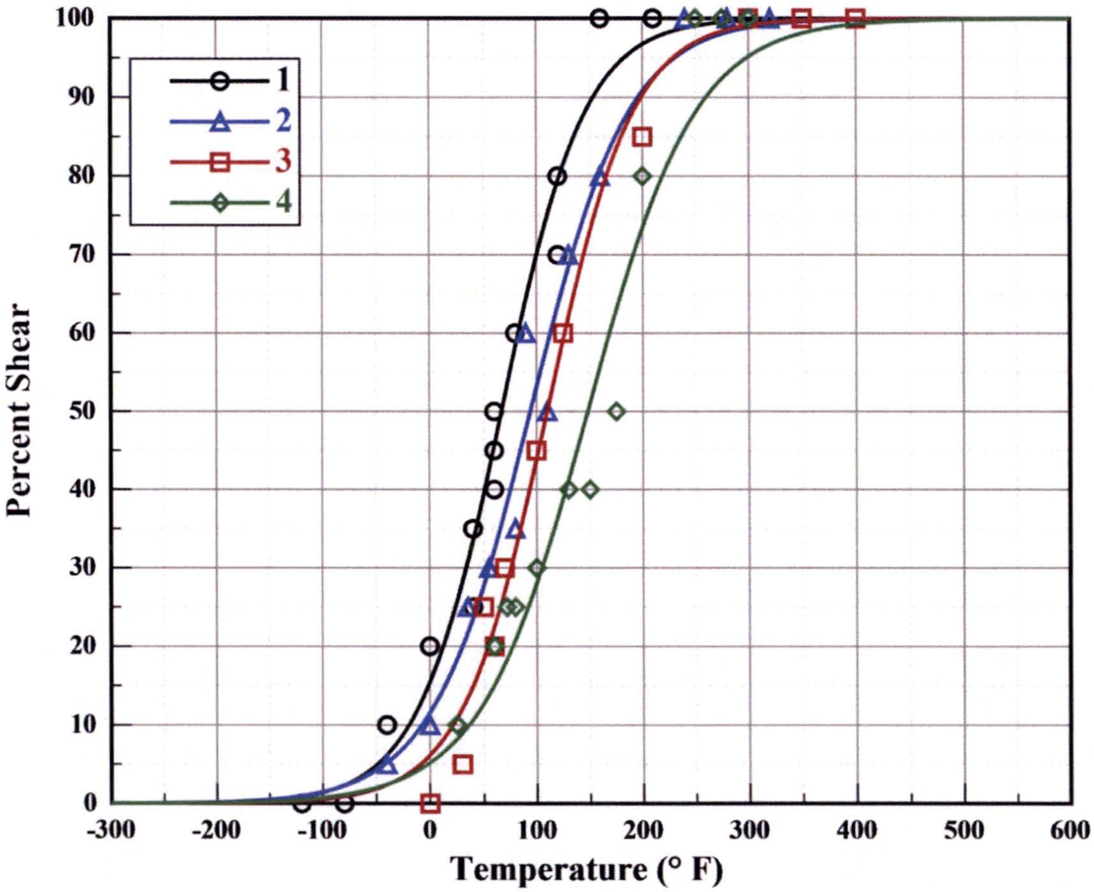


Figure 5-6 Charpy V-Notch Percent Shear vs. Temperature for ANO-2 Reactor Vessel Intermediate Shell Plate C-8009-3 (Transverse Orientation)

Note: Data for Capsule 284° was taken from Table 5-2.

Intermediate Shell Plate C-8009-3 (Transverse)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 2:49 PM

Curve	Fluence	LSE	USE	d-USE	T @50	d-T @50
1	---	0	100	0	67	0
2	---	0	100	0	94.2	27.2
3	---	0	100	0	110	43
4	---	0	100	0	148	81

Figure 5-6 Charpy V-Notch Percent Shear vs. Temperature for ANO-2 Reactor Vessel Intermediate Shell Plate C-8009-3 (Transverse Orientation) – Continued

Surveillance Program Weld Metal

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 2:52 PM

Curve	Plant	Capsule	Material	Ori.	Heat #
1	Arkansas 2	UNIRR	WELD	N/A	83650
2	Arkansas 2	97°	WELD	N/A	83650
3	Arkansas 2	104°	WELD	N/A	83650
4	Arkansas 2	284°	WELD	N/A	83650

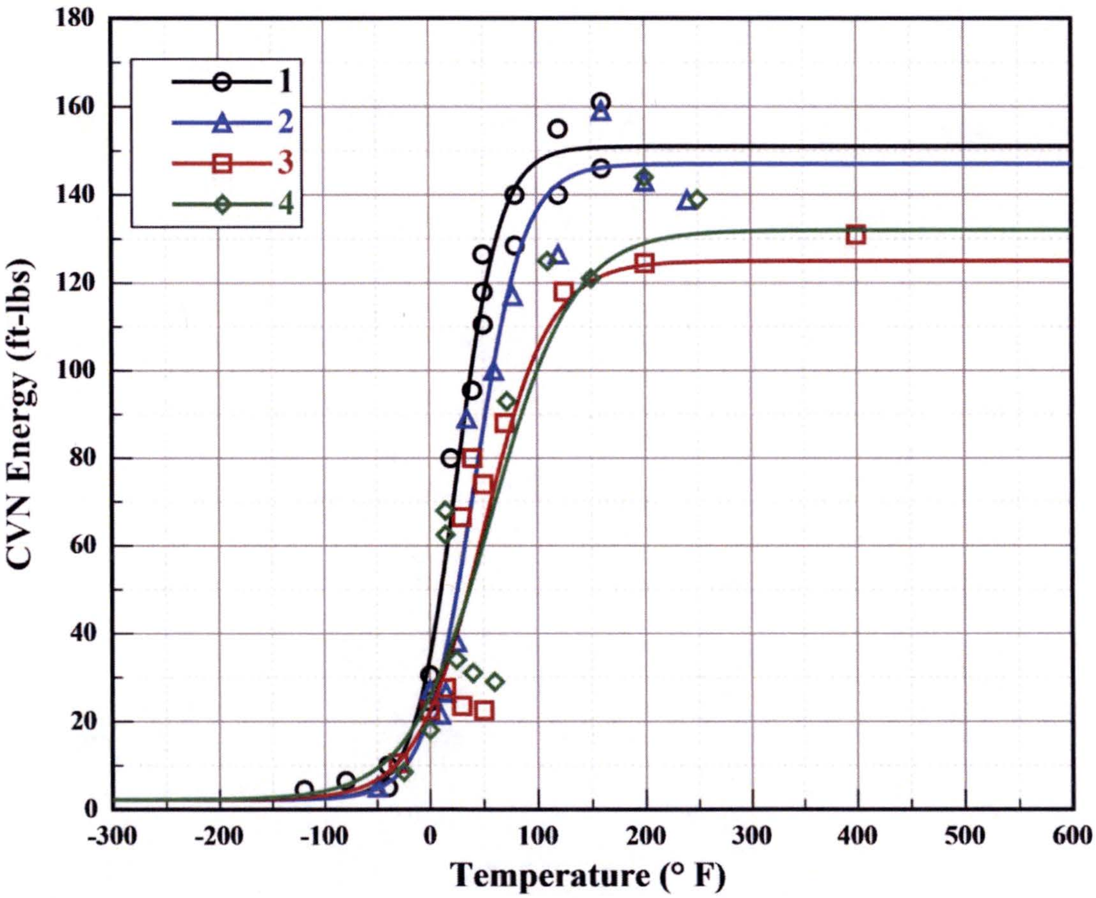


Figure 5-7 Charpy V-Notch Impact Energy vs. Temperature for ANO-2 Reactor Vessel Surveillance Program Weld Material (Heat # 83650)

Note: Data for Capsule 284° was taken from Table 5-3.

Surveillance Program Weld Metal

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 2:52 PM

Curve	Fluence	LSE	USE	d-USE	T @30	d-T @30	T @50	d-T @50
1	---	2.2	151	0	-3.8	0	10.8	0
2	---	2.2	147	-4	9.4	13.2	26.1	15.3
3	---	2.2	125	-26	12.3	16.1	36.4	25.6
4	---	2.2	132	-19	8.2	12	37.1	26.3

Figure 5-7 Charpy V-Notch Impact Energy vs. Temperature for ANO-2 Reactor Vessel Surveillance Program Weld Material (Heat # 83650) – Continued

Surveillance Program Weld Metal

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 2:52 PM

Curve	Plant	Capsule	Material	Ori.	Heat #
1	Arkansas 2	UNIRR	WELD	N/A	83650
2	Arkansas 2	97°	WELD	N/A	83650
3	Arkansas 2	104°	WELD	N/A	83650
4	Arkansas 2	284°	WELD	N/A	83650

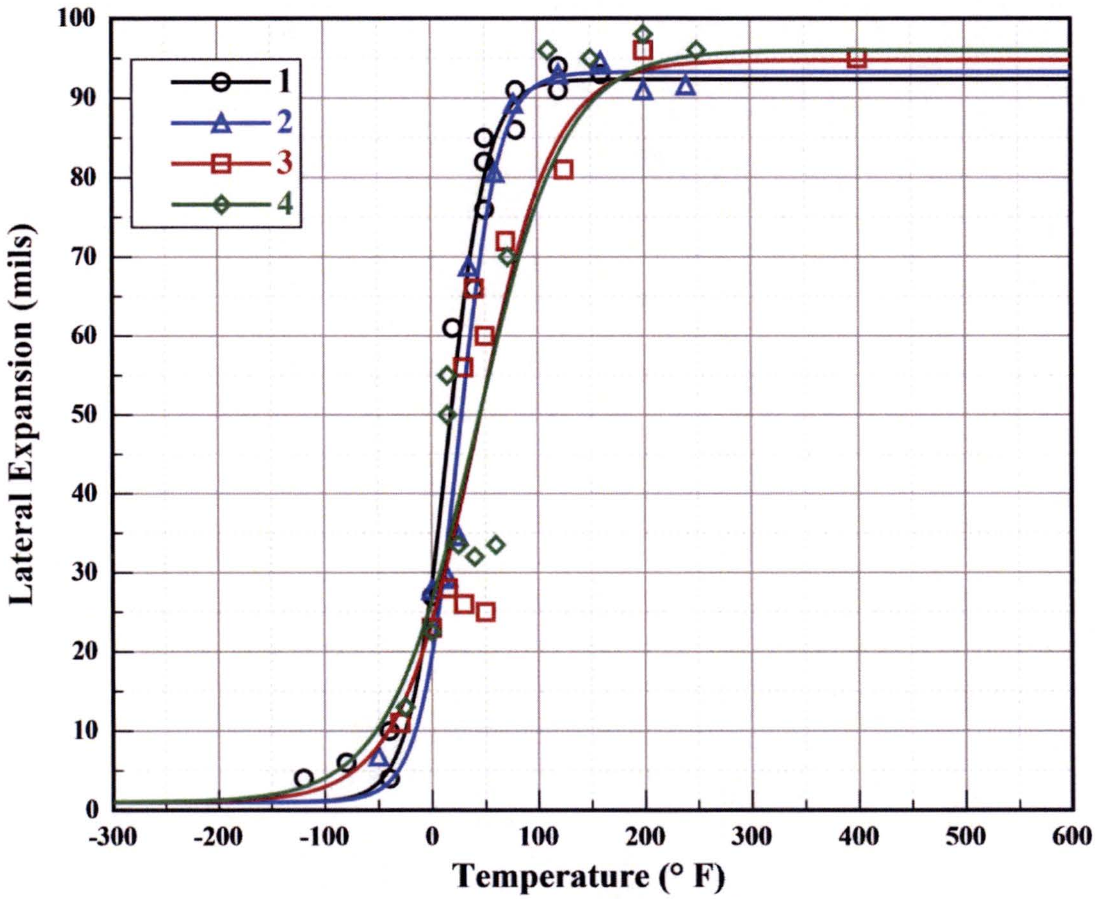


Figure 5-8 Charpy V-Notch Lateral Expansion vs. Temperature for ANO-2 Reactor Vessel Surveillance Program Weld Material (Heat # 83650)

Note: Data for Capsule 284° was taken from Table 5-3.

Surveillance Program Weld Metal

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 2:52 PM

Curve	Fluence	LSE	USE	d-USE	T @35	d-T @35
1	---	1	92.36	0	6	0
2	---	1	93.26	0.90	15.7	9.7
3	---	1	94.74	2.38	21.1	15.1
4	---	1	96*	3.64	17.8	11.8

* The upper-shelf LE value for Capsule 284° was fixed based on the average of four data points that achieved greater than or equal to 95% shear.

Figure 5-8 Charpy V-Notch Lateral Expansion vs. Temperature for ANO-2 Reactor Vessel Surveillance Program Weld Material (Heat # 83650) – Continued

Surveillance Program Weld Metal

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 2:53 PM

Curve	Plant	Capsule	Material	Ori.	Heat #
1	Arkansas 2	UNIRR	WELD	N/A	83650
2	Arkansas 2	97°	WELD	N/A	83650
3	Arkansas 2	104°	WELD	N/A	83650
4	Arkansas 2	284°	WELD	N/A	83650

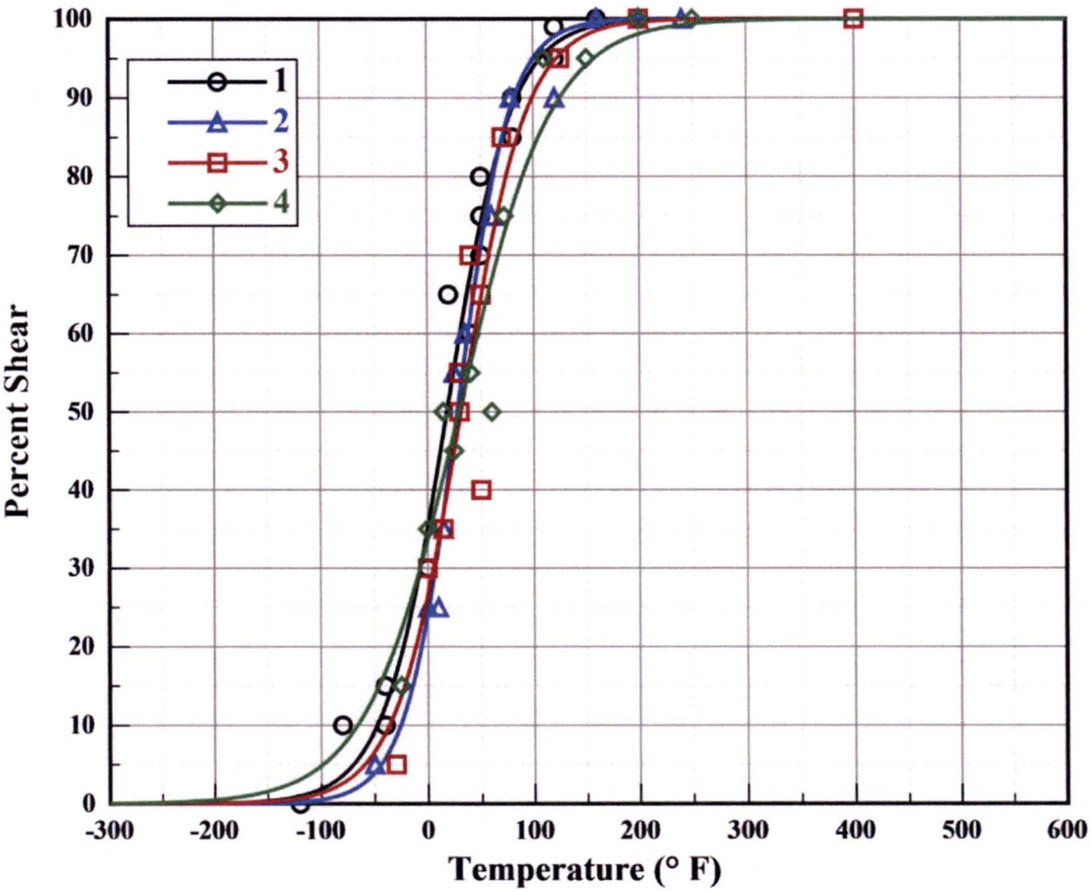


Figure 5-9 Charpy V-Notch Percent Shear vs. Temperature for ANO-2 Reactor Vessel Surveillance Program Weld Material (Heat # 83650)

Note: Data for Capsule 284° was taken from Table 5-3.

Surveillance Program Weld Metal

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 2:53 PM

Curve	Fluence	LSE	USE	d-USE	T @50	d-T @50
1	---	0	100	0	18.5	0
2	---	0	100	0	27.9	9.4
3	---	0	100	0	31.3	12.8
4	---	0	100	0	29.5	11

Figure 5-9 Charpy V-Notch Percent Shear vs. Temperature for ANO-2 Reactor Vessel Surveillance Program Weld Material (Heat # 83650) – Continued

Heat-Affected Zone

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 2:55 PM

Curve	Plant	Capsule	Material	Ori.	Heat #
1	Arkansas 2	UNIRR	SA533B CL1	N/A	C8182-2
2	Arkansas 2	97°	SA533B CL1	N/A	C8182-2
3	Arkansas 2	104°	SA533B CL1	N/A	C8182-2
4	Arkansas 2	284°	SA533B CL1	N/A	C8182-2

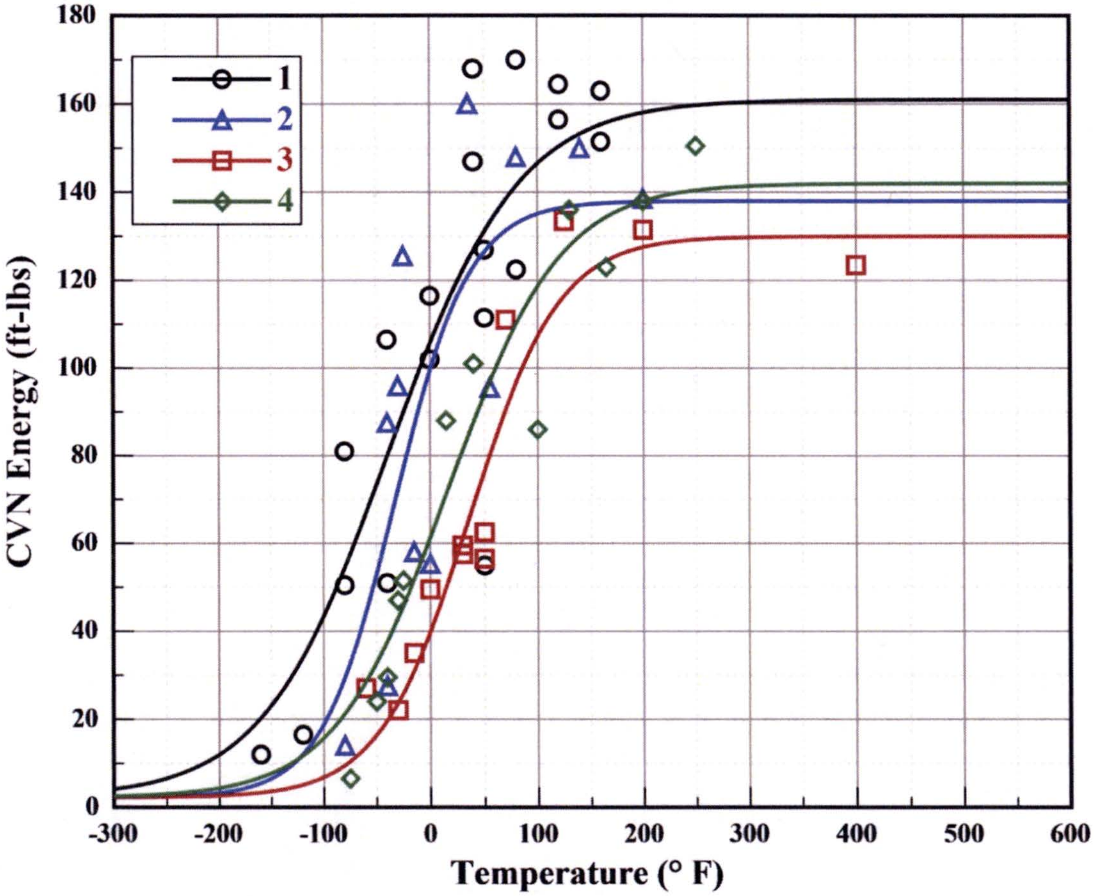


Figure 5-10 Charpy V-Notch Impact Energy vs. Temperature for ANO-2 Reactor Vessel Heat-Affected Zone Material

Note: Data for Capsule 284° was taken from Table 5-4.

Heat-Affected Zone

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 2:55 PM

Curve	Fluence	LSE	USE	d-USE	T @30	d-T @30	T @50	d-T @50
1	---	2.2	161	0	-129.9	0	-87.6	0
2	---	2.2	138	-23	-79	50.9	-53.2	34.4
3	---	2.2	130	-31	-16.8	113.1	15	102.6
4	---	2.2	142	-19	-56.4	73.5	-17.8	69.8

Figure 5-10 Charpy V-Notch Impact Energy vs. Temperature for ANO-2 Reactor Vessel Heat-Affected Zone Material – Continued

Heat-Affected Zone

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 2:55 PM

Curve	Plant	Capsule	Material	Ori.	Heat #
1	Arkansas 2	UNIRR	SA533B CL1	N/A	C8182-2
2	Arkansas 2	97°	SA533B CL1	N/A	C8182-2
3	Arkansas 2	104°	SA533B CL1	N/A	C8182-2
4	Arkansas 2	284°	SA533B CL1	N/A	C8182-2

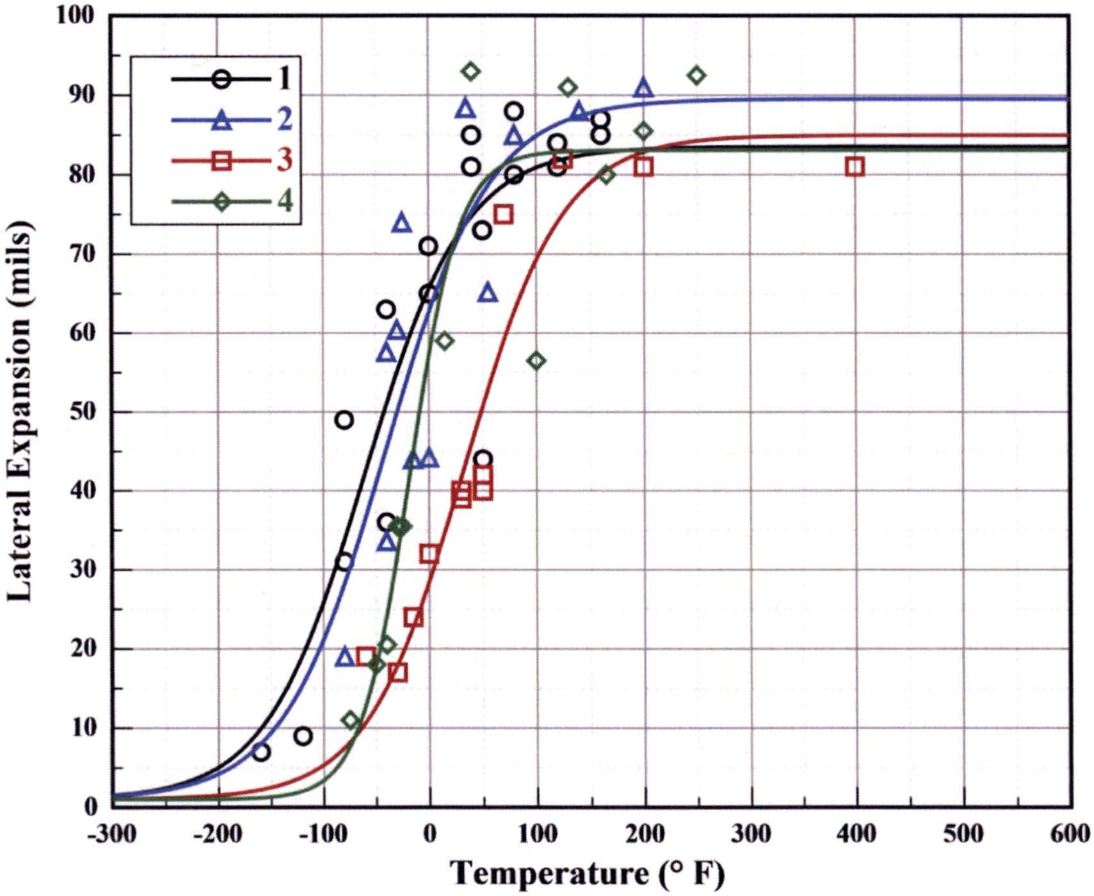


Figure 5-11 Charpy V-Notch Lateral Expansion vs. Temperature for ANO-2 Reactor Vessel Heat-Affected Zone Material

Note: Data for Capsule 284° was taken from Table 5-4.

Heat-Affected Zone

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 2:55 PM

Curve	Fluence	LSE	USE	d-USE	T @35	d-T @35
1	- - -	1	83.55	0	-77.1	0
2	- - -	1	89.53	5.98	-63.4	13.7
3	- - -	1	84.97	1.42	15.4	92.5
4	- - -	1	83.07	-0.48	-26.2	50.9

Figure 5-11 Charpy V-Notch Lateral Expansion vs. Temperature for ANO-2 Reactor Vessel Heat-Affected Zone Material – Continued

Heat-Affected Zone

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 2:56 PM

Curve	Plant	Capsule	Material	Ori.	Heat #
1	Arkansas 2	UNIRR	SA533B CL1	N/A	C8182-2
2	Arkansas 2	97°	SA533B CL1	N/A	C8182-2
3	Arkansas 2	104°	SA533B CL1	N/A	C8182-2
4	Arkansas 2	284°	SA533B CL1	N/A	C8182-2

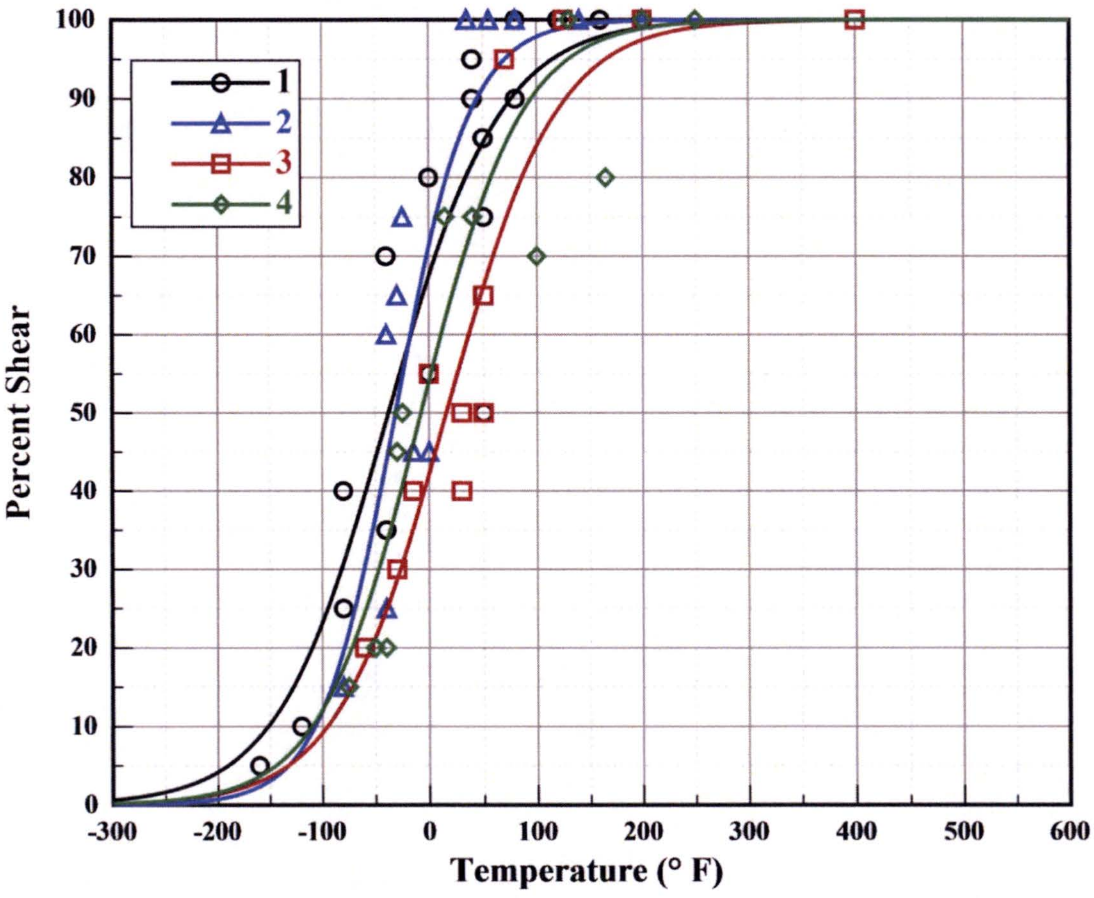


Figure 5-12 Charpy V-Notch Percent Shear vs. Temperature for ANO-2 Reactor Vessel Heat-Affected Zone Material

Note: Data for Capsule 284° was taken from Table 5-4.

Heat-Affected Zone

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 2:56 PM

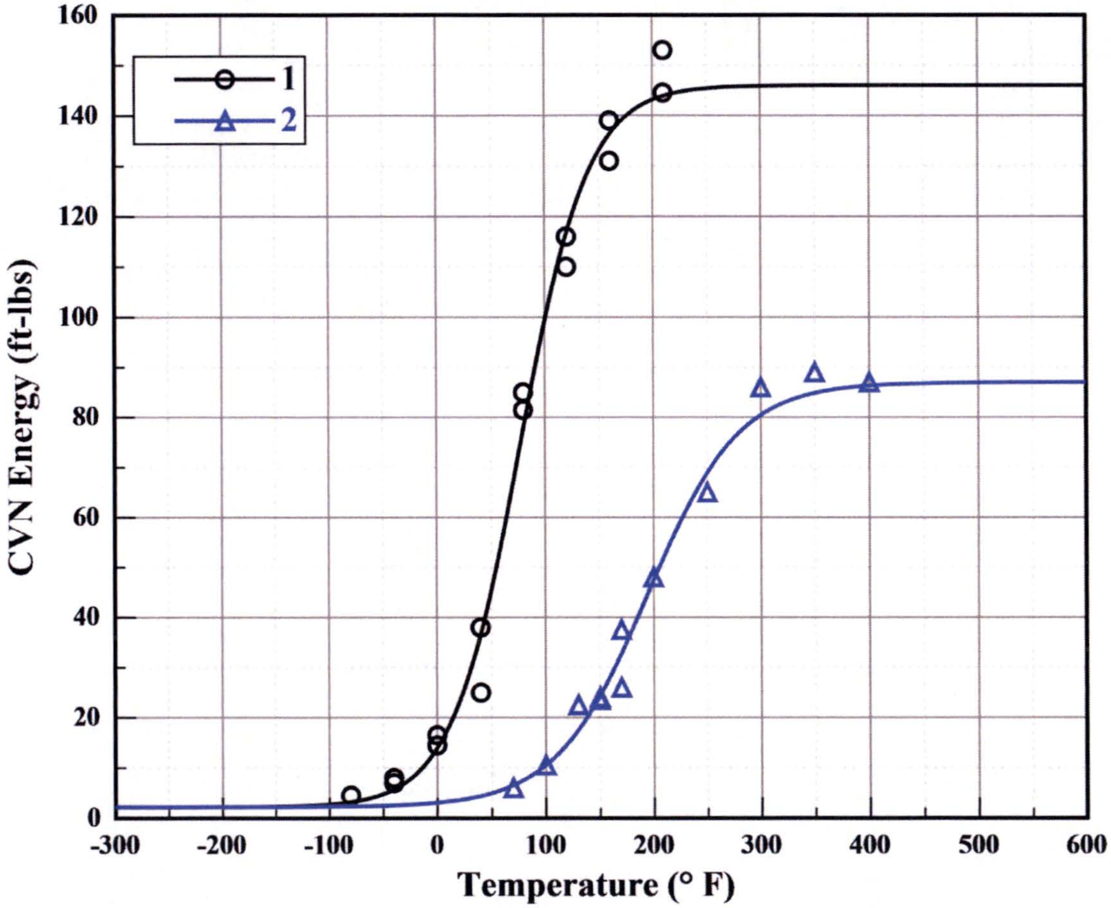
Curve	Fluence	LSE	USE	d-USE	T @50	d-T @50
1	---	0	100	0	-37.8	0
2	---	0	100	0	-31.3	6.5
3	---	0	100	0	16	53.8
4	---	0	100	0	-7.5	30.3

Figure 5-12 Charpy V-Notch Percent Shear vs. Temperature for ANO-2 Reactor Vessel Heat-Affected Zone Material – Continued

Standard Reference Material

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 3:02 PM

Curve	Plant	Capsule	Material	Ori.	Heat #
1	Arkansas 2	UNIRR	SA533B CL1	LT	HSST-01MY
2	Arkansas 2	104°	SA533B CL1	LT	HSST-01MY



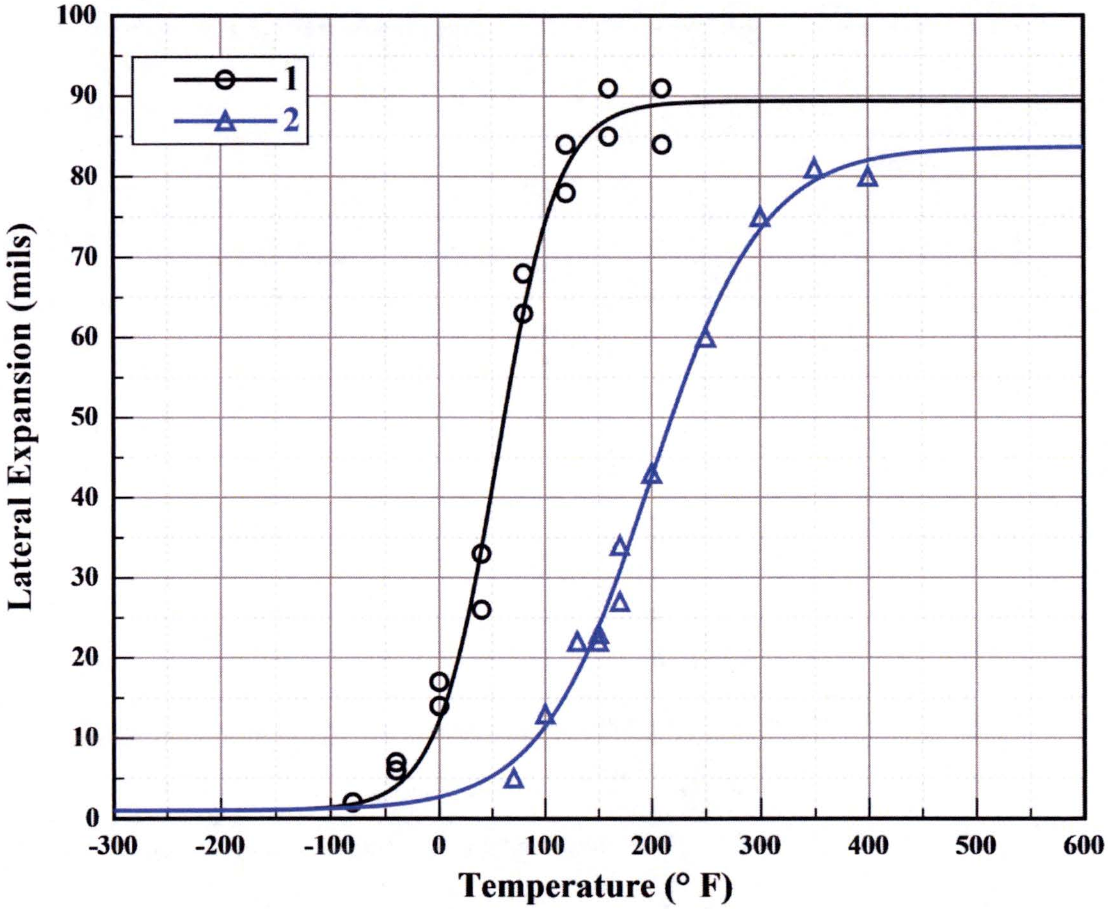
Curve	Fluence	LSE	USE	d-USE	T @30	d-T @30	T @50	d-T @50
1	- - -	2.2	146	0	31.5	0	54.7	0
2	- - -	2.2	87	-59	163.8	132.3	205.3	150.6

Figure 5-13 Charpy V-Notch Impact Energy vs. Temperature for ANO-2 Reactor Vessel Standard Reference Material

Standard Reference Material

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 3:02 PM

Curve	Plant	Capsule	Material	Ori.	Heat #
1	Arkansas 2	UNIRR	SA533B CL1	LT	HSST-01MY
2	Arkansas 2	104°	SA533B CL1	LT	HSST-01MY



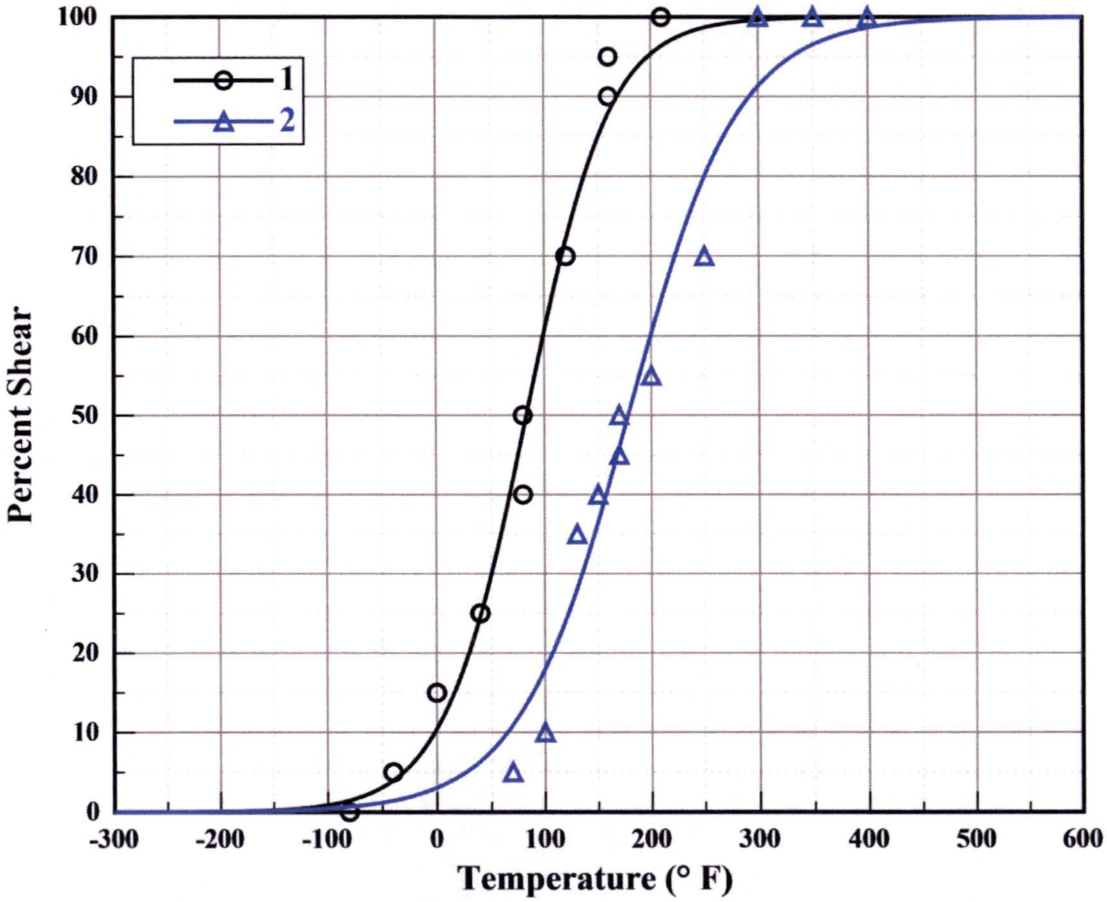
Curve	Fluence	LSE	USE	d-USE	T @35	d-T @35
1	- - -	1	89.39	0	41.9	0
2	- - -	1	83.67	-5.72	180.9	139

Figure 5-14 Charpy V-Notch Lateral Expansion vs. Temperature for ANO-2 Reactor Vessel Standard Reference Material

Standard Reference Material

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 3:06 PM

Curve	Plant	Capsule	Material	Ori.	Heat #
1	Arkansas 2	UNIRR	SA533B CL1	LT	HSST-01MY
2	Arkansas 2	104°	SA533B CL1	LT	HSST-01MY



Curve	Fluence	LSE	USE	d-USE	T @50	d-T @50
1	- - -	0	100	0	83.3	0
2	- - -	0	100	0	178.5	95.2

Figure 5-15 Charpy V-Notch Percent Shear vs. Temperature for ANO-2 Reactor Vessel Standard Reference Material

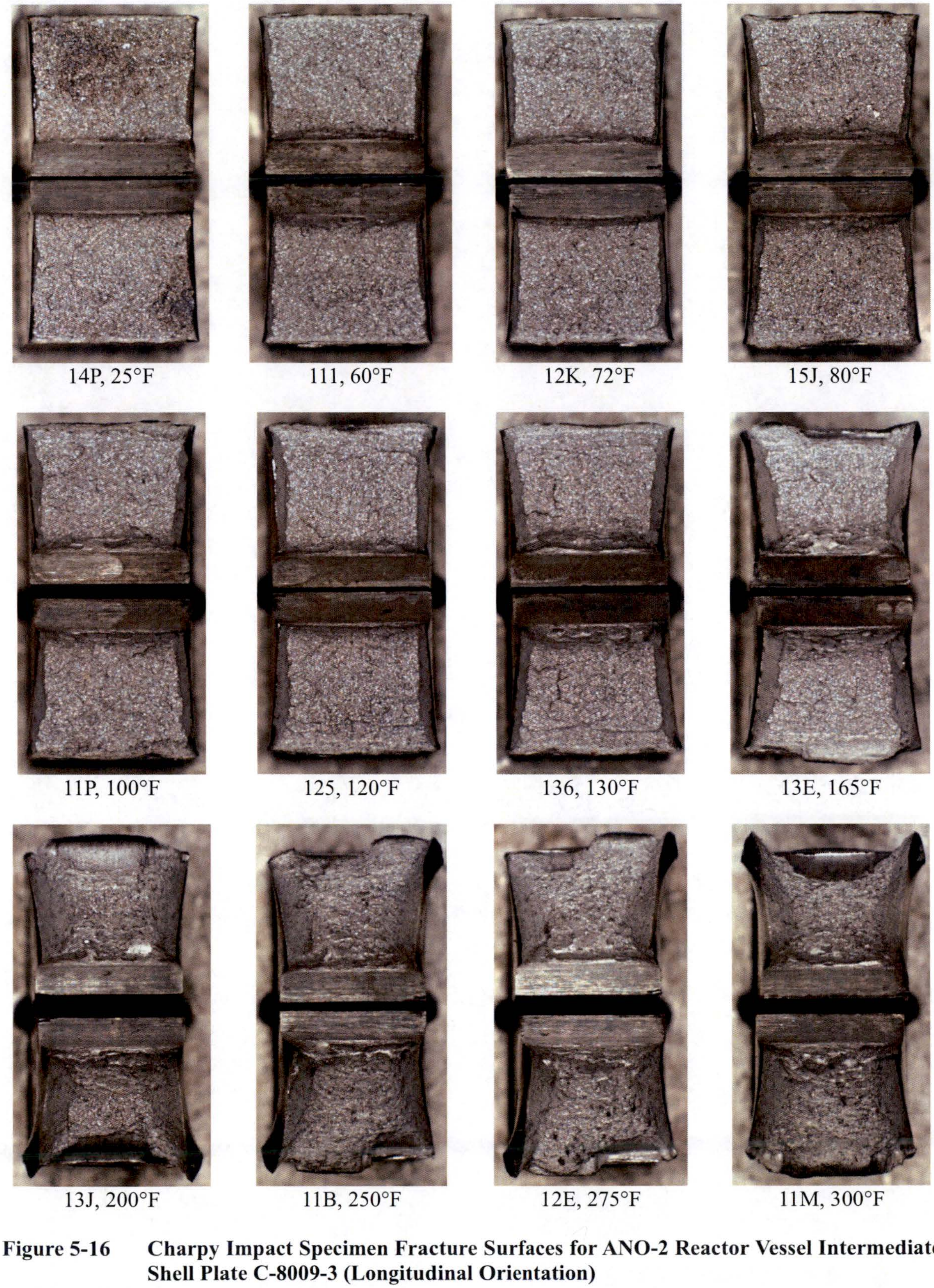


Figure 5-16 Charpy Impact Specimen Fracture Surfaces for ANO-2 Reactor Vessel Intermediate Shell Plate C-8009-3 (Longitudinal Orientation)

Figure 5-17 Charpy Impact Specimen Fracture Surfaces for ANO-2 Reactor Vessel Intermediate Shell Plate C-8009-3 (Transverse Orientation)

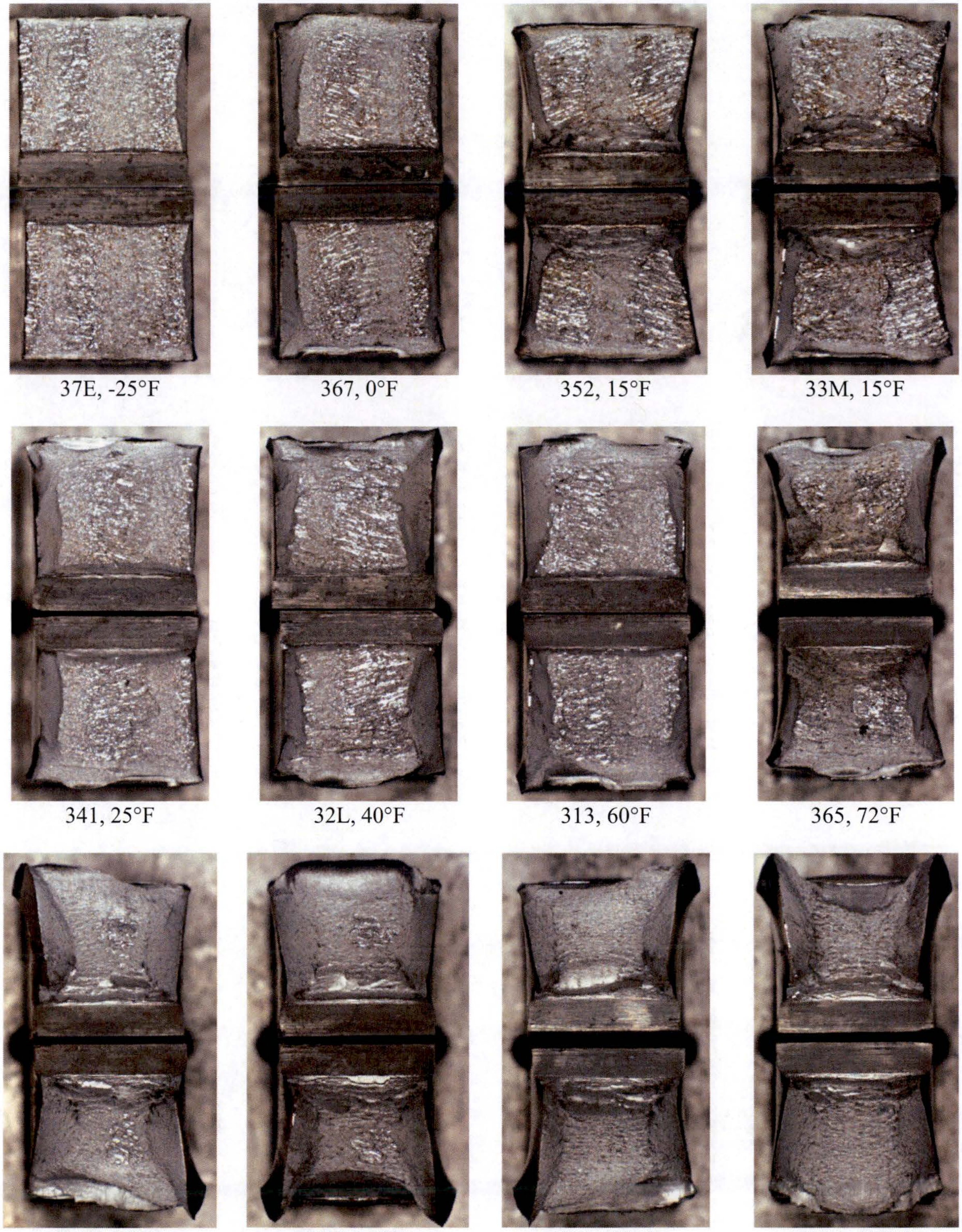


Figure 5-18 Charpy Impact Specimen Fracture Surfaces for the ANO-2 Reactor Vessel Surveillance Program Weld Material (Heat # 83650)

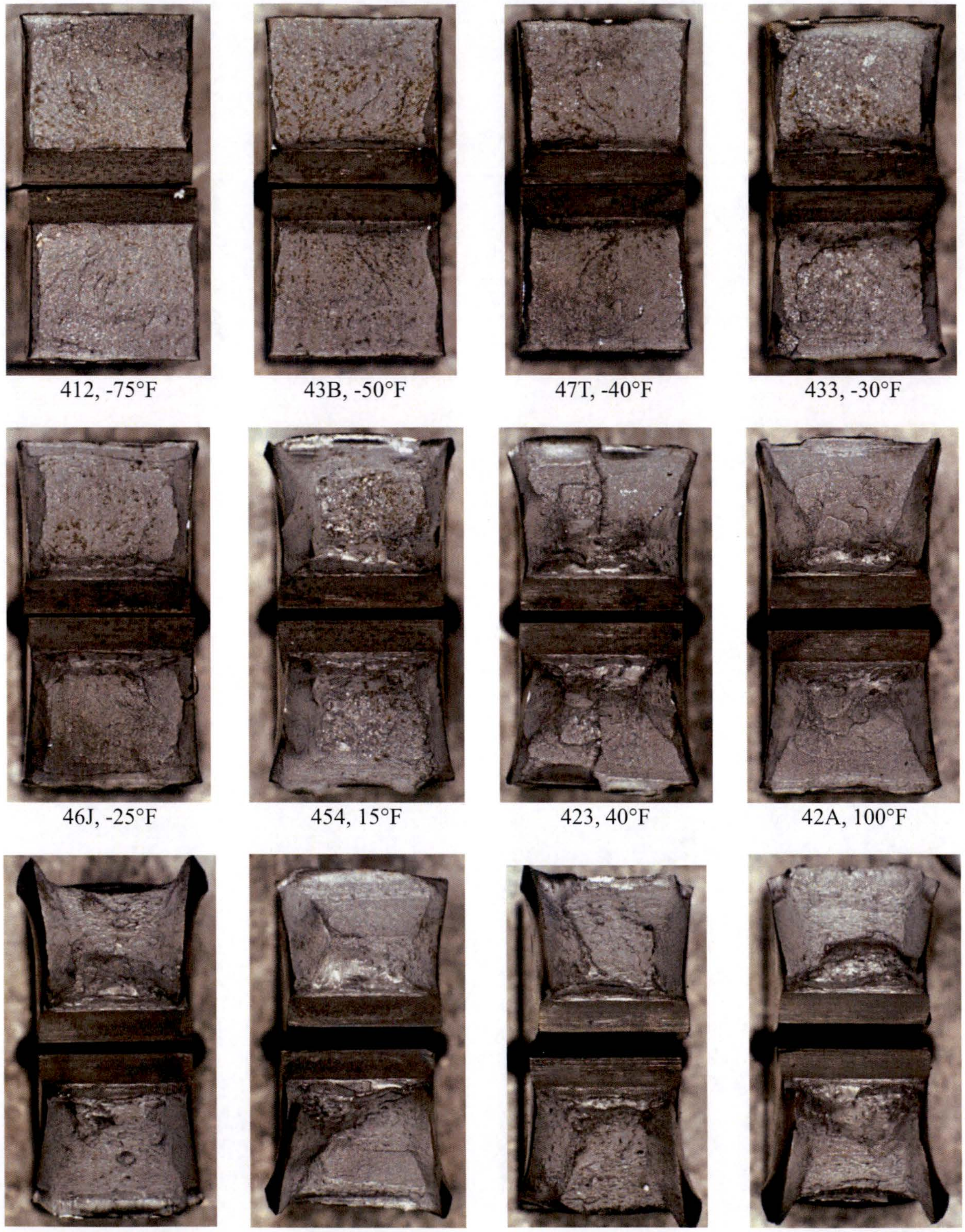
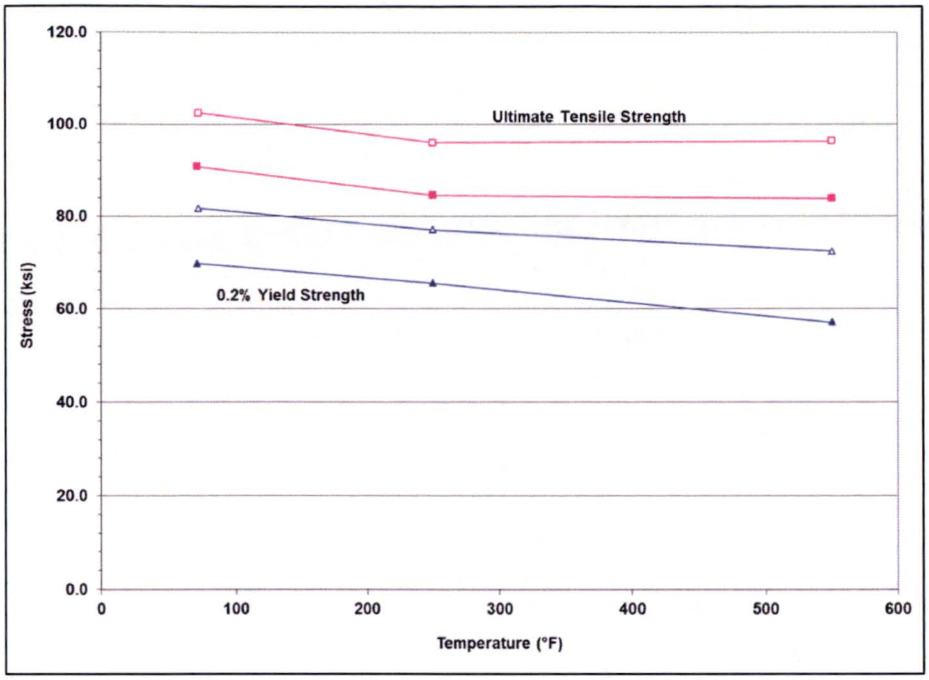


Figure 5-19 Charpy Impact Specimen Fracture Surfaces for the ANO-2 Reactor Vessel Heat-Affected Zone Material



Legend: ▲, ●, and ■ are unirradiated
Δ, ○, and □ are irradiated to 3.67 x 10^{19} n/cm^2 (E > 1.0 MeV)

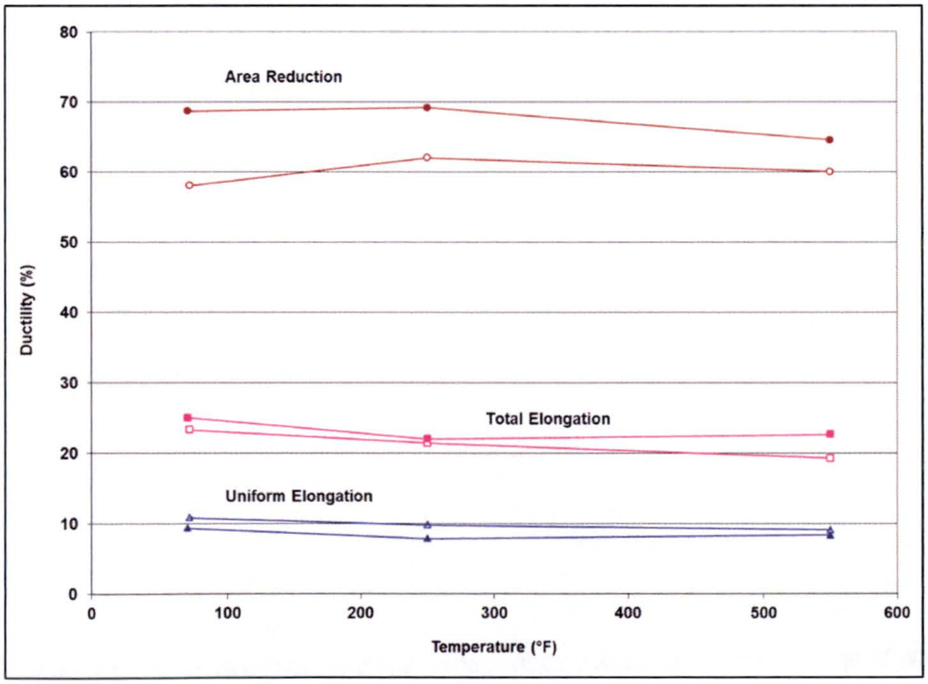
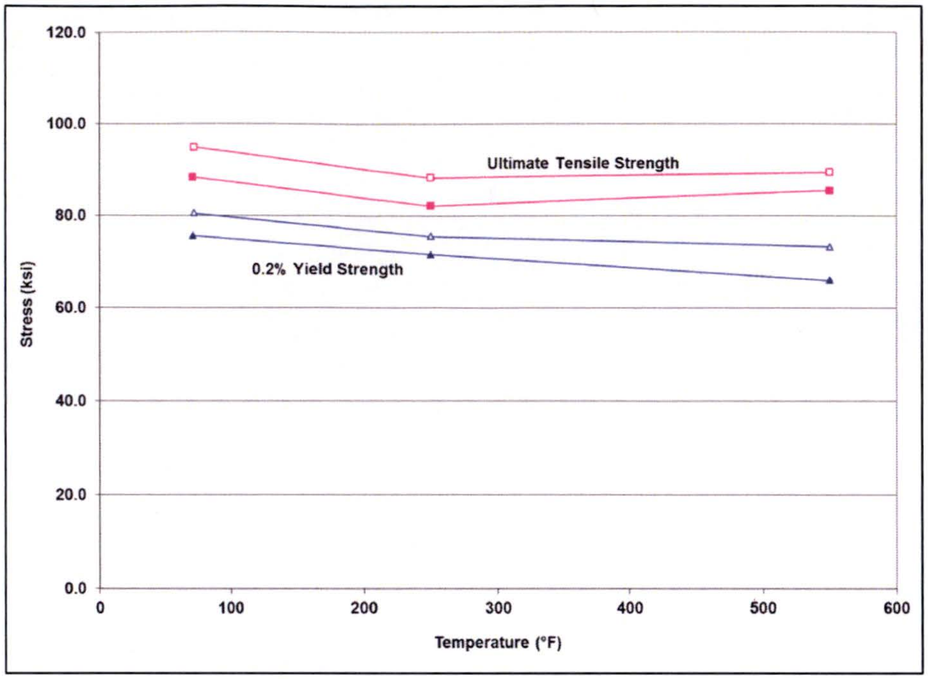


Figure 5-20 Tensile Properties for ANO-2 Reactor Vessel Intermediate Shell Plate C-8009-3 (Transverse Orientation)



Legend: ▲, ●, and ■ are unirradiated
Δ, ○, and □ are irradiated to 3.67×10^{19} n/cm^2 (E > 1.0 MeV)
Note that the irradiated 72°F weld specimen failed at the knife edge; see Table 5-11 for more information.

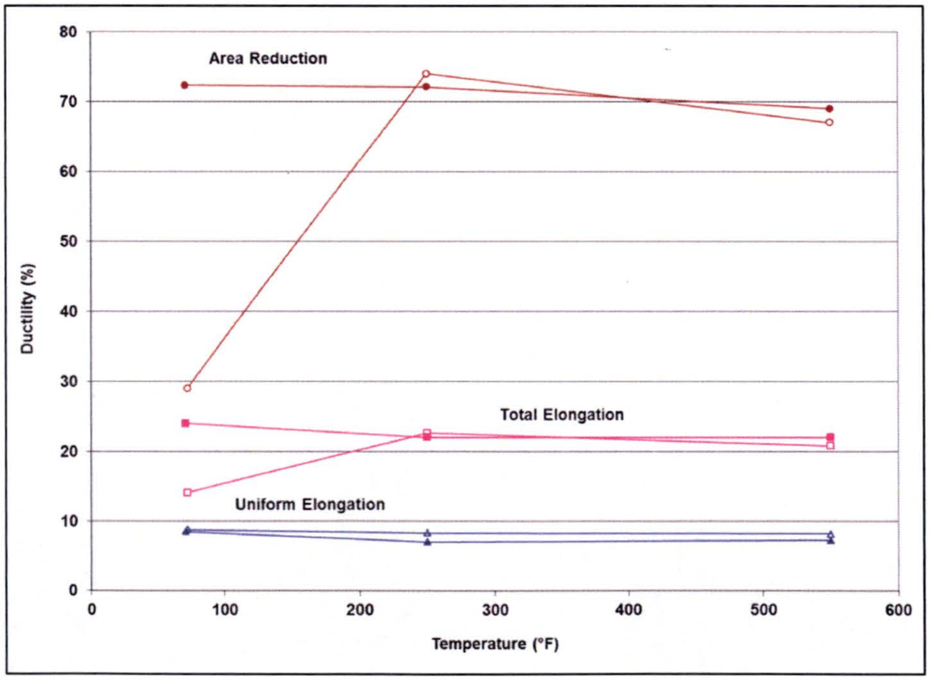
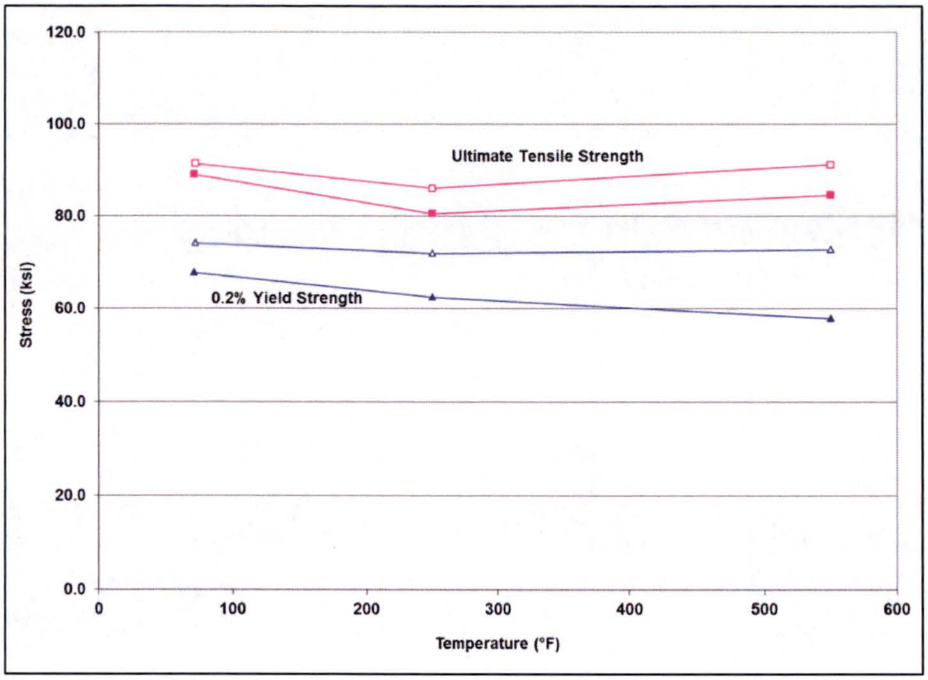


Figure 5-21 Tensile Properties for ANO-2 Reactor Vessel Surveillance Program Weld Material (Heat # 83650)



Legend: ▲, ●, and ■ are unirradiated
Δ, ○, and □ are irradiated to 3.67×10^{19} n/cm^2 (E > 1.0 MeV)

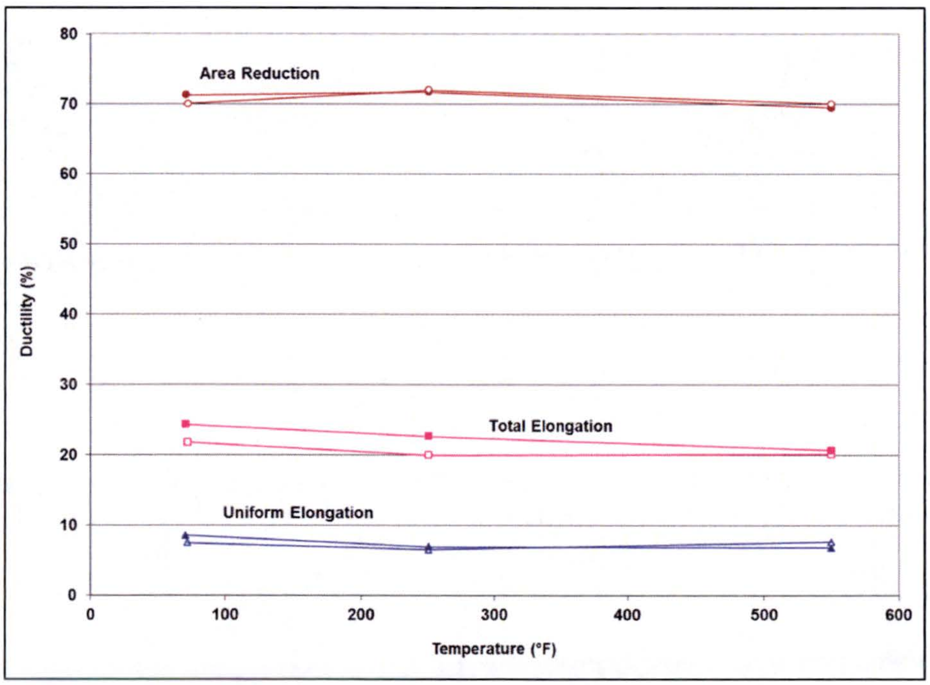
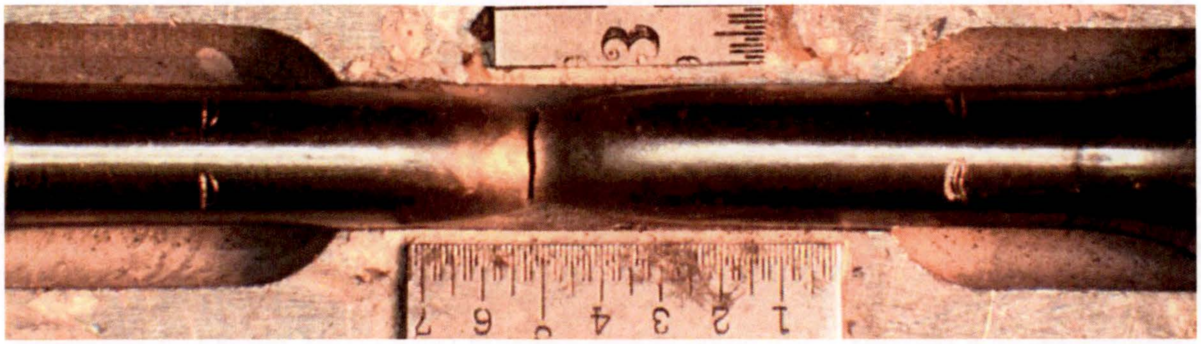
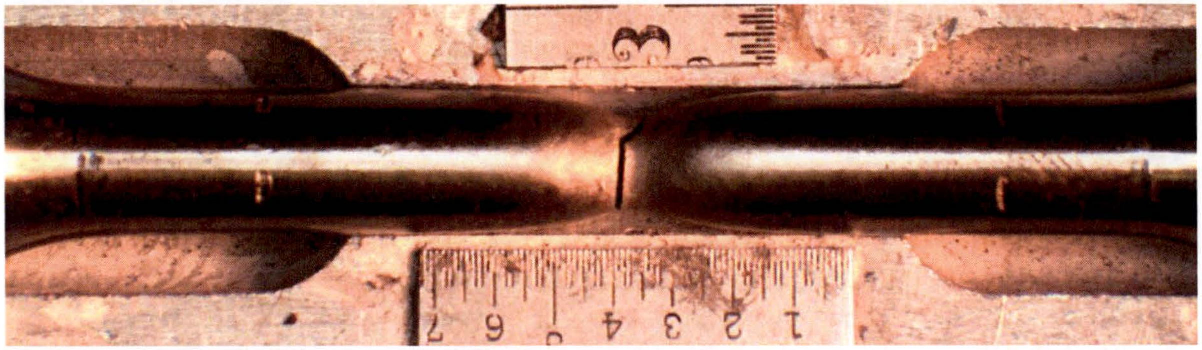


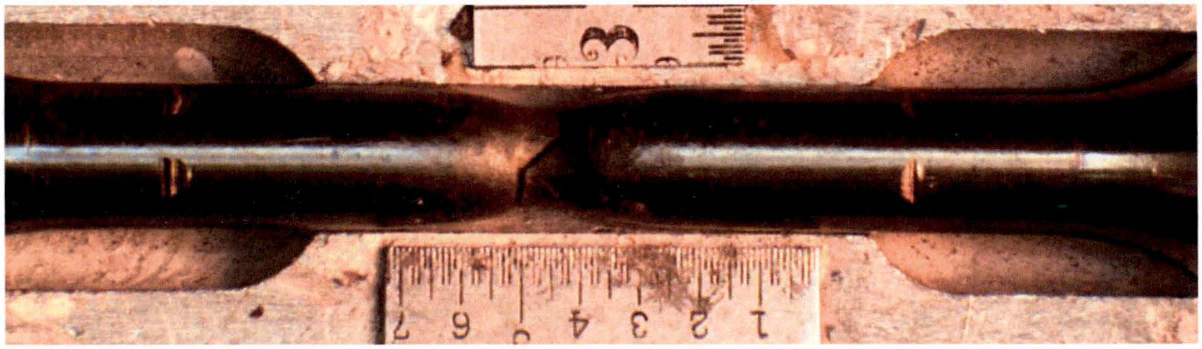
Figure 5-22 Tensile Properties for the ANO-2 Reactor Vessel Heat-Affected Zone Material



2KE – Tested at 72°F

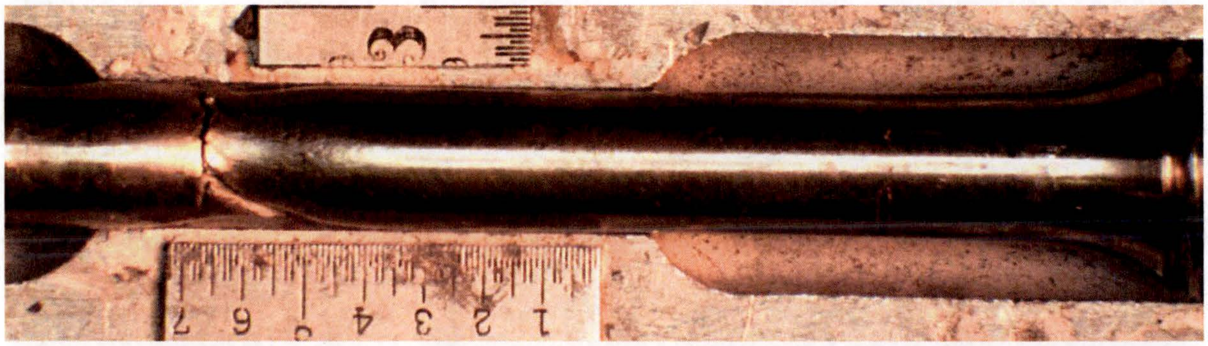


2KY – Tested at 250°F

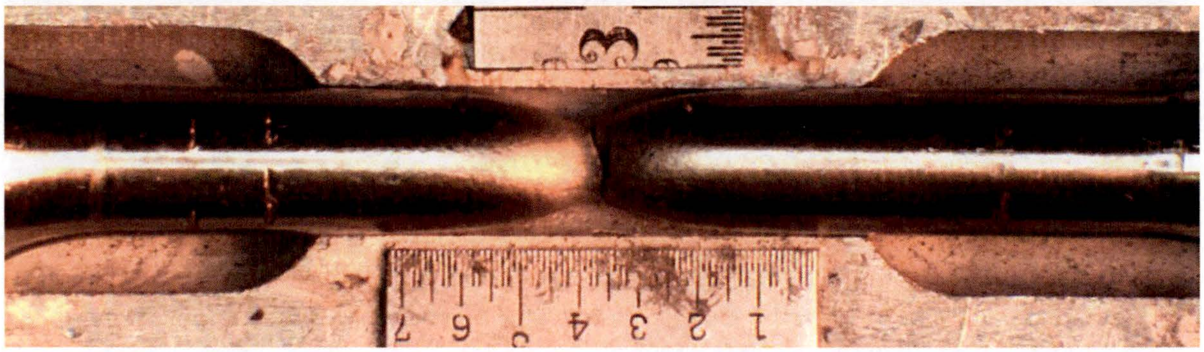


2KU – Tested at 550°F

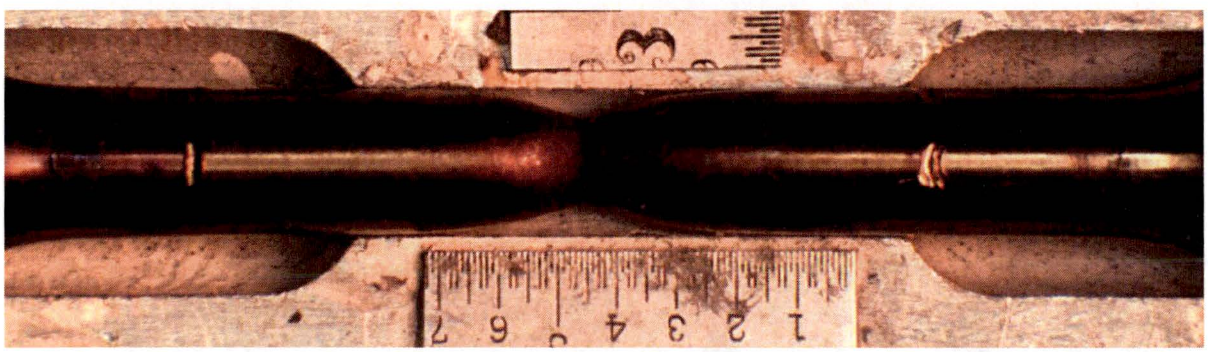
Figure 5-23 Fractured Tensile Specimens from ANO-2 Reactor Vessel Intermediate Shell Plate C-8009-3 (Transverse Orientation)



3JU – Tested at 72°F

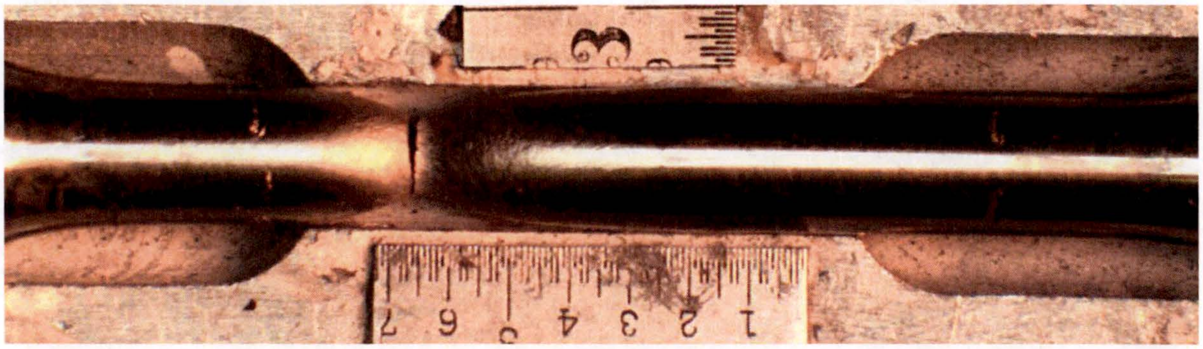


3JB – Tested at 250°F



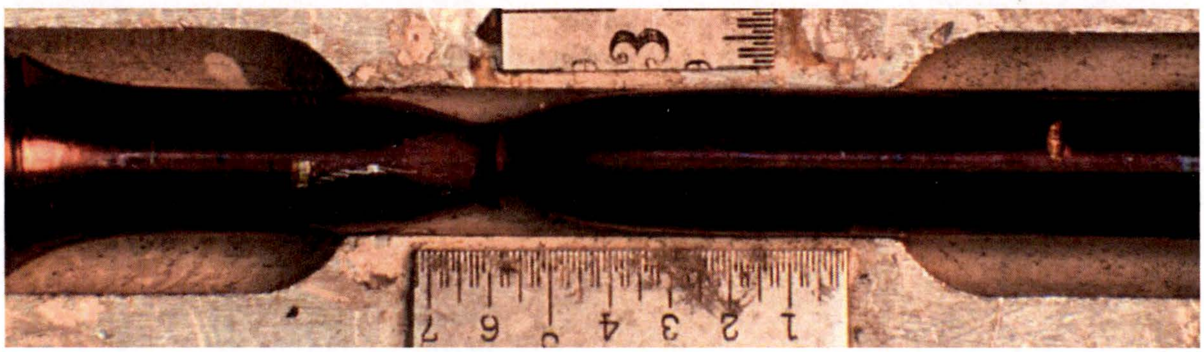
3KD – Tested at 550°F

Figure 5-24 Fractured Tensile Specimens from ANO-2 Reactor Vessel Surveillance Program Weld Material (Heat # 83650)



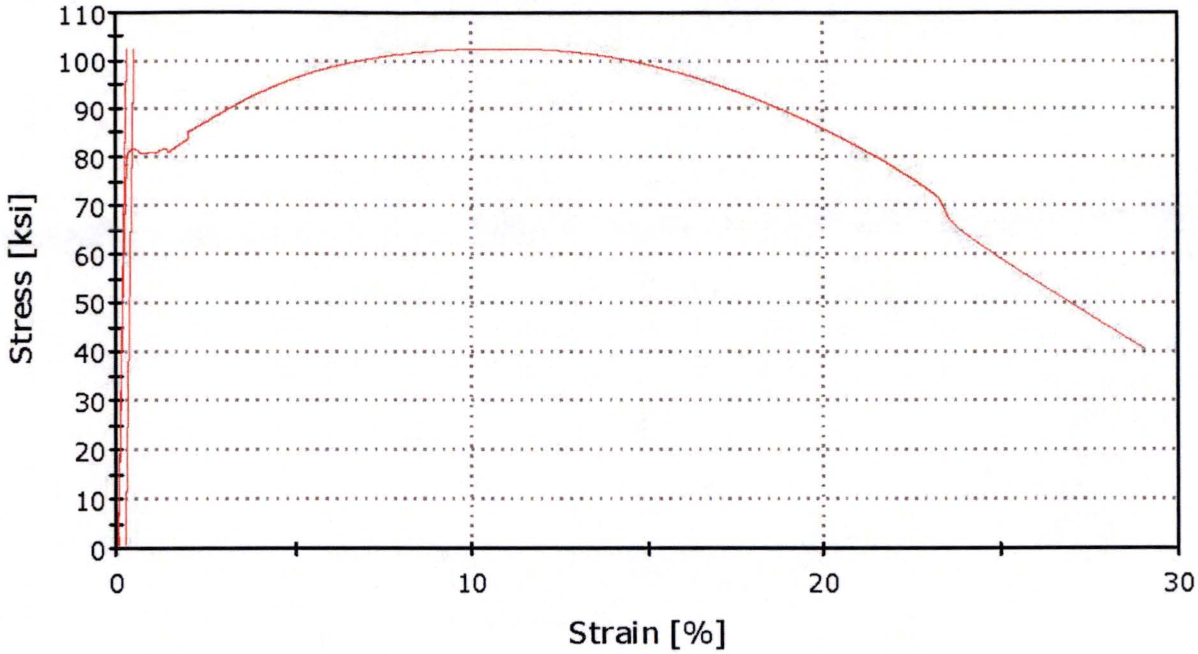
4KT – Tested at 72°F

4KE – Tested at 250°F

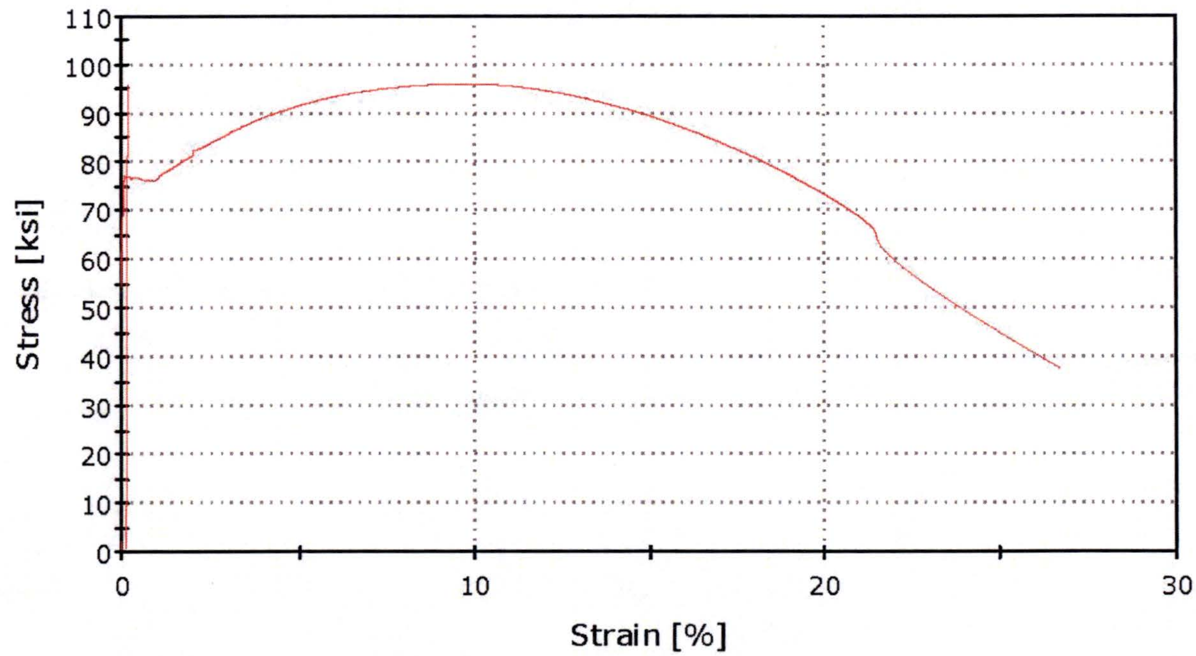


4JL – Tested at 550°F

Figure 5-25 Fractured Tensile Specimens from the ANO-2 Reactor Vessel Heat-Affected Zone Material

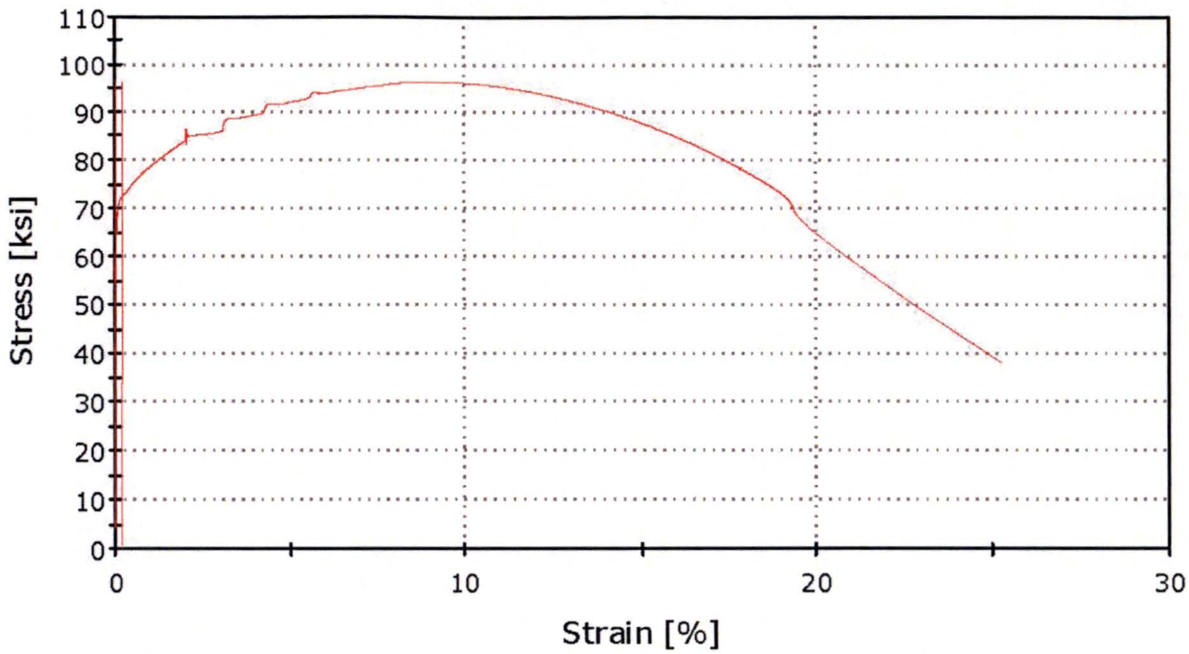


Tensile Specimen 2KE Tested at 72°F



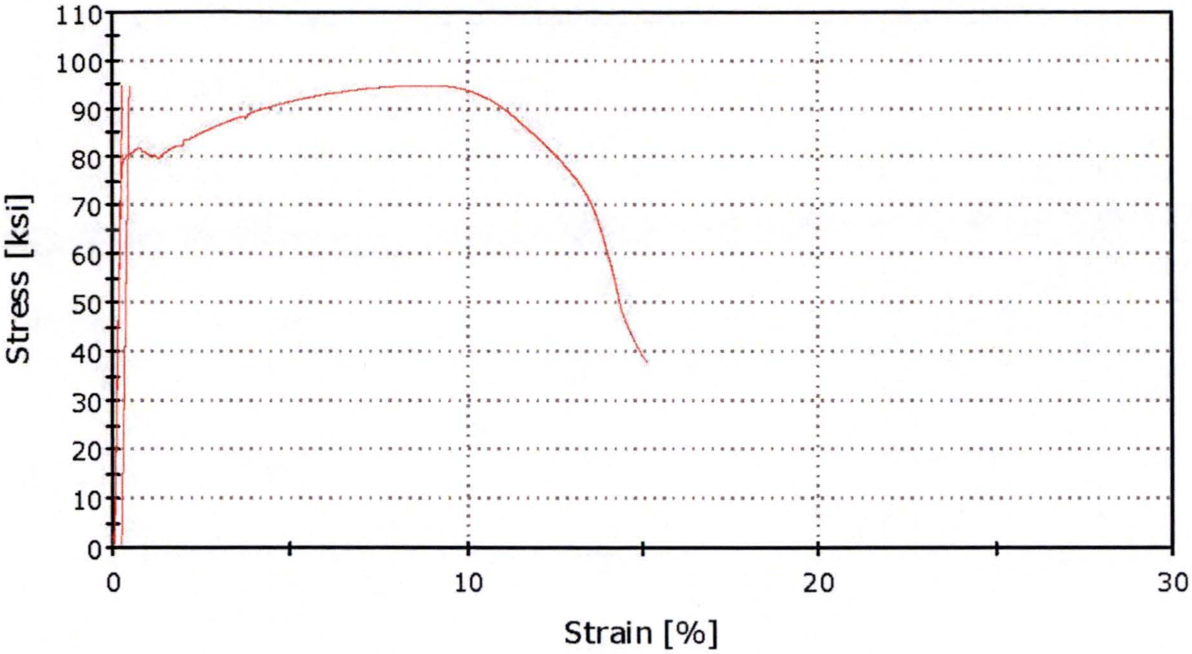
Tensile Specimen 2KY Tested at 250°F

Figure 5-26 Engineering Stress-Strain Curves for ANO-2 Intermediate Shell Plate C-8009-3 Tensile Specimens 2KE and 2KY (Transverse Orientation)

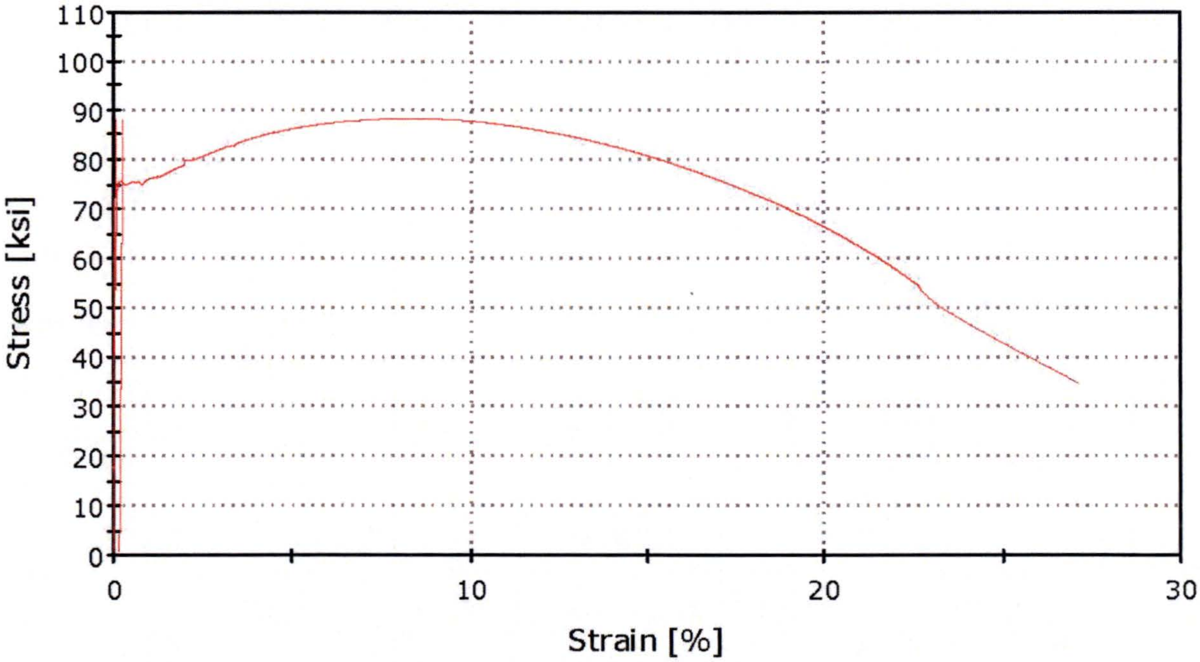


Tensile Specimen 2KU Tested at 550°F

Figure 5-27 Engineering Stress-Strain Curve for ANO-2 Intermediate Shell Plate C-8009-3 Tensile Specimen 2KU (Transverse Orientation)



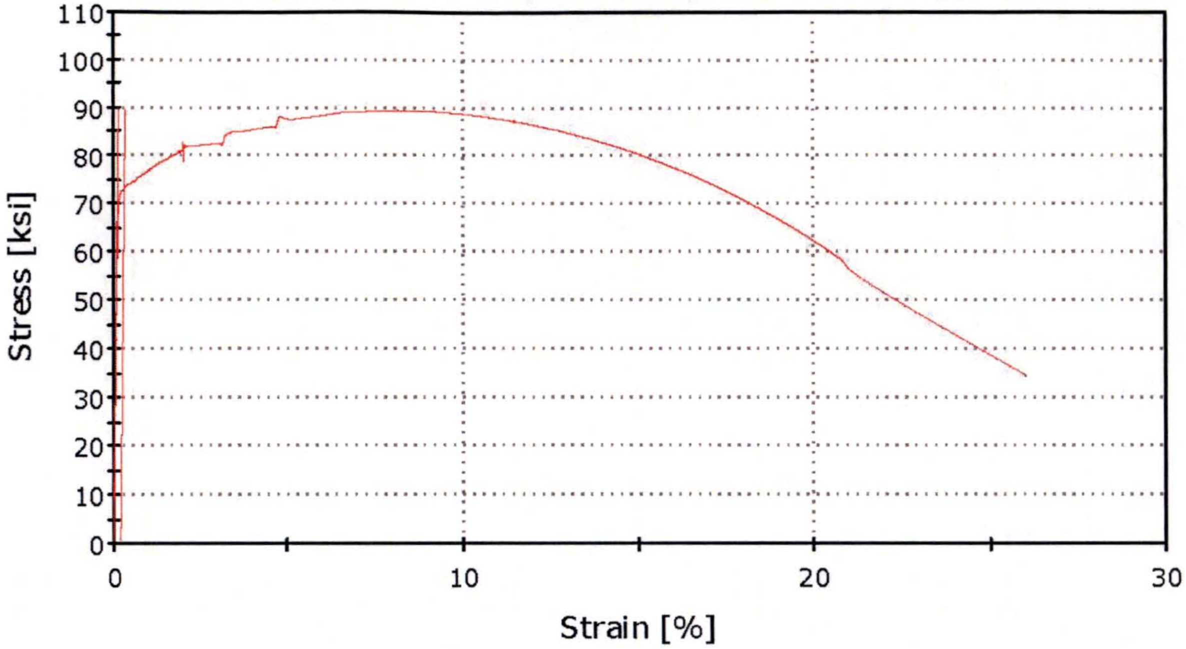
Tensile Specimen 3JU* Tested at 72°F



Tensile Specimen 3JB Tested at 250°F

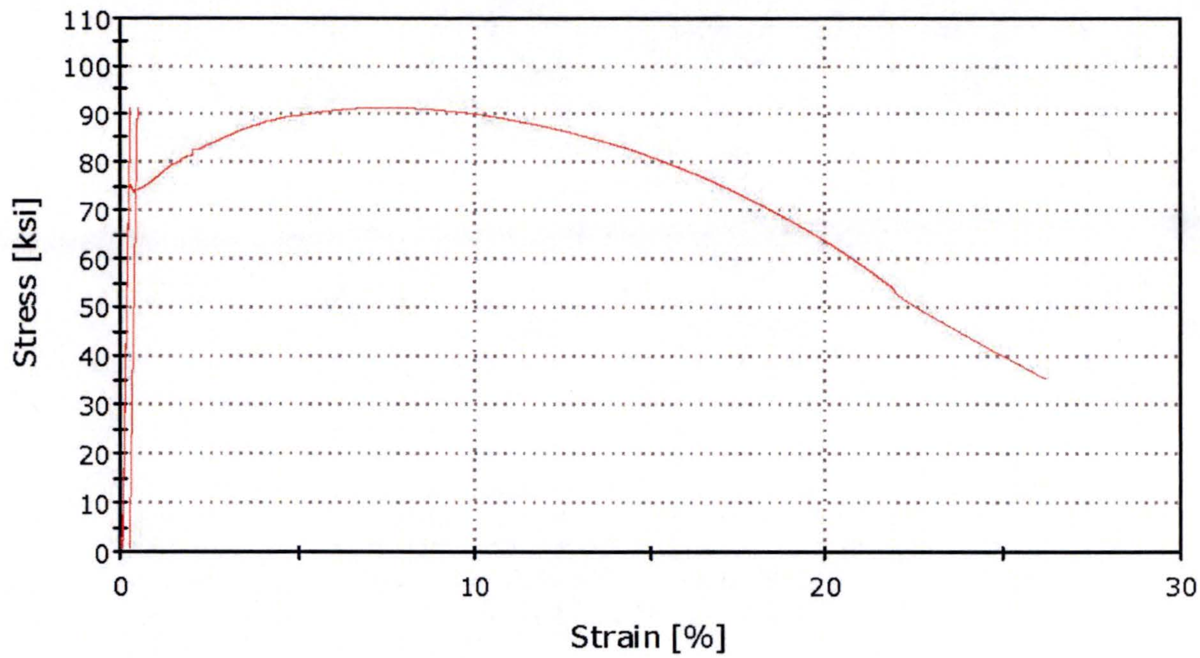
Figure 5-28 Engineering Stress-Strain Curves for ANO-2 Surveillance Program Weld Material (Heat # 83650) Tensile Specimens 3JU and 3JB

*Note: Specimen 3JU failed at the extensometer knife edge. As a result, the stress-strain curve is atypical and may not reflect the weld behavior.

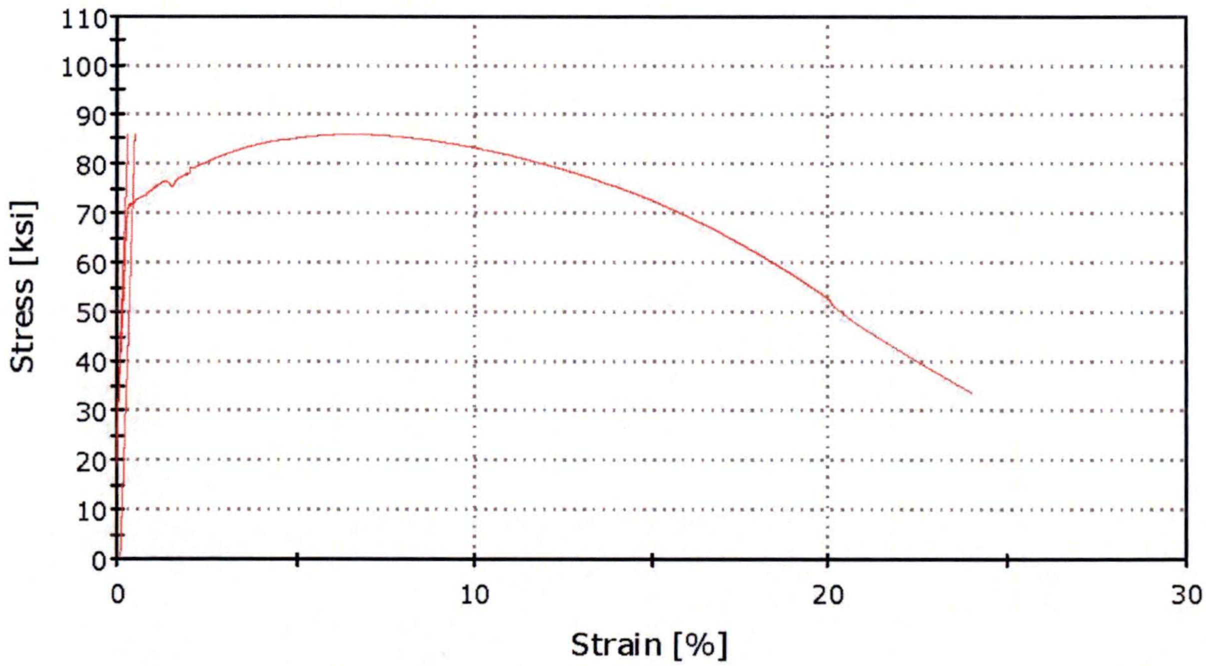


Tensile Specimen 3KD Tested at 550°F

Figure 5-29 Engineering Stress-Strain Curve for ANO-2 Surveillance Program Weld Material (Heat # 83650) Tensile Specimen 3KD

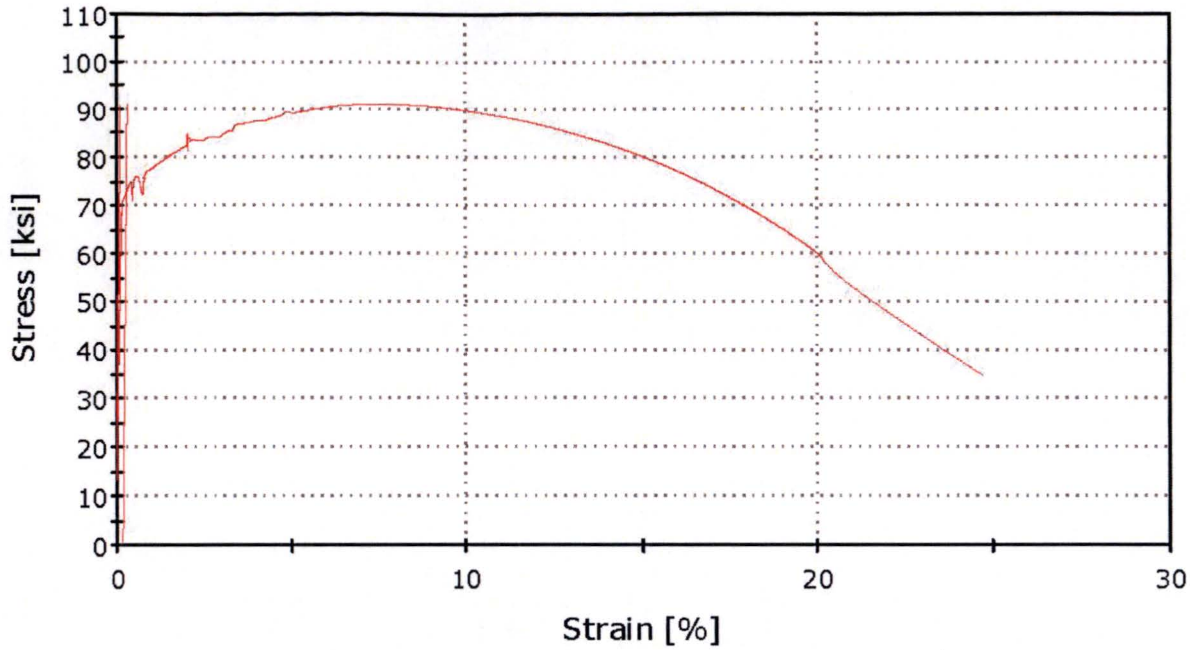


Tensile Specimen 4KT Tested at 72°F



Tensile Specimen 4KE Tested at 250°F

Figure 5-30 Engineering Stress-Strain Curves for ANO-2 Heat-Affected Zone Material Tensile Specimens 4KT and 4KE



Tensile Specimen 4JL Tested at 550°F

Figure 5-31 Engineering Stress-Strain Curve for ANO-2 Heat-Affected Zone Material Tensile Specimen 4JL

6 RADIATION ANALYSIS AND NEUTRON DOSIMETRY

6.1 INTRODUCTION

This section describes a discrete ordinates (S_n) transport analysis performed for the Arkansas Nuclear One Unit 2 reactor to determine the neutron radiation environment within the reactor pressure vessel and surveillance capsules. In this analysis, fast neutron exposure parameters in terms of fast neutron (E > 1.0 MeV) fluence and iron atom displacements (dpa) were established on a plant- and fuel-cycle-specific basis. An evaluation of the most recent dosimetry sensor set from Capsule 284°, withdrawn at the end of the 24th plant operating cycle, is provided. In addition, the sensor set from the previously withdrawn and evaluated Capsule 97° was also re-analyzed. However, the sensor set from the previously withdrawn and evaluated Capsule 104° was not re-analyzed since the counting results for this sensor set were not included in the Capsule 104° analysis report. Comparisons of the results from the dosimetry evaluations with the analytical predictions served to validate the plant-specific neutron transport calculations. These validated calculations subsequently form the basis for projections of the neutron exposure of the reactor pressure vessel for operating periods extending to 54 effective full-power years (EFPY).

The use of fast neutron (E > 1.0 MeV) fluence to correlate measured material property changes to the neutron exposure of the material has traditionally been accepted for the development of damage trend curves as well as for the implementation of trend curve data to assess the condition of the vessel. However, in recent years, it has been suggested that an exposure model that accounts for differences in neutron energy spectra between surveillance capsule locations and positions within the vessel wall could lead to an improvement in the uncertainties associated with damage trend curves and improved accuracy in the evaluation of damage gradients through the reactor vessel wall.

Because of this potential shift away from a threshold fluence toward an energy-dependent damage function for data correlation, ASTM Standard Practice E853-13, "Standard Practice for Analysis and Interpretation of Light-Water Reactor Surveillance Results," [Ref. 18] recommends reporting displacements per iron atom along with fluence (E > 1.0 MeV) to provide a database for future reference. The energy-dependent dpa function to be used for this evaluation is specified in ASTM Standard Practice E693-94, "Standard Practice for Characterizing Neutron Exposures in Iron and Low Alloy Steels in Terms of Displacements per Atom" [Ref. 19]. The application of the dpa parameter to the assessment of embrittlement gradients through the thickness of the reactor vessel wall has already been promulgated in Revision 2 to Regulatory Guide 1.99, "Radiation Embrittlement of Reactor Vessel Materials" [Ref. 1].

All of the calculations and dosimetry evaluations described in this section and in Appendix A were based on nuclear cross-section data derived from ENDF/B-VI. Furthermore, the neutron transport and dosimetry evaluation methodologies follow the guidance of Regulatory Guide 1.190, "Calculational and Dosimetry Methods for Determining Pressure Vessel Neutron Fluence" [Ref. 20]. Additionally, the methods used to develop the calculated pressure vessel fluence are consistent with the NRC-approved methodology described in WCAP-14040-A, Revision 4, Methodology Used to Develop Cold Overpressure Mitigating System Setpoints and RCS Heatup and Cooldown Limit Curves" [Ref. 21].

6.2 DISCRETE ORDINATES ANALYSIS

The arrangement of the surveillance capsules in the Arkansas Nuclear One Unit 2 reactor vessel is shown in Figure 4-1. Six irradiation capsules attached to the pressure vessel inner wall are included in the reactor design that constitutes the reactor vessel surveillance program. The capsules are located at azimuthal angles of 83°, 97°, 104°, 263°, 277°, and 284°, as shown in Figure 4-1. These full-core positions correspond to the octant symmetric locations shown in Figure 6-1: 7° from the core cardinal axes (for the 83°, 97°, 263°, and 277° capsules) and 14° from the core cardinal axes (for the 104° and 284° capsules). The stainless steel specimen containers are 1.5-inch by 0.75-inch and are approximately 98 inches in height. The containers are positioned axially such that the test specimens are centered on the core midplane, thus spanning the approximate central 8 feet of the 12.5-foot-high reactor core.

From a neutronic standpoint, the surveillance capsules and associated support structures are significant. The presence of these materials has a significant effect on both the spatial distribution of neutron fluence rate and the neutron spectrum in the vicinity of the capsules. However, the capsules are far enough apart that they do not interfere with one another. In order to determine the neutron environment at the test specimen location, the capsules themselves must be included in the analytical model.

In performing the fast neutron exposure evaluations for the Arkansas Nuclear One Unit 2 reactor vessel and surveillance capsules, a series of fuel-cycle-specific forward transport calculations were carried out using the following three-dimensional fluence rate synthesis technique:

$$\phi(r,\theta,z) = \phi(r,\theta) \times \frac{\phi(r,z)}{\phi(r)} \qquad \text{(Eqn. 6-1)}$$

where $\phi(r,\theta,z)$ is the synthesized three-dimensional neutron fluence rate distribution, $\phi(r,\theta)$ is the transport solution in r,θ geometry, $\phi(r,z)$ is the two-dimensional solution for a cylindrical reactor model using the actual axial core power distribution, and $\phi(r)$ is the one-dimensional solution for a cylindrical reactor model using the same source per unit height as that used in the r,θ two-dimensional calculation. This synthesis procedure was carried out for each operating cycle at Arkansas Nuclear One Unit 2.

For the Arkansas Nuclear One Unit 2 transport calculations, the r,θ models depicted in Figure 6-1 and Figure 6-2 were utilized since, with the exception of the capsules, the reactor is octant symmetric. These r,θ models include the core, the reactor internals, octants with suviellance capules at 7° and 14° and octants without surveillance capsules, the pressure vessel cladding and vessel wall, the insulation external to the pressure vessel, and the primary biological shield wall. These models formed the basis for the calculated results and enabled making comparisons to the surveillance capsule dosimetry evaluations. In developing these analytical models, nominal design dimensions were generally employed for the various structural components. Note that for the pressure vessel inner radius, however, the average of the as-built inner radii was used. In addition, water temperatures, and hence, coolant densities in the reactor core and downcomer regions of the reactor were taken to be representative of full-power operating conditions. The coolant densities were treated on a fuel-cycle-specific basis. The reactor core itself was treated as a homogeneous mixture of fuel, cladding, water, and miscellaneous core structures such as fuel assembly grids, guide tubes, et cetera. The geometric mesh description of the r,θ reactor model in Figure 6-1 consisted of 166 radial by 123 azimuthal intervals. The geometric mesh description of the r,θ reactor model in Figure 6-2 consisted of 166 radial by 116 azimuthal intervals. Mesh sizes were chosen to assure

that proper convergence of the inner iterations was achieved on a pointwise basis. The pointwise inner iteration fluence rate convergence criterion utilized in the r,θ calculations was set at a value of 0.001.

The r,z model used for the Arkansas Nuclear One Unit 2 calculations is shown in Figure 6-3 and extends radially from the centerline of the reactor core out to the primary biological shield and over an axial span from an elevation approximately 4.9 feet below to 6 feet above the active core. As in the case of the r,θ models, nominal design dimensions, with the exception of the pressure vessel inner radius, and full-power coolant densities were employed in the calculations. In the r,z model, the homogenous core region was treated as an equivalent cylinder with a volume equal to that of the active core zone. The stainless steel girth ribs located between the core shroud and core barrel regions were also explicitly included in the model. The geometric mesh description of the r,z reactor model in Figure 6-3 consisted of 161 radial by 222 axial intervals. As in the case of the r,θ calculations, mesh sizes were chosen to assure that proper convergence of the inner iterations was achieved on a pointwise basis. The pointwise inner iteration fluence rate convergence criterion utilized in the r,z calculations was set at a value of 0.001.

The one-dimensional radial model used in the synthesis procedure consisted of the same 161 radial mesh intervals included in the r,z model. Thus, radial synthesis factors could be determined on a meshwise basis throughout the entire geometry.

The core power distributions used in the plant-specific transport analysis for each of the first 25 fuel cycles at Arkansas Nuclear One Unit 2 included cycle-dependent fuel assembly initial enrichments, burnups, and axial power distributions (note that Cycles 1–24 have been completed; Cycle 25 is based on the expected core design for this cycle and an assumed cycle length of 1.37 EFPY). This information was used to develop spatial- and energy-dependent core source distributions averaged over each individual fuel cycle. Therefore, the results from the neutron transport calculations provided data in terms of fuel-cycle-averaged neutron fluence rate, which when multiplied by the appropriate fuel cycle length, generated the incremental fast neutron exposure for each fuel cycle. In constructing these core source distributions, the energy distribution of the source was based on an appropriate fission split for uranium and plutonium isotopes based on the initial enrichment and burnup history of individual fuel assemblies. From these assembly-dependent fission splits, composite values of energy release per fission, neutron yield per fission, and fission spectrum were determined.

All of the transport calculations supporting this analysis were carried out using the DORT discrete ordinates code [Ref. 24] and the BUGLE-96 cross-section library [Ref. 23]. The BUGLE-96 library provides a coupled 47-neutron, 20-gamma-group cross-section data set produced specifically for light-water reactor (LWR) applications. In these analyses, anisotropic scattering was treated with a P_5 Legendre expansion, and angular discretization was modeled with an S_{16} order of angular quadrature. Energy- and space-dependent core power distributions, as well as system operating temperatures, were treated on a fuel-cycle-specific basis.

Selected results from the neutron transport analyses are provided in Table 6-1 through Table 6-10. In Table 6-1, the calculated exposure rates and integral exposures expressed in terms of fast neutron fluence rate ($E > 1.0$ MeV) and fast neutron fluence ($E > 1.0$ MeV), respectively, are given at the radial and azimuthal center of the surveillance capsule positions, i.e., at the 7° and 14° capsule locations. In Table 6-2, the calculated exposure rates and integral exposures expressed in terms of iron atom displacement rate and iron atom displacements, respectively, are given at the radial and azimuthal center

of the surveillance capsule positions, i.e., at the 7° and 14° capsule locations. These results, representative of the average axial exposure of the material specimens, establish the calculated exposure of the surveillance capsules to date and projected into the future.

Similar information in terms of calculated fast neutron fluence rate (E > 1.0 MeV), fast neutron fluence (E > 1.0 MeV), dpa/s, and dpa, are provided in Table 6-3 through Table 6-6, respectively, for the reactor vessel inner radius at four azimuthal locations, as well as the maximum exposure observed within the octant. The vessel data given in Table 6-3 through Table 6-6 were taken at the clad/base metal interface and represent maximum calculated exposure levels on the vessel. From the data provided in Table 6-4, it is noted that the peak clad/base metal interface vessel fluence (E > 1.0 MeV) at the end of Cycle 24 (i.e., after 29.24 EFPY of plant operation) was 2.77E+19 n/cm^2.

These data tabulations include both plant- and fuel-cycle-specific calculated neutron exposures at the end of Cycle 24, at the end of projected Cycle 25, and at further projections to 54 EFPY. The calculations account for the uprate from 2815 MWt to 3026 MWt that occurred at the beginning of Cycle 16. The projections are based on the assumption that the core power distributions and associated plant operating characteristics from Cycle 23, Cycle 24, and the design of Cycle 25 are representative of future plant operation. The future projections are based on the current reactor power level of 3026 MWt.

The calculated fast neutron exposures for the three surveillance capsules withdrawn from Arkansas Nuclear One Unit 2 are provided in Table 6-7. These neutron exposure levels are based on the plant- and fuel-cycle-specific neutron transport calculations performed for the Arkansas Nuclear One Unit 2 reactor. From the data provided in Table 6-7, Capsule 284° received a fast neutron fluence (E > 1.0 MeV) of 3.67E+19 n/cm^2 after exposure through the end of the 24th fuel cycle (i.e., after 29.24 EFPY).

Updated lead factors for the Arkansas Nuclear One Unit 2 surveillance capsules are provided in Table 6-8. The capsule lead factor is defined as the ratio of the calculated fluence (E > 1.0 MeV) at the geometric radial and azimuthal center of the surveillance capsule to the corresponding maximum calculated fluence at the pressure vessel clad/base metal interface. In Table 6-8, the lead factors for capsules that have been withdrawn from the reactor (97°, 104°, and 284°) were based on the calculated fluence values for the irradiation period corresponding to the time of withdrawal for the individual capsules. For the capsules remaining in the reactor (83°, 263°, and 277°), the lead factor corresponds to the calculated fluence at the projected end of Cycle 25.

Table 6-9 presents the maximum fast neutron fluences (E > 1.0 MeV) and Table 6-10 presents the maximum dpa for pressure vessel materials.

6.3 NEUTRON DOSIMETRY

The validity of the calculated neutron exposures previously reported in Section 6.2 is demonstrated by a direct comparison against the measured sensor reaction rates and a least-squares evaluation performed for each of the capsule dosimetry sets. However, since the neutron dosimetry measurement data merely serve to validate the calculated results, only the direct comparison of measured-to-calculated results for the most recent surveillance capsule removed from service is provided in this section of the report. For completeness, the assessment of all measured dosimetry removed to date, based on both direct and least-squares evaluation comparisons is documented in Appendix A.

The direct comparison of measured versus calculated fast neutron threshold reaction rates for the sensors from Capsule 284°, which was withdrawn from Arkansas Nuclear One Unit 2 at the end of the 24th fuel cycle, is summarized below.

Reaction	Reaction Rate (rps/atom)		M/C
	Measured (M)	Calculated (C)	
$^{63}Cu(Cd)\ (n,\alpha)\ ^{60}Co$	6.14E-17	5.60E-17	1.10
$^{54}Fe\ (n,p)\ ^{54}Mn$	5.42E-15	5.07E-15	1.07
$^{58}Ni(Cd)\ (n,p)\ ^{58}Co$	7.27E-15	6.63E-15	1.10
$^{46}Ti\ (n,p)\ ^{46}Sc$	9.68E-16	8.80E-16	1.10
$^{238}U(Cd)\ (n,f)\ ^{137}Cs$	1.51E-14	1.76E-14	0.86
Average			1.05
Standard Deviation (%)			10.0

The measured-to-calculated (M/C) reaction rate ratios for the Capsule 284° threshold reactions range from 0.86 to 1.10, and the average M/C ratio is 1.05 ± 10.0% (1σ). This direct comparison falls within the ± 20% criterion specified in Regulatory Guide 1.190. This comparison validates the current analytical results described in Section 6.2; therefore, the calculations are deemed applicable for Arkansas Nuclear One Unit 2.

6.4 CALCULATIONAL UNCERTAINTIES

The uncertainty associated with the calculated neutron exposure of the Arkansas Nuclear One Unit 2 surveillance capsule and reactor pressure vessel is based on the recommended approach provided in Regulatory Guide 1.190. In particular, the qualification of the methodology was carried out in the following four stages:

1. Comparison of calculations with benchmark measurements from the Pool Critical Assembly (PCA) simulator at the Oak Ridge National Laboratory (ORNL).

2. Comparisons of calculations with surveillance capsule and reactor cavity measurements from the H.B. Robinson power reactor benchmark experiment.

3. An analytical sensitivity study addressing the uncertainty components resulting from important input parameters applicable to the plant-specific transport calculations used in the neutron exposure assessments.

4. Comparisons of the plant-specific calculations with all available dosimetry results from the Arkansas Nuclear One Unit 2 surveillance program.

The first phase of the methods qualification (PCA comparisons) addressed the adequacy of basic transport calculation and dosimetry evaluation techniques and associated cross-sections. This phase, however, did not test the accuracy of commercial core neutron source calculations nor did it address uncertainties in operational or geometric variables that impact power reactor calculations. The second phase of the

qualification (H.B. Robinson comparisons) addressed uncertainties in these additional areas that are primarily methods-related and would tend to apply generically to all fast neutron exposure evaluations. The third phase of the qualification (analytical sensitivity study) identified the potential uncertainties introduced into the overall evaluation due to calculational methods approximations, as well as to a lack of knowledge relative to various plant-specific input parameters. The overall calculational uncertainty applicable to the Arkansas Nuclear One Unit 2 analysis was established from results of these three phases of the methods qualification.

The fourth phase of the uncertainty assessment (comparisons with Arkansas Nuclear One Unit 2 measurements) was used solely to demonstrate the validity of the transport calculations and to confirm the uncertainty estimates associated with the analytical results. The comparison was used only as a check and was not used in any way to modify the calculated surveillance capsule and pressure vessel neutron exposures previously described in Section 6.2. As such, the validation of the Arkansas Nuclear One Unit 2 analytical model based on the measured plant dosimetry is completely described in Appendix A.

The following summarizes the uncertainties developed from the first three phases of the methodology qualification. Additional information pertinent to these evaluations is provided in Reference 22.

Description	**Capsule and Vessel IR**
PCA Comparisons	3%
H.B. Robinson Comparisons	3%
Analytical Sensitivity Studies	11%
Additional Uncertainty for Factors not Explicitly	5%
Net Calculational Uncertainty	13%

The net calculational uncertainty was determined by combining the individual components in quadrature. Therefore, the resultant uncertainty was treated as random, and no systematic bias was applied to the analytical results. The plant-specific measurement comparisons described in Appendix A support these uncertainty assessments for Arkansas Nuclear One Unit 2.

Table 6-1 Calculated Fast Neutron (E > 1.0 MeV) Fluence Rate and Fluence at the Surveillance Capsule Center at Core Midplane

Cycle	Cycle Length (EFPY)	Cumulative Operating Time (EFPY)	Fluence Rate (n/cm^2-s)		Fluence (n/cm^2)	
			7° Capsule	14° Capsule	7° Capsule	14° Capsule
1	0.89	0.89	5.11E+10	5.08E+10	1.44E+18	1.43E+18
2	0.80	1.69	6.30E+10	6.21E+10	3.03E+18	3.00E+18
3	0.64	2.33	6.16E+10	6.01E+10	4.28E+18	4.21E+18
4	0.97	3.31	6.11E+10	5.88E+10	6.15E+18	6.02E+18
5	0.85	4.16	6.61E+10	6.44E+10	7.94E+18	7.76E+18
6	1.22	5.38	4.90E+10	4.81E+10	9.82E+18	9.61E+18
7	1.13	6.51	4.50E+10	4.28E+10	1.14E+19	1.11E+19
8	1.15	7.66	4.67E+10	4.52E+10	1.31E+19	1.28E+19
9	1.18	8.84	4.59E+10	4.45E+10	1.48E+19	1.44E+19
10	1.32	10.16	4.31E+10	4.21E+10	1.66E+19	1.62E+19
11	1.33	11.49	3.17E+10	2.90E+10	1.80E+19	1.74E+19
12	1.31	12.81	3.37E+10	3.25E+10	1.94E+19	1.87E+19
13	1.47	14.27	3.08E+10	2.79E+10	2.08E+19	2.00E+19
14	1.41	15.69	3.25E+10	3.18E+10	2.22E+19	2.15E+19
15	1.29	16.98	3.14E+10	3.08E+10	2.35E+19	2.27E+19
16	1.35	18.33	3.75E+10	3.52E+10	2.51E+19	2.42E+19
17	1.36	19.69	3.56E+10	3.46E+10	2.66E+19	2.57E+19
18	1.43	21.12	3.80E+10	3.85E+10	2.84E+19	2.74E+19
19	1.34	22.46	3.66E+10	3.66E+10	2.99E+19	2.90E+19
20	1.36	23.82	3.67E+10	3.66E+10	3.15E+19	3.05E+19
21	1.35	25.17	3.64E+10	3.63E+10	3.30E+19	3.21E+19
22	1.45	26.61	3.58E+10	3.58E+10	3.47E+19	3.37E+19
23	1.36	27.98	3.58E+10	3.71E+10	3.62E+19	3.53E+19
24	1.26	29.24	3.32E+10	3.45E+10	3.75E+19	3.67E+19
25[(a)]	1.37	30.60	3.86E+10	3.85E+10	3.92E+19	3.84E+19
Future[(b)]		32.00			4.08E+19	4.00E+19
Future[(b)]		36.00			4.53E+19	4.46E+19
Future[(b)]		40.00			4.98E+19	4.92E+19
Future[(b)]		48.00			5.89E+19	5.85E+19
Future[(b)]		54.00			6.57E+19	6.55E+19

Notes:

(a) Cycle 25 is the current operating cycle. Values listed for this cycle are projections based on the Cycle 25 design.

(b) Values beyond Cycle 25 are based on the average power distributions and core operating conditions of Cycles 23–25.

Table 6-2 Calculated Iron Atom Displacement Rate and Iron Atom Displacements at the Surveillance Capsule Center at Core Midplane

Cycle	Cycle Length (EFPY)	Cumulative Operating Time (EFPY)	Displacement Rate (dpa/s)		Displacements (dpa)	
			7° Capsule	14° Capsule	7° Capsule	14° Capsule
1	0.89	0.89	7.46E-11	7.40E-11	2.09E-03	2.08E-03
2	0.80	1.69	9.18E-11	9.05E-11	4.42E-03	4.37E-03
3	0.64	2.33	8.97E-11	8.76E-11	6.23E-03	6.14E-03
4	0.97	3.31	8.90E-11	8.57E-11	8.97E-03	8.77E-03
5	0.85	4.16	9.63E-11	9.38E-11	1.16E-02	1.13E-02
6	1.22	5.38	7.15E-11	7.02E-11	1.43E-02	1.40E-02
7	1.13	6.51	6.57E-11	6.25E-11	1.67E-02	1.62E-02
8	1.15	7.66	6.81E-11	6.59E-11	1.91E-02	1.86E-02
9	1.18	8.84	6.70E-11	6.49E-11	2.16E-02	2.10E-02
10	1.32	10.16	6.29E-11	6.15E-11	2.42E-02	2.36E-02
11	1.33	11.49	4.63E-11	4.24E-11	2.62E-02	2.54E-02
12	1.31	12.81	4.92E-11	4.75E-11	2.82E-02	2.73E-02
13	1.47	14.27	4.50E-11	4.08E-11	3.03E-02	2.92E-02
14	1.41	15.69	4.75E-11	4.64E-11	3.24E-02	3.13E-02
15	1.29	16.98	4.59E-11	4.50E-11	3.43E-02	3.31E-02
16	1.35	18.33	5.48E-11	5.14E-11	3.66E-02	3.53E-02
17	1.36	19.69	5.20E-11	5.06E-11	3.89E-02	3.75E-02
18	1.43	21.12	5.55E-11	5.62E-11	4.14E-02	4.00E-02
19	1.34	22.46	5.35E-11	5.35E-11	4.36E-02	4.23E-02
20	1.36	23.82	5.36E-11	5.34E-11	4.59E-02	4.46E-02
21	1.35	25.17	5.32E-11	5.31E-11	4.82E-02	4.68E-02
22	1.45	26.61	5.24E-11	5.23E-11	5.06E-02	4.92E-02
23	1.36	27.98	5.24E-11	5.42E-11	5.29E-02	5.16E-02
24	1.26	29.24	4.86E-11	5.04E-11	5.48E-02	5.36E-02
25[(a)]	1.37	30.60	5.64E-11	5.62E-11	5.72E-02	5.60E-02
Future[(b)]		32.00			5.95E-02	5.83E-02
Future[(b)]		36.00			6.62E-02	6.51E-02
Future[(b)]		40.00			7.28E-02	7.19E-02
Future[(b)]		48.00			8.60E-02	8.54E-02
Future[(b)]		54.00			9.60E-02	9.55E-02

Notes:

(a) Cycle 25 is the current operating cycle. Values listed for this cycle are projections based on the Cycle 25 design.

(b) Values beyond Cycle 25 are based on the average power distributions and core operating conditions of Cycles 23–25.

Table 6-3 Calculated Azimuthal Variation of the Maximum Fast Neutron (E > 1.0 MeV) Fluence Rate at the Reactor Vessel Clad/Base Metal Interface

Cycle	Cycle Length (EFPY)	Cumulative Operating Time (EFPY)	Fluence Rate (n/cm^2-s)				
			0°	15°	30°	45°	Maximum
1	0.89	0.89	3.62E+10	3.60E+10	2.71E+10	2.63E+10	3.81E+10
2	0.80	1.69	4.59E+10	4.51E+10	3.38E+10	3.22E+10	4.80E+10
3	0.64	2.33	4.34E+10	4.21E+10	3.18E+10	3.12E+10	4.52E+10
4	0.97	3.31	4.36E+10	4.12E+10	3.34E+10	3.33E+10	4.46E+10
5	0.85	4.16	4.68E+10	4.52E+10	3.34E+10	3.30E+10	4.86E+10
6	1.22	5.38	3.40E+10	3.40E+10	2.54E+10	2.34E+10	3.64E+10
7	1.13	6.51	3.17E+10	3.03E+10	2.39E+10	2.20E+10	3.30E+10
8	1.15	7.66	3.25E+10	3.20E+10	2.42E+10	2.17E+10	3.44E+10
9	1.18	8.84	3.20E+10	3.15E+10	2.38E+10	2.09E+10	3.38E+10
10	1.32	10.16	2.98E+10	2.98E+10	2.35E+10	2.26E+10	3.19E+10
11	1.33	11.49	2.36E+10	2.06E+10	1.73E+10	1.83E+10	2.36E+10
12	1.31	12.81	2.41E+10	2.30E+10	1.77E+10	1.75E+10	2.48E+10
13	1.47	14.27	2.29E+10	1.99E+10	1.63E+10	1.78E+10	2.29E+10
14	1.41	15.69	2.35E+10	2.28E+10	1.79E+10	1.78E+10	2.42E+10
15	1.29	16.98	2.31E+10	2.23E+10	1.90E+10	1.85E+10	2.34E+10
16	1.35	18.33	2.73E+10	2.49E+10	1.90E+10	1.92E+10	2.75E+10
17	1.36	19.69	2.56E+10	2.47E+10	1.96E+10	1.89E+10	2.63E+10
18	1.43	21.12	2.77E+10	2.83E+10	2.21E+10	2.13E+10	2.95E+10
19	1.34	22.46	2.71E+10	2.72E+10	2.09E+10	2.06E+10	2.85E+10
20	1.36	23.82	2.72E+10	2.72E+10	2.10E+10	2.11E+10	2.85E+10
21	1.35	25.17	2.72E+10	2.72E+10	2.12E+10	2.12E+10	2.86E+10
22	1.45	26.61	2.59E+10	2.59E+10	2.03E+10	2.05E+10	2.72E+10
23	1.36	27.98	2.50E+10	2.68E+10	2.13E+10	2.16E+10	2.76E+10
24	1.26	29.24	2.40E+10	2.57E+10	2.14E+10	2.20E+10	2.64E+10
25[(a)]	1.37	30.60	2.97E+10	2.96E+10	2.29E+10	2.32E+10	3.11E+10

Note:

(a) Cycle 25 is the current operating cycle. Values listed for this cycle are projections based on the Cycle 25 design.

Table 6-4 Calculated Azimuthal Variation of the Maximum Fast Neutron (E > 1.0 MeV) Fluence at the Reactor Vessel Clad/Base Metal Interface

Cycle	Cycle Length (EFPY)	Cumulative Operating Time (EFPY)	Fluence (n/cm^2)				
			0°	15°	30°	45°	Maximum
1	0.89	0.89	1.02E+18	1.01E+18	7.61E+17	7.37E+17	1.07E+18
2	0.80	1.69	2.16E+18	2.14E+18	1.61E+18	1.54E+18	2.27E+18
3	0.64	2.33	3.04E+18	2.99E+18	2.25E+18	2.17E+18	3.18E+18
4	0.97	3.31	4.38E+18	4.26E+18	3.27E+18	3.19E+18	4.55E+18
5	0.85	4.16	5.64E+18	5.48E+18	4.17E+18	4.08E+18	5.86E+18
6	1.22	5.38	6.95E+18	6.78E+18	5.15E+18	4.98E+18	7.26E+18
7	1.13	6.51	8.08E+18	7.86E+18	6.00E+18	5.77E+18	8.44E+18
8	1.15	7.66	9.26E+18	9.02E+18	6.88E+18	6.56E+18	9.68E+18
9	1.18	8.84	1.04E+19	1.02E+19	7.76E+18	7.33E+18	1.09E+19
10	1.32	10.16	1.17E+19	1.14E+19	8.74E+18	8.27E+18	1.23E+19
11	1.33	11.49	1.27E+19	1.23E+19	9.47E+18	9.04E+18	1.32E+19
12	1.31	12.81	1.37E+19	1.32E+19	1.02E+19	9.76E+18	1.43E+19
13	1.47	14.27	1.47E+19	1.42E+19	1.09E+19	1.06E+19	1.53E+19
14	1.41	15.69	1.57E+19	1.51E+19	1.17E+19	1.14E+19	1.63E+19
15	1.29	16.98	1.67E+19	1.60E+19	1.25E+19	1.21E+19	1.73E+19
16	1.35	18.33	1.78E+19	1.71E+19	1.33E+19	1.29E+19	1.84E+19
17	1.36	19.69	1.89E+19	1.81E+19	1.41E+19	1.37E+19	1.95E+19
18	1.43	21.12	2.01E+19	1.94E+19	1.51E+19	1.46E+19	2.08E+19
19	1.34	22.46	2.12E+19	2.05E+19	1.59E+19	1.55E+19	2.20E+19
20	1.36	23.82	2.23E+19	2.16E+19	1.68E+19	1.64E+19	2.32E+19
21	1.35	25.17	2.35E+19	2.27E+19	1.77E+19	1.72E+19	2.43E+19
22	1.45	26.61	2.46E+19	2.39E+19	1.86E+19	1.81E+19	2.55E+19
23	1.36	27.98	2.57E+19	2.50E+19	1.95E+19	1.91E+19	2.67E+19
24	1.26	29.24	2.66E+19	2.60E+19	2.03E+19	1.99E+19	2.77E+19
25[(a)]	1.37	30.60	2.78E+19	2.72E+19	2.12E+19	2.08E+19	2.90E+19
Future[(b)]		32.00	2.89E+19	2.84E+19	2.22E+19	2.18E+19	3.02E+19[(c)]
Future[(b)]		36.00	3.22E+19	3.18E+19	2.49E+19	2.46E+19	3.37E+19
Future[(b)]		40.00	3.55E+19	3.53E+19	2.77E+19	2.74E+19	3.73E+19
Future[(b)]		48.00	4.21E+19	4.22E+19	3.32E+19	3.30E+19	4.44E+19
Future[(b)]		54.00	4.71E+19	4.74E+19	3.73E+19	3.72E+19	4.98E+19

Notes:

(a) Cycle 25 is the current operating cycle. Values listed for this cycle are projections based on the Cycle 25 design.

(b) Values beyond Cycle 25 are based on the average power distributions and core operating conditions of Cycles 23–25.

(c) This updated 32 EFPY projected maximum fluence is bounded by the maximum 32 EFPY projected fluence value (3.791E+19 n/cm^2) in the analysis of record [Ref. 17].

Table 6-5 Calculated Azimuthal Variation of the Maximum Iron Atom Displacement Rate at the Reactor Vessel Clad/Base Metal Interface

Cycle	Cycle Length (EFPY)	Cumulative Operating Time (EFPY)	Displacement Rate (dpa/s)				
			0°	15°	30°	45°	Maximum
1	0.89	0.89	5.52E-11	5.47E-11	4.14E-11	4.01E-11	5.79E-11
2	0.80	1.69	6.99E-11	6.86E-11	5.16E-11	4.91E-11	7.29E-11
3	0.64	2.33	6.62E-11	6.40E-11	4.85E-11	4.76E-11	6.87E-11
4	0.97	3.31	6.65E-11	6.27E-11	5.10E-11	5.08E-11	6.78E-11
5	0.85	4.16	7.13E-11	6.87E-11	5.10E-11	5.04E-11	7.39E-11
6	1.22	5.38	5.20E-11	5.17E-11	3.88E-11	3.58E-11	5.53E-11
7	1.13	6.51	4.84E-11	4.61E-11	3.66E-11	3.37E-11	5.02E-11
8	1.15	7.66	4.97E-11	4.86E-11	3.69E-11	3.33E-11	5.24E-11
9	1.18	8.84	4.89E-11	4.79E-11	3.64E-11	3.21E-11	5.15E-11
10	1.32	10.16	4.56E-11	4.54E-11	3.59E-11	3.45E-11	4.84E-11
11	1.33	11.49	3.60E-11	3.14E-11	2.65E-11	2.80E-11	3.60E-11
12	1.31	12.81	3.68E-11	3.51E-11	2.71E-11	2.68E-11	3.78E-11
13	1.47	14.27	3.50E-11	3.03E-11	2.50E-11	2.73E-11	3.50E-11
14	1.41	15.69	3.59E-11	3.48E-11	2.73E-11	2.73E-11	3.69E-11
15	1.29	16.98	3.53E-11	3.41E-11	2.91E-11	2.83E-11	3.57E-11
16	1.35	18.33	4.17E-11	3.80E-11	2.91E-11	2.95E-11	4.19E-11
17	1.36	19.69	3.91E-11	3.76E-11	3.01E-11	2.89E-11	4.01E-11
18	1.43	21.12	4.23E-11	4.31E-11	3.38E-11	3.26E-11	4.49E-11
19	1.34	22.46	4.13E-11	4.14E-11	3.20E-11	3.16E-11	4.34E-11
20	1.36	23.82	4.15E-11	4.13E-11	3.21E-11	3.23E-11	4.34E-11
21	1.35	25.17	4.16E-11	4.14E-11	3.24E-11	3.25E-11	4.35E-11
22	1.45	26.61	3.95E-11	3.95E-11	3.10E-11	3.13E-11	4.14E-11
23	1.36	27.98	3.82E-11	4.08E-11	3.26E-11	3.29E-11	4.20E-11
24	1.26	29.24	3.67E-11	3.91E-11	3.27E-11	3.36E-11	4.02E-11
25[(a)]	1.37	30.60	4.53E-11	4.51E-11	3.50E-11	3.55E-11	4.74E-11

Note:

(a) Cycle 25 is the current operating cycle. Values listed for this cycle are projections based on the Cycle 25 design.

Table 6-6 Calculated Azimuthal Variation of the Maximum Iron Atom Displacements at the Reactor Vessel Clad/Base Metal Interface

Cycle	Cycle Length (EFPY)	Cumulative Operating Time (EFPY)	Displacements (dpa)				
			0°	15°	30°	45°	Maximum
1	0.89	0.89	1.55E-03	1.54E-03	1.16E-03	1.13E-03	1.63E-03
2	0.80	1.69	3.30E-03	3.25E-03	2.45E-03	2.36E-03	3.45E-03
3	0.64	2.33	4.63E-03	4.54E-03	3.43E-03	3.32E-03	4.83E-03
4	0.97	3.31	6.68E-03	6.47E-03	5.00E-03	4.88E-03	6.91E-03
5	0.85	4.16	8.60E-03	8.32E-03	6.37E-03	6.24E-03	8.90E-03
6	1.22	5.38	1.06E-02	1.03E-02	7.86E-03	7.61E-03	1.10E-02
7	1.13	6.51	1.23E-02	1.20E-02	9.17E-03	8.82E-03	1.28E-02
8	1.15	7.66	1.41E-02	1.37E-02	1.05E-02	1.00E-02	1.47E-02
9	1.18	8.84	1.59E-02	1.55E-02	1.19E-02	1.12E-02	1.66E-02
10	1.32	10.16	1.78E-02	1.74E-02	1.34E-02	1.27E-02	1.86E-02
11	1.33	11.49	1.94E-02	1.87E-02	1.45E-02	1.38E-02	2.01E-02
12	1.31	12.81	2.09E-02	2.02E-02	1.56E-02	1.49E-02	2.17E-02
13	1.47	14.27	2.25E-02	2.15E-02	1.67E-02	1.62E-02	2.32E-02
14	1.41	15.69	2.40E-02	2.31E-02	1.79E-02	1.74E-02	2.48E-02
15	1.29	16.98	2.54E-02	2.44E-02	1.91E-02	1.85E-02	2.63E-02
16	1.35	18.33	2.72E-02	2.60E-02	2.03E-02	1.97E-02	2.80E-02
17	1.36	19.69	2.89E-02	2.76E-02	2.16E-02	2.10E-02	2.97E-02
18	1.43	21.12	3.07E-02	2.95E-02	2.31E-02	2.24E-02	3.17E-02
19	1.34	22.46	3.24E-02	3.12E-02	2.44E-02	2.37E-02	3.35E-02
20	1.36	23.82	3.41E-02	3.29E-02	2.57E-02	2.50E-02	3.53E-02
21	1.35	25.17	3.58E-02	3.46E-02	2.70E-02	2.63E-02	3.70E-02
22	1.45	26.61	3.76E-02	3.64E-02	2.84E-02	2.77E-02	3.89E-02
23	1.36	27.98	3.92E-02	3.81E-02	2.98E-02	2.91E-02	4.06E-02
24	1.26	29.24	4.06E-02	3.96E-02	3.11E-02	3.04E-02	4.22E-02
25[(a)]	1.37	30.60	4.25E-02	4.14E-02	3.25E-02	3.19E-02	4.41E-02
Future[(b)]		32.00	4.42E-02	4.32E-02	3.39E-02	3.33E-02	4.59E-02
Future[(b)]		36.00	4.92E-02	4.84E-02	3.81E-02	3.76E-02	5.13E-02
Future[(b)]		40.00	5.42E-02	5.37E-02	4.23E-02	4.19E-02	5.67E-02
Future[(b)]		48.00	6.43E-02	6.42E-02	5.08E-02	5.05E-02	6.76E-02
Future[(b)]		54.00	7.19E-02	7.21E-02	5.71E-02	5.69E-02	7.58E-02

Note(s):

(a) Cycle 25 is the current operating cycle. Values listed for this cycle are projections based on the Cycle 25 design.

(b) Values beyond Cycle 25 are based on the average power distributions and core operating conditions of Cycles 23–25.

Table 6-7 Calculated Fast Neutron Exposure of Surveillance Capsules Withdrawn from Arkansas Nuclear One Unit 2

Capsule	Irradiation Cycle(s)	Cumulative Irradiation Time (EFPY)	Fluence (E > 1.0 MeV) (n/cm^2)	Iron Atom Displacements (dpa)
97°	1–2	1.69	3.03E+18	4.42E-03
104°	1–14	15.69	2.15E+19	3.13E-02
284°	1–24	29.24	3.67E+19	5.36E-02

Table 6-8 Calculated Surveillance Capsule Lead Factors

Capsule Location	Status	Lead Factor
7° (Capsule 97°)	Withdrawn EOC 2	1.34
14° (Capsule 104°)	Withdrawn EOC 14	1.31
14° (Capsule 284°)	Withdrawn EOC 24	1.32
7° (Capsules 83°, 263°, & 277°)	In Reactor[(a)]	1.35

Note:

(a) Lead factor is based on the calculated fluence at the projected end of Cycle 25.

Table 6-9 Calculated Maximum Fast Neutron (E > 1.0 MeV) Fluence at the Pressure Vessel Clad/Base Metal Interface

Material	Fluence (n/cm^2)				
	32 EFPY	36 EFPY	40 EFPY	48 EFPY	54 EFPY
Inlet Nozzle to Upper Shell Welds – Lowest Extent					
Nozzle 1	4.78E+16	5.36E+16	5.93E+16	7.09E+16	7.96E+16
Nozzle 2	4.78E+16	5.36E+16	5.93E+16	7.09E+16	7.96E+16
Nozzle 3	4.78E+16	5.36E+16	5.93E+16	7.09E+16	7.96E+16
Nozzle 4	4.78E+16	5.36E+16	5.93E+16	7.09E+16	7.96E+16
Outlet Nozzle to Upper Shell Welds – Lowest Extent					
Nozzle 1	6.05E+16	6.73E+16	7.41E+16	8.77E+16	9.80E+16
Nozzle 2	6.05E+16	6.73E+16	7.41E+16	8.77E+16	9.80E+16
Upper to Intermediate Shell Circumferential Weld					
8-203	3.53E+17	3.96E+17	4.38E+17	5.24E+17	5.89E+17
Intermediate Shell Plates					
C-8009-1, -2, -3	3.02E+19	3.36E+19	3.70E+19	4.39E+19	4.91E+19
Intermediate Shell Longitudinal Welds					
2-203 A	2.89E+19	3.21E+19	3.53E+19	4.16E+19	4.64E+19
2-203 B	2.22E+19	2.48E+19	2.75E+19	3.28E+19	3.68E+19
2-203 C	2.22E+19	2.48E+19	2.75E+19	3.28E+19	3.68E+19
Intermediate to Lower Shell Circumferential Weld					
9-203	3.00E+19	3.35E+19	3.69E+19	4.38E+19	4.89E+19
Lower Shell Plates					
C-8010-1, -2, -3	3.02E+19	3.37E+19	3.73E+19	4.44E+19	4.98E+19
Lower Shell Longitudinal Welds					
3-203 A	2.89E+19	3.22E+19	3.55E+19	4.21E+19	4.71E+19
3-203 B	2.22E+19	2.49E+19	2.77E+19	3.32E+19	3.73E+19
3-203 C	2.22E+19	2.49E+19	2.77E+19	3.32E+19	3.73E+19
Lower Shell to Bottom Head Circumferential Weld					
10-203	5.41E+16	6.06E+16	6.71E+16	8.01E+16	8.98E+16

Notes:

(a) The axial location used corresponds to the bottom of the vessel support pad of the inlet nozzle, instead of the nozzle to upper shell weld. This provides a bounding fluence for the nozzle to upper shell weld.

(b) Projected values are based on the average power distributions and core operating conditions of Cycles 23–25.

Table 6-10 Calculated Maximum Iron Atom Displacements at the Pressure Vessel Clad/Base Metal Interface

Material	Iron Atom Displacements (dpa)				
	32 EFPY	36 EFPY	40 EFPY	48 EFPY	54 EFPY
Inlet Nozzle to Upper Shell Welds – Lowest Extent					
Nozzle 1	2.83E-04	3.17E-04	3.51E-04	4.19E-04	4.70E-04
Nozzle 2	2.83E-04	3.17E-04	3.51E-04	4.19E-04	4.70E-04
Nozzle 3	2.83E-04	3.17E-04	3.51E-04	4.19E-04	4.70E-04
Nozzle 4	2.83E-04	3.17E-04	3.51E-04	4.19E-04	4.70E-04
Outlet Nozzle to Upper Shell Welds – Lowest Extent					
Nozzle 1	3.37E-04	3.75E-04	4.14E-04	4.91E-04	5.48E-04
Nozzle 2	3.37E-04	3.75E-04	4.14E-04	4.91E-04	5.48E-04
Upper to Intermediate Shell Circumferential Weld					
8-203	6.41E-04	7.18E-04	7.95E-04	9.50E-04	1.07E-03
Intermediate Shell Plates					
C-8009-1, -2, -3	4.59E-02	5.11E-02	5.64E-02	6.69E-02	7.47E-02
Intermediate Shell Longitudinal Welds					
2-203 A	4.42E-02	4.90E-02	5.39E-02	6.36E-02	7.09E-02
2-203 B	3.39E-02	3.80E-02	4.20E-02	5.02E-02	5.63E-02
2-203 C	3.39E-02	3.80E-02	4.20E-02	5.02E-02	5.63E-02
Intermediate to Lower Shell Circumferential Weld					
9-203	4.57E-02	5.10E-02	5.62E-02	6.67E-02	7.45E-02
Lower Shell Plates					
C-8010-1, -2, -3	4.59E-02	5.13E-02	5.67E-02	6.76E-02	7.58E-02
Lower Shell Longitudinal Welds					
3-203 A	4.41E-02	4.92E-02	5.42E-02	6.43E-02	7.19E-02
3-203 B	3.39E-02	3.81E-02	4.23E-02	5.08E-02	5.71E-02
3-203 C	3.39E-02	3.81E-02	4.23E-02	5.08E-02	5.71E-02
Lower Shell to Bottom Head Circumferential Weld					
10-203	2.85E-04	3.19E-04	3.53E-04	4.22E-04	4.73E-04

Notes:

(a) The axial location used corresponds to the bottom of the vessel support pad of the inlet nozzle, instead of the nozzle to upper shell weld. This provides a bounding fluence for the nozzle to upper shell weld.

(b) Projected values are based on the average power distributions and core operating conditions of Cycles 23–25.

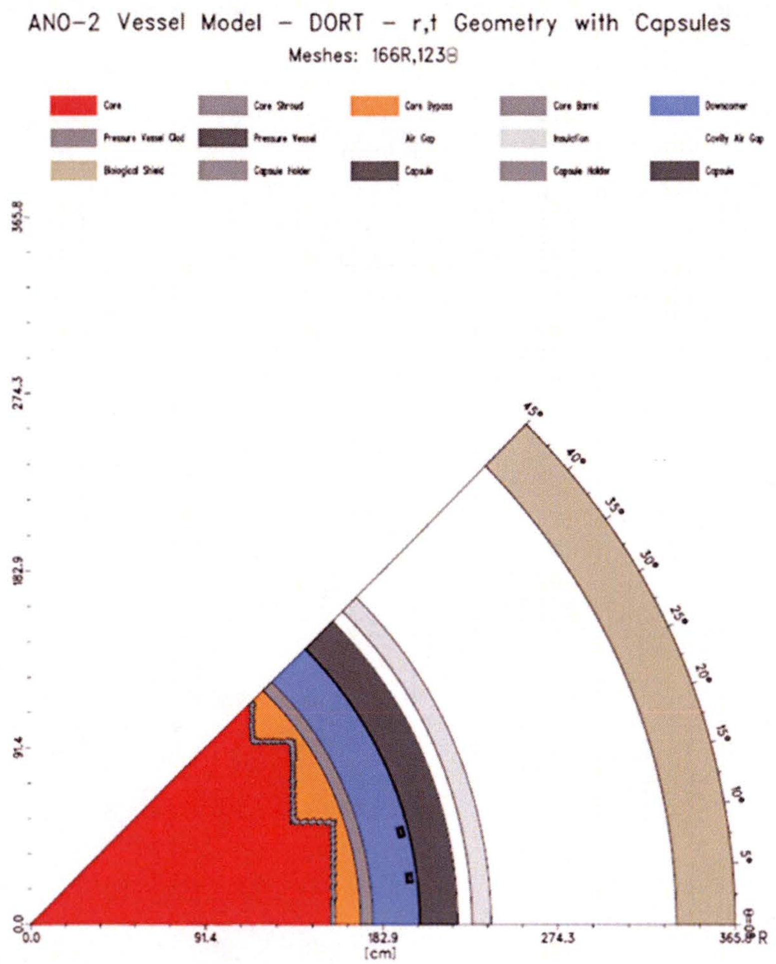


Figure 6-1 **Arkansas Nuclear One Unit 2 r,θ Reactor Geometry Plan View at the Core Midplane with Surveillance Capsules**

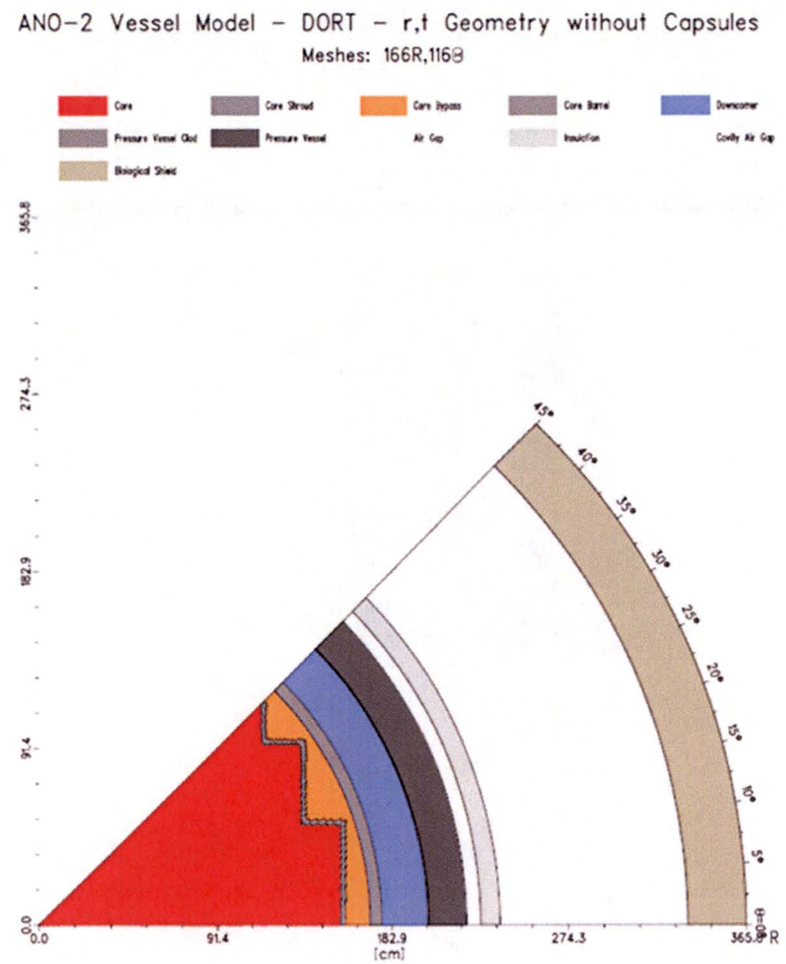


Figure 6-2 Arkansas Nuclear One Unit 2 r,θ Reactor Geometry Plan View at the Core Midplane without Surveillance Capsules

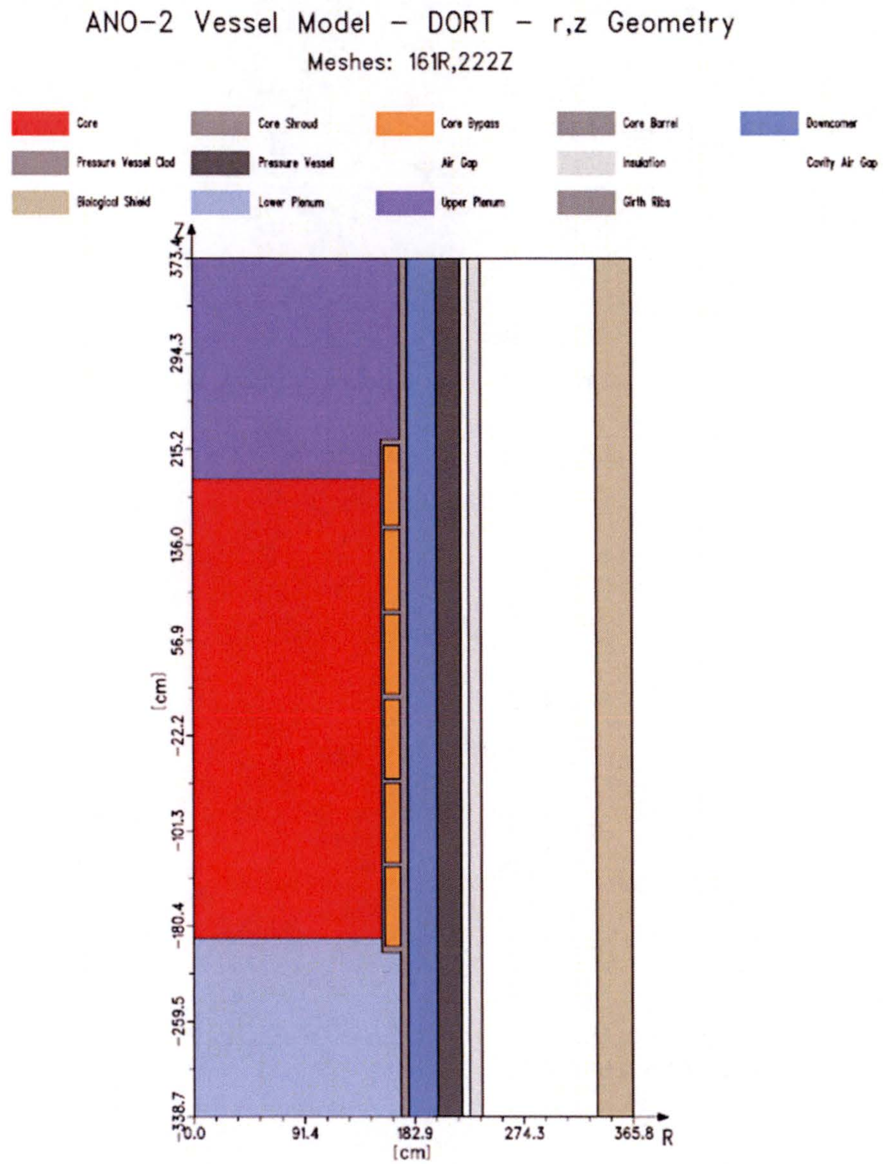


Figure 6-3 Arkansas Nuclear One Unit 2 r,z Reactor Geometry Section View

7 SURVEILLANCE CAPSULE REMOVAL SCHEDULE

The following surveillance capsule removal schedule (Table 7-1) meets the requirements of ASTM E185-82 [Ref. 10]. Note that it is recommended for future capsule(s) to be removed from the ANO-2 reactor vessel.

Table 7-1 Surveillance Capsule Withdrawal Schedule

Capsule ID and Location	Status	Capsule Lead Factor[(a)]	Withdrawal EFPY[(b, c)]	Capsule Fluence (n/cm^2, E > 1.0 MeV)[(c)]
97°	Withdrawn (EOC 2)	1.34	1.69	0.303×10^{19}
104°	Withdrawn (EOC 14)	1.31	15.69	2.15×10^{19}
284°	Withdrawn (EOC 24)	1.32	29.24	3.67×10^{19}
277°	In Reactor	1.35	40.00[(d)]	4.98×10^{19}[(d)]
83°	In Reactor	1.35	Note (e)	Note (e)
263°	In Reactor	1.35	Note (f)	Note (f)

Notes:

(a) Updated in Capsule 284° dosimetry analysis; see Table 6-8.

(b) EFPY from plant startup.

(c) Updated in Capsule 284° dosimetry analysis; see Table 6-7.

(d) Capsule 277° should be withdrawn at the vessel refueling outage nearest to but following 40 EFPY of plant operation, which is when the fluence on the capsule will have reached the projected 60-year (54 EFPY) peak vessel fluence (4.98×10^{19} n/cm^2).

(e) Capsule 83° should remain in the reactor. If additional metallurgical data is needed for ANO-2, such as in support of a second license renewal to 80 total years of operation, withdrawal and testing of Capsule 83° should be considered.

(f) Capsule 263° should remain in the reactor and continue to accrue irradiation for potential future testing, if needed.

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APPENDIX A VALIDATION OF THE RADIATION TRANSPORT MODELS BASED ON NEUTRON DOSIMETRY MEASUREMENTS

A.1 NEUTRON DOSIMETRY

Comparisons of measured dosimetry results to both the calculated and least-squares adjusted values for Capsules 97° and 284° are provided in this appendix. The sensor sets have been analyzed in accordance with the current dosimetry evaluation methodology described in Regulatory Guide 1.190, "Calculational and Dosimetry Methods for Determining Pressure Vessel Neutron Fluence" [Ref. A-1]. As noted in Section 6.1, the sensor set from the previously withdrawn and evaluated Capsule 104° was not re-analyzed since the counting results for this sensor set were not included in the Capsule 104° analysis report. One of the main purposes for providing this material is to demonstrate that the overall measurements agree with the calculated and least-squares adjusted values to within ± 20% as specified by Regulatory Guide 1.190, thus serving to validate the calculated neutron exposures previously reported in Section 6.2 of this report.

A.1.1 Sensor Reaction Rate Determinations

In this section, the results of the evaluations of two of the three surveillance capsules analyzed to date as part of the Arkansas Nuclear One Unit 2 reactor vessel materials surveillance program are presented. The capsule designation, location within the reactor, and time of withdrawal of each of these dosimetry sets were as follows:

Capsule	Azimuthal Location	Withdrawal Time	Irradiation Time (EFPY)
97°	97°	End of Cycle 2	1.69
284°	284°	End of Cycle 24	29.24

The passive neutron sensors included in the evaluations of Surveillance Capsules 97° and 284° are summarized as follows:

Sensor Material	Reaction Of Interest	Capsule 97°	Capsule 284°
Copper (Cd)	^{63}Cu(Cd) (n,α) ^{60}Co	X	X
Iron	^{54}Fe (n,p) ^{54}Mn	X	X
Nickel (Cd)	^{58}Ni(Cd) (n,p) ^{58}Co	X	X
Titanium	^{46}Ti (n,p) ^{46}Sc	X	X
Cobalt-Aluminum[(a)]	^{59}Co (n,γ) ^{60}Co	X	X
Uranium-238[(a)]	^{238}U (n,f) FP	X	X

Notes:

(a) The cobalt-aluminum and uranium sensors include both bare and cadmium-covered sensors.

(b) The surveillance capsules also contained sulfur monitors which, due to the short half-life of their activation product isotope (^{32}P, 14.3 days), were not analyzed.

Pertinent physical and nuclear characteristics of the passive neutron sensors analyzed are listed in Table A-1.

The use of passive monitors does not yield a direct measure of the energy-dependent neutron fluence rate at the point of interest. Rather, the activation or fission process is a measure of the integrated effect that the time- and energy-dependent neutron fluence rate has on the target material over the course of the irradiation period. An accurate assessment of the average neutron fluence rate level incident on the various monitors may be derived from the activation measurements only if the irradiation parameters are well known. In particular, the following variables are of interest:

- the measured specific activity of each monitor,
- the physical characteristics of each monitor,
- the operating history of the reactor,
- the energy response of each monitor, and
- the neutron energy spectrum at the monitor location.

The radiometric counting of the sensors from Capsule 284° was carried out by Pace Analytical Services, Inc. The radiometric counting followed established ASTM procedures.

The irradiation history of the reactor over the irradiation periods experienced by Capsules 97° and 284° was based on the monthly power generation of Arkansas Nuclear One Unit 2 from initial reactor criticality through the end of the dosimetry evaluation period (Cycle 24). For the sensor sets utilized in the surveillance capsules, the half-lives of the product isotopes are long enough that a monthly histogram describing reactor operation has proven to be an adequate representation for use in radioactive decay corrections for the reactions of interest in the exposure evaluations. The irradiation history applicable to Capsules 97° and 284° is given in Table A-2.

Having the measured specific activities, the physical characteristics of the sensors, and the operating history of the reactor, reaction rates referenced to full-power operation were determined from the following equation:

$$R = \frac{A}{N_0 F Y \sum \frac{P_j}{P_{ref}} C_j \left[1 - e^{-\lambda t_j}\right]\left[e^{-\lambda t_{d,j}}\right]}$$

where:

R	=	Reaction rate averaged over the irradiation period and referenced to operation at a core power level of P_{ref} (rps/nucleus).
A	=	Measured specific activity (dps/g).
N_0	=	Number of target element atoms per gram of sensor.
F	=	Atom fraction of the target isotope in the target element.
Y	=	Number of product atoms produced per reaction.
P_j	=	Average core power level during irradiation period j (MW).
P_{ref}	=	Maximum or reference power level of the reactor (MW).
C_j	=	Calculated ratio of ϕ (E > 1.0 MeV) during irradiation period j to the time weighted average ϕ (E > 1.0 MeV) over the entire irradiation period.
λ	=	Decay constant of the product isotope (1/sec).
t_j	=	Length of irradiation period j (sec).
$t_{d,j}$	=	Decay time following irradiation period j (sec).

The summation is carried out over the total number of monthly intervals comprising the irradiation period.

In the equation describing the reaction rate calculation, the ratio $[P_j]/[P_{ref}]$ accounts for month-by-month variation of reactor core power level within any given fuel cycle as well as over multiple fuel cycles. The ratio C_j, which was calculated for each fuel cycle using the transport methodology discussed in Section 6.2, accounts for the change in sensor reaction rates caused by variations in fluence rate level induced by changes in core spatial power distributions from fuel cycle to fuel cycle. For a single-cycle irradiation, C_j is normally taken to be 1.0. However, for multiple-cycle irradiations, the additional C_j term should be employed. The impact of changing fluence rate levels for constant power operation can be quite significant for sensor sets that have been irradiated for many cycles in a reactor that has transitioned from

non-low-leakage to low-leakage fuel management or for sensor sets contained in surveillance capsules that have been moved from one capsule location to another.

The fuel-cycle-specific neutron fluence rates and the computed values for C_j are listed in Table A-3 and Table A-4, respectively, for Capsules 97° and 284°. These fluence rates represent the capsule- and cycle-dependent results at the radial and azimuthal center of the respective capsules at core midplane.

Prior to using the measured reaction rates in the least-squares evaluations of the dosimetry sensor sets, additional corrections were made to the ^{238}U cadmium-covered measurements to account for the presence of ^{235}U impurities in the sensors, as well as to adjust for the build-in of plutonium isotopes over the course of the irradiation. Corrections were also made to the ^{238}U sensor reaction rates to account for gamma-ray-induced fission reactions that occurred over the course of the surveillance capsule irradiations. The correction factors corresponding to the Arkansas Nuclear One Unit 2 fission sensor reaction rates are summarized as follows:

Correction	Capsule 97°	Capsule 284°
^{235}U Impurity/Pu Build-in	N/A[(a)]	0.7536
$^{238}U(\gamma,f)$	N/A[(a)]	0.8869
Net ^{238}U Correction	N/A[(a)]	0.6684

Note:

(a) The uranium sensor dosimetry results were not used in the Capsule 97° analysis report to calculate fluence rates or fluences.

The correction factors for Capsule 284° were applied in a multiplicative fashion to the decay-corrected cadmium-covered uranium fission sensor reaction rates.

Results of the sensor reaction rate determinations for surveillance Capsules 97° and 284° are given in Table A-5 and Table A-6. In Table A-5 and Table A-6, the measured specific activities, decay-corrected saturated specific activities, and computed reaction rates for each sensor are listed. The cadmium-covered fission sensor reaction rates are listed both with and without the applied corrections for ^{235}U impurities, plutonium build-in, and gamma-ray-induced fission effects.

A.1.2 Least-Squares Evaluation of Sensor Sets

Least-squares adjustment methods provide the capability of combining the measurement data with the corresponding neutron transport calculations resulting in a best-estimate neutron energy spectrum with associated uncertainties. Best-estimates for key exposure parameters such as fluence rate ($E > 1.0$ MeV) or dpa/s along with their uncertainties are then easily obtained from the adjusted spectrum. In general, the least-squares methods, as applied to dosimetry evaluations, act to reconcile the measured sensor reaction rate data, dosimetry reaction cross-sections, and the calculated neutron energy spectrum within their respective uncertainties. For example,

$$R_i \pm \delta_{R_i} = \sum_g (\sigma_{ig} \pm \delta_{\sigma_{ig}})(\varphi_g \pm \delta_{\varphi_g})$$

relates a set of measured reaction rates, R_i, to a single neutron spectrum, ϕ_g, through the multigroup dosimeter reaction cross-sections, σ_{ig}, each with an uncertainty δ. The primary objective of the least-squares evaluation is to produce unbiased estimates of the neutron exposure parameters at the location of the measurement.

For the least-squares evaluation of the Arkansas Nuclear One Unit 2 dosimetry, the FERRET code [Ref. A-2] was employed to combine the results of the plant-specific neutron transport calculations and sensor set reaction rate measurements to determine the best-estimate values of exposure parameters (fluence rate (E > 1.0 MeV) and dpa) and their associated uncertainties.

The application of the least-squares methodology requires the following input:

1. The calculated neutron energy spectrum and associated uncertainties at the measurement location.

2. The measured reaction rates and associated uncertainty for each sensor contained in the multiple foil set.

3. The energy-dependent dosimetry reaction cross-sections and associated uncertainties for each sensor contained in the multiple foil sensor set.

For the Arkansas Nuclear One Unit 2 application, the calculated neutron spectrum was obtained from the results of plant-specific neutron transport calculations described in Section 6.2 of this report. The sensor reaction rates were derived from the measured specific activities using the procedures described in Section A.1.1. The dosimetry reaction cross-sections and uncertainties were obtained from the SNLRML dosimetry cross-section library [Ref. A-3].

The uncertainties associated with the measured reaction rates, dosimetry cross-sections, and calculated neutron spectrum were input to the least-squares procedure in the form of variances and covariances. The assignment of the input uncertainties followed the guidance provided in ASTM Standard E944, "Standard Guide for Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance" [Ref. A-4].

The following provides a summary of the uncertainties associated with the least-squares evaluation of the Arkansas Nuclear One Unit 2 surveillance capsule sensor sets.

Reaction Rate Uncertainties

The overall uncertainty associated with the measured reaction rates includes components due to the basic measurement process, irradiation history corrections, and corrections for competing reactions. A high level of accuracy in the reaction rate determinations is ensured by utilizing laboratory procedures that conform to the ASTM National Consensus Standards for reaction rate determinations for each sensor type.

After combining all of these uncertainty components, the sensor reaction rates derived from the counting and data evaluation procedures were assigned the following net uncertainties for input to the least-squares evaluation:

Reaction	Uncertainty
$^{63}Cu\ (n,\alpha)\ ^{60}Co$	5%
$^{54}Fe\ (n,p)\ ^{54}Mn$	5%
$^{58}Ni\ (n,p)\ ^{58}Co$	5%
$^{46}Ti\ (n,p)\ ^{46}Sc$	5%
$^{59}Co\ (n,\gamma)\ ^{60}Co$	5%
$^{238}U\ (n,f)$ FP	10%

These uncertainties are given at the 1σ level.

Dosimetry Cross-Section Uncertainties

The reaction rate cross-sections used in the least-squares evaluations were taken from the SNLRML library. This data library provides reaction cross-sections and associated uncertainties, including covariances, for 66 dosimetry sensors in common use. Both cross-sections and uncertainties are provided in a fine multigroup structure for use in least-squares adjustment applications. These cross-sections were compiled from recent cross-section evaluations, and they have been tested for accuracy and consistency for least-squares evaluations. Further, the library has been empirically tested for use in fission spectra determination, as well as in the fluence and energy characterization of 14 MeV neutron sources.

For sensors included in the Arkansas Nuclear One Unit 2 surveillance program, the following uncertainties in the fission spectrum averaged cross-sections are provided in the SNLRML documentation package.

Reaction	Uncertainty
$^{63}Cu\ (n,\alpha)\ ^{60}Co$	4.08–4.16%
$^{54}Fe\ (n,p)\ ^{54}Mn$	3.05–3.11%
$^{58}Ni\ (n,p)\ ^{58}Co$	4.49–4.56%
$^{46}Ti\ (n,p)\ ^{46}Sc$	4.50–4.87%
$^{59}Co\ (n,\gamma)\ ^{60}Co$	0.79–3.59%
$^{238}U\ (n,f)\ ^{137}Cs$	0.54–0.64%

These tabulated ranges provide an indication of the dosimetry cross-section uncertainties associated with the sensor sets used in LWR irradiations.

Calculated Neutron Spectrum

The neutron spectra inputs to the least-squares adjustment procedure were obtained directly from the results of plant-specific transport calculations for each surveillance capsule irradiation period and location. The spectrum for each capsule was input in an absolute sense (rather than as simply a relative spectral shape). Therefore, within the constraints of the assigned uncertainties, the calculated data were treated equally with the measurements.

While the uncertainties associated with the reaction rates were obtained from the measurement procedures and counting benchmarks and the dosimetry cross-section uncertainties were supplied directly with the SNLRML library, the uncertainty matrix for the calculated spectrum was constructed from the following relationship:

$$M_{gg'} = R_n^2 + R_g * R_{g'} * P_{gg'}$$

where R_n specifies an overall fractional normalization uncertainty and the fractional uncertainties R_g and $R_{g'}$ specify additional random groupwise uncertainties that are correlated with a correlation matrix given by:

$$P_{gg'} = [1 - \theta]\delta_{gg'} + \theta\, e^{-H}$$

Where:

$$H = \frac{(g - g')^2}{2\gamma^2}$$

The first term in the correlation matrix equation specifies purely random uncertainties, while the second term describes the short-range correlations over a group range γ (θ specifies the strength of the latter term). The value of δ is 1.0 when g = g′, and is 0.0 otherwise.

The set of parameters defining the input covariance matrix for the Arkansas Nuclear One Unit 2 calculated spectra was as follows:

Fluence Rate Normalization Uncertainty (R_n)	15%
Fluence Rate Group Uncertainties (R_g, $R_{g'}$)	
(E > 0.0055 MeV)	15%
(0.68 eV < E < 0.0055 MeV)	25%
(E < 0.68 eV)	50%
Short Range Correlation (θ)	
(E > 0.0055 MeV)	0.9
(0.68 eV < E < 0.0055 MeV)	0.5
(E < 0.68 eV)	0.5

Fluence Rate Group Correlation Range (γ)	
(E > 0.0055 MeV)	6
(0.68 eV < E < 0.0055 MeV)	3
(E < 0.68 eV)	2

A.1.3 Comparisons of Measurements and Calculations

Results of the least-squares evaluations of the dosimetry from Capsules 97° and 284° are provided in Table A-7 and Table A-8, respectively. In these tables, measured, calculated, and best-estimate values for sensor reaction rates are given for each capsule. Also provided in these tabulations are ratios of the measured reaction rates to both the calculated and least-squares adjusted reaction rates. These ratios of M/C and M/BE illustrate the consistency of the fit of the calculated neutron energy spectra to the measured reaction rates both before and after adjustment. Additionally, comparisons of the calculated and best-estimate values of neutron fluence rate (E > 1.0 MeV) and iron atom displacement rate are tabulated along with the BE/C ratios observed for each of the capsules.

The data comparisons provided in Table A-7 and Table A-8 show that the adjustments to the calculated spectra are relatively small and within the assigned uncertainties for the calculated spectra, measured sensor reaction rates, and dosimetry reaction cross-sections. Further, these results indicate that the use of the least-squares evaluation results in a reduction in the uncertainties associated with the exposure of the surveillance capsules. From Section 6.4 of this report, the calculational uncertainty is specified as 13% at the 1σ level.

Further comparisons of the measurement results with calculations are given in Table A-9 and Table A-10. In Table A-9, calculations of individual threshold sensor reaction rates are compared directly with the corresponding measurements. These threshold reaction rate comparisons provide a good evaluation of the accuracy of the fast neutron portion of the calculated energy spectra. In Table A-10, calculations of fast neutron exposure rates in terms of fast neutron (E > 1.0 MeV) fluence rate and dpa/s are compared with the best-estimate results obtained from the least-squares evaluation of the capsule dosimetry results. These comparisons yield consistent and similar results with all measurement-to-calculation comparisons falling within the 20% limits specified as the acceptance criteria in Regulatory Guide 1.190.

In the case of the direct comparison of the measured and calculated sensor reaction rates, for the individual threshold foils considered in the least-squares analysis, the M/C comparisons of the fast neutron threshold reactions range from 0.86 to 1.12. The overall average M/C ratio is 1.07 with an associated standard deviation of 7.7%.

In the case of the comparison of the best-estimate and calculated fast neutron exposure parameters, the BE/C comparisons range from 1.01 to 1.05 for both the fast neutron (E > 1.0 MeV) fluence rate and the iron atom displacement rate. The overall average BE/C ratio is 1.03 with an associated standard deviation of 2.7% for the fast neutron (E > 1.0 MeV) fluence rate, and 1.03 with an associated standard deviation of 2.7% for the iron atom displacement rate.

Based on these comparisons, it is concluded that the calculated fast neutron exposures provided in Section 6.2 of this report are validated for use in the assessment of the condition of the materials comprising the beltline region of the Arkansas Nuclear One Unit 2 reactor pressure vessel.

Table A-1 Nuclear Parameters Used in the Evaluation of Neutron Sensors

Reaction of Interest	Atomic Weight (g/g-atom)	Target Atom Fraction	Product Half-life (days)	Fission Yield (%)	90% Response Range[(a)] (MeV)
^{63}Cu (n,α) ^{60}Co	63.546	0.6917	1925.5	n/a	4.53–11.0
^{54}Fe (n,p) ^{54}Mn	55.845	0.05845	312.11	n/a	2.27–7.54
^{58}Ni (n,p) ^{58}Co	58.693	0.68077	70.82	n/a	1.98–7.51
^{46}Ti (n,p) ^{46}Sc	47.867	0.0825	83.79	n/a	3.70–9.43
^{59}Co (n,γ) ^{60}Co	58.933	0.0017	1925.5	n/a	non-threshold
^{238}U (n,f) ^{137}Cs	238.051	1.0	10983.07	6.02	1.44–6.69

Note:

(a) Energies between which 90% of activity is produced (^{235}U fission spectrum) [Ref. A-5]

Table A-2 Monthly Thermal Generation during the First 24 Fuel Cycles of the Arkansas Nuclear One Unit 2 Reactor

Cycle 1		Cycle 2		Cycle 3		Cycle 4	
Month	**MWt-h**	**Month**	**MWt-h**	**Month**	**MWt-h**	**Month**	**MWt-h**
Dec-78	44610	Apr-81	0	Sep-82	0	Oct-83	0
Jan-79	321275	May-81	0	Oct-82	0	Nov-83	0
Feb-79	568	Jun-81	0	Nov-82	228218	Dec-83	0
Mar-79	0	Jul-81	951468	Dec-82	1300179	Jan-84	0
Apr-79	0	Aug-81	1639884	Jan-83	387247	Feb-84	1178875
May-79	0	Sep-81	1642113	Feb-83	1246428	Mar-84	1834869
Jun-79	260849	Oct-81	1096188	Mar-83	2062107	Apr-84	2000857
Jul-79	886333	Nov-81	1664611	Apr-83	2021530	May-84	2036346
Aug-79	763394	Dec-81	1851833	May-83	1991108	Jun-84	1898909
Sep-79	301182	Jan-82	854080	Jun-83	1702512	Jul-84	1372853
Oct-79	105975	Feb-82	1848171	Jul-83	2050169	Aug-84	1803663
Nov-79	0	Mar-82	1906705	Aug-83	1175145	Sep-84	1715686
Dec-79	813240	Apr-82	1015224	Sep-83	1664408	Oct-84	1725334
Jan-80	1323007	May-82	1265831			Nov-84	1852495
Feb-80	0	Jun-82	1329783			Dec-84	2087030
Mar-80	472488	Jul-82	1767012			Jan-85	2091428
Apr-80	895643	Aug-82	947070			Feb-85	1533774
May-80	1696850					Mar-85	913141
Jun-80	1254184						
Jul-80	1785023						
Aug-80	1845969						
Sep-80	204301						
Oct-80	1899794						
Nov-80	1182232						
Dec-80	784128						
Jan-81	1778112						
Feb-81	1754722						
Mar-81	1562183						

Table A-2 Monthly Thermal Generation during the First 24 Fuel Cycles of the Arkansas Nuclear One Unit 2 Reactor – Continued

Cycle 5		Cycle 6		Cycle 7		Cycle 8	
Month	MWt-h	Month	MWt-h	Month	MWt-h	Month	MWt-h
Apr-85	0	Jul-86	0	Mar-88	0	Oct-89	0
May-85	100110	Aug-86	0	Apr-88	0	Nov-89	462718
Jun-85	1172909	Sep-86	494337	May-88	329862	Dec-89	2068599
Jul-85	1682609	Oct-86	2092056	Jun-88	2015855	Jan-90	1493698
Aug-85	1860629	Nov-86	1523343	Jul-88	1621035	Feb-90	1886951
Sep-85	1167234	Dec-86	2057080	Aug-88	975343	Mar-90	1735806
Oct-85	1142264	Jan-87	2088705	Sep-88	2014234	Apr-90	2018895
Nov-85	1967415	Feb-87	1886383	Oct-88	2088496	May-90	2089752
Dec-85	1348977	Mar-87	2059594	Nov-88	2021328	Jun-90	1871344
Jan-86	2091009	Apr-87	1603604	Dec-88	1901679	Jul-90	1382696
Feb-86	1745075	May-87	162732	Jan-89	1421652	Aug-90	1984197
Mar-86	2064830	Jun-87	2000452	Feb-89	1886762	Sep-90	1938837
Apr-86	1811148	Jul-87	1303949	Mar-89	2089334	Oct-90	2088915
May-86	2091218	Aug-87	2087867	Apr-89	1173517	Nov-90	2024368
Jun-86	861998	Sep-87	1925257	May-89	1461654	Dec-90	2091637
		Oct-87	2039907	Jun-89	1506926	Jan-91	1993202
		Nov-87	1745480	Jul-89	1786280	Feb-91	1222971
		Dec-87	2087030	Aug-89	2089334		
		Jan-88	2083888	Sep-89	1620224		
		Feb-88	732364				

Table A-2 Monthly Thermal Generation during the First 24 Fuel Cycles of the Arkansas Nuclear One Unit 2 Reactor – Continued

Cycle 9		Cycle 10		Cycle 11		Cycle 12	
Month	**MWt-h**	**Month**	**MWt-h**	**Month**	**MWt-h**	**Month**	**MWt-h**
Mar-91	0	Oct-92	586211	Apr-94	269159	Oct-95	0
Apr-91	457854	Nov-92	1960118	May-94	2059803	Nov-95	54926
May-91	2092056	Dec-92	2091428	Jun-94	1973292	Dec-95	1876965
Jun-91	1941674	Jan-93	2090590	Jul-94	2093732	Jan-96	2048912
Jul-91	2091218	Feb-93	1879573	Aug-94	2093941	Feb-96	1917704
Aug-91	2091847	Mar-93	2073207	Sep-94	2026395	Mar-96	2049960
Sep-91	1979373	Apr-93	2020517	Oct-94	2093941	Apr-96	1983629
Oct-91	1524694	May-93	960892	Nov-94	2026395	May-96	2049960
Nov-91	1973698	Jun-93	2023354	Dec-94	2078652	Jun-96	1984035
Dec-91	2071950	Jul-93	2091218	Jan-95	767374	Jul-96	2050169
Jan-92	2092475	Aug-93	2081375	Feb-95	1858008	Aug-96	2049750
Feb-92	1956889	Sep-93	1802231	Mar-95	2058546	Sep-96	1983832
Mar-92	596055	Oct-93	2093313	Apr-95	1990520	Oct-96	2050378
Apr-92	0	Nov-93	2023152	May-95	2024199	Nov-96	1043397
May-92	1831727	Dec-93	2076139	Jun-95	1988899	Dec-96	863295
Jun-92	1943499	Jan-94	2060641	Jul-95	2057709	Jan-97	2031529
Jul-92	2089962	Feb-94	1890734	Aug-95	2015193	Feb-97	1836632
Aug-92	2090800	Mar-94	691558	Sep-95	1236145	Mar-97	1977914
Sep-92	268551					Apr-97	1969847
						May-97	536366

Table A-2 Monthly Thermal Generation during the First 24 Fuel Cycles of the Arkansas Nuclear One Unit 2 Reactor – Continued

Cycle 13		Cycle 14		Cycle 15		Cycle 16	
Month	**MWt-h**	**Month**	**MWt-h**	**Month**	**MWt-h**	**Month**	**MWt-h**
Jun-97	1271006	Feb-99	103213	Oct-00	0	May-02	1790044
Jul-97	2093103	Mar-99	2083033	Nov-00	0	Jun-02	2177849
Aug-97	2093313	Apr-99	2016463	Dec-00	1221850	Jul-02	2249993
Sep-97	2025381	May-99	2092781	Jan-01	1383325	Aug-02	2250443
Oct-97	2093522	Jun-99	2025381	Feb-01	1890167	Sep-02	2177596
Nov-97	2025989	Jul-99	2093313	Mar-01	2092685	Oct-02	2249993
Dec-97	2093313	Aug-99	2093313	Apr-01	2025584	Nov-02	2177855
Jan-98	2093522	Sep-99	2025989	May-01	2093313	Dec-02	2141028
Feb-98	1347444	Oct-99	2093313	Jun-01	2025787	Jan-03	2250443
Mar-98	554168	Nov-99	723365	Jul-01	2090381	Feb-03	2028592
Apr-98	2025381	Dec-99	2085564	Aug-01	2093313	Mar-03	2250443
May-98	1795704	Jan-00	2086401	Sep-01	2025584	Apr-03	2177849
Jun-98	2011194	Feb-00	1940431	Oct-01	2093522	May-03	2250443
Jul-98	2093522	Mar-00	2093313	Nov-01	1883911	Jun-03	2177631
Aug-98	2093103	Apr-00	2025787	Dec-01	2093522	Jul-03	2229281
Sep-98	2025989	May-00	2030691	Jan-02	2078862	Aug-03	2016754
Oct-98	2093522	Jun-00	2010586	Feb-02	1884113	Sep-03	1203743
Nov-98	2025787	Jul-00	1361543	Mar-02	2092475		
Dec-98	1967023	Aug-00	968223	Apr-02	790655		
Jan-99	421385	Sep-00	977323				

Table A-2 Monthly Thermal Generation during the First 24 Fuel Cycles of the Arkansas Nuclear One Unit 2 Reactor – Continued

Cycle 17		Cycle 18		Cycle 19		Cycle 20	
Month	MWt-h	Month	MWt-h	Month	MWt-h	Month	MWt-h
Oct-03	1183081	Apr-05	1320740	Oct-06	73844	Apr-08	1350153
Nov-03	2177975	May-05	2249768	Nov-06	2123816	May-08	2249289
Dec-03	1885342	Jun-05	2177195	Dec-06	2249768	Jun-08	2177195
Jan-04	2249318	Jul-05	2249543	Jan-07	1787117	Jul-08	2159939
Feb-04	1851048	Aug-05	2249543	Feb-07	1935459	Aug-08	2249993
Mar-04	2249733	Sep-05	2134928	Mar-07	2249663	Sep-08	2176977
Apr-04	2177195	Oct-05	2249543	Apr-07	2146039	Oct-08	2248790
May-04	2249768	Nov-05	2176759	May-07	2245026	Nov-08	2175541
Jun-04	2177195	Dec-05	2249768	Jun-07	2176957	Dec-08	2249318
Jul-04	2249768	Jan-06	2249768	Jul-07	2249675	Jan-09	1990638
Aug-04	2182228	Feb-06	2032049	Aug-07	2249813	Feb-09	1931798
Sep-04	1963027	Mar-06	2249993	Sep-07	2167810	Mar-09	1922423
Oct-04	2111761	Apr-06	2177195	Oct-07	2249543	Apr-09	2176323
Nov-04	2177195	May-06	2249768	Nov-07	2176759	May-09	2248868
Dec-04	2249768	Jun-06	2176977	Dec-07	2249224	Jun-09	2176106
Jan-05	2249543	Jul-06	2249264	Jan-08	2249543	Jul-09	2248868
Feb-05	2031845	Aug-06	2237836	Feb-08	1853364	Aug-09	2240312
Mar-05	580622	Sep-06	1286970	Mar-08	1110950		

Table A-2 Monthly Thermal Generation during the First 24 Fuel Cycles of the Arkansas Nuclear One Unit 2 Reactor – Continued

Cycle 21		Cycle 22		Cycle 23		Cycle 24	
Month	**MWt-h**	**Month**	**MWt-h**	**Month**	**MWt-h**	**Month**	**MWt-h**
Sep-09	358152	Mar-11	343286	Oct-12	1503448	May-14	0
Oct-09	2249543	Apr-11	2014880	Nov-12	2175888	Jun-14	1275205
Nov-09	2176977	May-11	2093750	Dec-12	2249093	Jul-14	2248642
Dec-09	2036116	Jun-11	2176323	Jan-13	2246616	Aug-14	2248642
Jan-10	2249543	Jul-11	2249318	Feb-13	2031439	Sep-14	2176106
Feb-10	1861237	Aug-11	2249318	Mar-13	2199338	Oct-14	2248868
Mar-10	2248477	Sep-11	2176106	Apr-13	105420	Nov-14	2176106
Apr-10	2176387	Oct-11	2248642	May-13	2248417	Dec-14	2184479
May-10	2248219	Nov-11	2176323	Jun-13	2175888	Jan-15	2248417
Jun-10	2176106	Dec-11	2202322	Jul-13	2248192	Feb-15	2030828
Jul-10	2248192	Jan-12	2248417	Aug-13	2247580	Mar-15	2247742
Aug-10	1607910	Feb-12	2103569	Sep-13	2175452	Apr-15	2175452
Sep-10	1931217	Mar-12	2247742	Oct-13	2248192	May-15	2248192
Oct-10	2247967	Apr-12	2175234	Nov-13	2174145	Jun-15	2175452
Nov-10	2175452	May-12	2247967	Dec-13	603810	Jul-15	2222527
Dec-10	2247828	Jun-12	2175452	Jan-14	1483861	Aug-15	2154311
Jan-11	2248188	Jul-12	2247292	Feb-14	2030625	Sep-15	1344270
Feb-11	1402079	Aug-12	2115138	Mar-14	2247066		
		Sep-12	859069	Apr-14	1781539		

Table A-3 Surveillance Capsule Fluence Rates for C_j Calculation, CoreMidplane Elevation

Cycle	Cycle Length (EFPY)	Fluence Rate (n/cm^2-s)	
		Capsule 97°	Capsule 284°
1	0.89	5.11E+10	5.08E+10
2	0.80	6.30E+10	6.21E+10
3	0.64		6.01E+10
4	0.97		5.88E+10
5	0.86		6.44E+10
6	1.22		4.81E+10
7	1.13		4.28E+10
8	1.15		4.52E+10
9	1.18		4.45E+10
10	1.32		4.21E+10
11	1.33		2.90E+10
12	1.31		3.25E+10
13	1.47		2.79E+10
14	1.41		3.18E+10
15	1.29		3.08E+10
16	1.35		3.52E+10
17	1.36		3.46E+10
18	1.43		3.85E+10
19	1.34		3.66E+10
20	1.36		3.66E+10
21	1.35		3.63E+10
22	1.45		3.58E+10
23	1.36		3.71E+10
24	1.26		3.45E+10
Average	--	5.67E+10	3.98E+10

Table A-4 Surveillance Capsule C_j Factors, Core Midplane Elevation

Cycle	Cycle Length (EFPY)	C_j	
		Capsule 97°	Capsule 284°
1	0.89	0.90	1.28
2	0.80	1.11	1.56
3	0.64		1.51
4	0.97		1.48
5	0.86		1.62
6	1.22		1.21
7	1.13		1.08
8	1.15		1.14
9	1.18		1.12
10	1.32		1.06
11	1.33		0.73
12	1.31		0.82
13	1.47		0.70
14	1.41		0.80
15	1.29		0.77
16	1.35		0.88
17	1.36		0.87
18	1.43		0.97
19	1.34		0.92
20	1.36		0.92
21	1.35		0.91
22	1.45		0.90
23	1.36		0.93
24	1.26		0.87

Table A-5 Measured Sensor Activities and Reaction Rates for Surveillance Capsule 97°

Reaction	Measured Activity (dps/g)	Saturated Activity (dps/g)	Reaction Rate (rps/atom)	Average Reaction Rate (rps/atom)	Corrected Average Reaction Rate (rps/atom)
^{63}Cu(Cd) (n,α) ^{60}Co	1.11E+05	5.88E+05	8.97E-17	8.95E-17	8.95E-17
^{63}Cu(Cd) (n,α) ^{60}Co	1.08E+05	5.72E+05	8.73E-17		
^{63}Cu(Cd) (n,α) ^{60}Co	1.13E+05	5.99E+05	9.13E-17		
^{54}Fe (n,p) ^{54}Mn	2.94E+06	4.89E+06	7.76E-15	7.65E-15	7.65E-15
^{54}Fe (n,p) ^{54}Mn	2.93E+06	4.88E+06	7.74E-15		
^{54}Fe (n,p) ^{54}Mn	2.82E+06	4.69E+06	7.45E-15		
^{58}Ni(Cd) (n,p) ^{58}Co	5.85E+07	7.44E+07	1.07E-14	1.01E-14	1.01E-14
^{58}Ni(Cd) (n,p) ^{58}Co	5.25E+07	6.68E+07	9.56E-15		
^{58}Ni(Cd) (n,p) ^{58}Co	5.48E+07	6.97E+07	9.98E-15		
^{46}Ti (n,p) ^{46}Sc	1.21E+06	1.56E+06	1.50E-15	1.40E-15	1.40E-15
^{46}Ti (n,p) ^{46}Sc	1.09E+06	1.40E+06	1.35E-15		
^{46}Ti (n,p) ^{46}Sc	1.10E+06	1.42E+06	1.36E-15		
^{59}Co (n,γ) ^{60}Co	1.72E+07	9.11E+07	5.95E-12	5.12E-12	5.12E-12
^{59}Co (n,γ) ^{60}Co	1.53E+07	8.11E+07	5.29E-12		
^{59}Co (n,γ) ^{60}Co	1.19E+07	6.31E+07	4.11E-12		
^{59}Co(Cd) (n,γ) ^{60}Co	1.89E+06	1.00E+07	6.53E-13	6.49E-13	6.49E-13
^{59}Co(Cd) (n,γ) ^{60}Co	1.90E+06	1.01E+07	6.57E-13		
^{59}Co(Cd) (n,γ) ^{60}Co	1.84E+06	9.75E+06	6.36E-13		

Note:

(a) Measured activity is decay corrected to August 20, 1982.

Table A-6 Measured Sensor Activities and Reaction Rates for Surveillance Capsule 284°

Reaction	Measured Activity (dps/g)	Saturated Activity (dps/g)	Reaction Rate (rps/atom)	Average Reaction Rate (rps/atom)	Corrected Average Reaction Rate (rps/atom)
^{63}Cu(Cd) (n,α) ^{60}Co	3.00E+05	4.08E+05	6.23E-17	6.14E-17	6.14E-17
^{63}Cu(Cd) (n,α) ^{60}Co	2.75E+05	3.74E+05	5.71E-17		
^{63}Cu(Cd) (n,α) ^{60}Co	3.12E+05	4.25E+05	6.48E-17		
^{54}Fe (n,p) ^{54}Mn	1.61E+06	3.37E+06	5.35E-15	5.43E-15	5.43E-15
^{54}Fe (n,p) ^{54}Mn	1.58E+06	3.31E+06	5.25E-15		
^{54}Fe (n,p) ^{54}Mn	1.71E+06	3.58E+06	5.68E-15		
^{58}Ni(Cd) (n,p) ^{58}Co	4.12E+06	5.08E+07	7.27E-15	7.27E-15	7.27E-15
^{58}Ni(Cd) (n,p) ^{58}Co	3.80E+06	4.69E+07	6.71E-15		
^{58}Ni(Cd) (n,p) ^{58}Co	4.44E+06	5.47E+07	7.84E-15		
^{46}Ti (n,p) ^{46}Sc	1.16E+05	9.97E+05	9.60E-16	9.69E-16	9.69E-16
^{46}Ti (n,p) ^{46}Sc	1.13E+05	9.71E+05	9.35E-16		
^{46}Ti (n,p) ^{46}Sc	1.22E+05	1.05E+06	1.01E-15		
^{59}Co (n,γ) ^{60}Co	2.68E+07	3.65E+07	2.38E-12	2.64E-12	2.64E-12
^{59}Co (n,γ) ^{60}Co	3.18E+07	4.33E+07	2.83E-12		
^{59}Co (n,γ) ^{60}Co	3.05E+07	4.15E+07	2.71E-12		
^{59}Co(Cd) (n,γ) ^{60}Co	4.69E+06	6.39E+06	4.17E-13	4.22E-13	4.22E-13
^{59}Co(Cd) (n,γ) ^{60}Co	4.69E+06	6.39E+06	4.17E-13		
^{59}Co(Cd) (n,γ) ^{60}Co	4.88E+06	6.64E+06	4.33E-13		
^{238}U(Cd) (n,f) ^{137}Cs	1.38E+06	3.08E+06	2.30E-14	2.26E-14	1.51E-14
^{238}U(Cd) (n,f) ^{137}Cs	1.28E+06	2.85E+06	2.13E-14		
^{238}U(Cd) (n,f) ^{137}Cs	1.41E+06	3.14E+06	2.35E-14		

Note:

(a) Measured activity is decay corrected to May 16, 2016.

Table A-7 Least-Squares Evaluation of Dosimetry in Capsule 97° (7° Azimuth, Core Midplane, Withdrawn at the End of Cycle 2)

Reaction	Reaction Rate (rps/atom)			M/C	M/BE	BE/C
	Measured (M)	Calculated (C)	Best-Estimate (BE)			
^{63}Cu(Cd) (n,α) ^{60}Co	8.94E-17	7.94E-17	8.82E-17	1.13	1.01	1.11
^{54}Fe (n,p) ^{54}Mn	7.65E-15	7.25E-15	7.78E-15	1.05	0.98	1.07
^{58}Ni(Cd) (n,p) ^{58}Co	1.01E-14	9.48E-15	1.02E-14	1.06	0.99	1.07
^{46}Ti (n,p) ^{46}Sc	1.40E-15	1.26E-15	1.38E-15	1.12	1.02	1.10
^{59}Co (n,γ) ^{60}Co	5.12E-12	3.56E-12	5.09E-12	1.44	1.00	1.43
^{59}Co(Cd) (n,γ) ^{60}Co	6.49E-13	6.30E-13	6.50E-13	1.03	1.00	1.03
^{238}U(Cd) (n,f) ^{137}Cs	Rejected	Rejected	Rejected	--	--	--
Average of Fast Energy Threshold Reactions				1.09	1.00	1.09
Standard Deviation				3.7%	1.8%	1.9%

Integral Quantity	Calculated (C)	Best-Estimate (BE)	Uncertainty (%)	BE/C
Fluence Rate E > 1.0 MeV	5.67E+10	5.96E+10	7	1.05
Fluence Rate E > 0.1 MeV	1.08E+11	1.13E+11	9	1.04
dpa/s	8.17E-11	8.66E-11	6	1.05

Table A-8 Least-Squares Evaluation of Dosimetry in Capsule 284° (14° Azimuth, Core Midplane, Withdrawn at the End of Cycle 24)

Reaction	Reaction Rate (rps/atom)			M/C	M/BE	BE/C
	Measured (M)	Calculated (C)	Best-Estimate (BE)			
^{63}Cu(Cd) (n,α) ^{60}Co	6.14E-17	5.60E-17	6.13E-17	1.10	1.00	1.09
^{54}Fe (n,p) ^{54}Mn	5.42E-15	5.07E-15	5.39E-15	1.07	1.01	1.06
^{58}Ni(Cd) (n,p) ^{58}Co	7.27E-15	6.63E-15	7.09E-15	1.10	1.03	1.07
^{46}Ti (n,p) ^{46}Sc	9.68E-16	8.80E-16	9.58E-16	1.10	1.01	1.09
^{59}Co (n,γ) ^{60}Co	2.64E-12	2.58E-12	2.64E-12	1.02	1.00	1.02
^{59}Co(Cd) (n,γ) ^{60}Co	4.22E-13	4.49E-13	4.24E-13	0.94	1.00	0.94
^{238}U(Cd) (n,f) ^{137}Cs	1.51E-14	1.76E-14	1.82E-14	0.86	0.83	1.03
Average of Fast Energy Threshold Reactions				1.05	0.98	1.07
Standard Deviation				10.0%	8.4%	2.3%

Integral Quantity	Calculated (C)	Best-Estimate (BE)	Uncertainty (%)	BE/C
Fluence Rate E > 1.0 MeV	3.97E+10	4.03E+10	6	1.01
Fluence Raet E > 0.1 MeV	7.59E+10	7.54E+10	9	0.99
dpa/s	5.74E-11	5.84E-11	6	1.01

Table A-9 Comparison of Measured/Calculated (M/C) Sensor Reaction Rate Ratios for Fast Neutron Threshold Reactions

Reaction	Capsule		Average	Std. Dev.
	97°	284°		
$^{63}Cu(Cd)\ (n,\alpha)\ ^{60}Co$	1.13	1.10	1.12	1.9%
$^{54}Fe\ (n,p)\ ^{54}Mn$	1.05	1.07	1.06	1.3%
$^{58}Ni(Cd)\ (n,p)\ ^{58}Co$	1.06	1.10	1.08	2.6%
$^{46}Ti\ (n,p)\ ^{46}Sc$	1.12	1.10	1.11	1.3%
$^{238}U(Cd)\ (n,f)\ ^{137}Cs$	Rejected	0.86	0.86	N/A
Average of M/C Results			1.07	7.7%

Table A-10 Comparison of Best-Estimate/Calculated (BE/C) Exposure Rate Ratios

Capsule	Fast (E > 1.0 MeV) Fluence Rate		Iron Atom Displacement Rate	
	BE/C	Std. Dev.	BE/C	Std. Dev.
97°	1.05	7.0%	1.05	6.0%
284°	1.01	6.0%	1.01	6.0%
Average	1.03	2.7%	1.03	2.7%

A.2 REFERENCES

A-1 U.S. Nuclear Regulatory Commission Regulatory Guide 1.190, *Calculational and Dosimetry Methods for Determining Pressure Vessel Neutron Fluence*, March 2001.

A-2 A. Schmittroth, *FERRET Data Analysis Core*, HEDL-TME 79-40, Hanford Engineering Development Laboratory, Richland, WA, September 1979.

A-3 RSICC Data Library Collection DLC-178, *SNLRML Recommended Dosimetry Cross-Section Compendium*, July 1994.

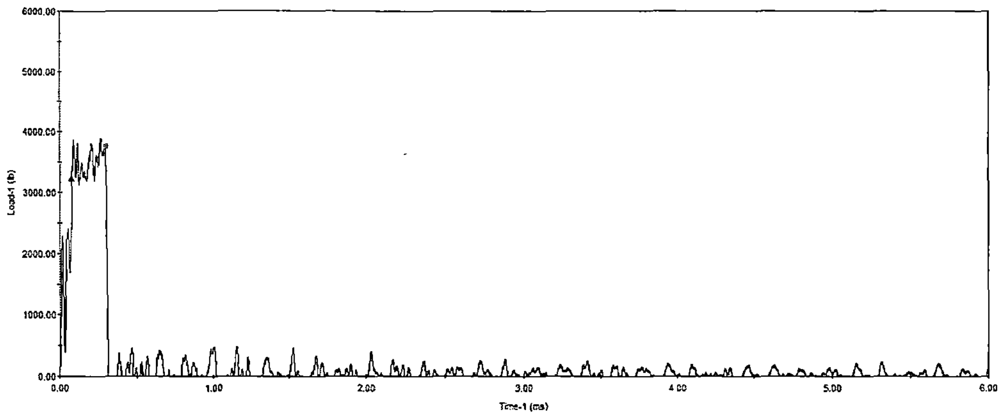
A-4 ASTM Standard E944-13, *Standard Guide for Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance, E 706 (IIA),* 2013.

A-5 ASTM Standard E844-09 (Reapproved 2014), *Standard Guide for Sensor Set Design and Irradiation for Reactor Surveillance, E 706 (IIC)*, 2014.

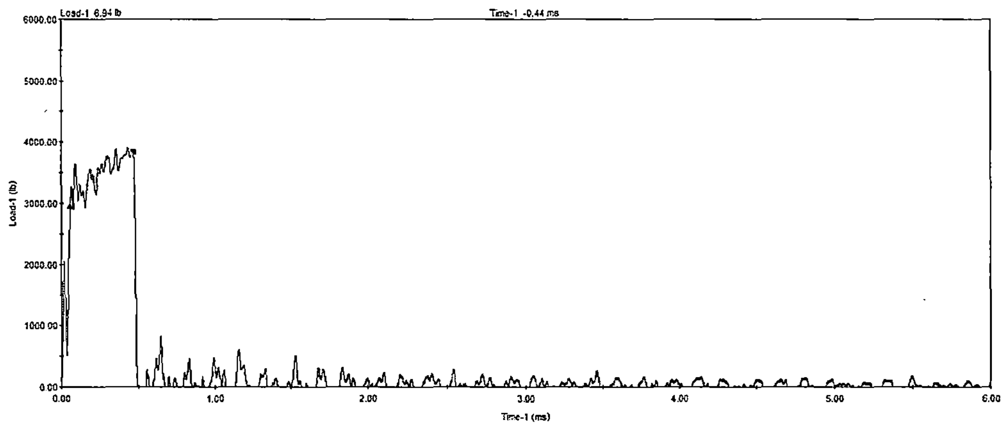
APPENDIX B LOAD-TIME RECORDS FOR CHARPY SPECIMEN TESTS

- "1XX" denotes Intermediate Shell Plate C-8009-3, longitudinal orientation
- "2XX" denotes Intermediate Shell Plate C-8009-3, transverse orientation
- "3XX" denotes weld material
- "4XX" denotes heat-affected zone material

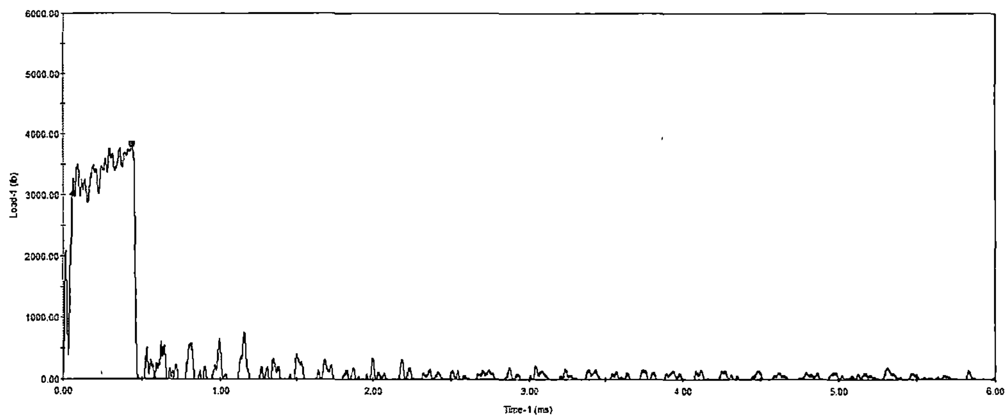
Note that the instrumented Charpy data is not required per ASTM Standards E185-82 or E23-07a.



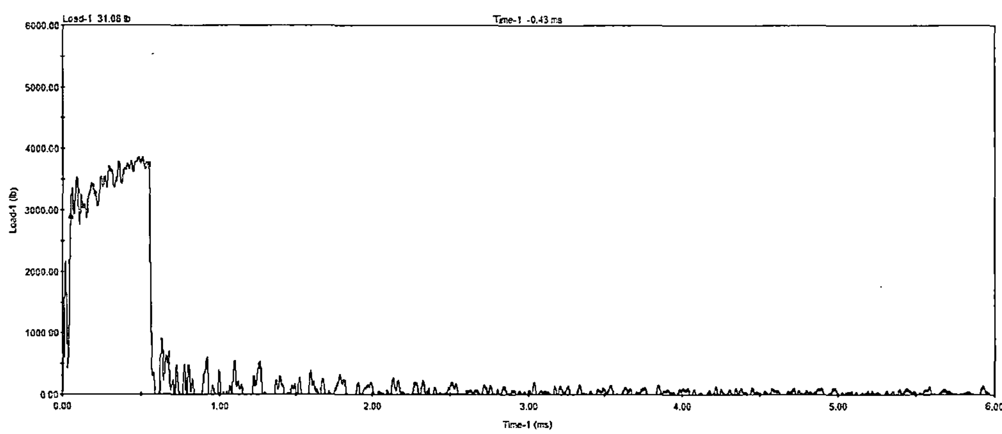
14P: Tested at 25°F



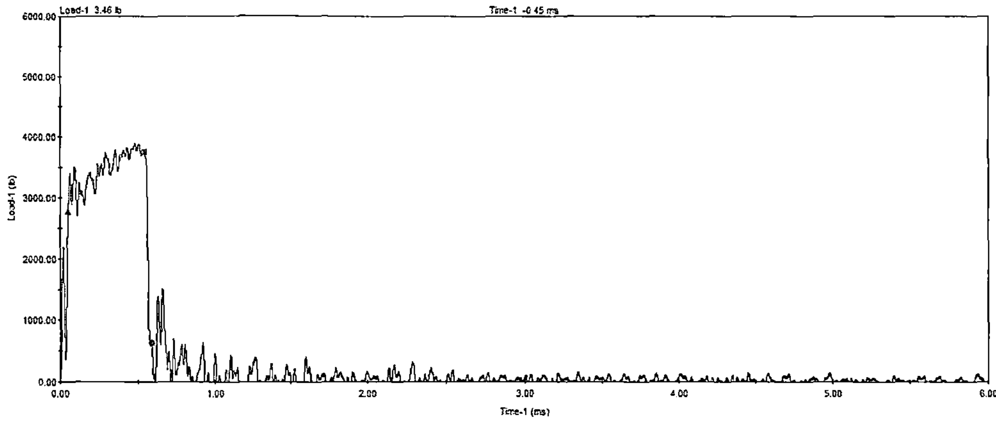
111: Tested at 60°F



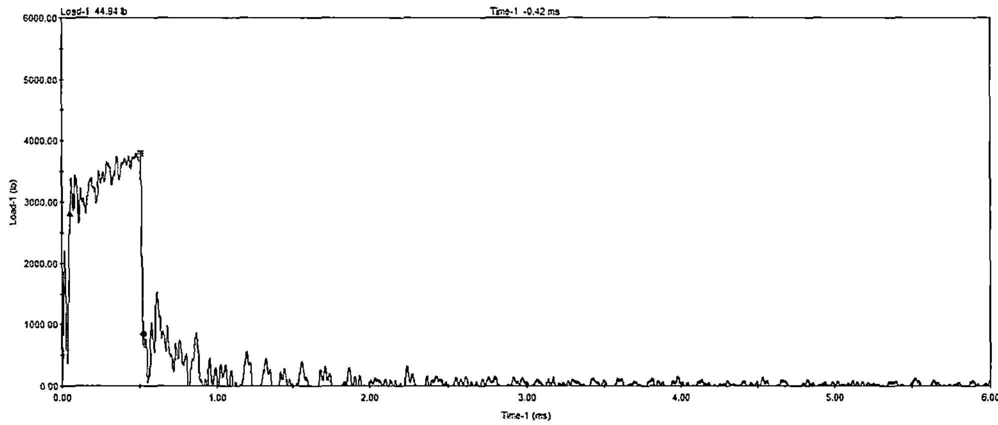
12K: Tested at 72°F



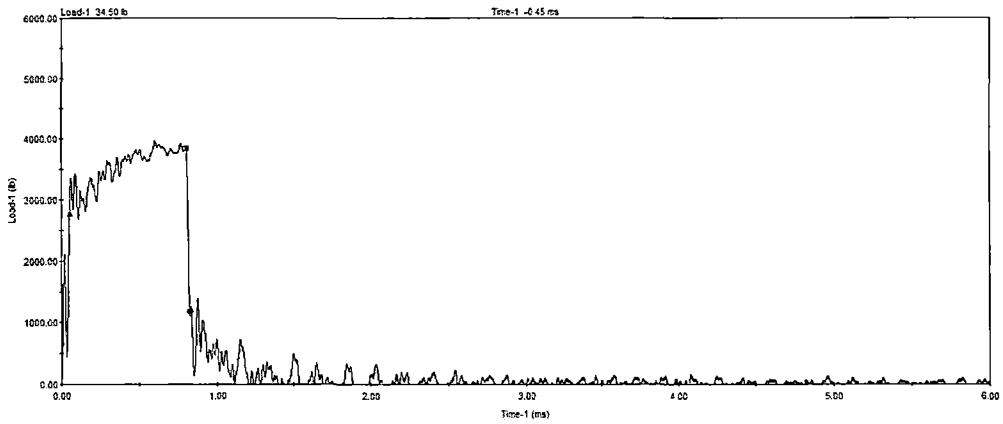
15J: Tested at 80°F



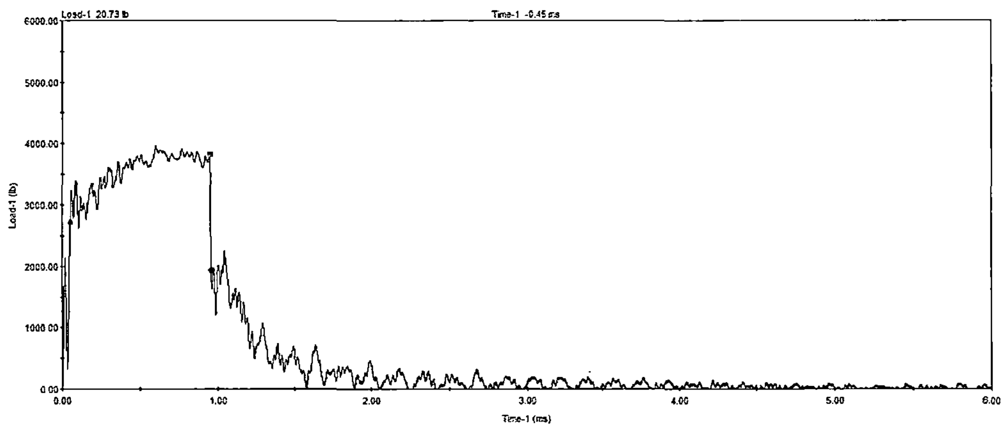
11P: Tested at 100°F



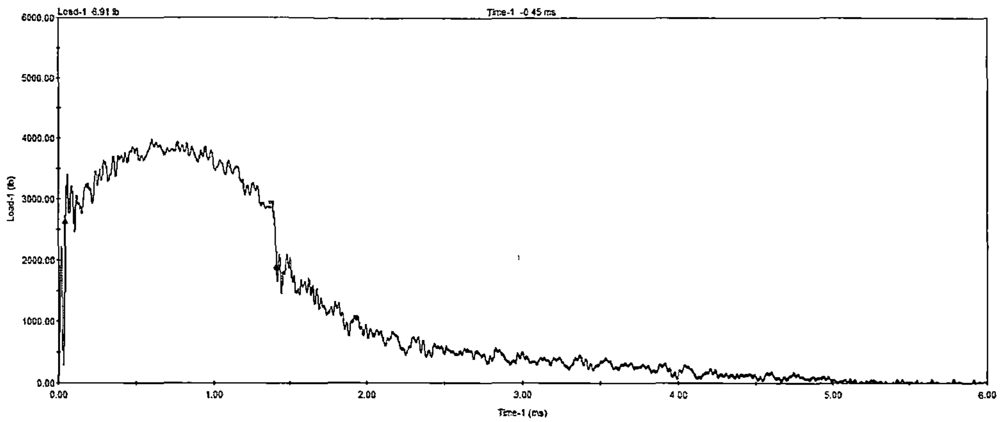
125: Tested at 120°F



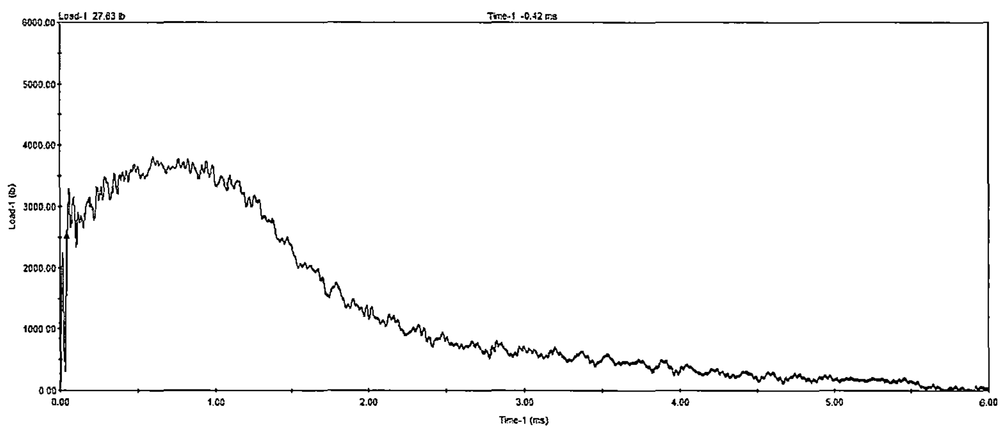
136: Tested at 130°F



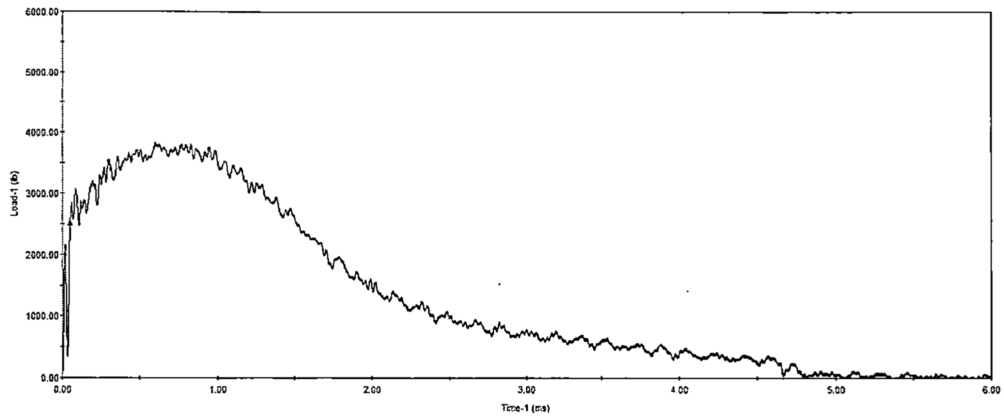
13E: Tested at 165°F



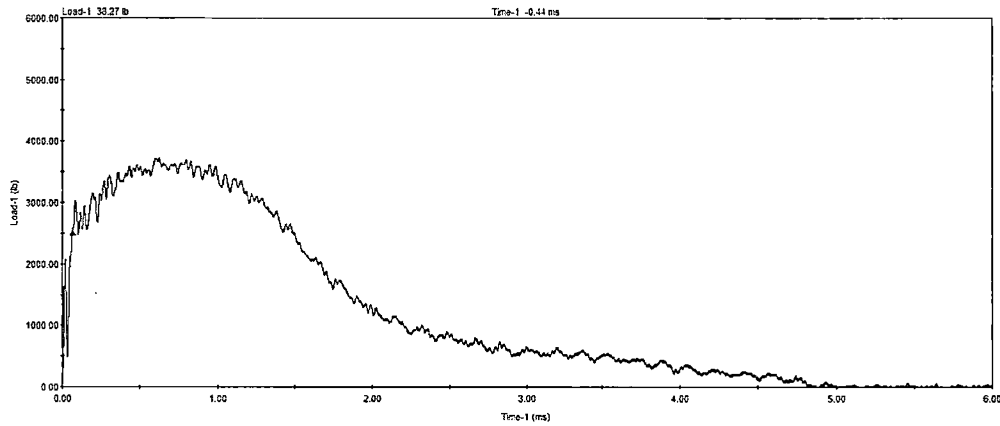
13J: Tested at 200°F



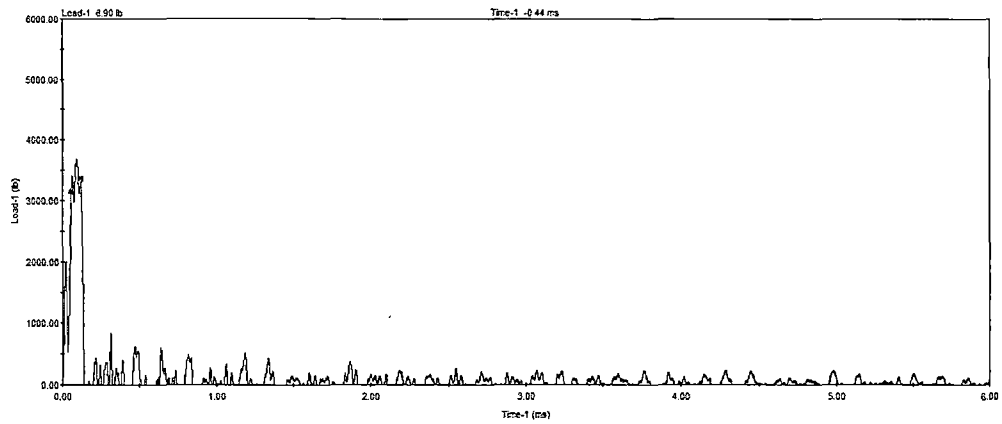
11B: Tested at 250°F



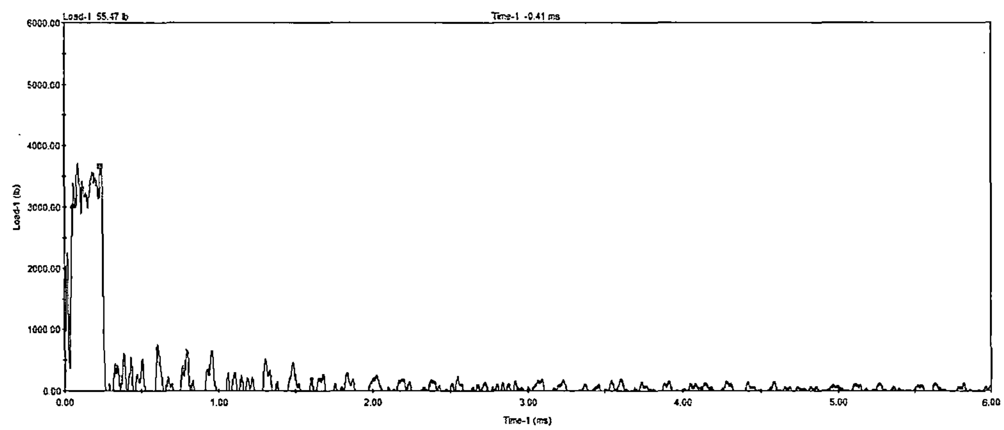
12E: Tested at 275°F



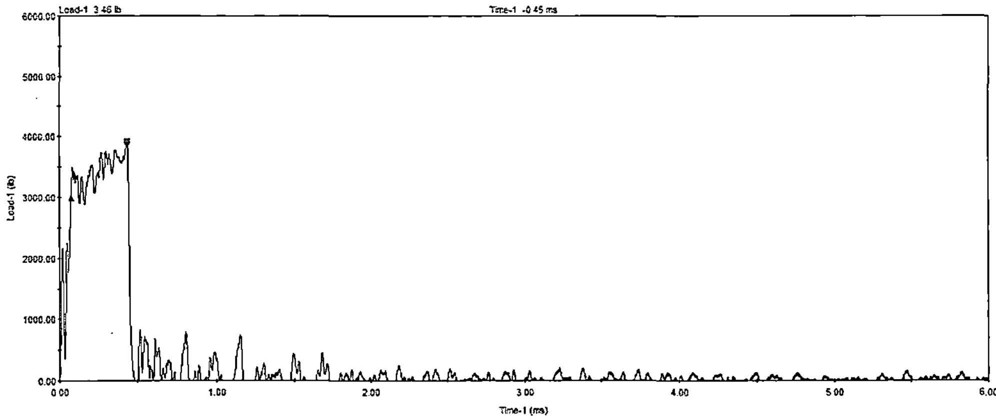
11M: Tested at 300°F



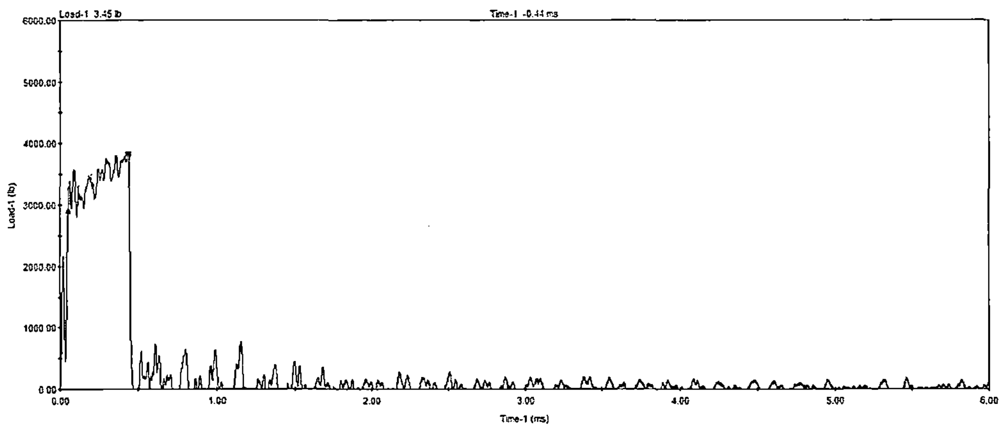
267: Tested at 25°F



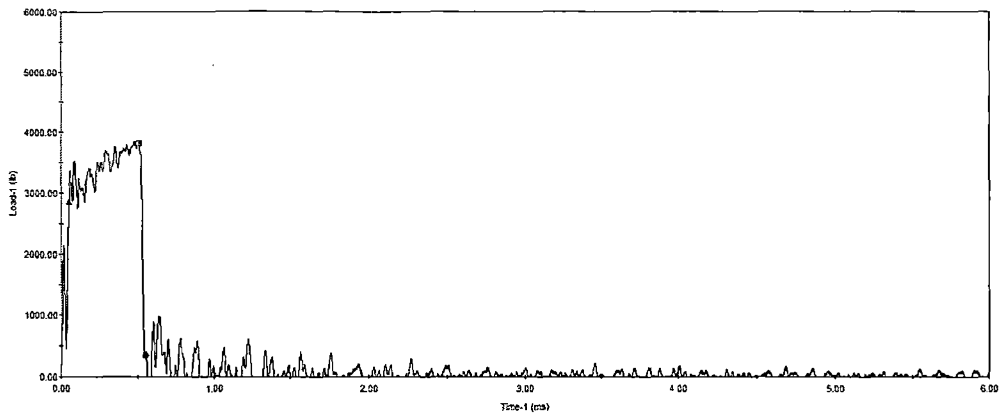
237: Tested at 60°F



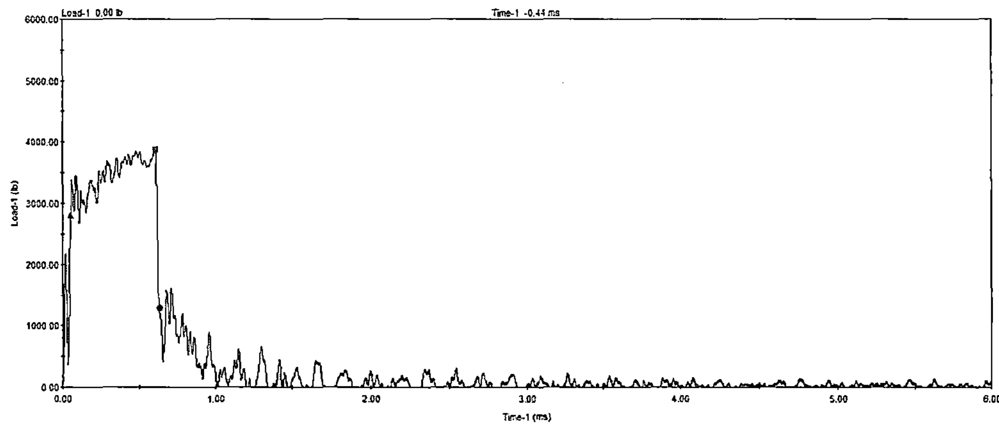
221: Tested at 72°F



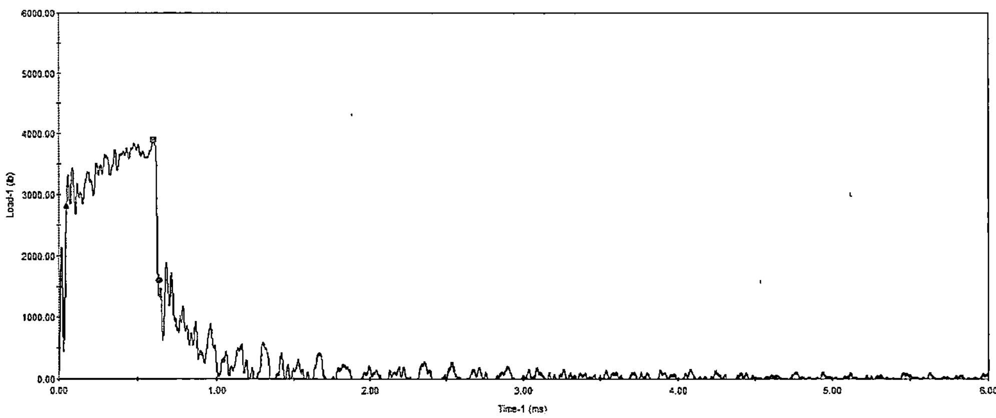
21J: Tested at 80°F



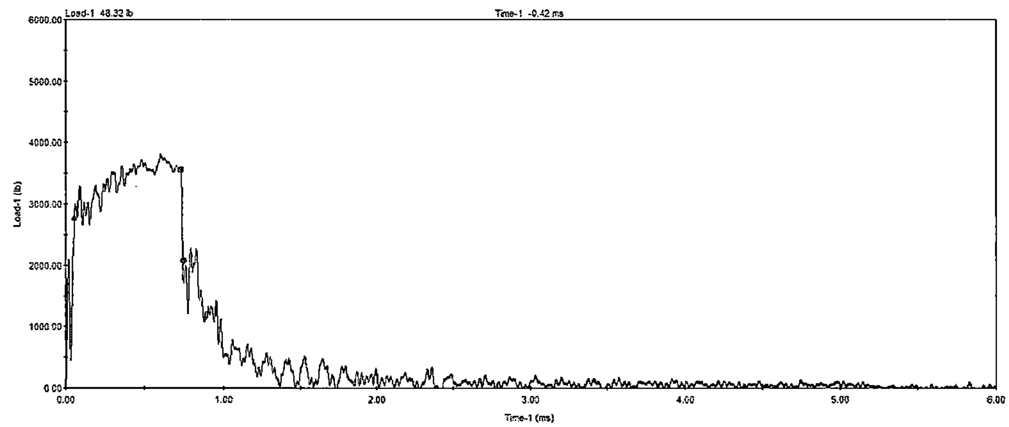
233: Tested at 100°F



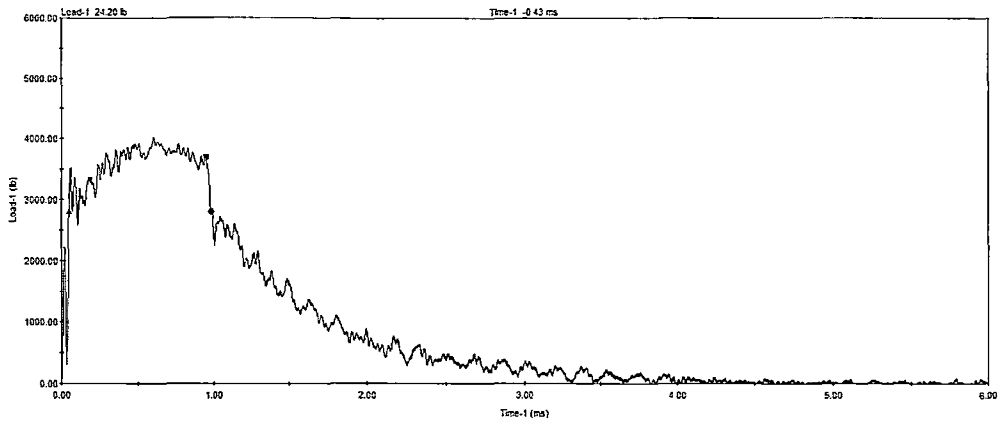
235: Tested at 130°F



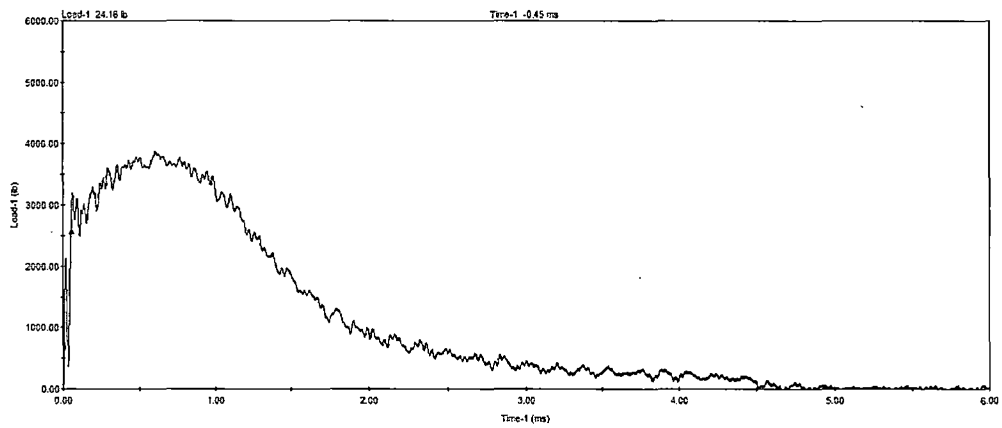
23M: Tested at 150°F



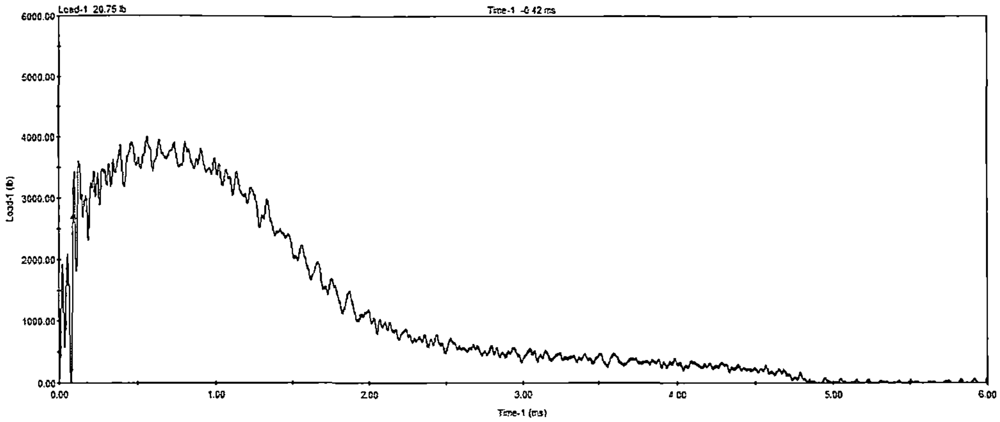
21T: Tested at 175°F



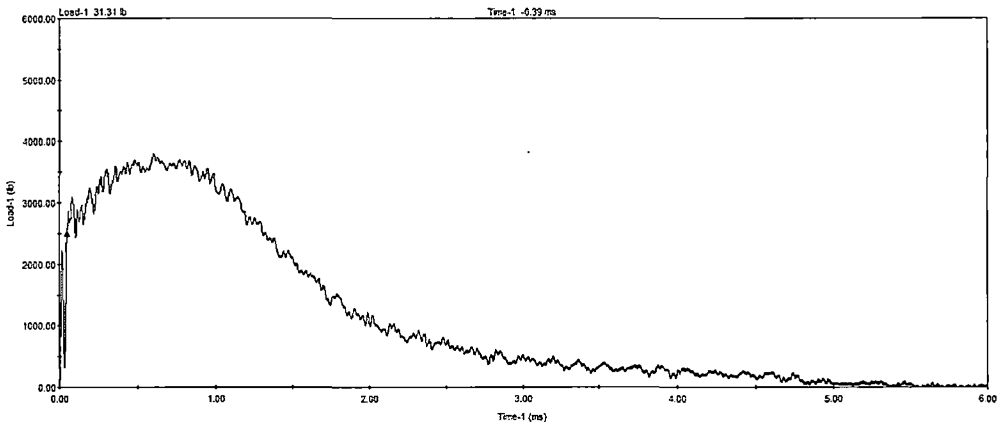
23P: Tested at 200°F



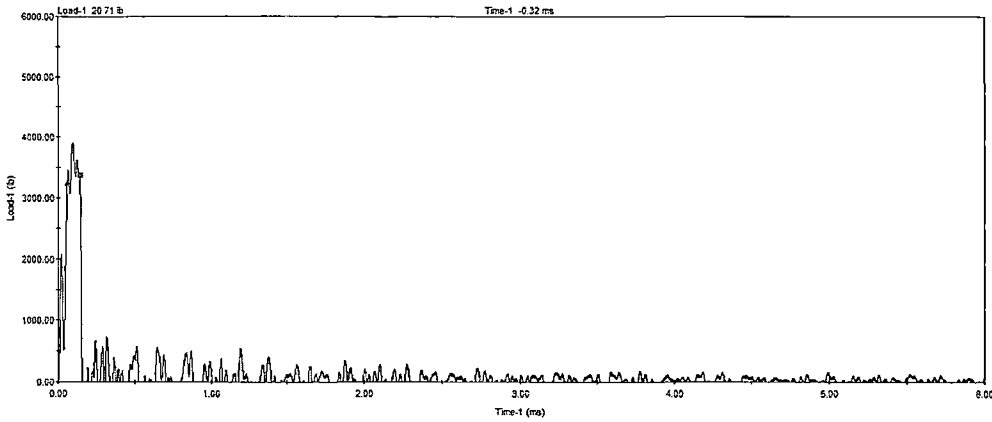
21M: Tested at 250°F



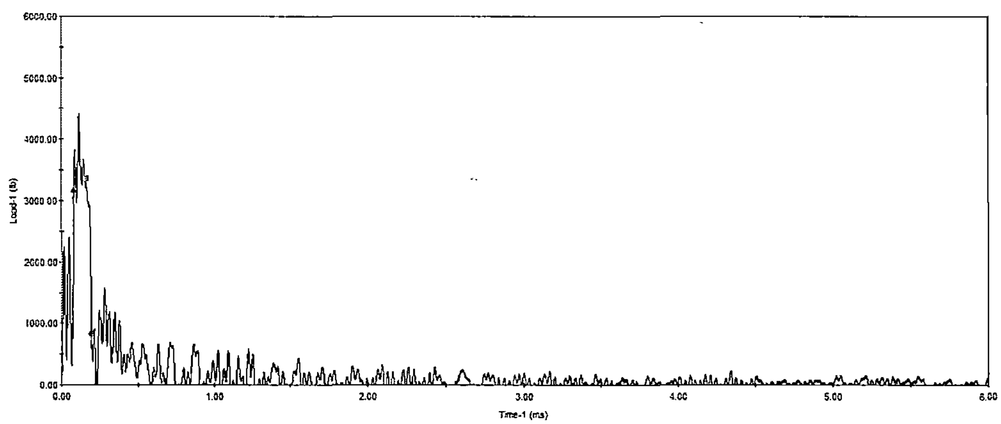
22C: Tested at 275°F



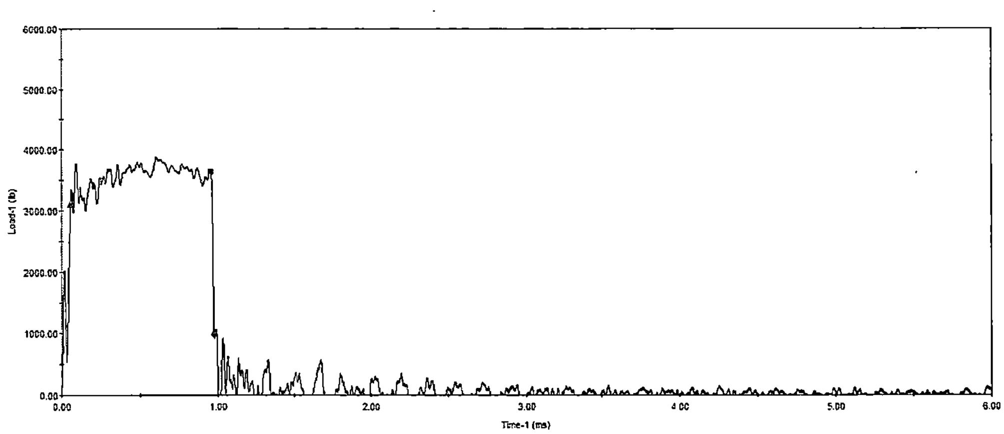
265: Tested at 300°F



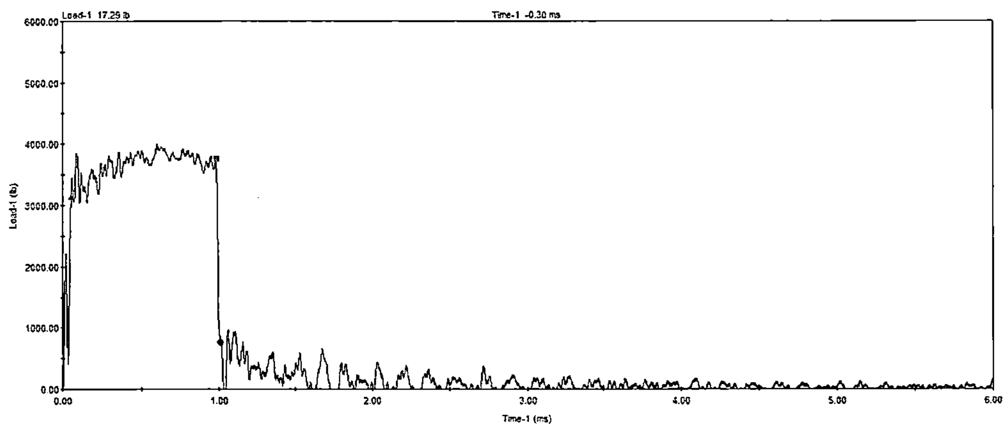
37E: Tested at -25°F



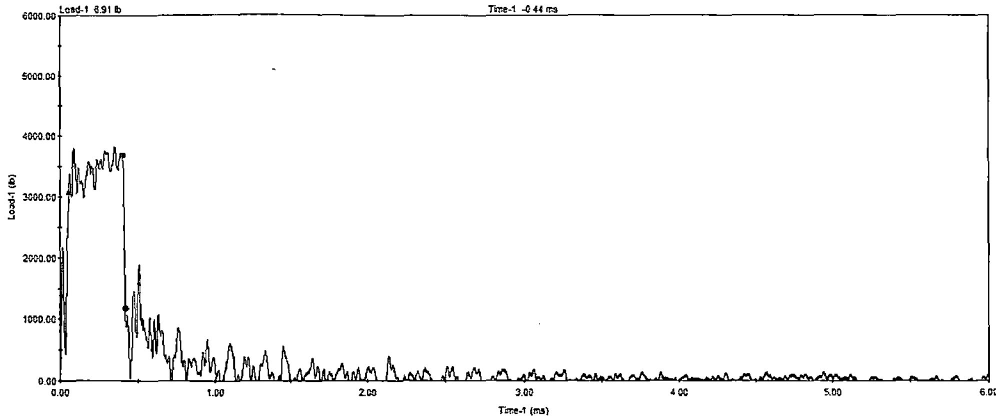
367: Tested at 0°F



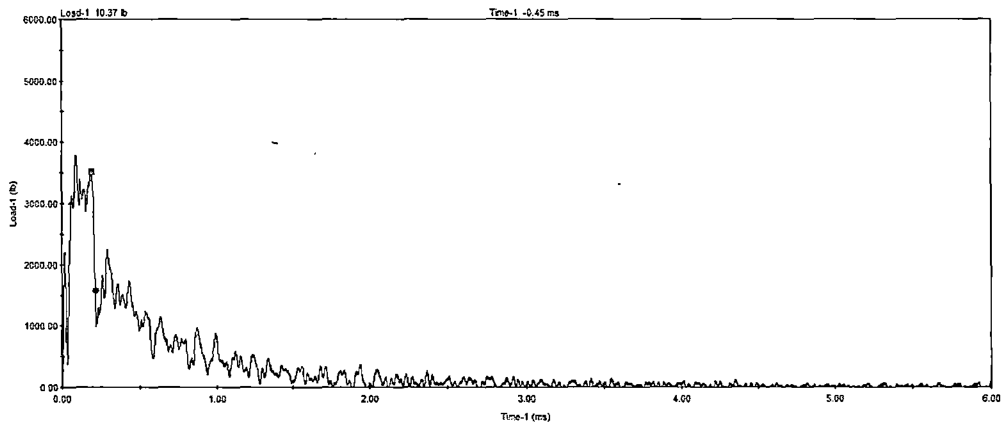
352: Tested at 15°F



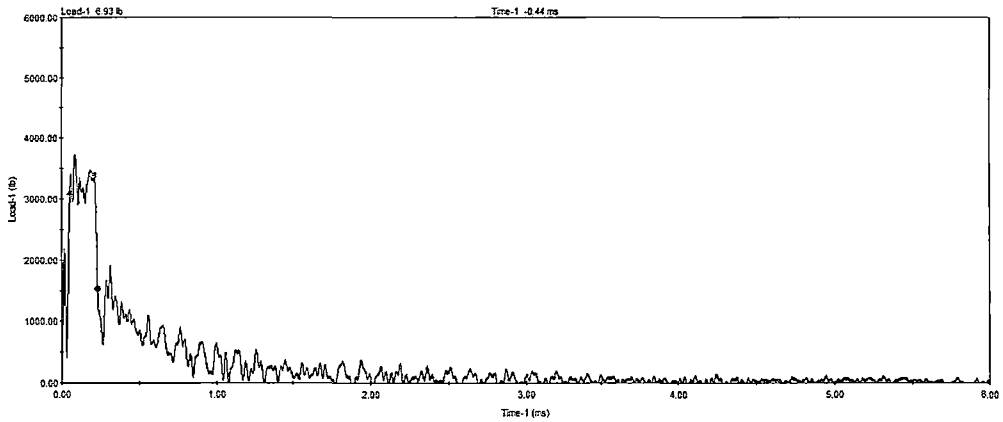
33M: Tested at 15°F



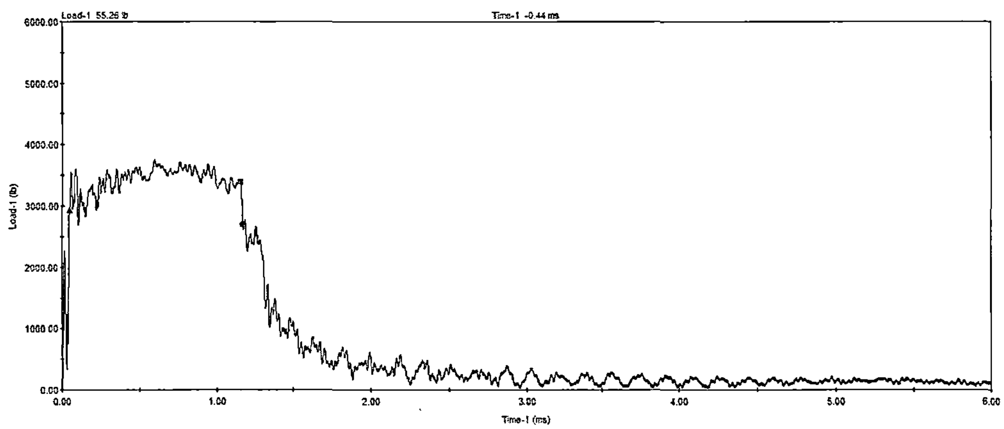
341: Tested at 25°F



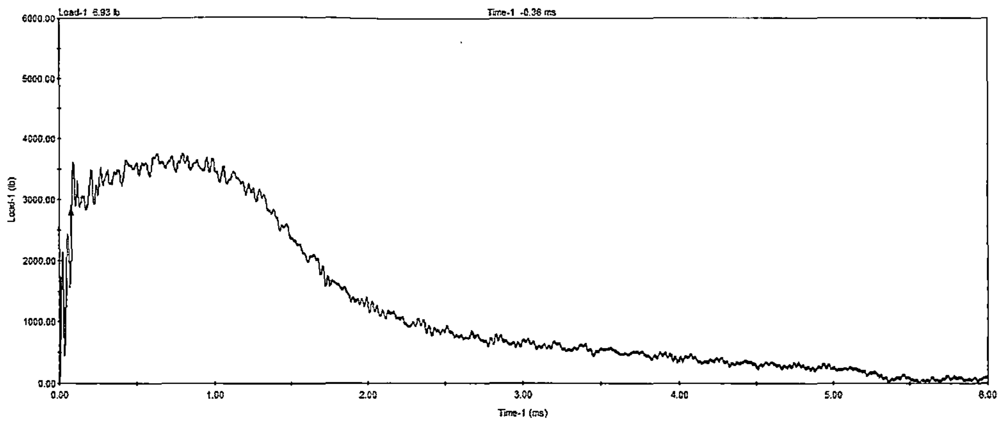
32L: Tested at 40°F



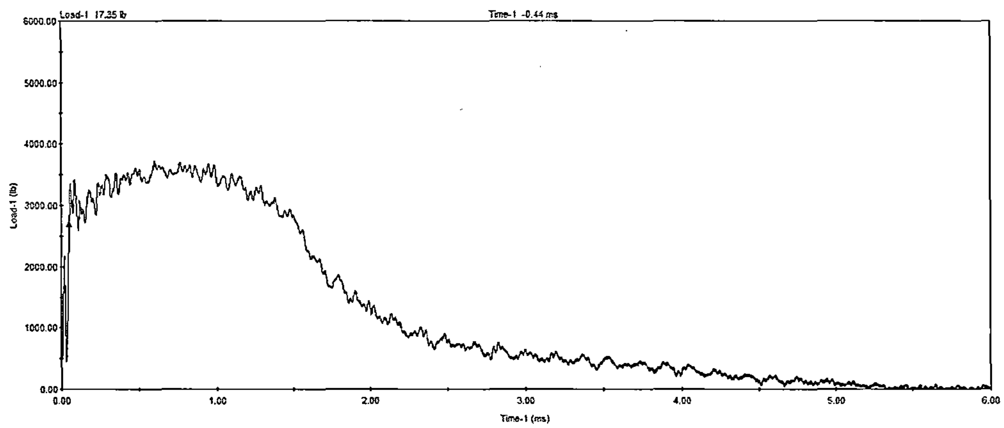
313: Tested at 60°F



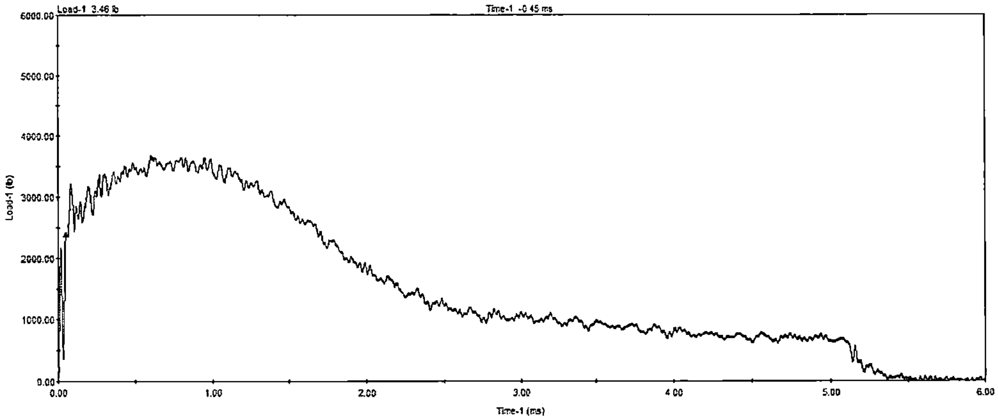
365: Tested at 72°F



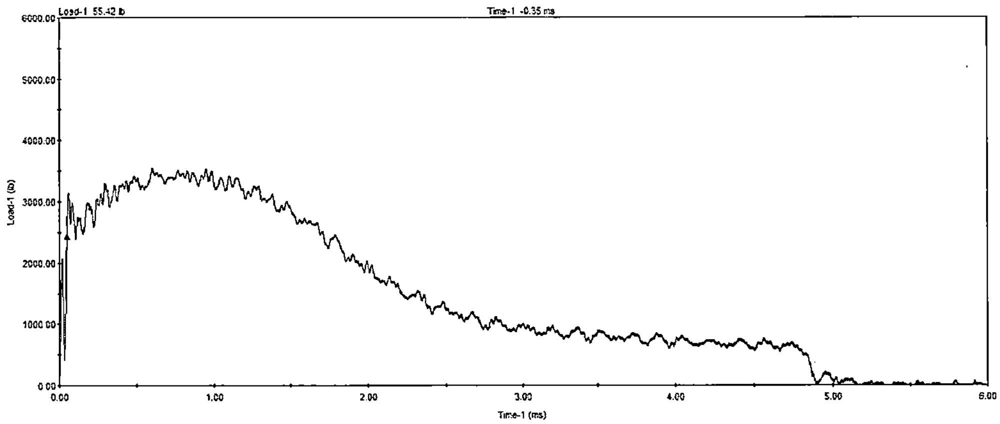
33T: Tested at 110°F



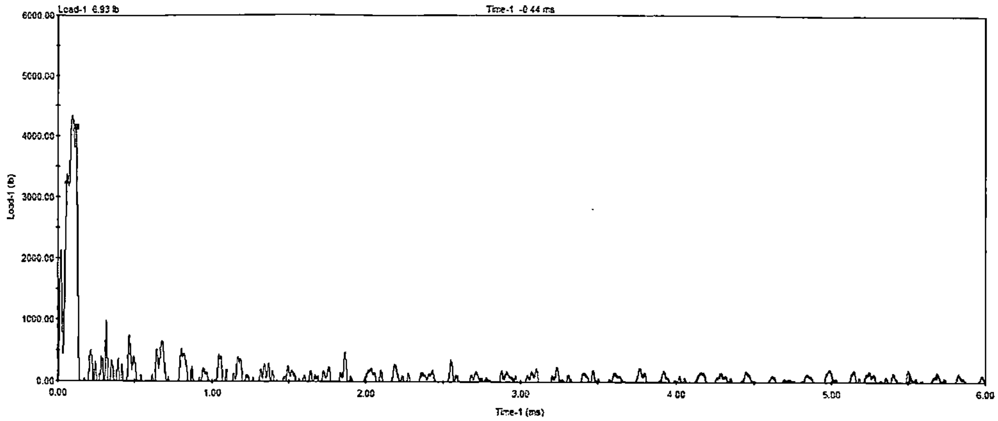
35C: Tested at 150°F



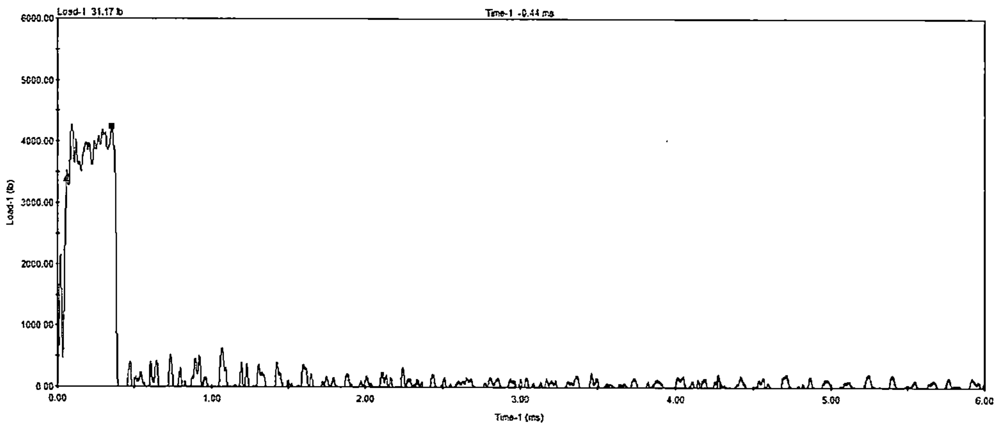
311: Tested at 200°F



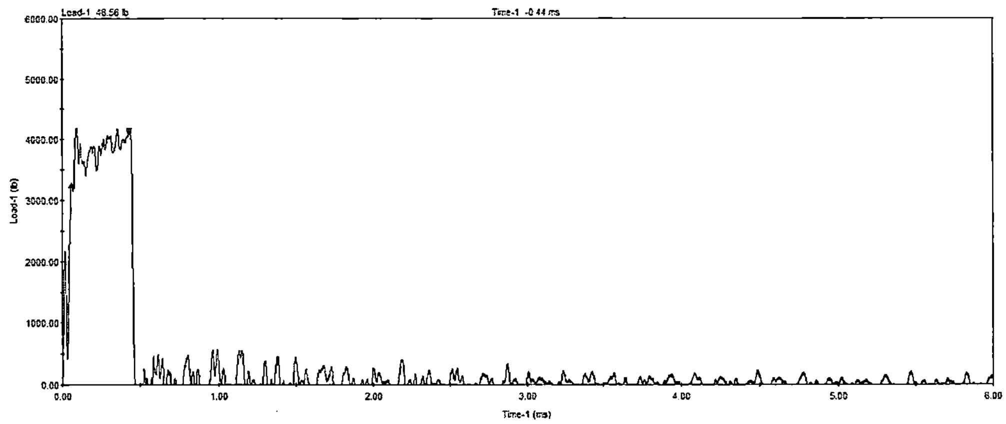
37U: Tested at 250°F



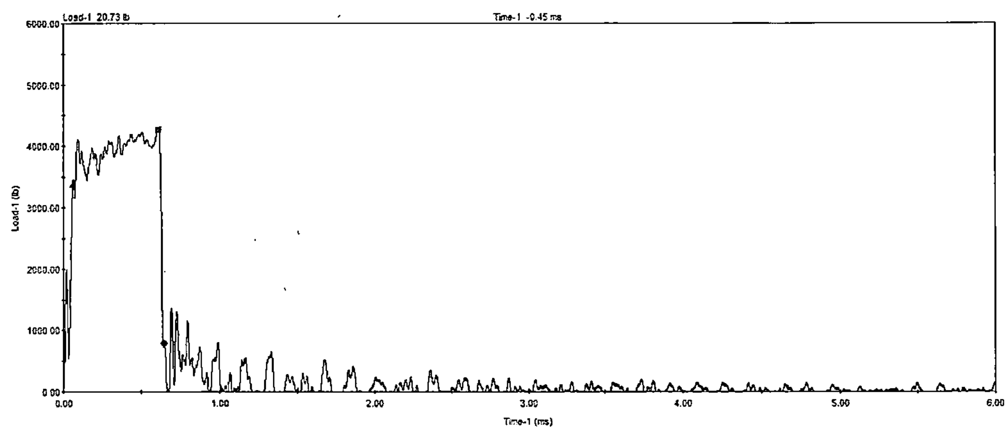
412: Tested at -75°F



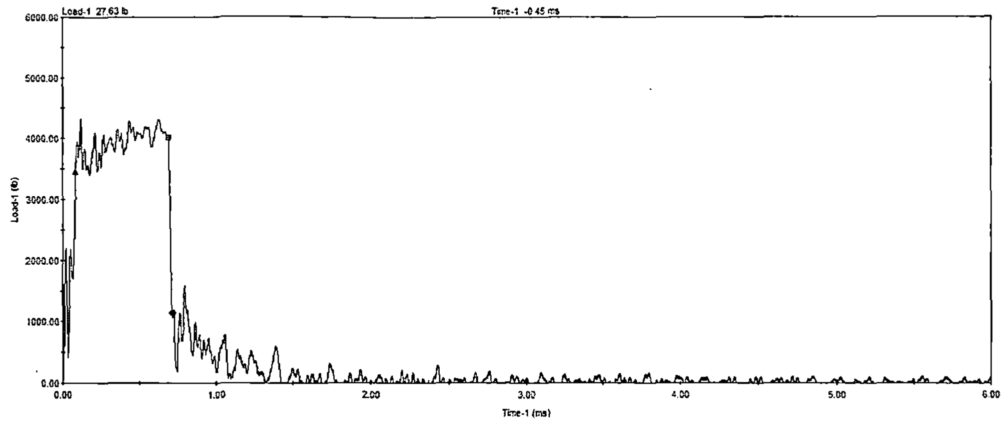
43B: Tested at -50°F



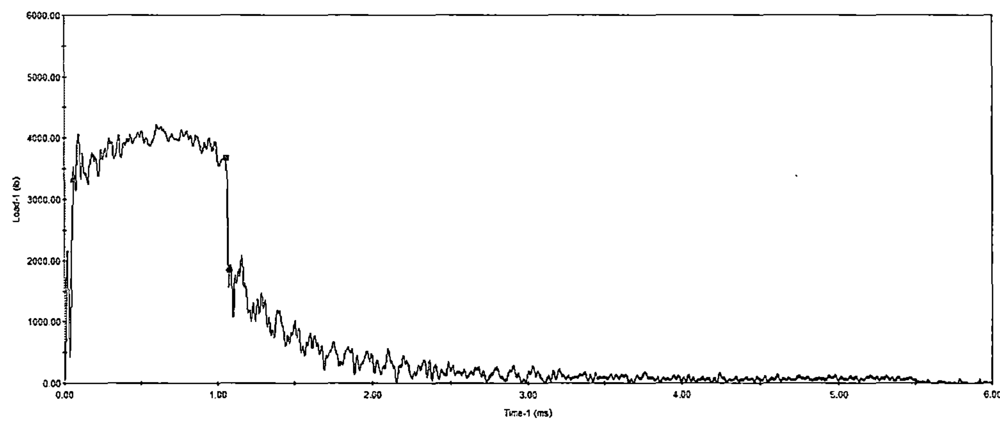
47T: Tested at -40°F



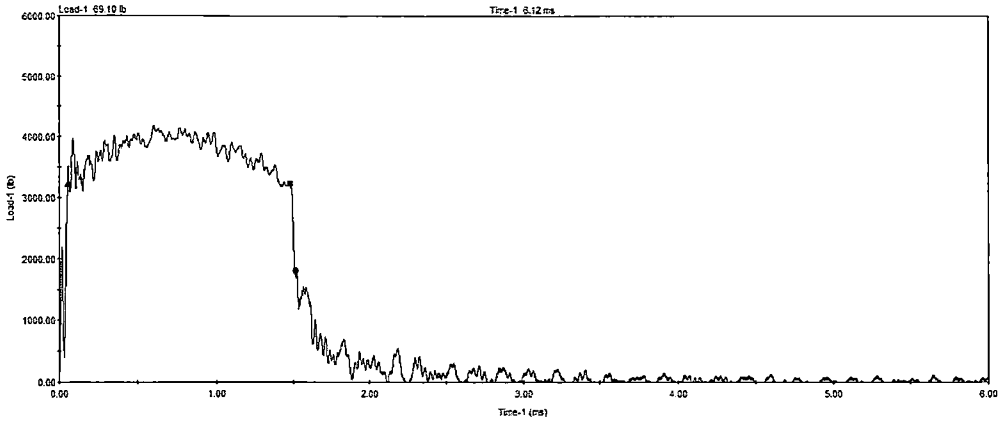
433: Tested at -30°F



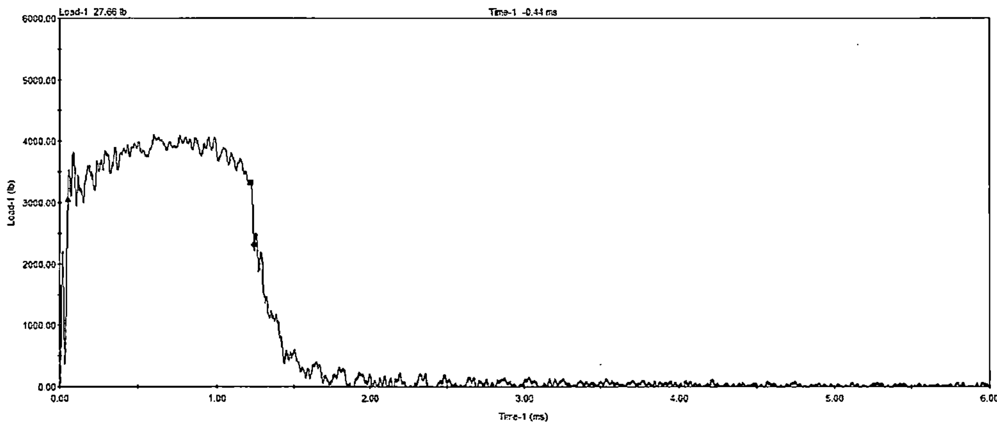
46J: Tested at -25°F



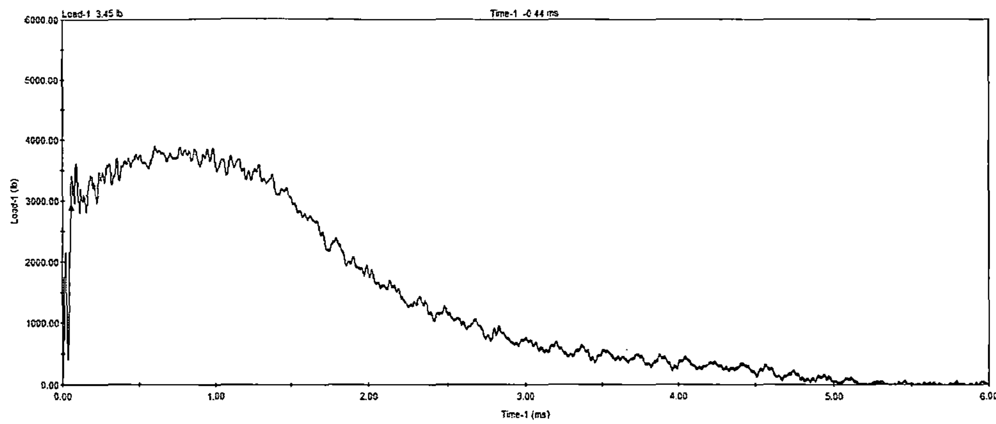
454: Tested at 15°F



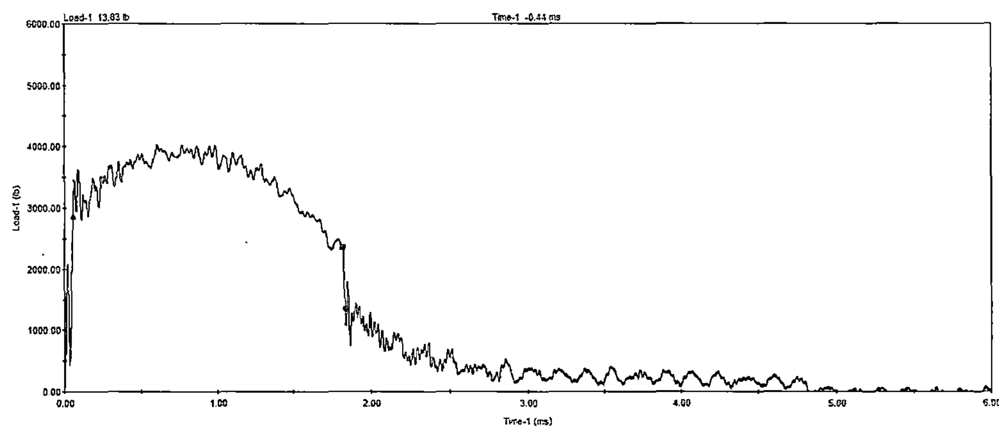
423: Tested at 40°F



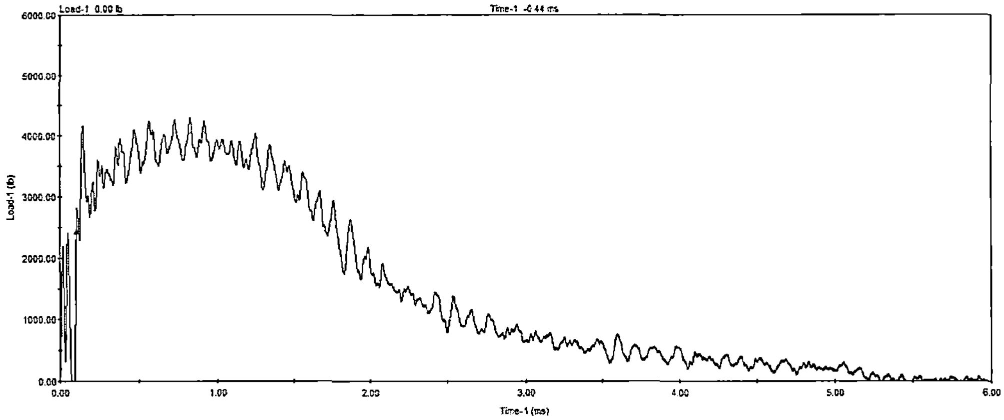
42A: Tested at 100°F



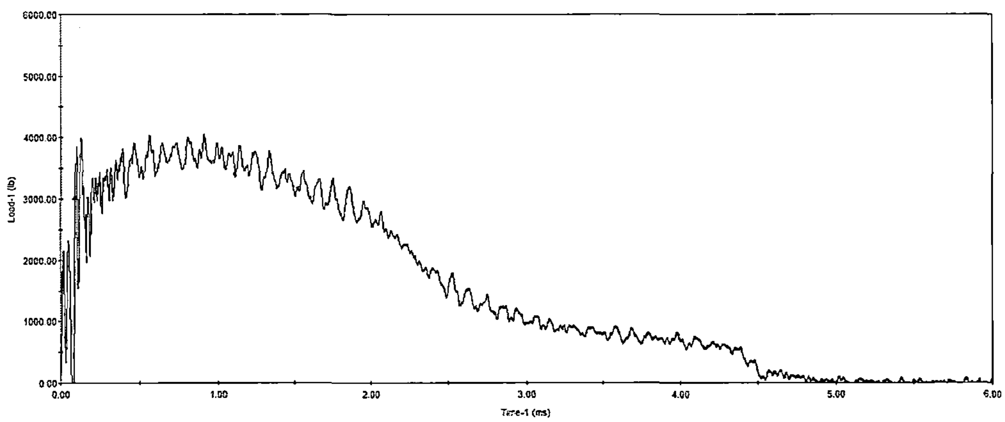
47M: Tested at 130°F



411: Tested at 165°F



41P: Tested at 200°F



42B: Tested at 250°F

APPENDIX C CHARPY V-NOTCH PLOTS FOR EACH CAPSULE USING SYMMETRIC HYPERBOLIC TANGENT CURVE-FITTING METHOD

C.1 METHODOLOGY

Contained in Table C-1 are the upper-shelf energy (USE) values that are used as input for the generation of the Charpy V-notch plots using CVGRAPH, Version 6.02. The definition for USE is given in ASTM E185-82 [Ref. C-1], Section 4.18, and reads as follows:

> "*upper shelf energy level* – the average energy value for all Charpy specimens (normally three) whose test temperature is above the upper end of the transition region. For specimens tested in sets of three at each test temperature, the set having the highest average may be regarded as defining the upper shelf energy."

Westinghouse reports the average of all Charpy data (≥ 95% shear) as the USE, excluding any values that are deemed outliers using engineering judgment. Hence, the Capsule 284° USE values reported in Table C-1 were determined by applying this methodology to the Charpy data tabulated in Tables 5-1 through 5-4 of this report. USE values documented in Table C-1 for the unirradiated material, as well as Capsules 97° and 104°, were also determined by applying the methodology described above to the Charpy impact data reported in TR-MCD-002 [Ref. C-2], BMI-0584 [Ref. C-3], and BAW-2399, Revision 1 [Ref. C-4]. The USE values reported in Table C-1 were used in generation of the Charpy V-notch curves.

The lower-shelf energy values were fixed at 2.2 ft-lb for all cases. The lower-shelf lateral expansion values were fixed at 1.0 mil in order to be consistent with the previous capsule analysis [Ref. C-4]. Upper-shelf L.E. is not typically fixed in CVGRAPH; however, due to excessive data scatter for three capsule materials, the upper-shelf L.E. value is fixed in the summary plots (contained in Section 5) for these three Capsule 284° materials. The individual L.E. plots for these materials still allow the upper-shelf L.E. to float for comparison between the two methods. The fixed upper-shelf L.E. values were determined using the same Charpy V-Notch test specimens that were used for the upper-shelf energy determination and are shown in Table C-2.

USE is expected to decrease as a function of fluence and copper content (see Appendix E), and a decrease in USE was exhibited from the unirradiated materials to the Capsule 97° materials. An additional USE decrease took place from the Capsule 97° materials to the Capsule 104° materials. However, the USE values for each material increased from the Capsule 104° analysis to the Capsule 284° results documented in Section 5. While this increase is not expected, USE increases after additional irradiation are not uncommon as a result of the inherent data scatter with Charpy test specimens.

Table C-1 Upper-Shelf Energy Values (ft-lb) Fixed in CVGRAPH

Material	Capsule			
	Unirradiated (ft-lbs)	97° (ft-lbs)	104° (ft-lbs)	284° (ft-lbs)
Intermediate Shell Plate C-8009-3 (Longitudinal Orientation)	159	140	---	122
Intermediate Shell Plate C-8009-3 (Transverse Orientation)	134	120	92	109
Surveillance Program Weld Metal (Heat #83650)	151	147	125	132
Heat-Affected Zone (HAZ) Material	161	138	130	142
Standard Reference Material (SRM)	146	---	87	---

Table C-2 Select Upper-Shelf L.E. Values (mils) Fixed for CVGRAPH Analysis

Material (Capsule 284°)	Upper-shelf L.E. (mils)
Intermediate Shell Plate C-8009-3 (Longitudinal Orientation)	92
Intermediate Shell Plate C-8009-3 (Transverse Orientation)	87
Surveillance Program Weld Metal (Heat # 83650)	96

CVGRAPH, Version 6.02 plots of all surveillance data are provided in this appendix, on the pages following the reference list.

C.2 REFERENCES

C-1 ASTM E185-82, *Standard Practice for Conducting Surveillance Tests for Light-Water Cooled Nuclear Power Reactor Vessels, E706(IF)*, 1982.

C-2 Combustion Engineering Report TR-MCD-002, *Arkansas Power & Light Arkansas Nuclear One – Unit 2 Evaluation of Baseline Specimens Reactor Vessel Materials Irradiation Surveillance Program,* March 1976.

C-3 Battelle – Columbus Laboratories Report BMI-0584, *Final Report on Examination, Testing, and Evaluation of Irradiated Pressure Vessel Surveillance Specimens from the Arkansas Nuclear One Unit 2 Generating Plant to Arkansas Power and Light Company,* May 1984.

C-4 AREVA NP, Inc. Report BAW-2399, Revision 1, *Analysis of Capsule W-104 Entergy Operations, Inc. Arkansas Nuclear One Unit 2 Power Plant Reactor Vessel Material Surveillance Program,* Feburary 2005.

C.3 CVGRAPH VERSION 6.02 INDIVIDUAL PLOTS

ANO UNIT 2 UNIRRADIATED (LONGITUDINAL)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 5/9/2016 1:37 PM

A = 80.60 B = 78.40 C = 61.00 T0 = 47.28 D = 0.00

Correlation Coefficient = 0.988

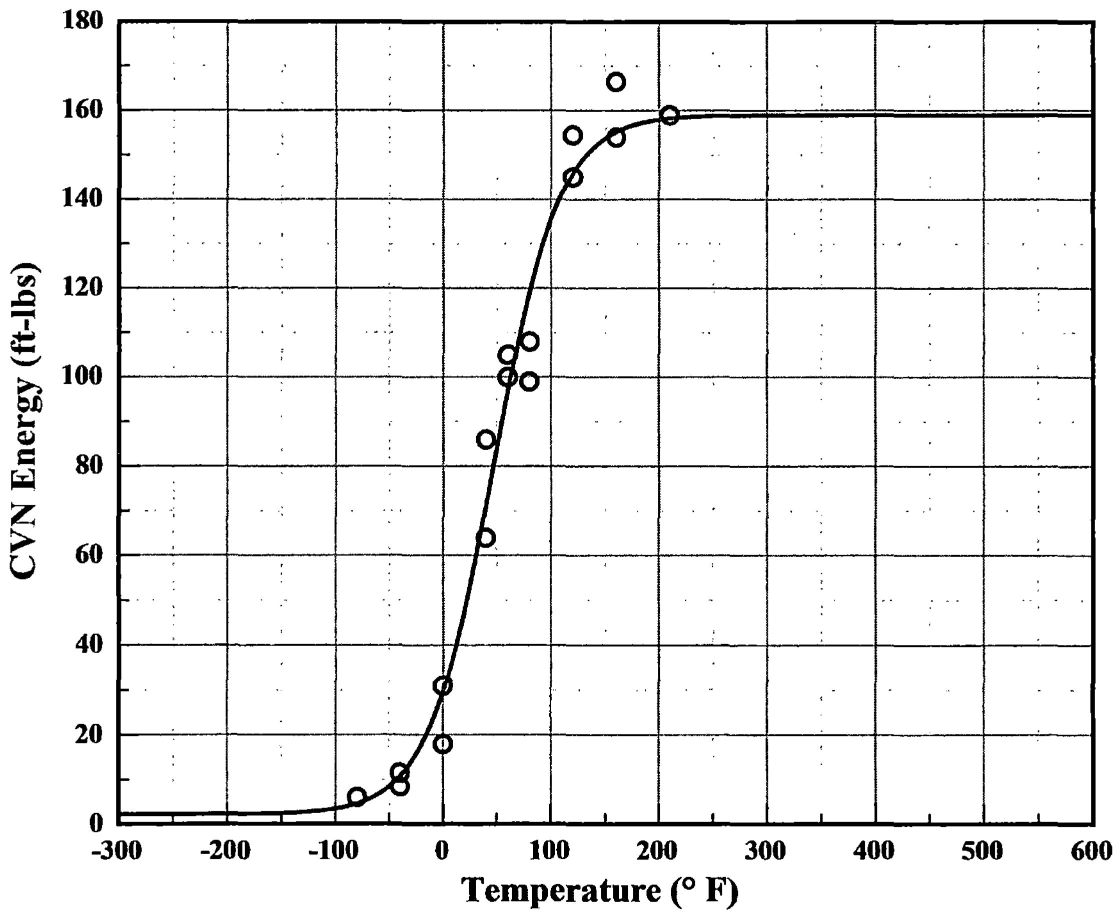
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf Energy = 159.00 (Fixed) Lower Shelf Energy = 2.20 (Fixed)

Temp@30 ft-lbs= 0.50° F Temp@35 ft-lbs= 6.80° F Temp@50 ft-lbs= 22.20° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **LT** Capsule: **UNIRR**



CVGraph 6.02 05/09/2016 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **LT** Capsule: **UNIRR**

ANO UNIT 2 UNIRRADIATED (LONGITUDINAL)

Charpy V-Notch Data

Temperature (° F)	Input CVN	Computed CVN	Differential
-80	6.0	4.6	1.42
-40	8.5	10.7	-2.18
-40	11.5	10.7	0.82
0	18.0	29.7	-11.65
0	31.0	29.7	1.35
40	64.0	71.3	-7.29
40	86.0	71.3	14.71
60	105.0	96.7	8.28
60	100.0	96.7	3.28
60	105.0	96.7	8.28
80	99.0	119.0	-20.04
80	108.0	119.0	-11.04
120	145.0	145.8	-0.77
120	154.5	145.8	8.73
160	154.0	155.2	-1.20
160	166.5	155.2	11.30
210	159.0	158.2	0.75

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ANO UNIT 2 UNIRRADIATED (LONGITUDINAL)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 5/9/2016 1:38 PM

A = 48.09 B = 47.09 C = 58.92 T0 = 31.81 D = 0.00

Correlation Coefficient = 0.985

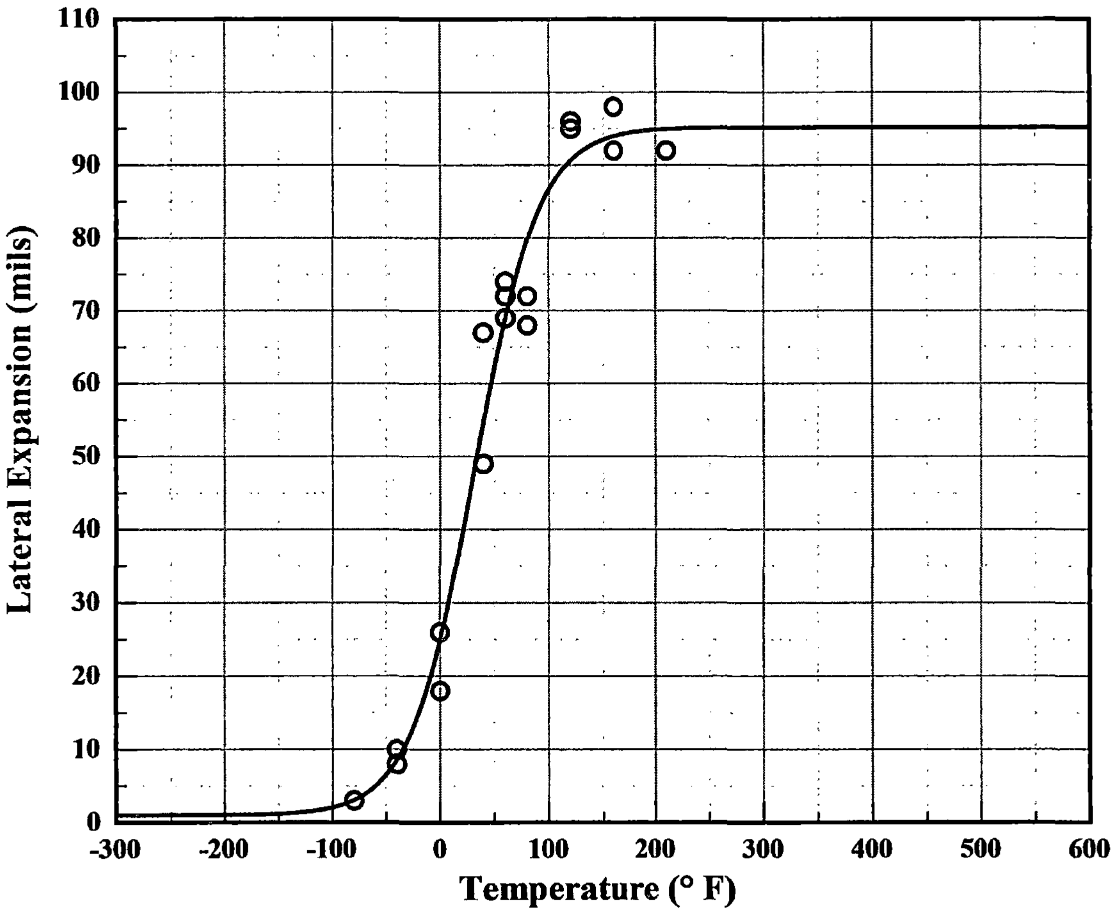
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf L.E. = 95.17 Lower Shelf L.E. = 1.00 (Fixed)

Temp@35 mils= 15.00° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **LT** Capsule: **UNIRR**



CVGraph 6.02 05/09/2016 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **LT** Capsule: **UNIRR**

ANO UNIT 2 UNIRRADIATED (LONGITUDINAL)

Charpy V-Notch Data

Temperature (° F)	Input L. E.	Computed L. E.	Differential
-80	3.0	3.1	-0.07
-40	8.0	8.6	-0.57
-40	10.0	8.6	1.43
0	18.0	24.9	-6.88
0	26.0	24.9	1.12
40	49.0	54.6	-5.59
40	67.0	54.6	12.41
60	72.0	69.0	2.96
60	69.0	69.0	-0.04
60	74.0	69.0	4.96
80	68.0	79.8	-11.82
80	72.0	79.8	-7.82
120	95.0	90.7	4.32
120	96.0	90.7	5.32
160	92.0	94.0	-1.97
160	98.0	94.0	4.03
210	92.0	95.0	-2.95

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ANO UNIT 2 UNIRRADIATED (LONGITUDINAL)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 12/17/2015 12:47 PM

A = 50.00 B = 50.00 C = 70.73 T0 = 48.02 D = 0.00

Correlation Coefficient = 0.988

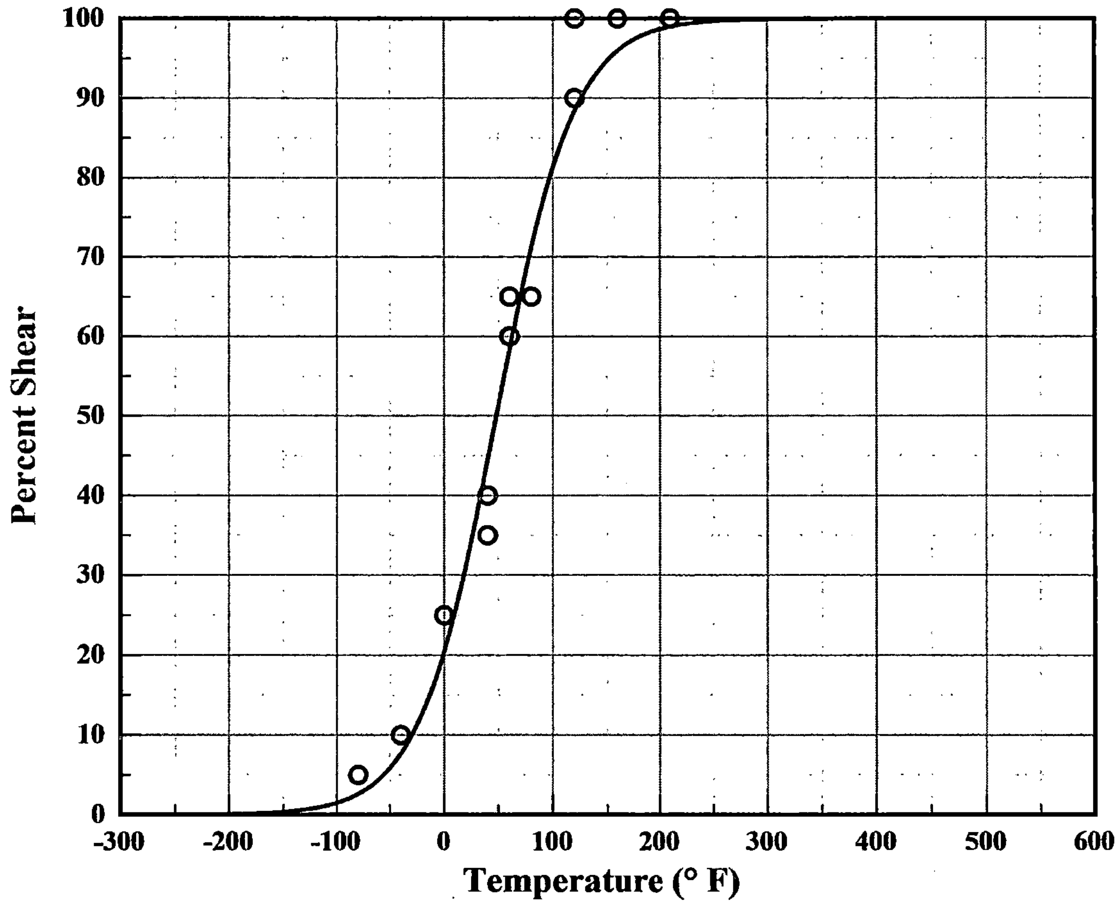
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf %Shear = 100.00 (Fixed) Lower Shelf %Shear = 0.00 (Fixed)

Temperature at 50% Shear = 48.10

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **LT** Capsule: **UNIRR**



CVGraph 6.02 12/17/2015 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **LT** Capsule: **UNIRR**

ANO UNIT 2 UNIRRADIATED (LONGITUDINAL)

Charpy V-Notch Data

Temperature (° F)	Input %Shear	Computed %Shear	Differential
-80	5.0	2.6	2.39
-40	10.0	7.7	2.34
-40	10.0	7.7	2.34
0	25.0	20.5	4.54
0	25.0	20.5	4.54
40	35.0	44.4	-9.36
40	40.0	44.4	-4.36
60	60.0	58.4	1.61
60	65.0	58.4	6.61
60	60.0	58.4	1.61
80	65.0	71.2	-6.18
80	65.0	71.2	-6.18
120	90.0	88.4	1.55
120	100.0	88.4	11.55
160	100.0	96.0	4.04
160	100.0	96.0	4.04
210	100.0	99.0	1.01

CVGraph 6.02 12/17/2015 Page 2/2

ANO UNIT 2 UNIRRADIATED (TRANSVERSE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 5/9/2016 1:39 PM

A = 68.10 B = 65.90 C = 72.96 T0 = 62.99 D = 0.00

Correlation Coefficient = 0.990

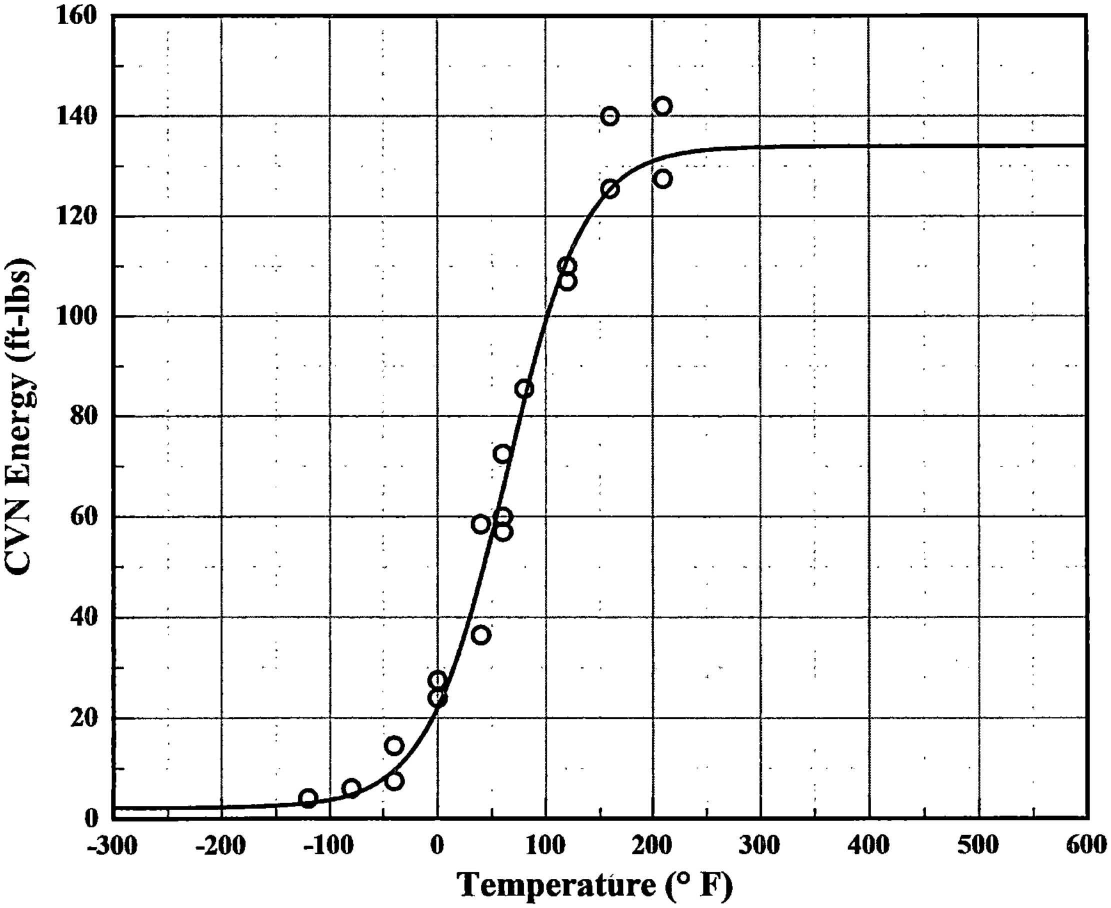
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf Energy = 134.00 (Fixed) Lower Shelf Energy = 2.20 (Fixed)

Temp@30 ft-lbs= 14.90° F Temp@35 ft-lbs= 22.70° F Temp@50 ft-lbs= 42.50° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **TL** Capsule: **UNIRR**



CVGraph 6.02 05/09/2016 Page 1/2

Plant: **Arkansas 2**
Orientation: **TL**

Material: **SA533B CL1**
Capsule: **UNIRR**

Heat: **C8182-2**

ANO UNIT 2 UNIRRADIATED (TRANSVERSE)

Charpy V-Notch Data

Temperature (° F)	Input CVN	Computed CVN	Differential
-120	4.0	3.1	0.93
-80	6.0	4.8	1.23
-40	7.5	9.6	-2.09
-40	14.5	9.6	4.91
0	24.0	22.1	1.90
0	27.5	22.1	5.40
40	36.5	48.0	-11.50
40	58.5	48.0	10.50
60	57.0	65.4	-8.40
60	60.0	65.4	-5.40
60	72.5	65.4	7.10
80	85.5	83.2	2.31
120	107.0	111.2	-4.17
120	110.0	111.2	-1.17
160	125.5	125.4	0.12
160	140.0	125.4	14.62
210	127.5	131.7	-4.20
210	142.0	131.7	10.30

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ANO UNIT 2 UNIRRADIATED (TRANSVERSE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 12/17/2015 12:51 PM

A = 45.81 B = 44.81 C = 83.86 T0 = 49.24 D = 0.00

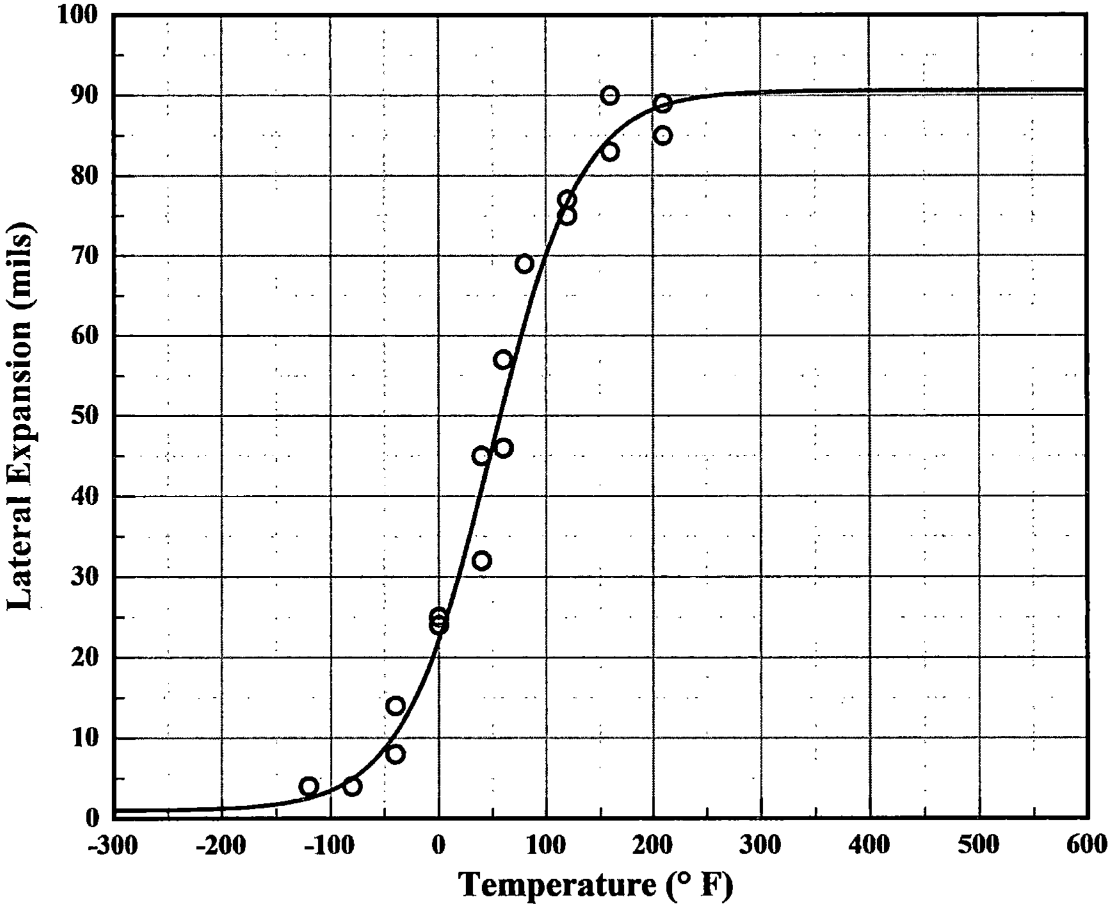
Correlation Coefficient = 0.990

Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf L.E. = 90.61 Lower Shelf L.E. = 1.00 (Fixed)

Temp@35 mils= 28.70° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **TL** Capsule: **UNIRR**



CVGraph 6.02 12/17/2015 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **TL** Capsule: UNIRR

ANO UNIT 2 UNIRRADIATED (TRANSVERSE)

Charpy V-Notch Data

Temperature (° F)	Input L. E.	Computed L. E.	Differential
-120	4.0	2.6	1.44
-80	4.0	4.9	-0.93
-40	8.0	10.5	-2.53
-40	14.0	10.5	3.47
0	24.0	22.2	1.85
0	25.0	22.2	2.85
40	32.0	40.9	-8.89
40	45.0	40.9	4.11
60	46.0	51.5	-5.52
60	46.0	51.5	-5.52
60	57.0	51.5	5.48
80	69.0	61.5	7.46
120	77.0	76.6	0.38
120	75.0	76.6	-1.62
160	83.0	84.7	-1.65
160	90.0	84.7	5.35
210	85.0	88.7	-3.72
210	89.0	88.7	0.28

CVGraph 6.02 12/17/2015 Page 2/2

ANO UNIT 2 UNIRRADIATED (TRANSVERSE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 12/17/2015 12:51 PM

A = 50.00 B = 50.00 C = 78.66 T0 = 66.91 D = 0.00

Correlation Coefficient = 0.990

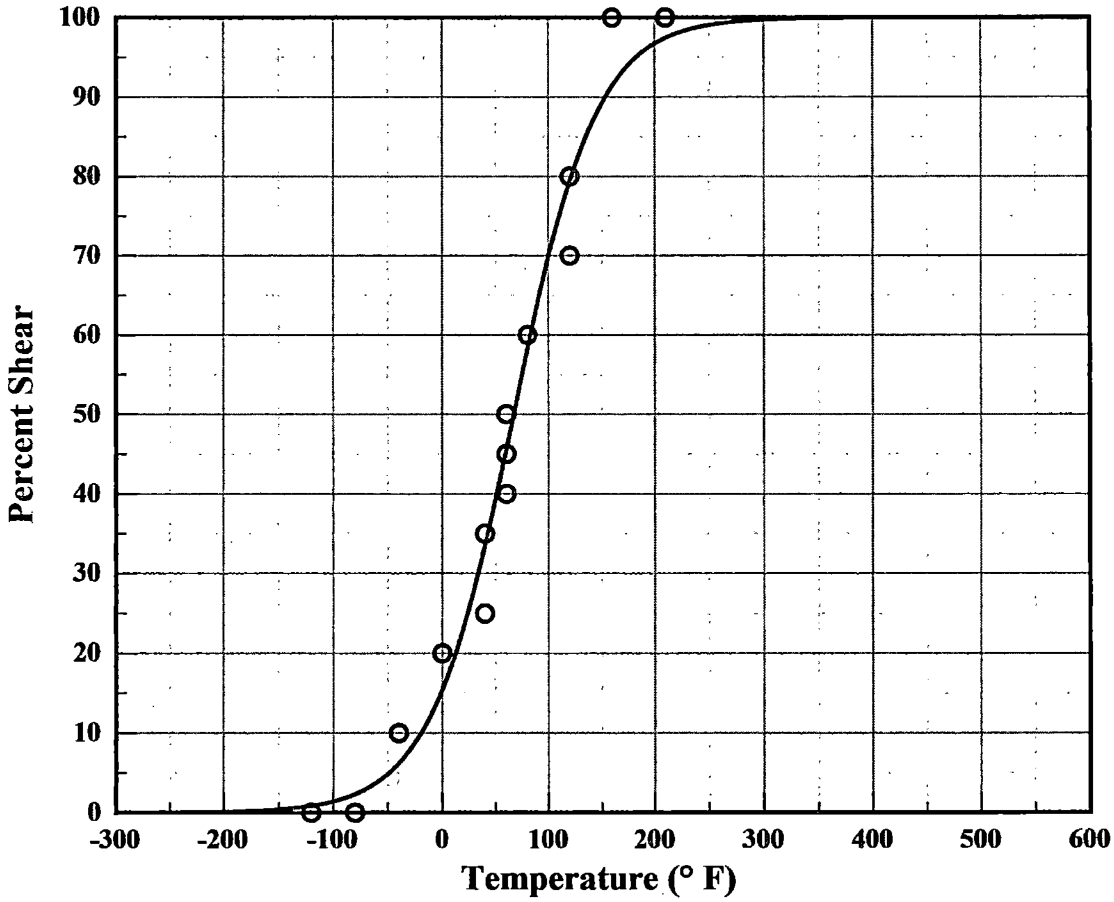
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf %Shear = 100.00 (Fixed) Lower Shelf %Shear = 0.00 (Fixed)

Temperature at 50% Shear = 67.00

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **TL** Capsule: **UNIRR**



CVGraph 6.02 12/17/2015 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **TL** Capsule: **UNIRR**

ANO UNIT 2 UNIRRADIATED (TRANSVERSE)

Charpy V-Notch Data

Temperature (° F)	Input %Shear	Computed %Shear	Differential
-120	0.0	0.9	-0.86
-80	0.0	2.3	-2.33
-40	10.0	6.2	3.81
-40	10.0	6.2	3.81
0	20.0	15.4	4.57
0	20.0	15.4	4.57
40	25.0	33.5	-8.53
40	35.0	33.5	1.47
60	40.0	45.6	-5.62
60	45.0	45.6	-0.62
60	50.0	45.6	4.38
80	60.0	58.2	1.76
120	70.0	79.4	-9.41
120	80.0	79.4	0.59
160	100.0	91.4	8.57
160	100.0	91.4	8.57
210	100.0	97.4	2.56
210	100.0	97.4	2.56

CVGraph 6.02 12/17/2015 Page 2/2

ANO UNIT 2 UNIRRADIATED (WELD)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 5/9/2016 1:46 PM

A = 76.60 B = 74.40 C = 40.52 T0 = 25.94 D = 0.00

Correlation Coefficient = 0.992

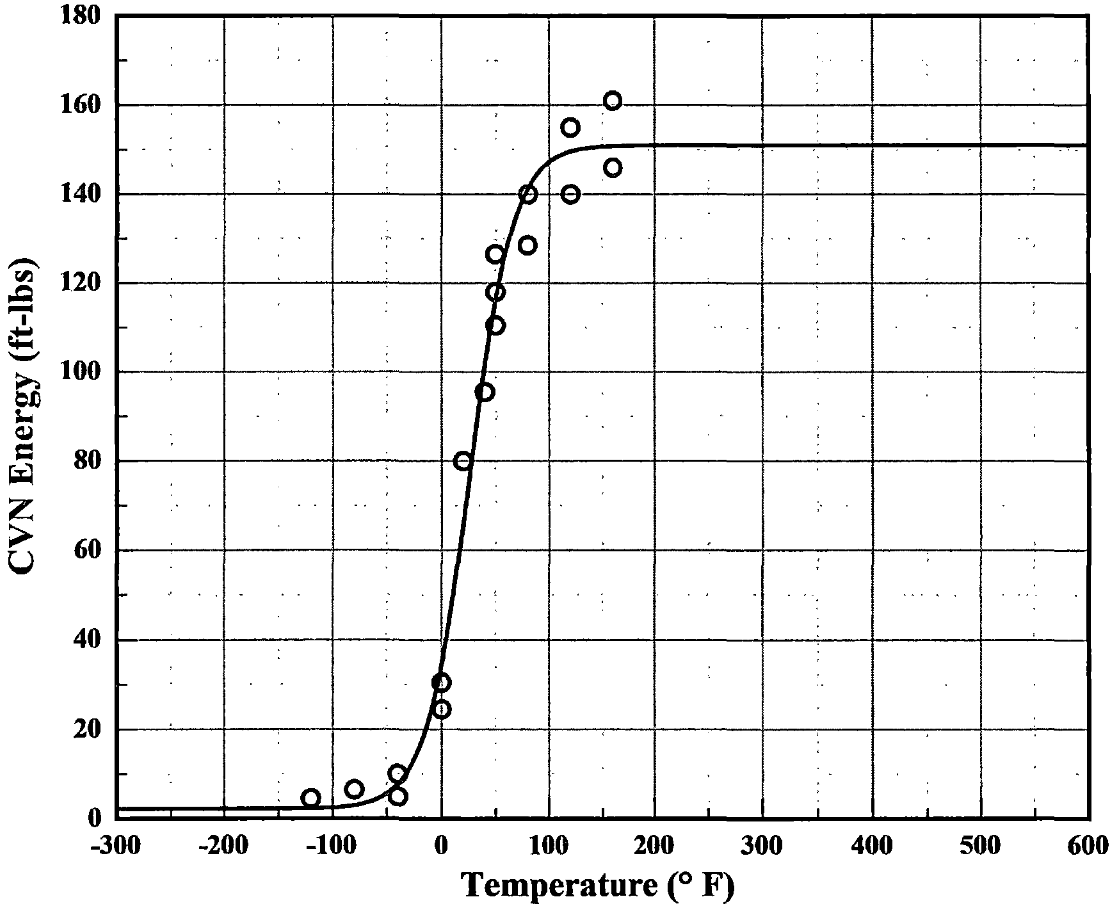
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf Energy = 151.00 (Fixed) Lower Shelf Energy = 2.20 (Fixed)

Temp@30 ft-lbs= -3.80° F Temp@35 ft-lbs= 0.40° F Temp@50 ft-lbs= 10.80° F

Plant: **Arkansas 2** Material: **WELD** Heat: **83650**

Orientation: **N/A** Capsule: **UNIRR**



CVGraph 6.02 05/09/2016 Page 1/2

Plant: **Arkansas 2**
Orientation: **N/A**
Material: **WELD**
Capsule: **UNIRR**
Heat: **83650**

ANO UNIT 2 UNIRRADIATED (WELD)

Charpy V-Notch Data

Temperature (° F)	Input CVN	Computed CVN	Differential
-120	4.5	2.3	2.19
-80	6.5	3.0	3.51
-40	5.0	7.7	-2.73
-40	10.0	7.7	2.27
0	24.5	34.6	-10.07
0	30.5	34.6	-4.07
20	80.0	65.8	14.22
40	95.5	101.4	-5.93
50	126.5	116.2	10.27
50	110.5	116.2	-5.73
50	118.0	116.2	1.77
80	128.5	141.3	-12.85
80	140.0	141.3	-1.35
120	140.0	149.6	-9.58
120	155.0	149.6	5.42
160	146.0	150.8	-4.80
160	161.0	150.8	10.20

CVGraph 6.02 05/09/2016 Page 2/2

ANO UNIT 2 UNIRRADIATED (WELD)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 12/17/2015 12:53 PM

A = 46.68 B = 45.68 C = 36.97 T0 = 15.60 D = 0.00

Correlation Coefficient = 0.994

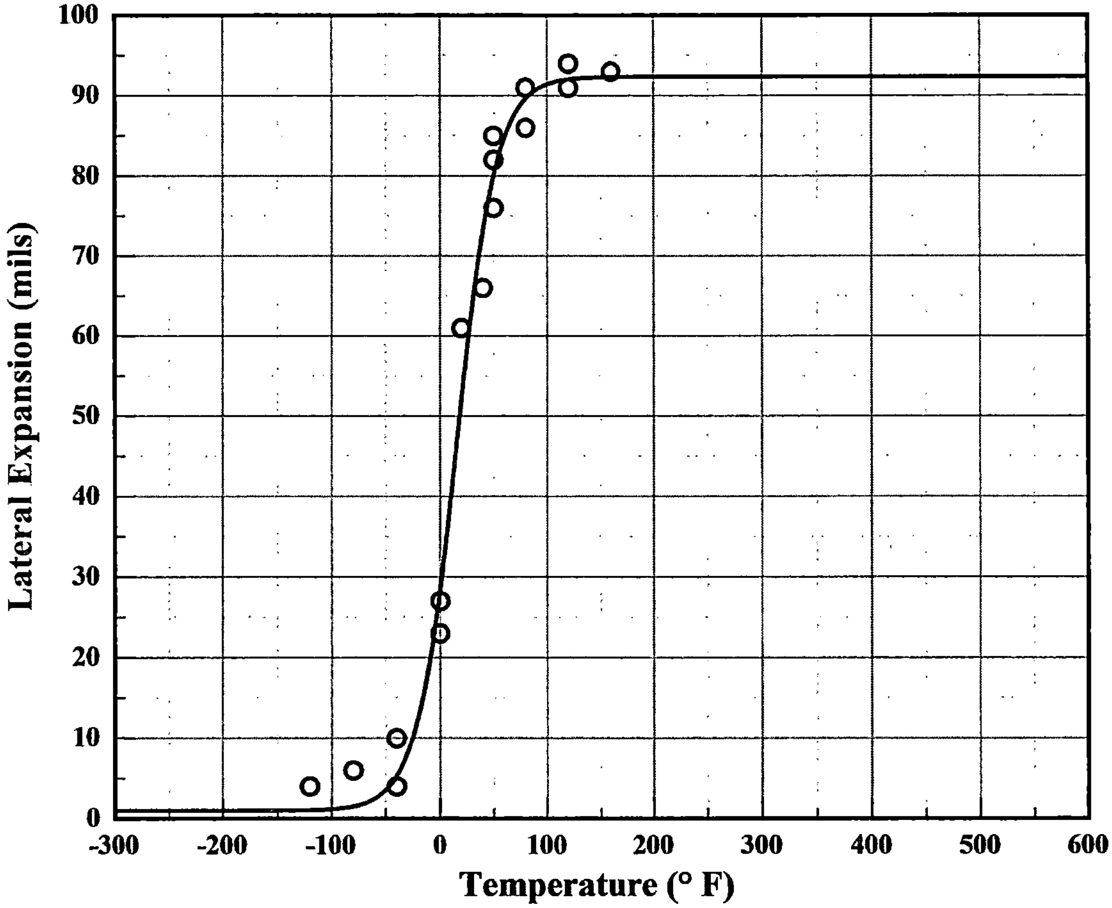
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf L.E. = 92.36 Lower Shelf L.E. = 1.00 (Fixed)

Temp@35 mils= 6.00° F

Plant: **Arkansas 2** Material: **WELD** Heat: **83650**

Orientation: **N/A** Capsule: **UNIRR**



CVGraph 6.02 12/17/2015 Page 1/2

Plant: **Arkansas 2** Material: **WELD** Heat: **83650**
Orientation: **N/A** Capsule: **UNIRR**

ANO UNIT 2 UNIRRADIATED (WELD)

Charpy V-Notch Data

Temperature (° F)	Input L. E.	Computed L. E.	Differential
-120	4.0	1.1	2.94
-80	6.0	1.5	4.48
-40	4.0	5.3	-1.30
-40	10.0	5.3	4.70
0	23.0	28.5	-5.48
0	27.0	28.5	-1.48
20	61.0	52.1	8.91
40	66.0	73.1	-7.10
50	85.0	80.1	4.94
50	76.0	80.1	-4.06
50	82.0	80.1	1.94
80	86.0	89.6	-3.64
80	91.0	89.6	1.36
120	91.0	92.0	-1.04
120	94.0	92.0	1.96
160	93.0	92.3	0.68
160	93.0	92.3	0.68

CVGraph 6.02 12/17/2015 Page 2/2

ANO UNIT 2 UNIRRADIATED (WELD)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 12/17/2015 12:53 PM

A = 50.00 B = 50.00 C = 60.06 T0 = 18.40 D = 0.00

Correlation Coefficient = 0.990

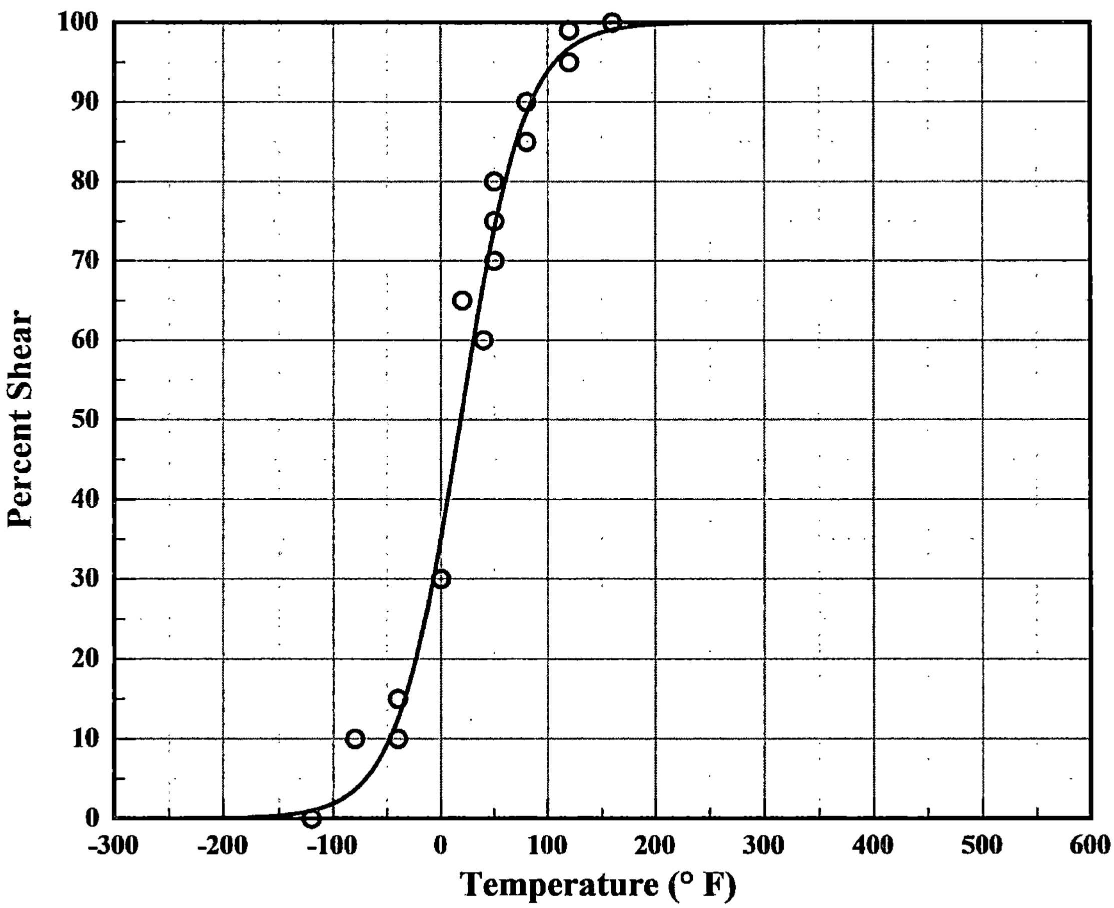
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf %Shear = 100.00 (Fixed) Lower Shelf %Shear = 0.00 (Fixed)

Temperature at 50% Shear = 18.50

Plant: **Arkansas 2** Material: **WELD** Heat: **83650**

Orientation: **N/A** Capsule: **UNIRR**



CVGraph 6.02 12/17/2015 Page 1/2

Plant: **Arkansas 2**
Orientation: **N/A**

Material: **WELD**
Capsule: **UNIRR**

Heat: **83650**

ANO UNIT 2 UNIRRADIATED (WELD)

Charpy V-Notch Data

Temperature (° F)	Input %Shear	Computed %Shear	Differential
-120	0.0	1.0	-0.99
-80	10.0	3.6	6.36
-40	10.0	12.5	-2.51
-40	15.0	12.5	2.49
0	30.0	35.1	-5.15
0	30.0	35.1	-5.15
20	65.0	51.3	13.67
40	60.0	67.2	-7.24
50	80.0	74.1	5.88
50	70.0	74.1	-4.12
50	75.0	74.1	0.88
80	85.0	88.6	-3.61
80	90.0	88.6	1.39
120	95.0	96.7	-1.72
120	99.0	96.7	2.28
160	100.0	99.1	0.89
160	100.0	99.1	0.89

CVGraph 6.02 12/17/2015 Page 2/2

ANO UNIT 2 UNIRRADIATED (HEAT-AFFECTED ZONE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 5/9/2016 1:45 PM

A = 81.60 B = 79.40 C = 119.53 T0 = -37.34 D = 0.00

Correlation Coefficient = 0.859

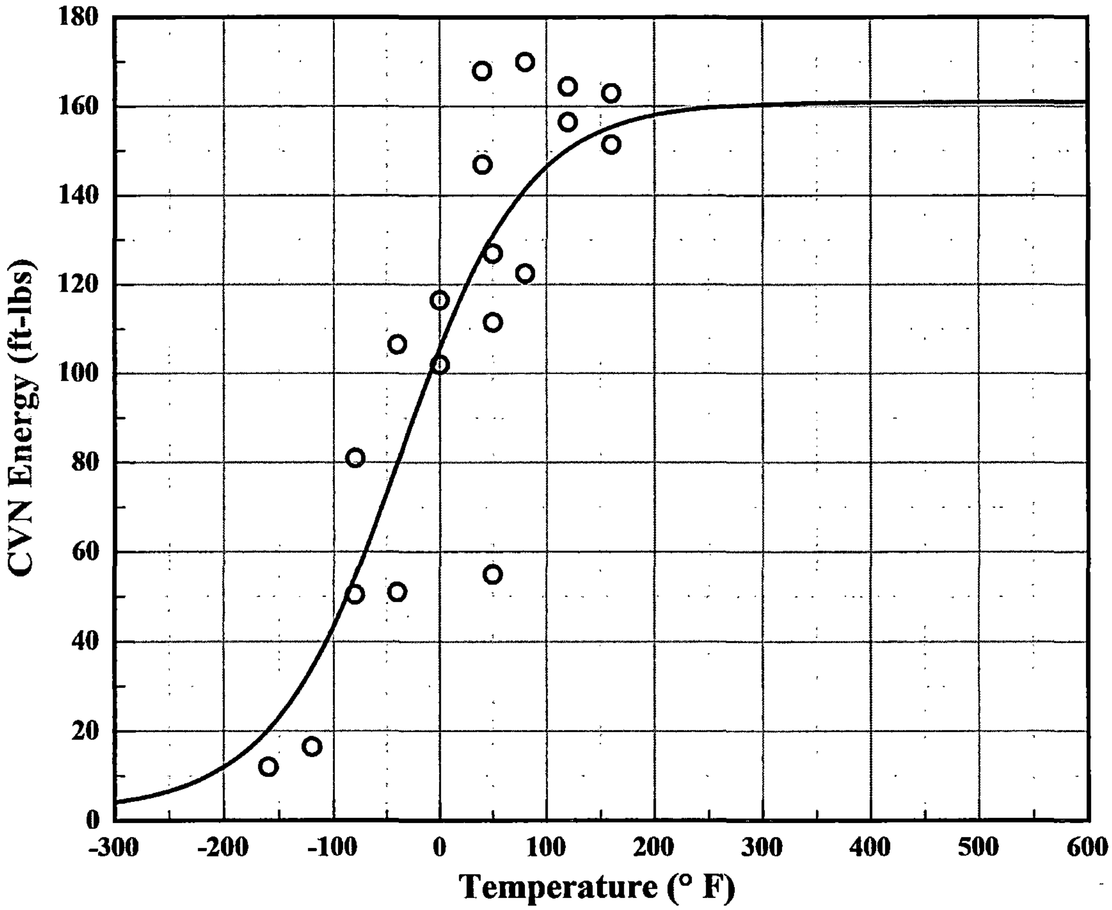
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf Energy = 161.00 (Fixed) Lower Shelf Energy = 2.20 (Fixed)

Temp@30 ft-lbs=-129.90° F Temp@35 ft-lbs=-117.70° F Temp@50 ft-lbs=-87.60° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **N/A** Capsule: **UNIRR**



CVGraph 6.02 05/09/2016 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **N/A** Capsule: **UNIRR**

ANO UNIT 2 UNIRRADIATED (HEAT-AFFECTED ZONE)

Charpy V-Notch Data

Temperature (° F)	Input CVN	Computed CVN	Differential
-160	12.0	20.3	-8.28
-120	16.5	34.0	-17.55
-80	50.5	54.4	-3.91
-80	81.0	54.4	26.59
-40	51.0	79.8	-28.84
-40	106.5	79.8	26.66
0	102.0	105.6	-3.63
0	116.5	105.6	10.87
40	147.0	126.8	20.17
40	168.0	126.8	41.17
50	55.0	131.1	-76.11
50	111.5	131.1	-19.61
50	127.0	131.1	-4.11
80	122.5	141.5	-18.95
80	170.0	141.5	28.55
120	156.5	150.4	6.15
120	164.5	150.4	14.15
160	151.5	155.4	-3.86
160	163.0	155.4	7.64

CVGraph 6.02 05/09/2016 Page 2/2

ANO UNIT 2 UNIRRADIATED (HEAT-AFFECTED ZONE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 12/17/2015 12:55 PM

A = 42.27 B = 41.27 C = 94.44 T0 = -60.33 D = 0.00

Correlation Coefficient = 0.912

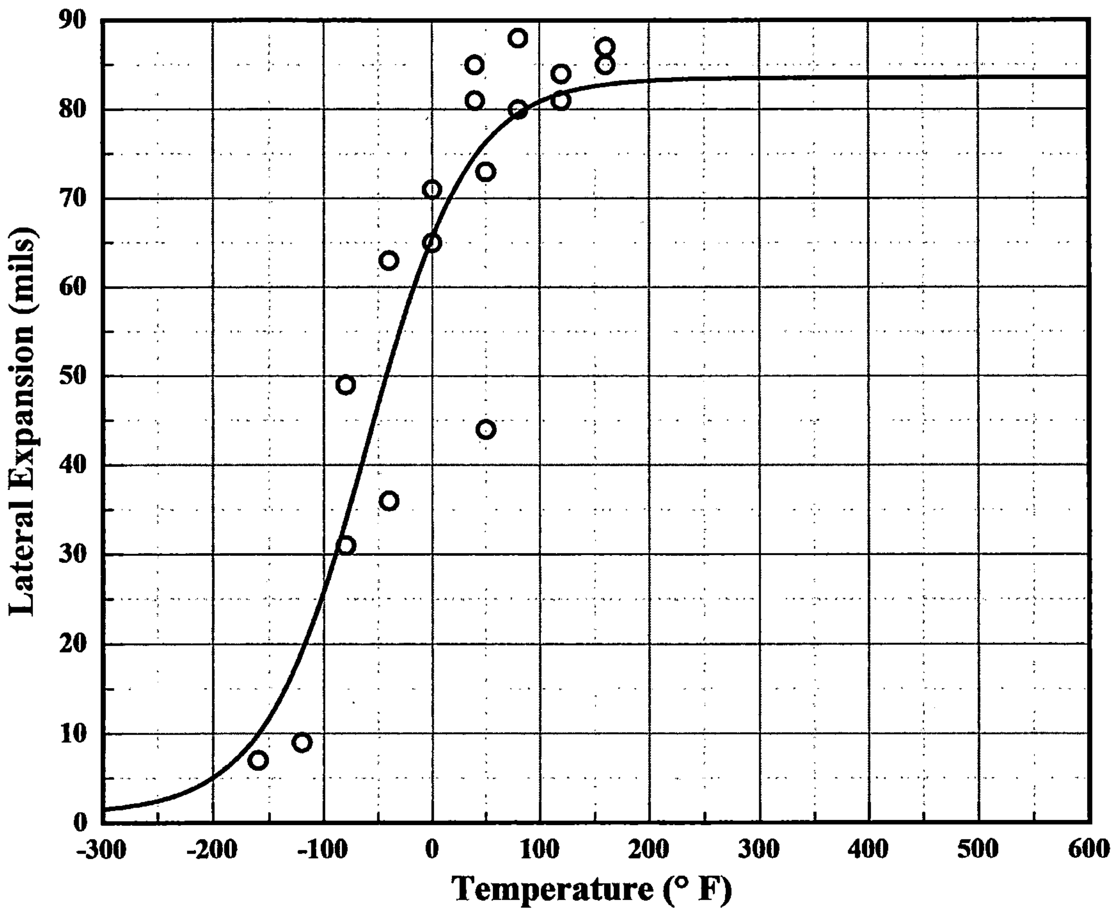
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf L.E. = 83.55 Lower Shelf L.E. = 1.00 (Fixed)

Temp@35 mils=-77.10° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **N/A** Capsule: **UNIRR**



CVGraph 6.02 12/17/2015 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **N/A** Capsule: **UNIRR**

ANO UNIT 2 UNIRRADIATED (HEAT-AFFECTED ZONE)

Charpy V-Notch Data

Temperature (° F)	Input L. E.	Computed L. E.	Differential
-160	7.0	9.9	-2.92
-120	9.0	19.2	-10.19
-80	31.0	33.8	-2.80
-80	49.0	33.8	15.20
-40	36.0	51.0	-15.03
-40	63.0	51.0	11.97
0	65.0	65.6	-0.56
0	71.0	65.6	5.44
40	81.0	74.7	6.26
40	85.0	74.7	10.26
50	44.0	76.3	-32.27
50	73.0	76.3	-3.27
50	73.0	76.3	-3.27
80	80.0	79.5	0.47
80	88.0	79.5	8.47
120	81.0	81.8	-0.78
120	84.0	81.8	2.22
160	85.0	82.8	2.22
160	87.0	82.8	4.22

CVGraph 6.02 12/17/2015 Page 2/2

ANO UNIT 2 UNIRRADIATED (HEAT-AFFECTED ZONE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 12/17/2015 12:55 PM

A = 50.00 B = 50.00 C = 103.80 T0 = -37.83 D = 0.00

Correlation Coefficient = 0.923

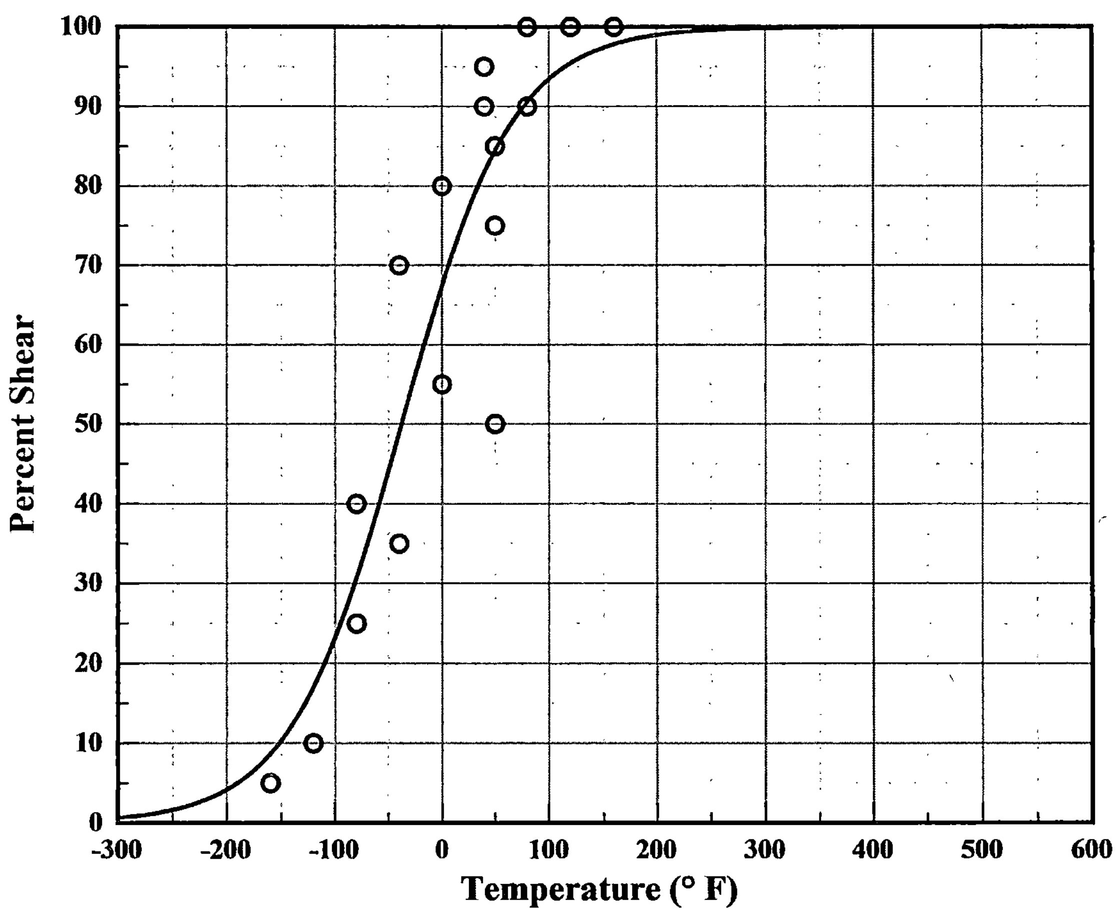
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf %Shear = 100.00 (Fixed) Lower Shelf %Shear = 0.00 (Fixed)

Temperature at 50% Shear = -37.80

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **N/A** Capsule: **UNIRR**



CVGraph 6.02 12/17/2015 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **N/A** Capsule: **UNIRR**

ANO UNIT 2 UNIRRADIATED (HEAT-AFFECTED ZONE)

Charpy V-Notch Data

Temperature (° F)	Input %Shear	Computed %Shear	Differential
-160	5.0	8.7	-3.68
-120	10.0	17.0	-7.03
-80	25.0	30.7	-5.74
-80	40.0	30.7	9.26
-40	35.0	49.0	-13.95
-40	70.0	49.0	21.05
0	55.0	67.5	-12.46
0	80.0	67.5	12.54
40	90.0	81.8	8.25
40	95.0	81.8	13.25
50	50.0	84.5	-34.45
50	85.0	84.5	0.55
50	75.0	84.5	-9.45
80	90.0	90.6	-0.64
80	100.0	90.6	9.36
120	100.0	95.4	4.56
120	100.0	95.4	4.56
160	100.0	97.8	2.16
160	100.0	97.8	2.16

CVGraph 6.02 12/17/2015 Page 2/2

ANO UNIT 2 UNIRRADIATED (SRM)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 5/9/2016 2:03 PM

A = 74.10 B = 71.90 C = 63.41 T0 = 76.76 D = 0.00

Correlation Coefficient = 0.996

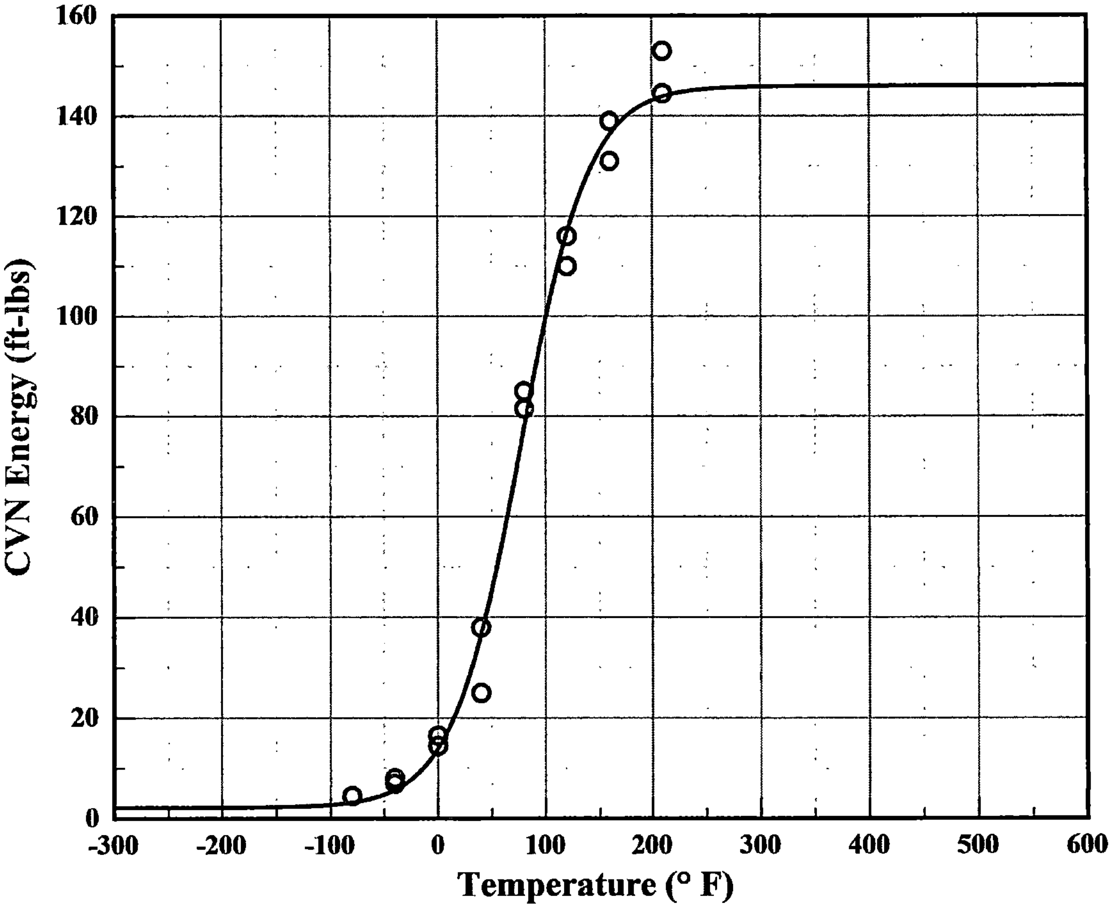
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf Energy = 146.00 (Fixed) Lower Shelf Energy = 2.20 (Fixed)

Temp@30 ft-lbs= 31.50° F Temp@35 ft-lbs= 38.20° F Temp@50 ft-lbs= 54.70° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **HSST-01MY**

Orientation: **LT** Capsule: **UNIRR**



CVGraph 6.02 05/09/2016 Page 1/2

Plant: **Arkansas 2**
Orientation: **LT**

Material: **SA533B CL1**
Capsule: **UNIRR**

Heat: **HSST-01MY**

ANO UNIT 2 UNIRRADIATED (SRM)

Charpy V-Notch Data

Temperature (° F)	Input CVN	Computed CVN	Differential
-80	4.5	3.2	1.28
-40	7.0	5.7	1.27
-40	8.0	5.7	2.27
0	14.5	13.9	0.57
0	16.5	13.9	2.57
40	25.0	36.5	-11.54
40	38.0	36.5	1.46
80	85.0	77.8	7.23
80	81.5	77.8	3.73
120	110.0	116.7	-6.72
120	116.0	116.7	-0.72
160	131.0	136.3	-5.29
160	139.0	136.3	2.71
210	144.5	143.9	0.62
210	153.0	143.9	9.12

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ANO UNIT 2 UNIRRADIATED (SRM)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 5/9/2016 2:04 PM

A = 45.19 B = 44.19 C = 57.30 T0 = 55.35 D = 0.00

Correlation Coefficient = 0.995

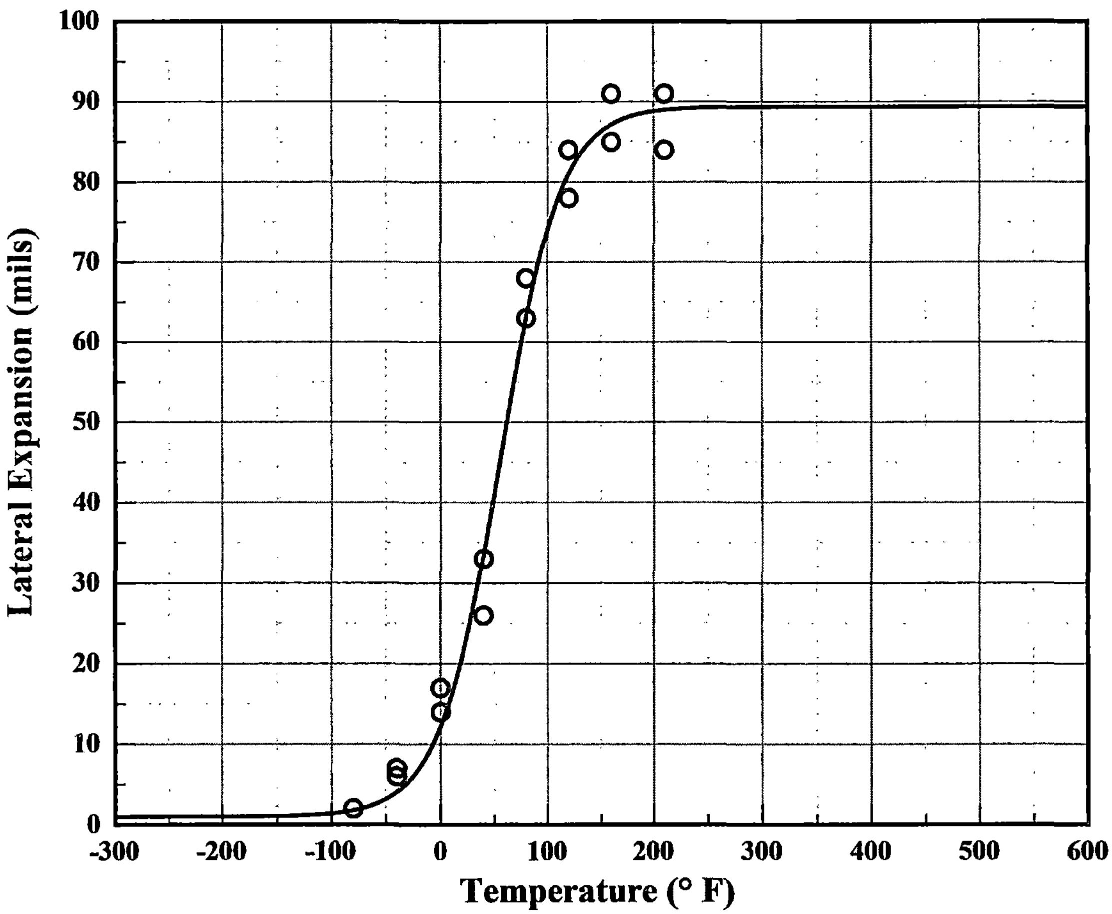
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf L.E. = 89.39 Lower Shelf L.E. = 1.00 (Fixed)

Temp@35 mils= 41.90° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **HSST-01MY**

Orientation: **LT** Capsule: **UNIRR**



CVGraph 6.02 05/09/2016 Page 1/2

Plant: **Arkansas 2**
Orientation: **LT**

Material: **SA533B CL1**
Capsule: **UNIRR**

Heat: **HSST-01MY**

ANO UNIT 2 UNIRRADIATED (SRM)

Charpy V-Notch Data

Temperature (° F)	Input L. E.	Computed L. E.	Differential
-80	2.0	1.8	0.22
-40	6.0	4.1	1.94
-40	7.0	4.1	2.94
0	14.0	12.2	1.81
0	17.0	12.2	4.81
40	26.0	33.6	-7.63
40	33.0	33.6	-0.63
80	68.0	63.1	4.89
80	63.0	63.1	-0.11
120	78.0	81.0	-3.01
120	84.0	81.0	2.99
160	85.0	87.2	-2.15
160	91.0	87.2	3.85
210	91.0	89.0	2.01
210	84.0	89.0	-4.99

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ANO UNIT 2 UNIRRADIATED (SRM)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 5/9/2016 2:05 PM

A = 50.00 B = 50.00 C = 77.50 T0 = 83.27 D = 0.00

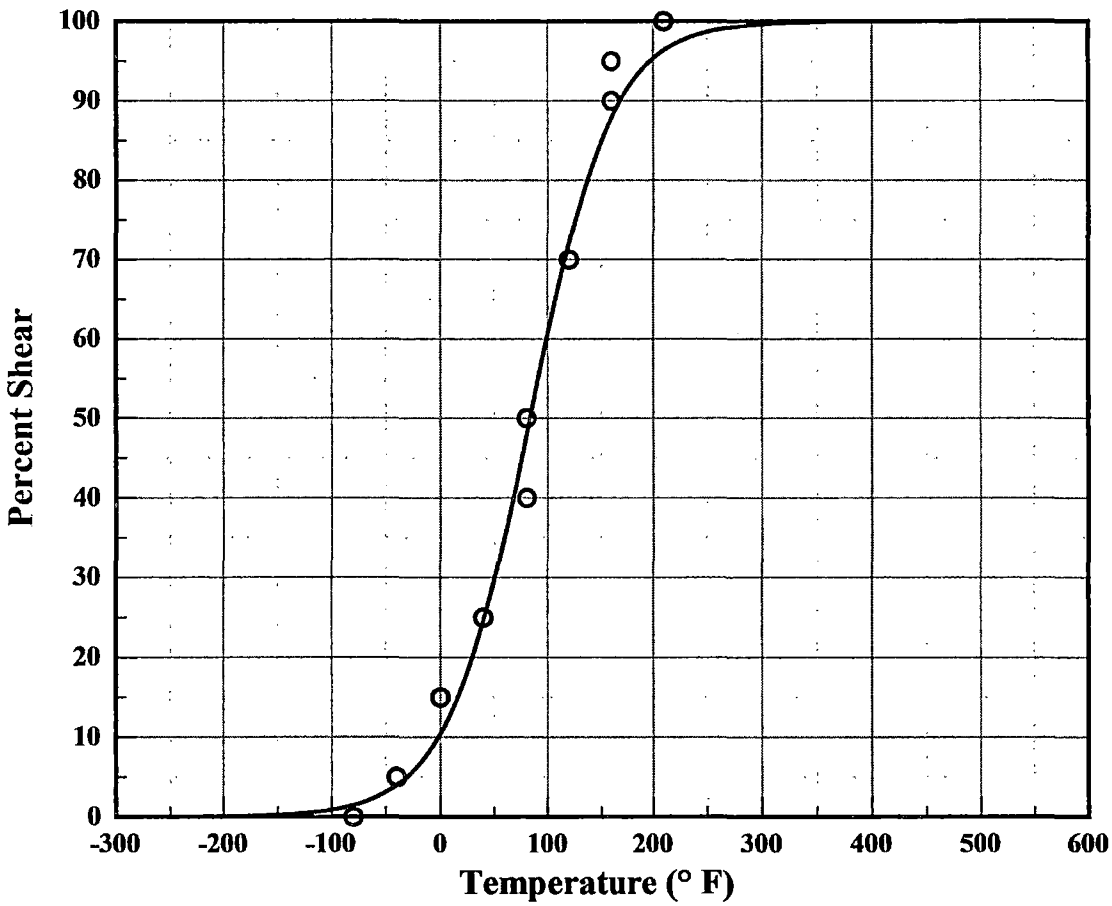
Correlation Coefficient = 0.995

Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf %Shear = 100.00 (Fixed) Lower Shelf %Shear = 0.00 (Fixed)

Temperature at 50% Shear = 83.30

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **HSST-01MY**
Orientation: **LT** Capsule: **UNIRR**



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Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **HSST-01MY**
Orientation: **LT** Capsule: **UNIRR**

ANO UNIT 2 UNIRRADIATED (SRM)

Charpy V-Notch Data

Temperature (° F)	Input %Shear	Computed %Shear	Differential
-80	0.0	1.5	-1.46
-40	5.0	4.0	1.01
-40	5.0	4.0	1.01
0	15.0	10.4	4.56
0	15.0	10.4	4.56
40	25.0	24.7	0.34
40	25.0	24.7	0.34
80	50.0	47.9	2.11
80	40.0	47.9	-7.89
120	70.0	72.1	-2.07
120	70.0	72.1	-2.07
160	90.0	87.9	2.13
160	95.0	87.9	7.13
210	100.0	96.3	3.66
210	100.0	96.3	3.66

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ANO UNIT 2 CAPSULE 97° (LONGITUDINAL)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 12/17/2015 1:42 PM

A = 71.10 B = 68.90 C = 86.14 T0 = 83.24 D = 0.00

Correlation Coefficient = 0.993

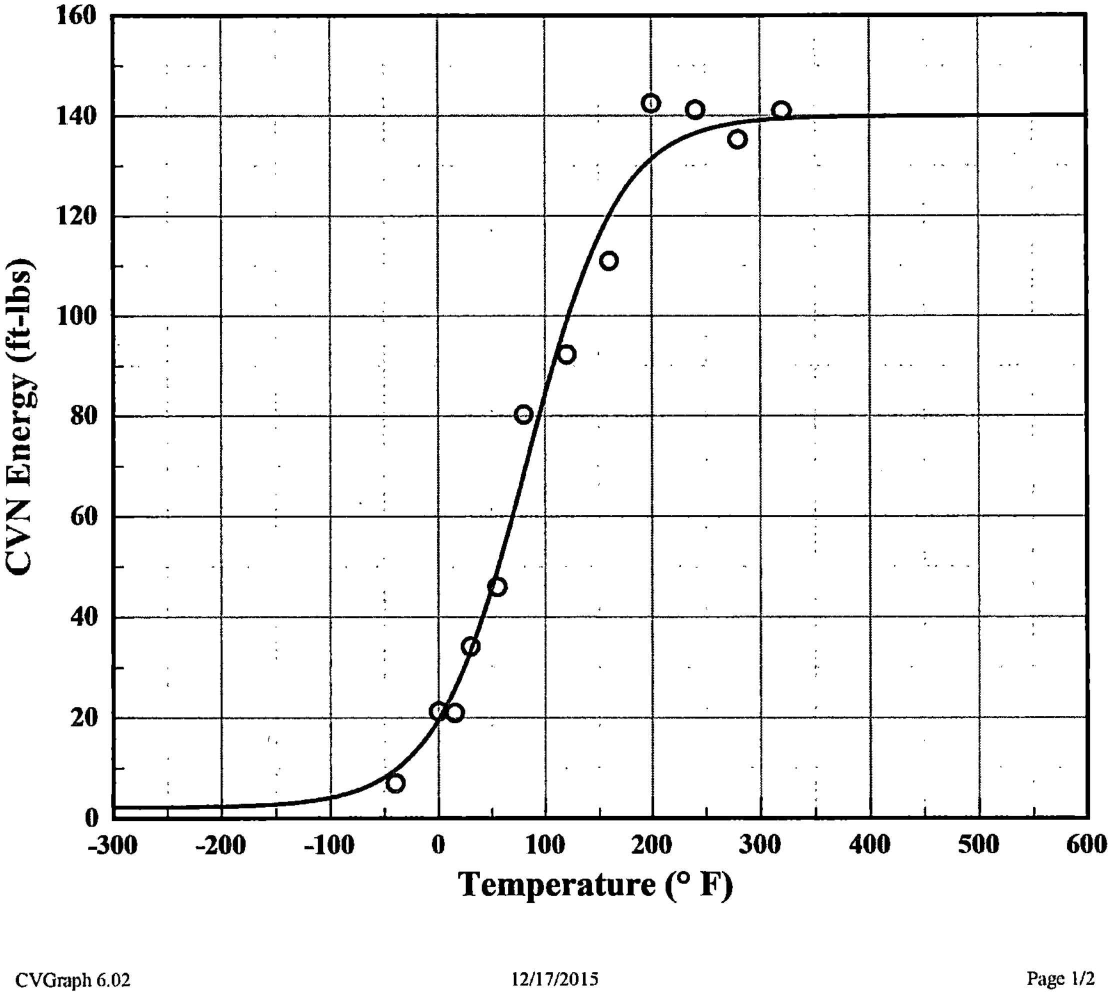
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf Energy = 140.00 (Fixed) Lower Shelf Energy = 2.20 (Fixed)

Temp@30 ft-lbs= 24.00° F Temp@35 ft-lbs= 33.20° F Temp@50 ft-lbs= 56.00° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **LT** Capsule: **97°**



CVGraph 6.02 12/17/2015 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **LT** Capsule: **97°**

ANO UNIT 2 CAPSULE 97° (LONGITUDINAL)

Charpy V-Notch Data

Temperature (° F)	Input CVN	Computed CVN	Differential
-40	7.0	9.7	-2.66
0	21.3	19.6	1.67
15	21.0	25.7	-4.65
30	34.2	33.2	0.98
55	46.0	49.3	-3.29
80	80.3	68.5	11.79
120	92.3	98.8	-6.54
160	111.0	120.2	-9.15
200	142.5	131.4	11.09
241	141.2	136.6	4.65
280	135.3	138.6	-3.29
320	141.0	139.4	1.56

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ANO UNIT 2 CAPSULE 97° (LONGITUDINAL)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 5/9/2016 2:06 PM

A = 48.76 B = 47.76 C = 84.06 T0 = 63.84 D = 0.00

Correlation Coefficient = 0.992

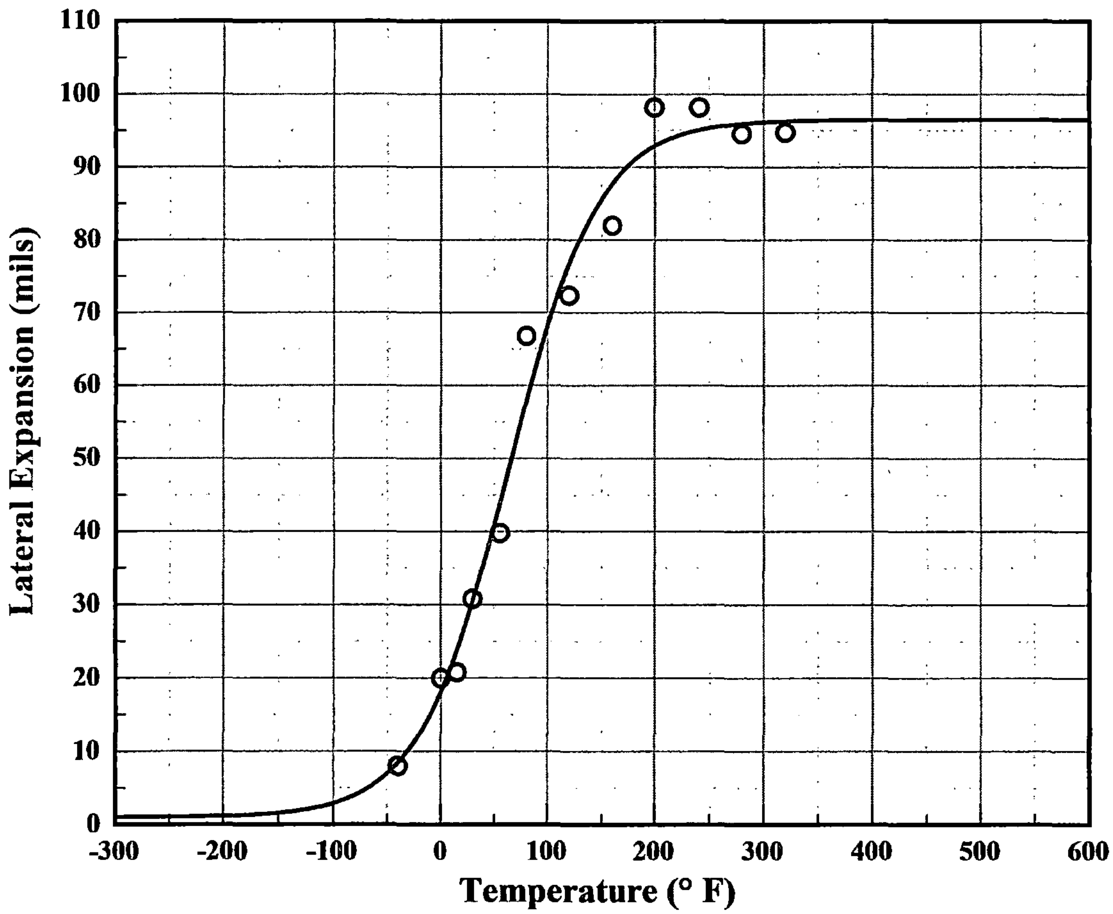
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf L.E. = 96.51 Lower Shelf L.E. = 1.00 (Fixed)

Temp@35 mils= 39.00° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **LT** Capsule: **97°**



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Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **LT** Capsule: **97°**

ANO UNIT 2 CAPSULE 97° (LONGITUDINAL)

Charpy V-Notch Data

Temperature (° F)	Input L. E.	Computed L. E.	Differential
-40	8.0	8.4	-0.44
0	20.0	18.2	1.84
15	20.8	23.8	-2.96
30	30.8	30.5	0.29
55	39.8	43.8	-3.95
80	66.8	57.8	8.98
120	72.4	76.6	-4.23
160	82.0	87.7	-5.71
200	98.2	92.9	5.29
241	98.2	95.1	3.08
280	94.6	96.0	-1.36
320	94.8	96.3	-1.50

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ANO UNIT 2 CAPSULE 97° (LONGITUDINAL)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 12/17/2015 1:43 PM

A = 50.00 B = 50.00 C = 94.55 T0 = 89.68 D = 0.00

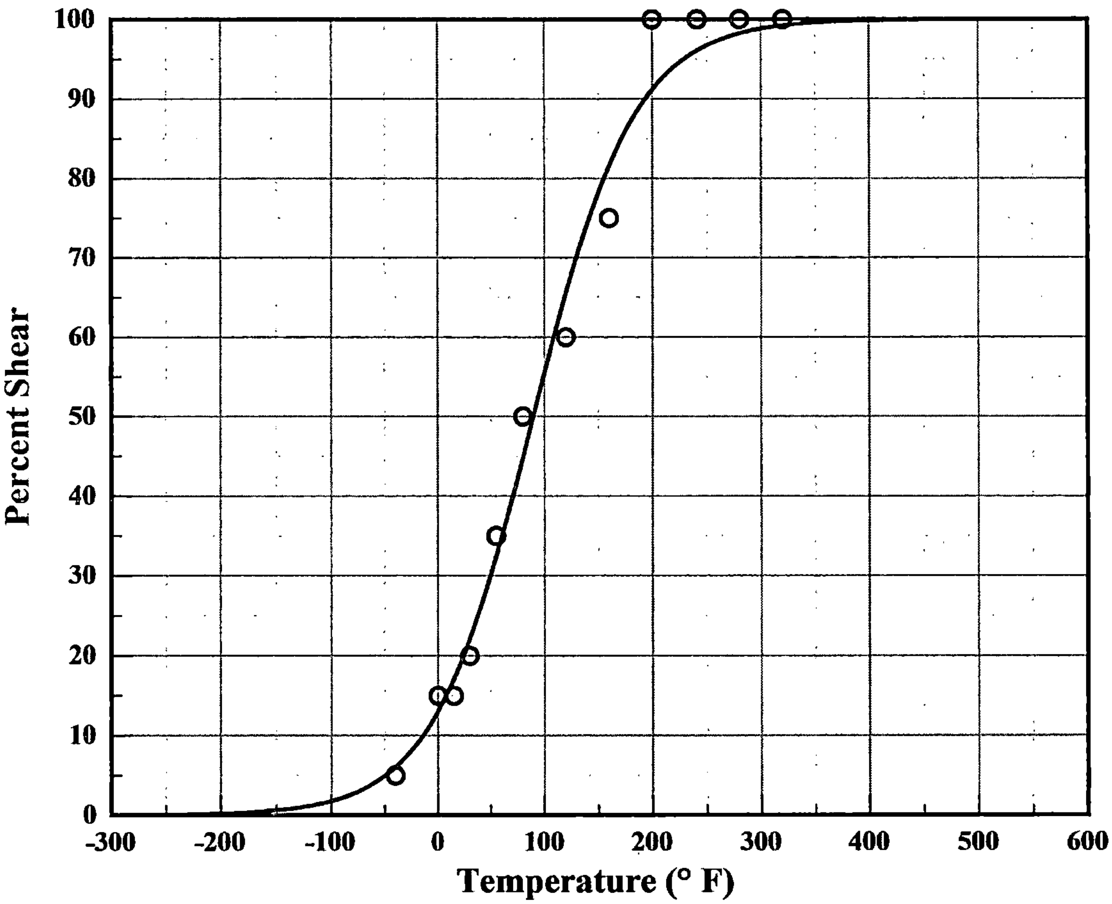
Correlation Coefficient = 0.994

Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf %Shear = 100.00 (Fixed) Lower Shelf %Shear = 0.00 (Fixed)

Temperature at 50% Shear = 89.70

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **LT** Capsule: **97°**



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Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **LT** Capsule: **97°**

ANO UNIT 2 CAPSULE 97° (LONGITUDINAL)

Charpy V-Notch Data

Temperature (° F)	Input %Shear	Computed %Shear	Differential
-40	5.0	6.0	-1.05
0	15.0	13.0	1.96
15	15.0	17.1	-2.08
30	20.0	22.1	-2.06
55	35.0	32.4	2.56
80	50.0	44.9	5.10
120	60.0	65.5	-5.51
160	75.0	81.6	-6.57
200	100.0	91.2	8.84
241	100.0	96.1	3.91
280	100.0	98.2	1.75
320	100.0	99.2	0.76

CVGraph 6.02 12/17/2015 Page 2/2

ANO UNIT 2 CAPSULE 97° (TRANSVERSE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 5/9/2016 2:08 PM

A = 61.10 B = 58.90 C = 91.97 T0 = 102.30 D = 0.00

Correlation Coefficient = 0.980

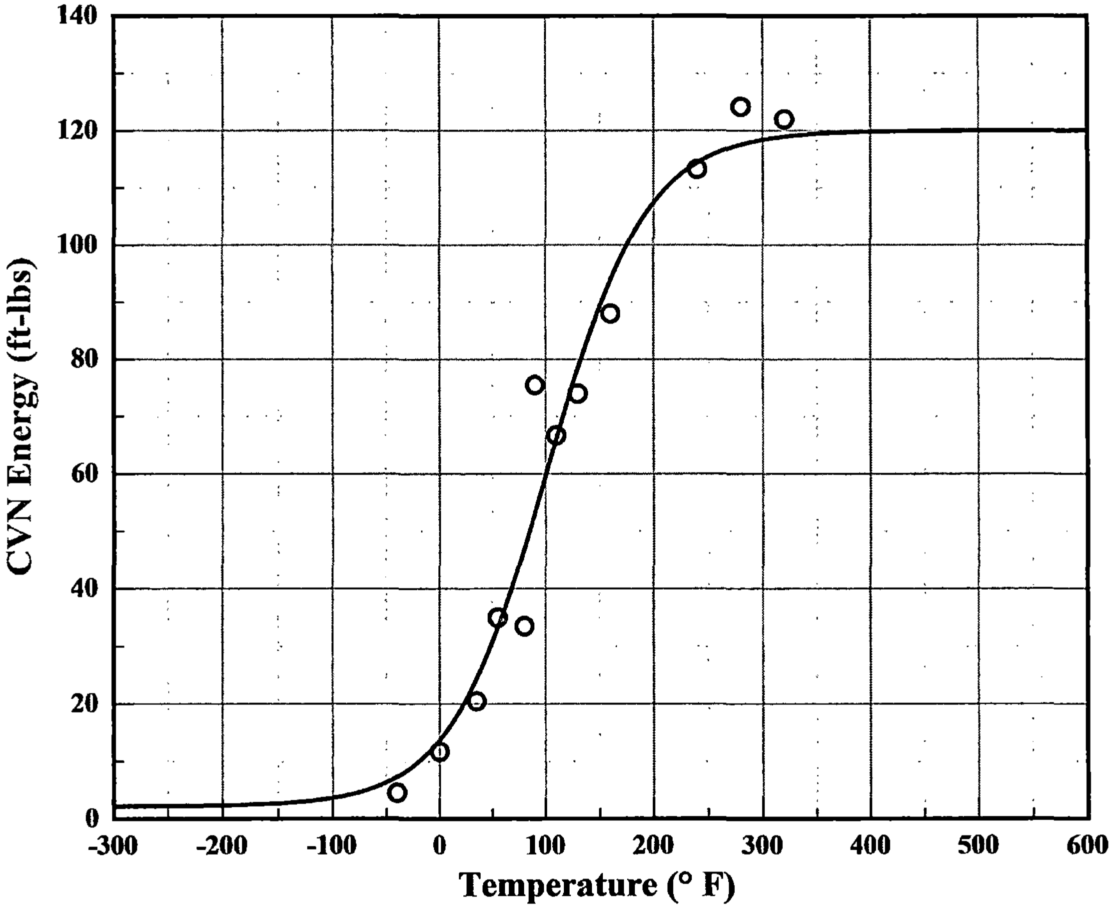
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf Energy = 120.00 (Fixed) Lower Shelf Energy = 2.20 (Fixed)

Temp@30 ft-lbs= 48.30° F Temp@35 ft-lbs= 58.60° F Temp@50 ft-lbs= 84.80° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **TL** Capsule: **97°**



CVGraph 6.02 05/09/2016 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **TL** Capsule: **97°**

ANO UNIT 2 CAPSULE 97° (TRANSVERSE)

Charpy V-Notch Data

Temperature (° F)	Input CVN	Computed CVN	Differential
-40	4.5	7.3	-2.80
0	11.7	13.7	-1.99
35	20.5	24.3	-3.84
55	35.0	33.2	1.78
80	33.5	47.1	-13.59
90	75.5	53.3	22.23
110	66.7	66.0	0.68
130	74.0	78.3	-4.32
160	88.0	93.9	-5.86
240	113.3	114.4	-1.08
280	124.2	117.6	6.62
320	122.0	119.0	3.03

CVGraph 6.02 05/09/2016 Page 2/2

ANO UNIT 2 CAPSULE 97° (TRANSVERSE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 5/9/2016 2:09 PM

A = 43.47 B = 42.47 C = 85.71 T0 = 74.21 D = 0.00

Correlation Coefficient = 0.965

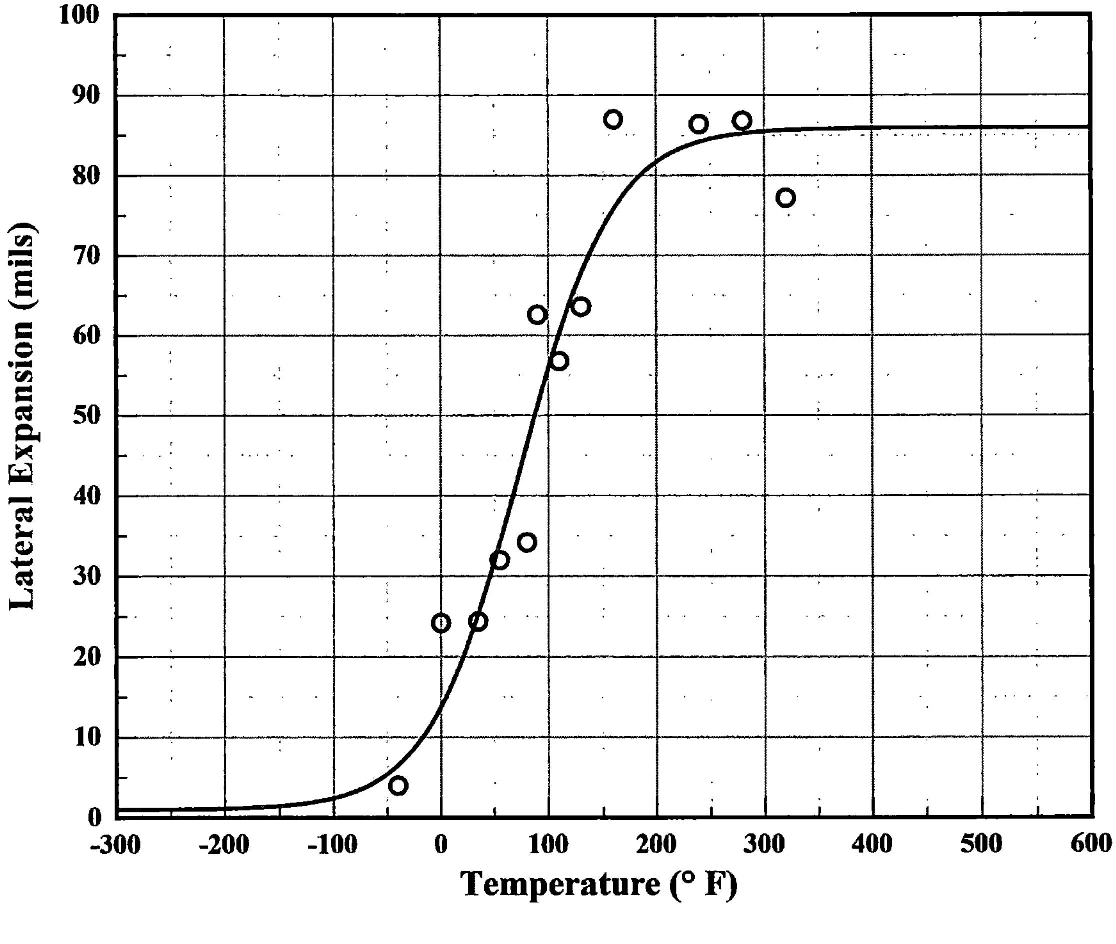
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf L.E. = 85.94 Lower Shelf L.E. = 1.00 (Fixed)

Temp@35 mils= 56.90° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **TL** Capsule: **97°**



CVGraph 6.02 05/09/2016 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **TL** Capsule: **97°**

ANO UNIT 2 CAPSULE 97° (TRANSVERSE)

Charpy V-Notch Data

Temperature (° F)	Input L. E.	Computed L. E.	Differential
-40	4.0	6.5	-2.53
0	24.2	13.8	10.43
35	24.4	25.3	-0.89
55	32.0	34.1	-2.11
80	34.2	46.3	-12.14
90	62.6	51.2	11.39
110	56.8	60.2	-3.44
130	63.6	67.8	-4.17
160	87.0	75.8	11.17
240	86.4	84.2	2.20
280	86.8	85.2	1.55
320	77.2	85.7	-8.46

CVGraph 6.02 05/09/2016 Page 2/2

ANO UNIT 2 CAPSULE 97° (TRANSVERSE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 12/17/2015 1:45 PM

A = 50.00 B = 50.00 C = 92.47 T0 = 94.15 D = 0.00

Correlation Coefficient = 0.989

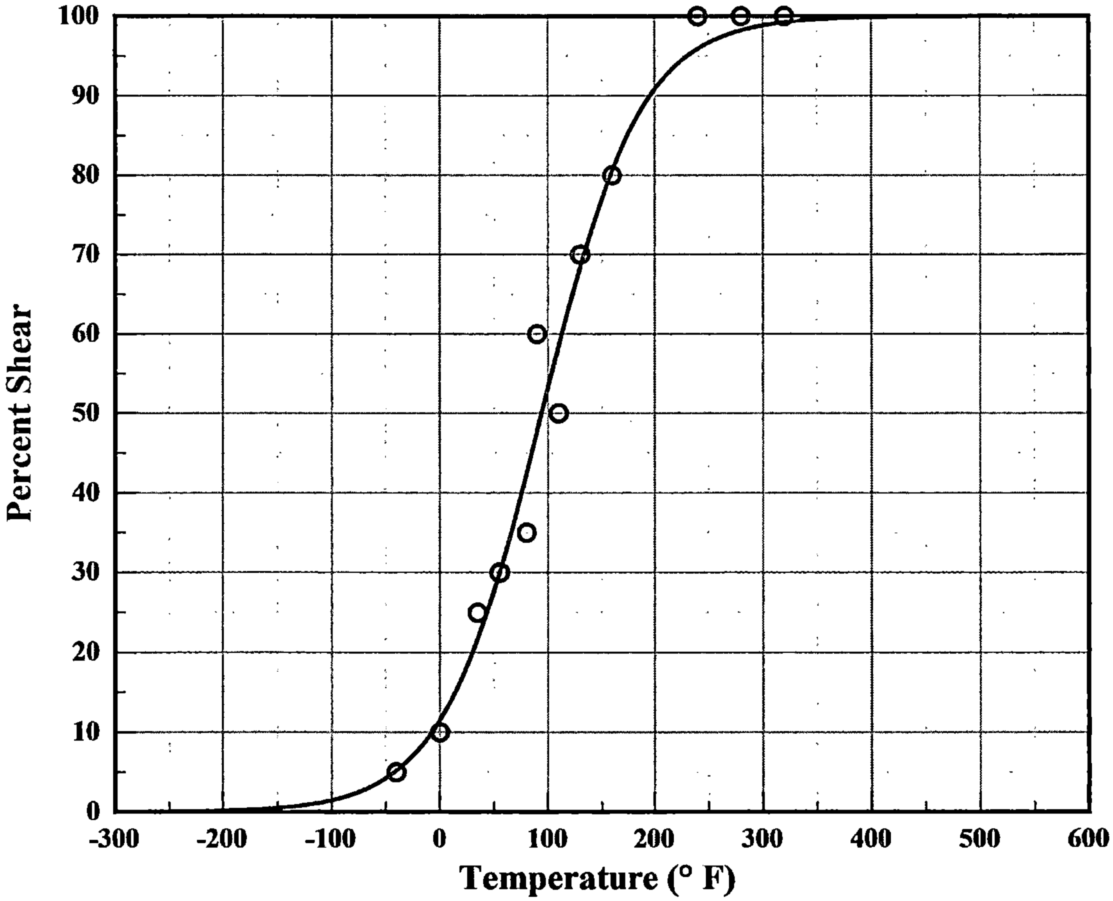
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf %Shear = 100.00 (Fixed) Lower Shelf %Shear = 0.00 (Fixed)

Temperature at 50% Shear = 94.20

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **TL** Capsule: **97°**



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Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **TL** Capsule: **97°**

ANO UNIT 2 CAPSULE 97° (TRANSVERSE)

Charpy V-Notch Data

Temperature (° F)	Input %Shear	Computed %Shear	Differential
-40	5.0	5.2	-0.21
0	10.0	11.5	-1.54
35	25.0	21.8	3.23
55	30.0	30.0	-0.01
80	35.0	42.4	-7.41
90	60.0	47.8	12.24
110	50.0	58.5	-8.49
130	70.0	68.5	1.53
160	80.0	80.6	-0.60
240	100.0	95.9	4.09
280	100.0	98.2	1.76
320	100.0	99.2	0.75

CVGraph 6.02 12/17/2015 Page 2/2

ANO UNIT 2 CAPSULE 97° (WELD)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 5/10/2016 11:18 AM

A = 74.60 B = 72.40 C = 45.72 T0 = 42.22 D = 0.00

Correlation Coefficient = 0.978

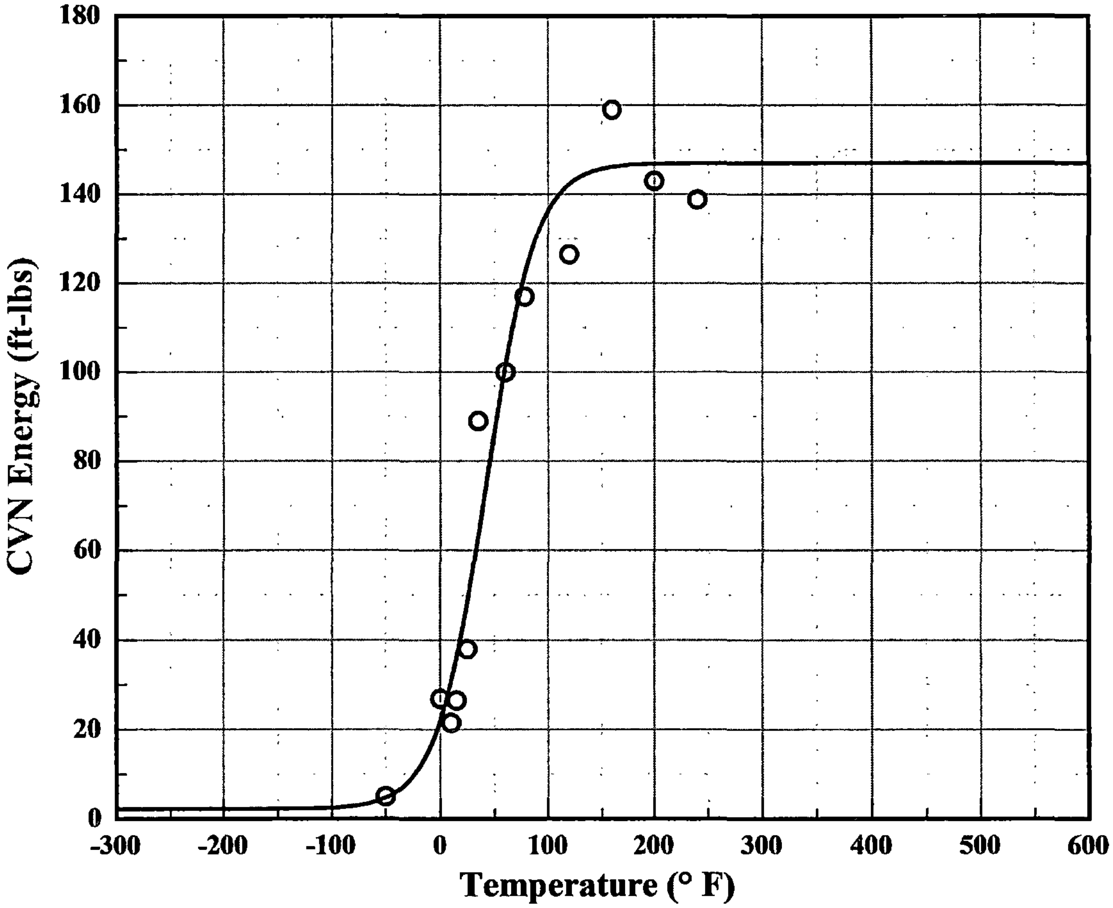
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf Energy = 147.00 (Fixed) Lower Shelf Energy = 2.20 (Fixed)

Temp@30 ft-lbs= 9.40° F Temp@35 ft-lbs= 14.20° F Temp@50 ft-lbs= 26.10° F

Plant: **Arkansas 2** Material: **WELD** Heat: **83650**

Orientation: **N/A** Capsule: **97°**



CVGraph 6.02 05/10/2016 Page 1/2

Plant: **Arkansas 2** Material: **WELD** Heat: **83650**
Orientation: **N/A** Capsule: **97°**

ANO UNIT 2 CAPSULE 97° (WELD)

Charpy V-Notch Data

Temperature (° F)	Input CVN	Computed CVN	Differential
-50	5.0	4.7	0.28
0	26.9	21.9	4.97
10	21.5	30.6	-9.13
15	26.5	36.0	-9.46
25	38.0	48.5	-10.55
35	89.0	63.3	25.74
60	100.0	101.4	-1.41
78	117.0	122.0	-4.96
120	126.5	142.3	-15.83
160	159.0	146.2	12.83
200	143.0	146.9	-3.85
240	138.8	147.0	-8.17

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ANO UNIT 2 CAPSULE 97° (WELD)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 12/17/2015 1:47 PM

A = 47.13 B = 46.13 C = 37.31 T0 = 25.73 D = 0.00

Correlation Coefficient = 0.985

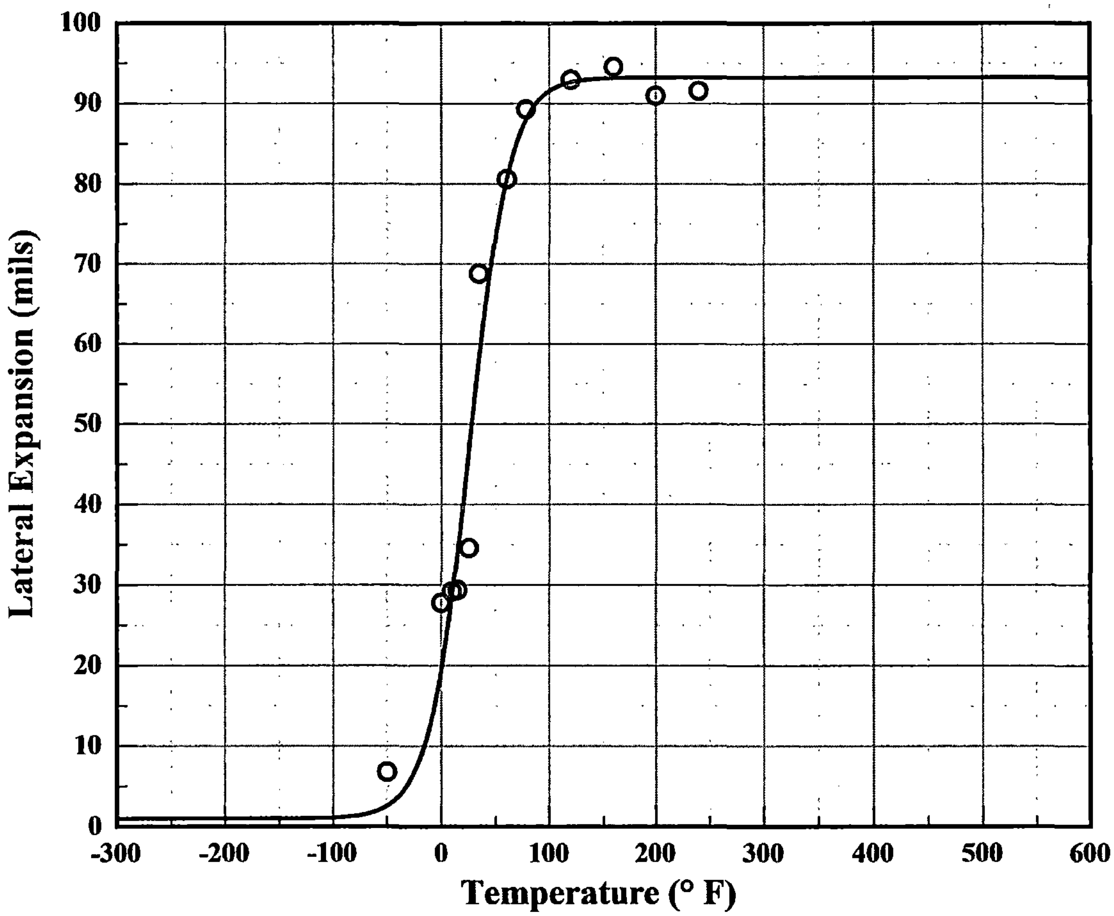
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf L.E. = 93.26 Lower Shelf L.E. = 1.00 (Fixed)

Temp@35 mils= 15.70° F

Plant: **Arkansas 2** Material: **WELD** Heat: **83650**

Orientation: **N/A** Capsule: **97°**



CVGraph 6.02 12/17/2015 Page 1/2

Plant: **Arkansas 2** Material: **WELD** Heat: **83650**
Orientation: **N/A** Capsule: **97°**

ANO UNIT 2 CAPSULE 97° (WELD)

Charpy V-Notch Data

Temperature (° F)	Input L. E.	Computed L. E.	Differential
-50	6.8	2.6	4.23
0	27.8	19.6	8.24
10	29.2	28.8	0.44
15	29.4	34.2	-4.82
25	34.6	46.2	-11.63
35	68.8	58.4	10.44
60	80.6	80.6	0.02
78	89.3	88.0	1.32
120	93.0	92.7	0.33
160	94.6	93.2	1.41
200	91.0	93.2	-2.25
240	91.6	93.3	-1.66

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ANO UNIT 2 CAPSULE 97° (WELD)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 12/17/2015 1:47 PM

A = 50.00 B = 50.00 C = 48.99 T0 = 27.86 D = 0.00

Correlation Coefficient = 0.992

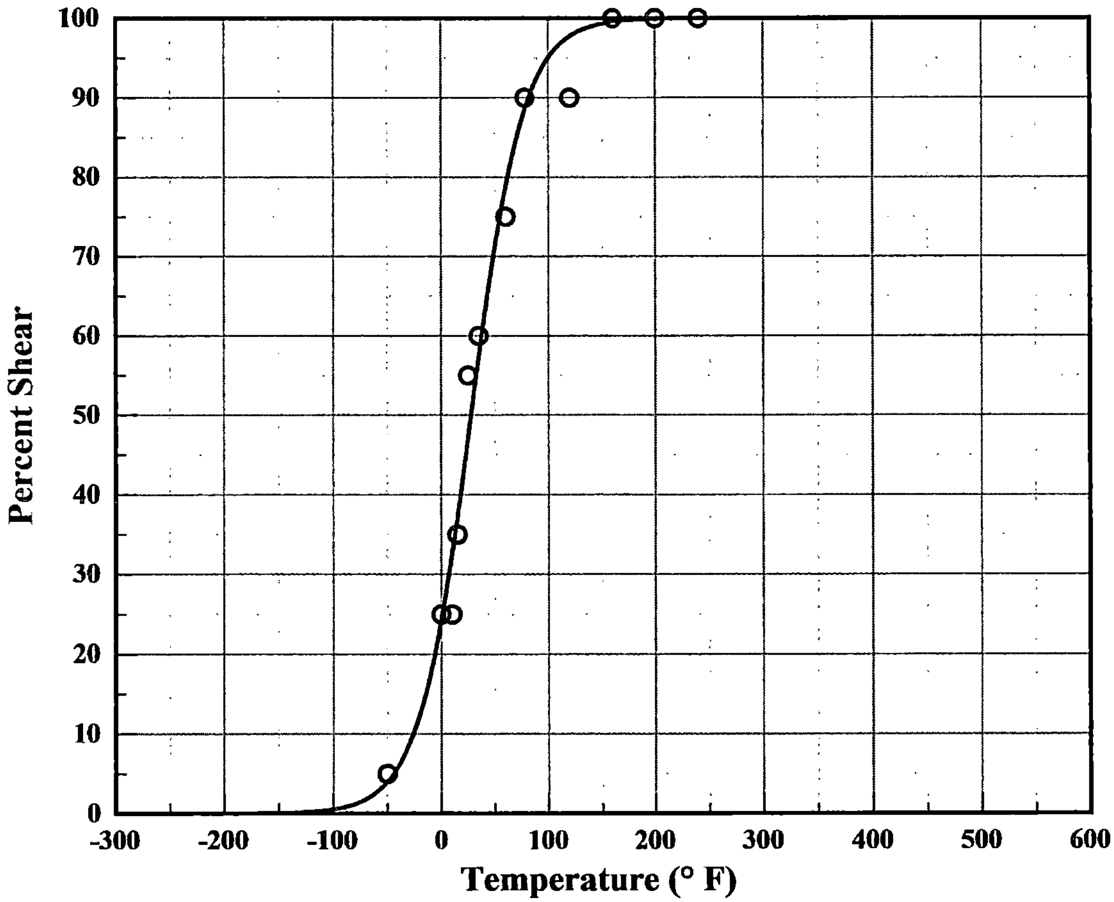
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf %Shear = 100.00 (Fixed) Lower Shelf %Shear = 0.00 (Fixed)

Temperature at 50% Shear = 27.90

Plant: **Arkansas 2** Material: **WELD** Heat: **83650**

Orientation: **N/A** Capsule: **97°**



CVGraph 6.02 12/17/2015 Page 1/2

Plant: **Arkansas 2** Material: **WELD** Heat: **83650**
Orientation: **N/A** Capsule: **97°**

ANO UNIT 2 CAPSULE 97° (WELD)

Charpy V-Notch Data

Temperature (° F)	Input % Shear	Computed % Shear	Differential
-50	5.0	4.0	1.00
0	25.0	24.3	0.72
10	25.0	32.5	-7.54
15	35.0	37.2	-2.17
25	55.0	47.1	7.91
35	60.0	57.2	2.76
60	75.0	78.8	-3.79
78	90.0	88.6	1.44
120	90.0	97.7	-7.73
160	100.0	99.5	0.45
200	100.0	99.9	0.09
240	100.0	100.0	0.02

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ANO UNIT 2 CAPSULE 97° (HEAT-AFFECTED ZONE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 5/10/2016 11:20 AM

A = 70.10 B = 67.90 C = 69.09 T0 = -32.12 D = 0.00

Correlation Coefficient = 0.778

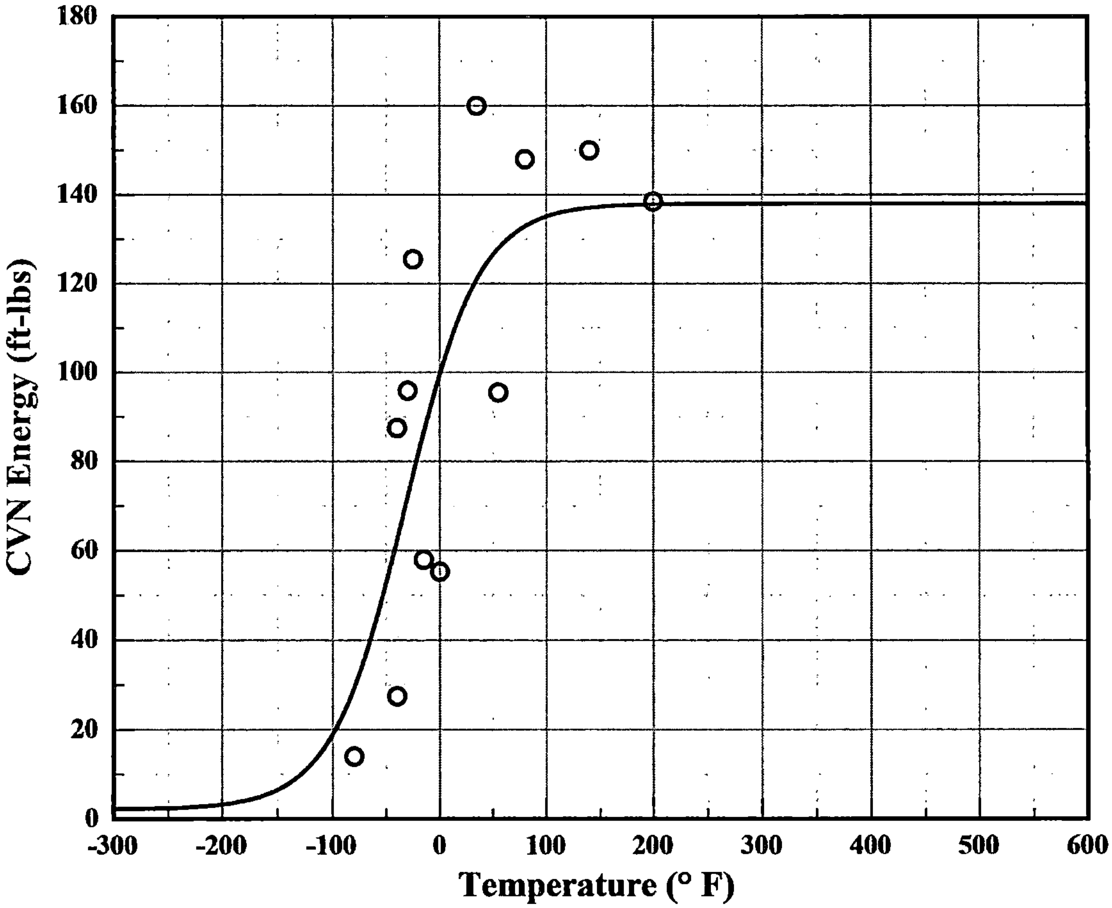
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf Energy = 138.00 (Fixed) Lower Shelf Energy = 2.20 (Fixed)

Temp@30 ft-lbs=-79.00° F Temp@35 ft-lbs=-71.60° F Temp@50 ft-lbs=-53.20° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **N/A** Capsule: **97°**



CVGraph 6.02 05/10/2016 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **N/A** Capsule: **97°**

ANO UNIT 2 CAPSULE 97° (HEAT-AFFECTED ZONE)

Charpy V-Notch Data

Temperature (° F)	Input CVN	Computed CVN	Differential
-80	14.0	29.4	-15.37
-40	27.5	62.4	-34.89
-40	87.5	62.4	25.11
-30	95.9	72.2	23.72
-25	125.5	77.1	48.43
-15	58.0	86.6	-28.59
0	55.3	99.6	-44.27
35	160.0	121.0	39.02
55	95.5	127.9	-32.41
80	148.0	132.9	15.09
140	150.0	137.1	12.92
200	138.5	137.8	0.66

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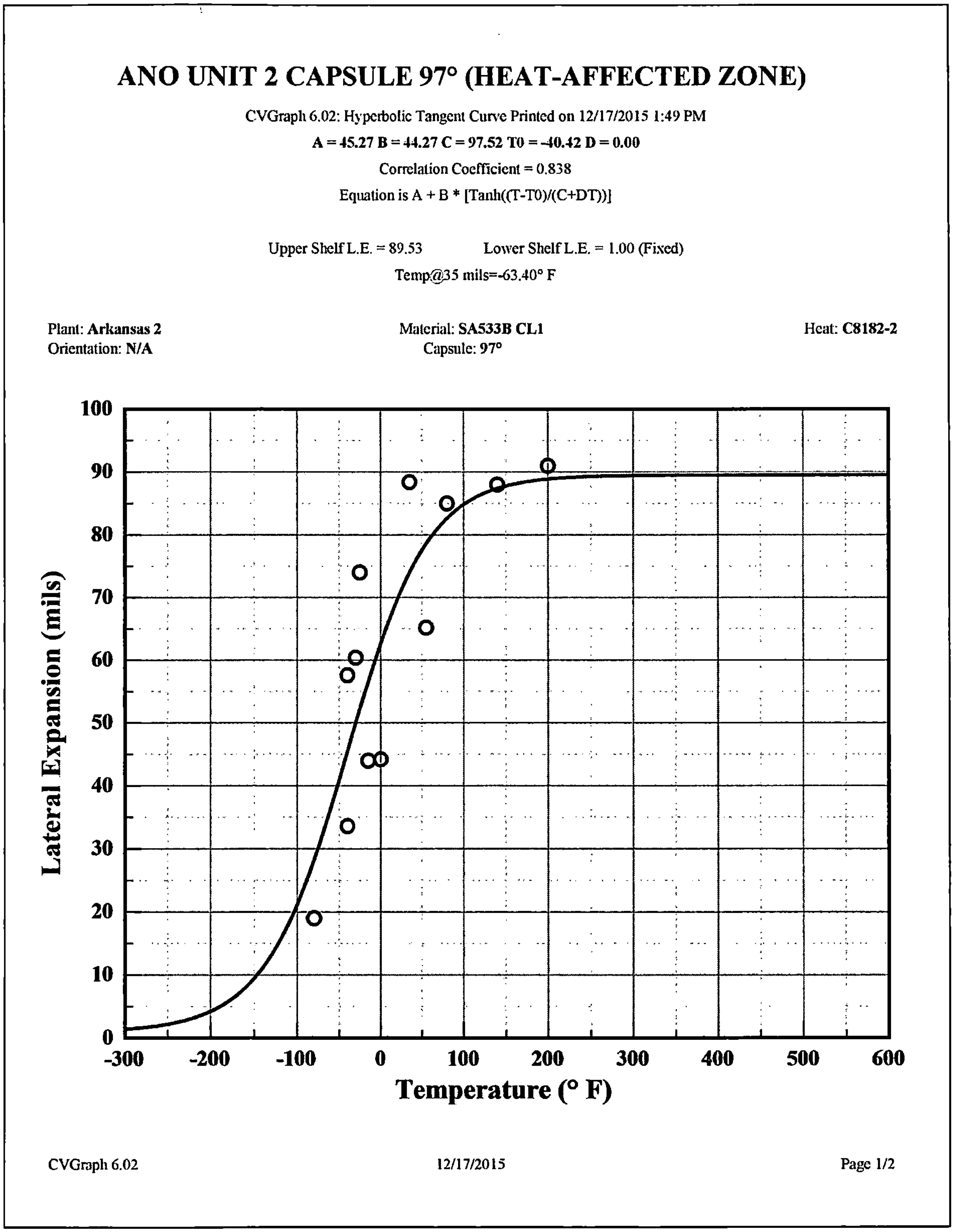
ANO UNIT 2 CAPSULE 97° (HEAT-AFFECTED ZONE)
CVGraph 6.02: Hyperbolic Tangent Curve Printed on 12/17/2015 1:49 PM
A = 45.27 B = 44.27 C = 97.52 T0 = -40.42 D = 0.00
Correlation Coefficient = 0.838
Equation is A + B * [Tanh((T-T0)/(C+DT))]
Upper Shelf L.E. = 89.53
Lower Shelf L.E. = 1.00 (Fixed)
Temp@35 mils=-63.40° F
Plant: Arkansas 2
Orientation: N/A
Material: SA533B CL1
Capsule: 97°
Heat: C8182-2
Lateral Expansion (mils)
100
90
80
70
60
50
40
30
20
10
0
-300
-200
-100
0
100
200
300
400
500
600
Temperature (° F)
CVGraph 6.02
12/17/2015
Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **N/A** Capsule: **97°**

ANO UNIT 2 CAPSULE 97° (HEAT-AFFECTED ZONE)

Charpy V-Notch Data

Temperature (° F)	Input L. E.	Computed L. E.	Differential
-80	19.0	28.2	-9.22
-40	33.6	45.5	-11.86
-40	57.6	45.5	12.14
-30	60.4	50.0	10.42
-25	74.0	52.2	21.79
-15	44.0	56.6	-12.55
0	44.2	62.6	-18.43
35	88.4	74.0	14.41
55	65.2	78.6	-13.37
80	85.0	82.6	2.37
140	88.0	87.4	0.60
200	91.0	88.9	2.10

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ANO UNIT 2 CAPSULE 97° (HEAT-AFFECTED ZONE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 12/17/2015 1:49 PM

A = 50.00 B = 50.00 C = 68.92 T0 = -31.34 D = 0.00

Correlation Coefficient = 0.882

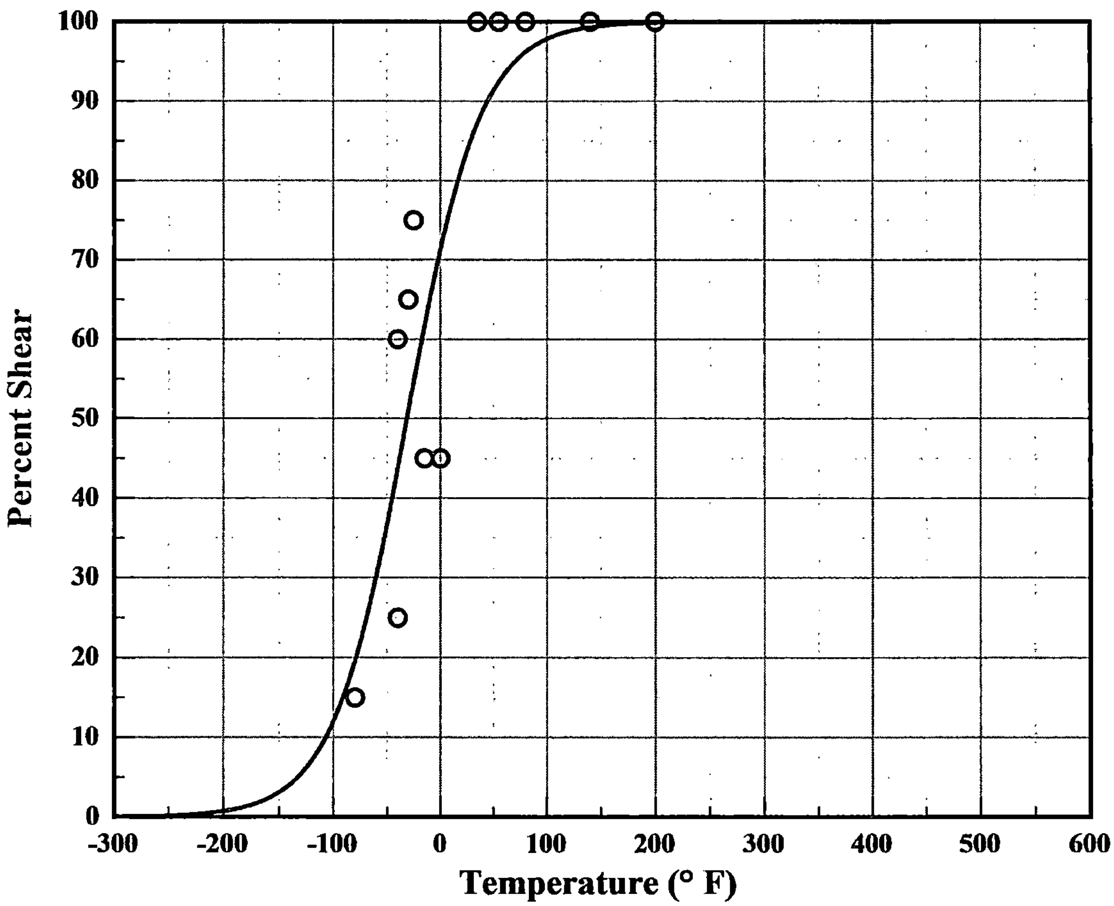
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf %Shear = 100.00 (Fixed) Lower Shelf %Shear = 0.00 (Fixed)

Temperature at 50% Shear = -31.30

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **N/A** Capsule: **97°**



CVGraph 6.02 12/17/2015 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **N/A** Capsule: **97°**

ANO UNIT 2 CAPSULE 97° (HEAT-AFFECTED ZONE)

Charpy V-Notch Data

Temperature (° F)	Input %Shear	Computed %Shear	Differential
-80	15.0	19.6	-4.59
-40	25.0	43.7	-18.75
-40	60.0	43.7	16.25
-30	65.0	51.0	14.03
-25	75.0	54.6	20.42
-15	45.0	61.6	-16.64
0	45.0	71.3	-26.29
35	100.0	87.3	12.73
55	100.0	92.5	7.55
80	100.0	96.2	3.80
140	100.0	99.3	0.69
200	100.0	99.9	0.12

CVGraph 6.02 12/17/2015 Page 2/2

ANO UNIT 2 CAPSULE 104° (TRANSVERSE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 5/9/2016 2:17 PM

A = 47.10 B = 44.90 C = 90.57 T0 = 104.07 D = 0.00

Correlation Coefficient = 0.997

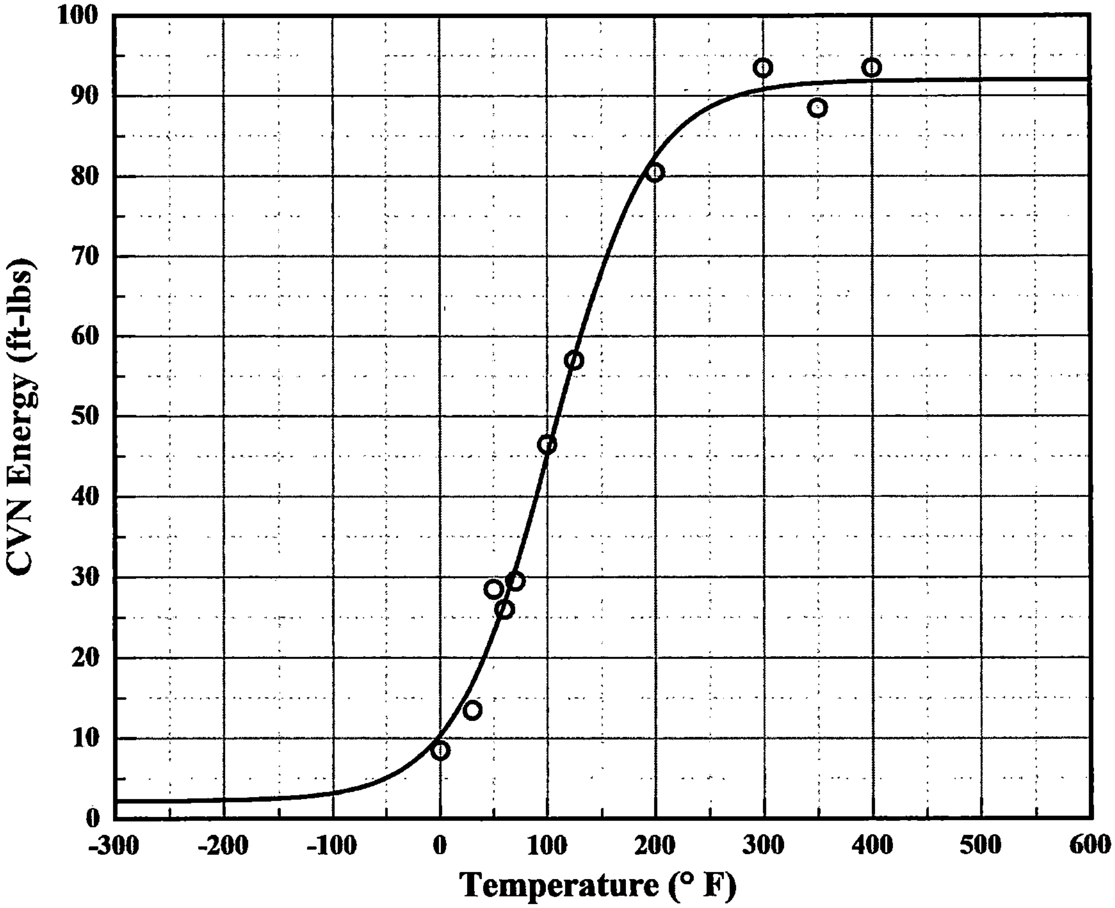
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf Energy = 92.00 (Fixed) Lower Shelf Energy = 2.20 (Fixed)

Temp@30 ft-lbs= 67.80° F Temp@35 ft-lbs= 79.10° F Temp@50 ft-lbs=110.00° F

Plant: **Arkansas 2** Material: **SA533BCL1** Heat: **C8182-2**

Orientation: **TL** Capsule: **104°**



CVGraph 6.02 05/09/2016 Page 1/2

Plant: **Arkansas 2** Material: **SA533BCL1** Heat: **C8182-2**
Orientation: **TL** Capsule: **104°**

ANO UNIT 2 CAPSULE 104° (TRANSVERSE)

Charpy V-Notch Data

Temperature (° F)	Input CVN	Computed CVN	Differential
0	8.5	10.4	-1.90
30	13.5	16.8	-3.34
50	28.5	23.1	5.42
60	26.0	26.8	-0.83
70	29.5	31.0	-1.46
100	46.5	45.1	1.42
125	57.0	57.3	-0.29
200	80.5	82.4	-1.86
300	93.5	90.8	2.67
350	88.5	91.6	-3.11
400	93.5	91.9	1.63

CVGraph 6.02 05/09/2016 Page 2/2

ANO UNIT 2 CAPSULE 104° (TRANSVERSE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 12/17/2015 1:51 PM

A = 40.17 B = 39.17 C = 96.58 T0 = 101.65 D = 0.00

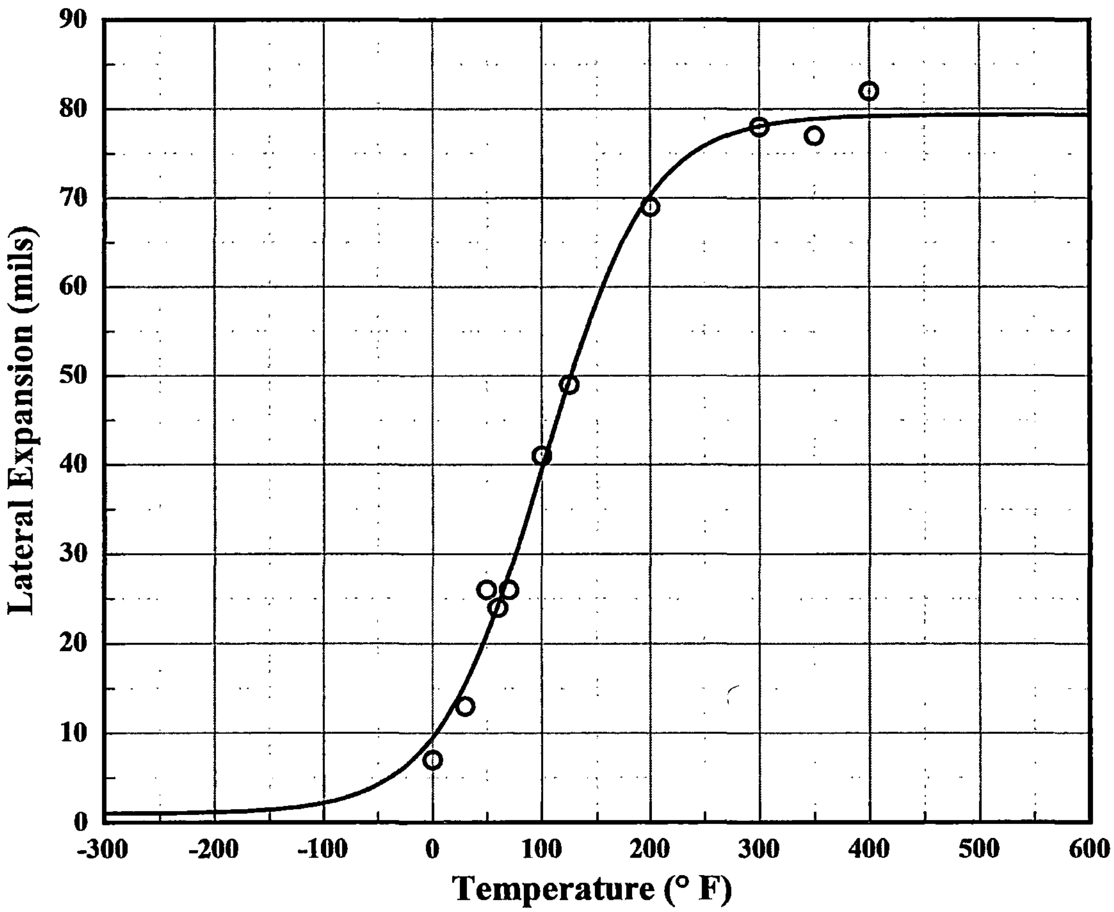
Correlation Coefficient = 0.996

Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf L.E. = 79.35 Lower Shelf L.E. = 1.00 (Fixed)

Temp@35 mils= 88.90° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **TL** Capsule: **104°**



CVGraph 6.02 12/17/2015 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **TL** Capsule: **104°**

ANO UNIT 2 CAPSULE 104° (TRANSVERSE)

Charpy V-Notch Data

Temperature (° F)	Input L. E.	Computed L. E.	Differential
0	7.0	9.5	-2.51
30	13.0	15.5	-2.49
50	26.0	21.0	4.98
60	24.0	24.3	-0.26
70	26.0	27.8	-1.78
100	41.0	39.5	1.49
125	49.0	49.5	-0.47
200	69.0	70.3	-1.30
300	78.0	78.1	-0.08
350	77.0	78.9	-1.89
400	82.0	79.2	2.82

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ANO UNIT 2 CAPSULE 104° (TRANSVERSE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 12/17/2015 1:51 PM

A = 50.00 B = 50.00 C = 80.73 T0 = 109.91 D = 0.00

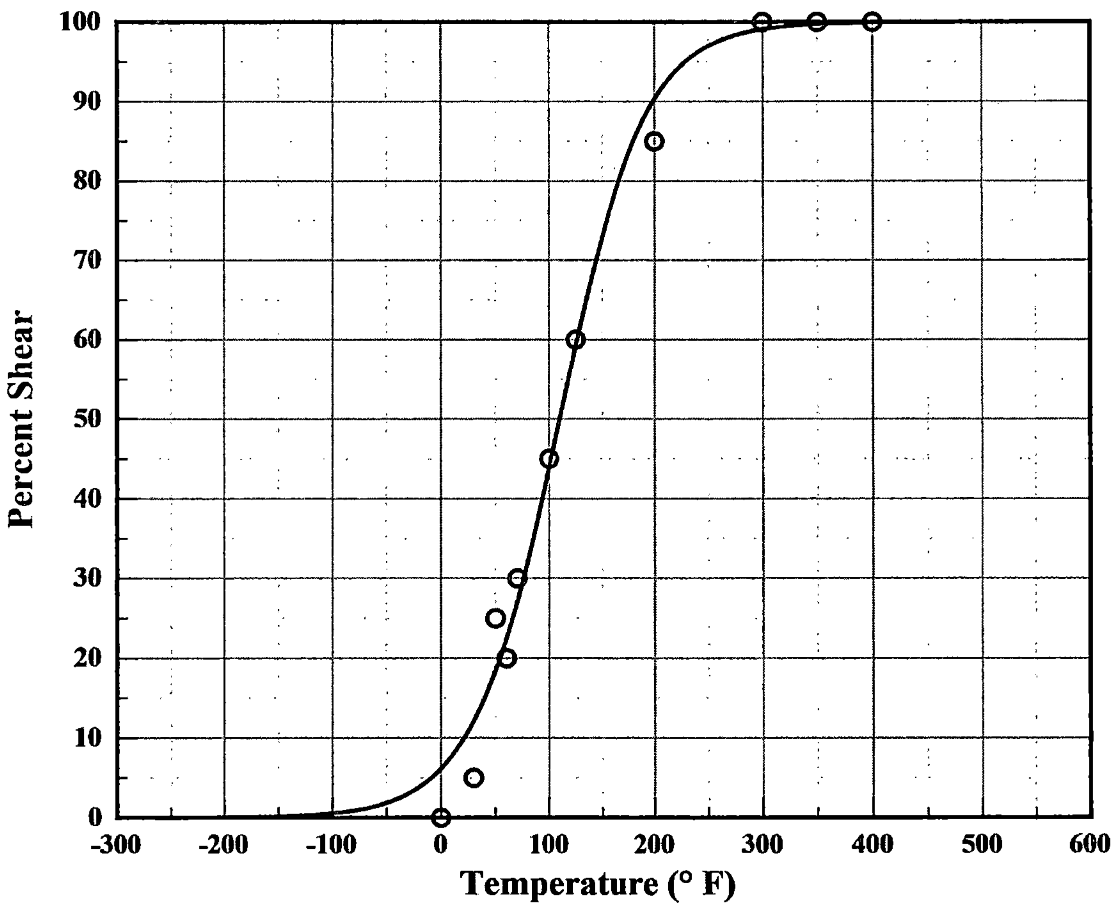
Correlation Coefficient = 0.995

Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf %Shear = 100.00 (Fixed) Lower Shelf %Shear = 0.00 (Fixed)

Temperature at 50% Shear = 110.00

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **TL** Capsule: **104°**



CVGraph 6.02 12/17/2015 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **TL** Capsule: **104°**

ANO UNIT 2 CAPSULE 104° (TRANSVERSE)

Charpy V-Notch Data

Temperature (° F)	Input %Shear	Computed %Shear	Differential
0	0.0	6.2	-6.16
30	5.0	12.1	-7.13
50	25.0	18.5	6.52
60	20.0	22.5	-2.50
70	30.0	27.1	2.88
100	45.0	43.9	1.11
125	60.0	59.2	0.76
200	85.0	90.3	-5.31
300	100.0	99.1	0.89
350	100.0	99.7	0.26
400	100.0	99.9	0.08

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ANO UNIT 2 CAPSULE 104° (WELD)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 5/9/2016 2:19 PM

A = 63.60 B = 61.40 C = 61.94 T0 = 50.33 D = 0.00

Correlation Coefficient = 0.914

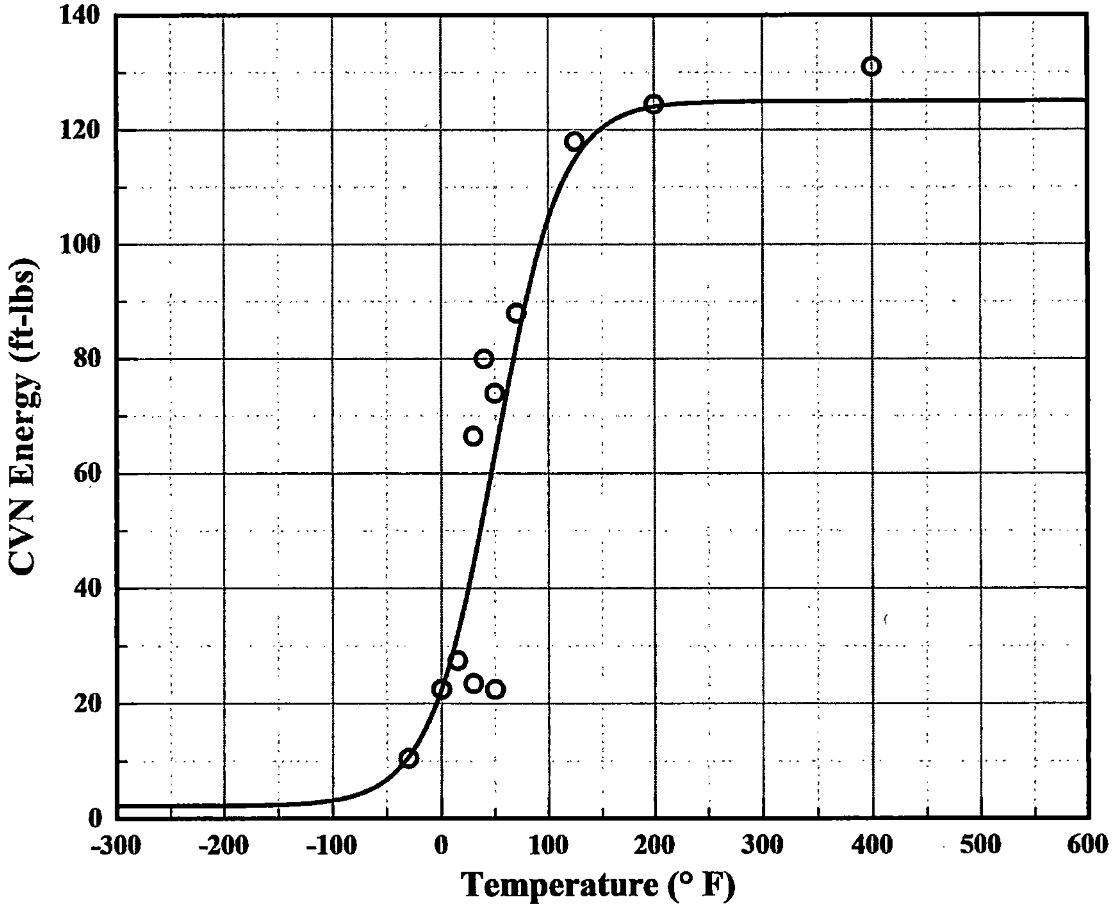
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf Energy = 125.00 (Fixed) Lower Shelf Energy = 2.20 (Fixed)

Temp@30 ft-lbs= 12.30° F Temp@35 ft-lbs= 19.10° F Temp@50 ft-lbs= 36.40° F

Plant: **Arkansas 2** Material: **WELD** Heat: **83650**

Orientation: **N/A** Capsule: **104°**



CVGraph 6.02 05/09/2016 Page 1/2

Plant: **Arkansas 2** Material: **WELD** Heat: **83650**
Orientation: **N/A** Capsule: **104°**

ANO UNIT 2 CAPSULE 104° (WELD)

Charpy V-Notch Data

Temperature (° F)	Input CVN	Computed CVN	Differential
-30	10.5	10.7	-0.24
0	22.5	22.4	0.10
15	27.5	31.9	-4.44
30	23.5	44.1	-20.64
30	66.5	44.1	22.36
40	80.0	53.5	26.54
50	22.5	63.3	-40.78
50	74.0	63.3	10.72
70	88.0	82.5	5.53
125	118.0	114.9	3.11
200	124.5	124.0	0.47
400	131.0	125.0	6.00

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ANO UNIT 2 CAPSULE 104° (WELD)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 5/9/2016 2:19 PM

A = 47.87 B = 46.87 C = 73.86 T0 = 41.90 D = 0.00

Correlation Coefficient = 0.906

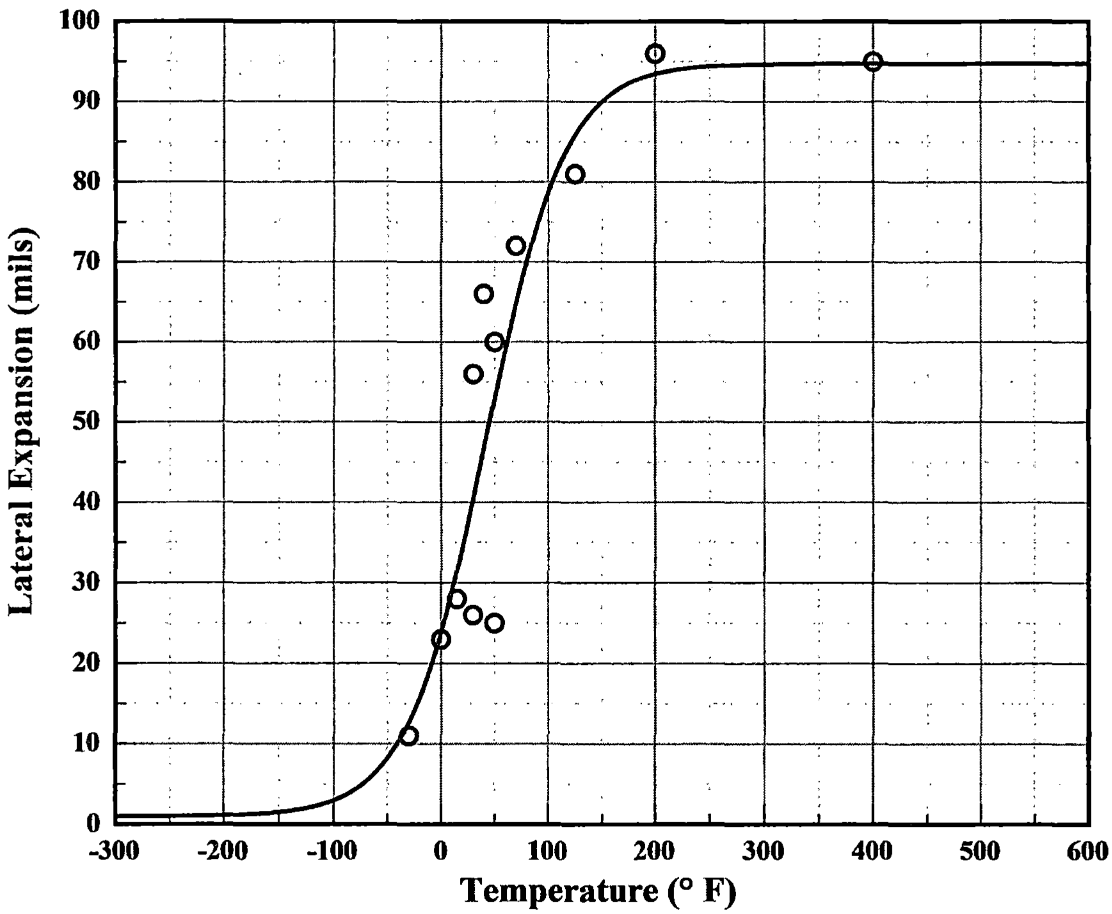
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf L.E. = 94.74 Lower Shelf L.E. = 1.00 (Fixed)

Temp@35 mils= 21.10° F

Plant: **Arkansas 2** Material: **WELD** Heat: **83650**

Orientation: **N/A** Capsule: **104°**



CVGraph 6.02 05/09/2016 Page 1/2

Plant: **Arkansas 2** Material: **WELD** Heat: **83650**
Orientation: **N/A** Capsule: **104°**

ANO UNIT 2 CAPSULE 104° (WELD)

Charpy V-Notch Data

Temperature (° F)	Input L. E.	Computed L. E.	Differential
-30	11.0	12.7	-1.71
0	23.0	23.8	-0.81
15	28.0	31.5	-3.52
30	26.0	40.4	-14.39
30	56.0	40.4	15.61
40	66.0	46.7	19.33
50	25.0	53.0	-27.99
50	60.0	53.0	7.01
70	72.0	64.9	7.11
125	81.0	85.8	-4.81
200	96.0	93.5	2.54
400	95.0	94.7	0.26

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ANO UNIT 2 CAPSULE 104° (WELD)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 12/17/2015 1:53 PM

A = 50.00 B = 50.00 C = 61.63 T0 = 31.27 D = 0.00

Correlation Coefficient = 0.953

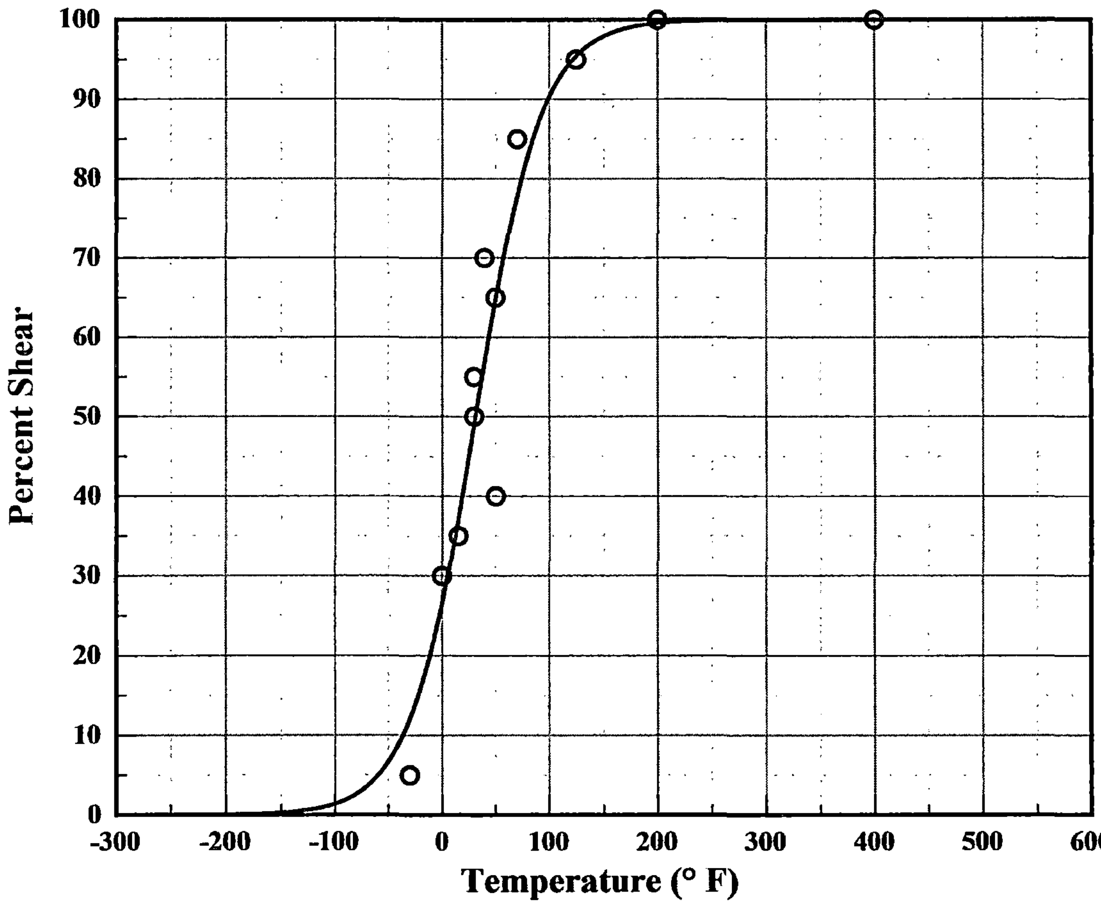
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf %Shear = 100.00 (Fixed) Lower Shelf %Shear = 0.00 (Fixed)

Temperature at 50% Shear = 31.30

Plant: **Arkansas 2** Material: **WELD** Heat: **83650**

Orientation: N/A Capsule: **104°**



CVGraph 6.02 12/17/2015 Page 1/2

Plant: **Arkansas 2** Material: **WELD** Heat: **83650**
Orientation: **N/A** Capsule: **104°**

ANO UNIT 2 CAPSULE 104° (WELD)

Charpy V-Notch Data

Temperature (° F)	Input %Shear	Computed %Shear	Differential
-30	5.0	12.0	-7.04
0	30.0	26.6	3.40
15	35.0	37.1	-2.10
30	50.0	49.0	1.03
30	55.0	49.0	6.03
40	70.0	57.0	12.97
50	40.0	64.7	-24.74
50	65.0	64.7	0.26
70	85.0	77.8	7.15
125	95.0	95.4	-0.44
200	100.0	99.6	0.42
400	100.0	100.0	0.00

CVGraph 6.02 12/17/2015 Page 2/2

ANO UNIT 2 CAPSULE 104° (HEAT-AFFECTED ZONE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 5/9/2016 2:21 PM

A = 66.10 B = 63.90 C = 83.21 T0 = 36.39 D = 0.00

Correlation Coefficient = 0.955

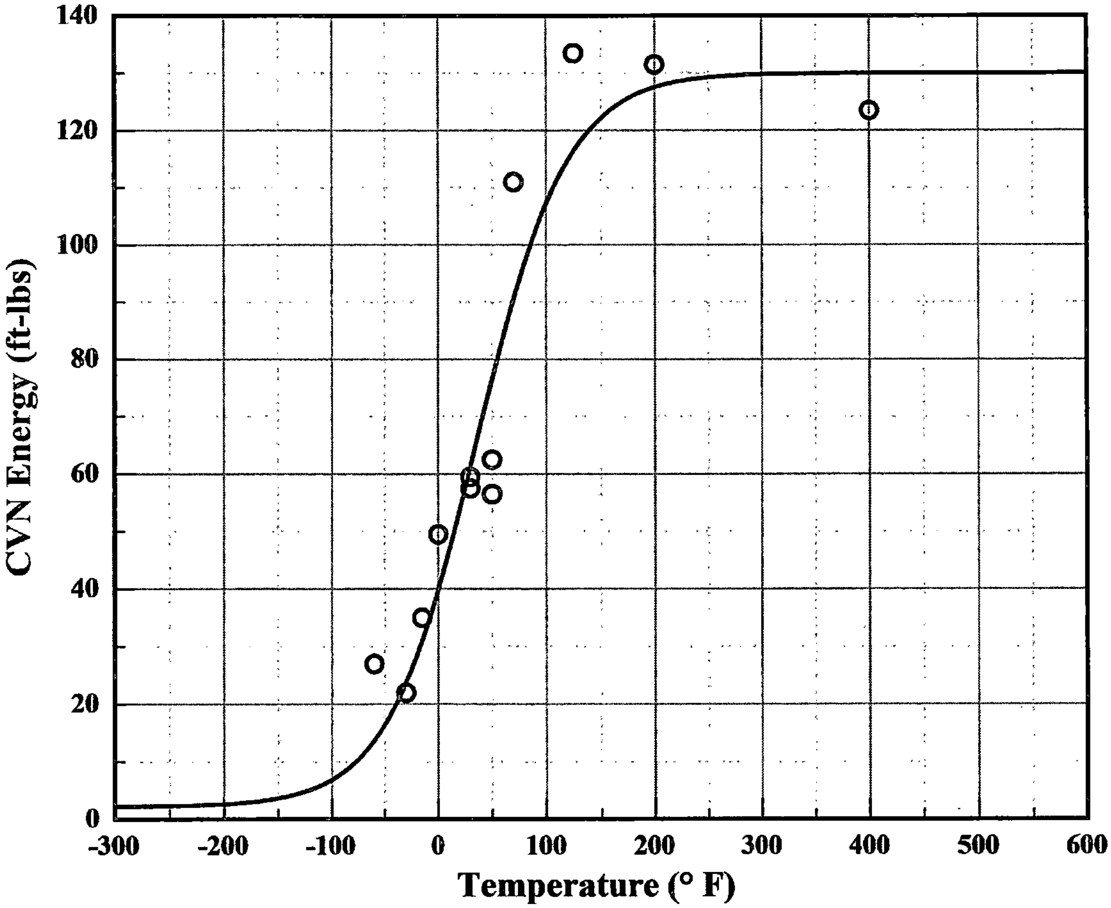
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf Energy = 130.00 (Fixed) Lower Shelf Energy = 2.20 (Fixed)

Temp@30 ft-lbs=-16.80° F Temp@35 ft-lbs= -7.80° F Temp@50 ft-lbs= 15.00° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **N/A** Capsule: **104°**



CVGraph 6.02 05/09/2016 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **N/A** Capsule: **104°**

ANO UNIT 2 CAPSULE 104° (HEAT-AFFECTED ZONE)

Charpy V-Notch Data

Temperature (° F)	**Input CVN**	**Computed CVN**	**Differential**
-60	27.0	13.7	13.33
-30	22.0	23.7	-1.75
-15	35.0	31.0	4.01
0	49.5	39.8	9.69
30	57.5	61.2	-3.71
30	59.5	61.2	-1.71
50	62.5	76.5	-13.96
50	56.5	76.5	-19.96
70	111.0	90.6	20.40
125	133.5	116.4	17.08
200	131.5	127.5	3.96
400	123.5	130.0	-6.48

CVGraph 6.02 05/09/2016 Page 2/2

ANO UNIT 2 CAPSULE 104° (HEAT-AFFECTED ZONE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 12/17/2015 1:55 PM

A = 42.98 B = 41.98 C = 91.41 T0 = 32.95 D = 0.00

Correlation Coefficient = 0.956

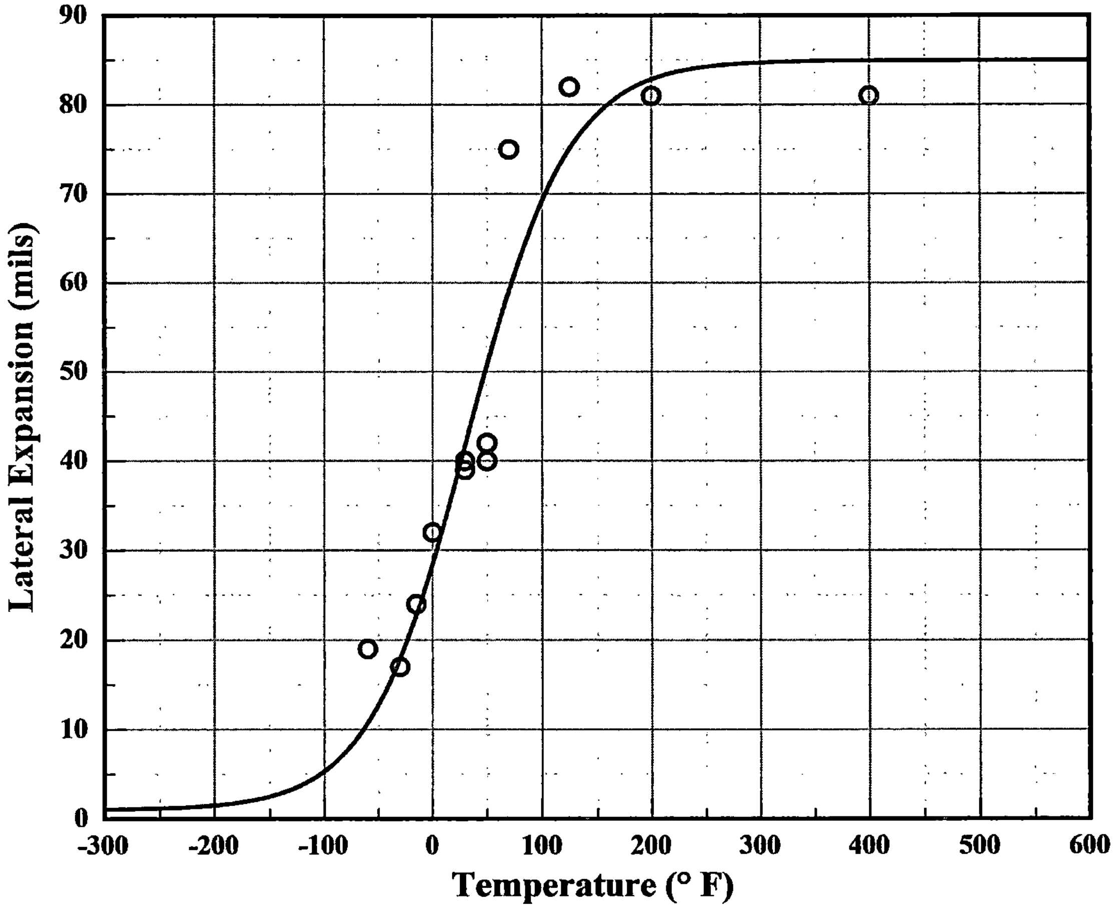
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf L.E. = 84.97 Lower Shelf L.E. = 1.00 (Fixed)

Temp@35 mils= 15.40° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **N/A** Capsule: **104°**



CVGraph 6.02 12/17/2015 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: N/A Capsule: **104°**

ANO UNIT 2 CAPSULE 104° (HEAT-AFFECTED ZONE)

Charpy V-Notch Data

Temperature (° F)	Input L. E.	Computed L. E.	Differential
-60	19.0	10.7	8.28
-30	17.0	17.9	-0.91
-15	24.0	22.8	1.22
0	32.0	28.5	3.53
30	39.0	41.6	-2.63
30	40.0	41.6	-1.63
50	42.0	50.7	-8.73
50	40.0	50.7	-10.73
70	75.0	59.1	15.87
125	82.0	75.1	6.92
200	81.0	82.9	-1.85
400	81.0	84.9	-3.94

CVGraph 6.02 12/17/2015 Page 2/2

ANO UNIT 2 CAPSULE 104° (HEAT-AFFECTED ZONE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 12/17/2015 1:56 PM

A = 50.00 B = 50.00 C = 101.30 T0 = 15.99 D = 0.00

Correlation Coefficient = 0.929

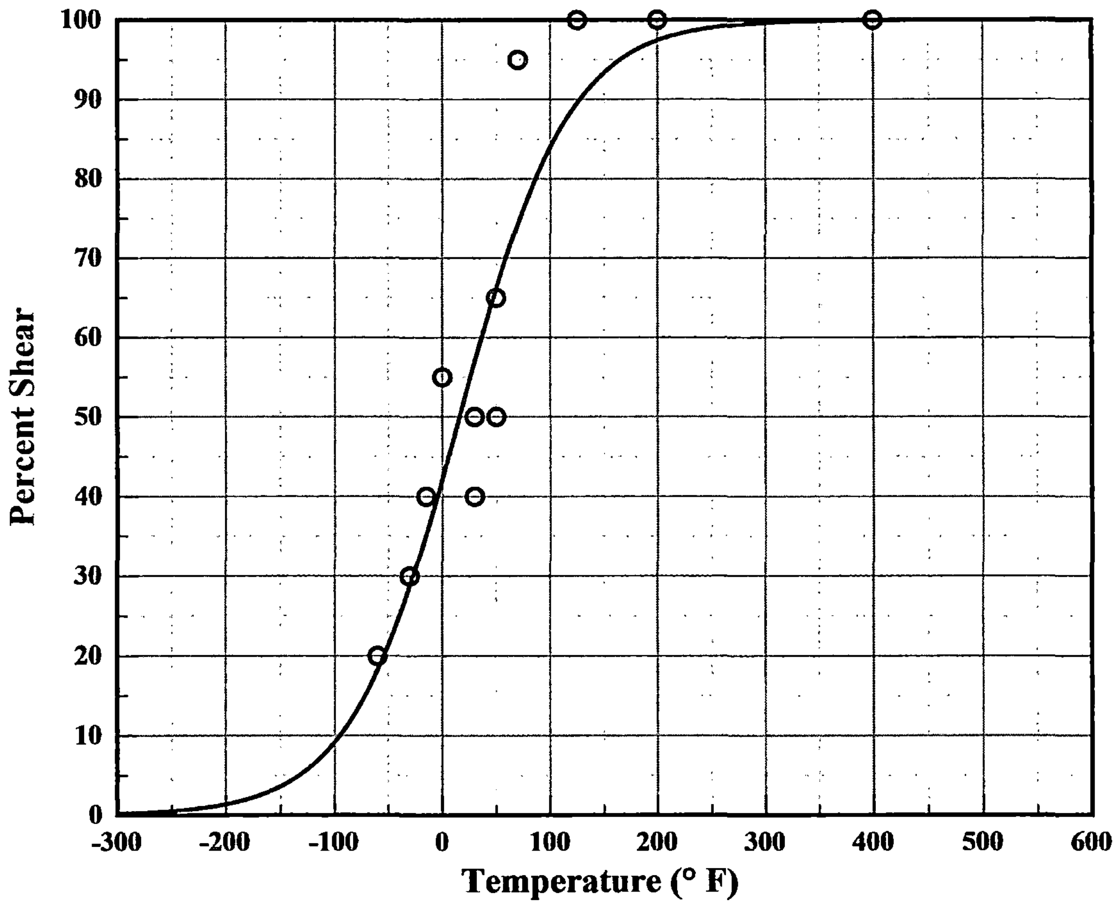
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf %Shear = 100.00 (Fixed) Lower Shelf %Shear = 0.00 (Fixed)

Temperature at 50% Shear = 16.00

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **N/A** Capsule: **104°**



CVGraph 6.02 12/17/2015 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **N/A** Capsule: **104°**

ANO UNIT 2 CAPSULE 104° (HEAT-AFFECTED ZONE)

Charpy V-Notch Data

Temperature (° F)	Input %Shear	Computed %Shear	Differential
-60	20.0	18.2	1.76
-30	30.0	28.7	1.26
-15	40.0	35.2	4.83
0	55.0	42.2	12.83
30	40.0	56.9	-16.87
30	50.0	56.9	-6.87
50	65.0	66.2	-1.19
50	50.0	66.2	-16.19
70	95.0	74.4	20.61
125	100.0	89.6	10.41
200	100.0	97.4	2.58
400	100.0	99.9	0.05

CVGraph 6.02 12/17/2015 Page 2/2

ANO UNIT 2 CAPSULE 104° (SRM)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 5/9/2016 2:23 PM

A = 44.60 B = 42.40 C = 85.15 T0 = 194.36 D = 0.00

Correlation Coefficient = 0.993

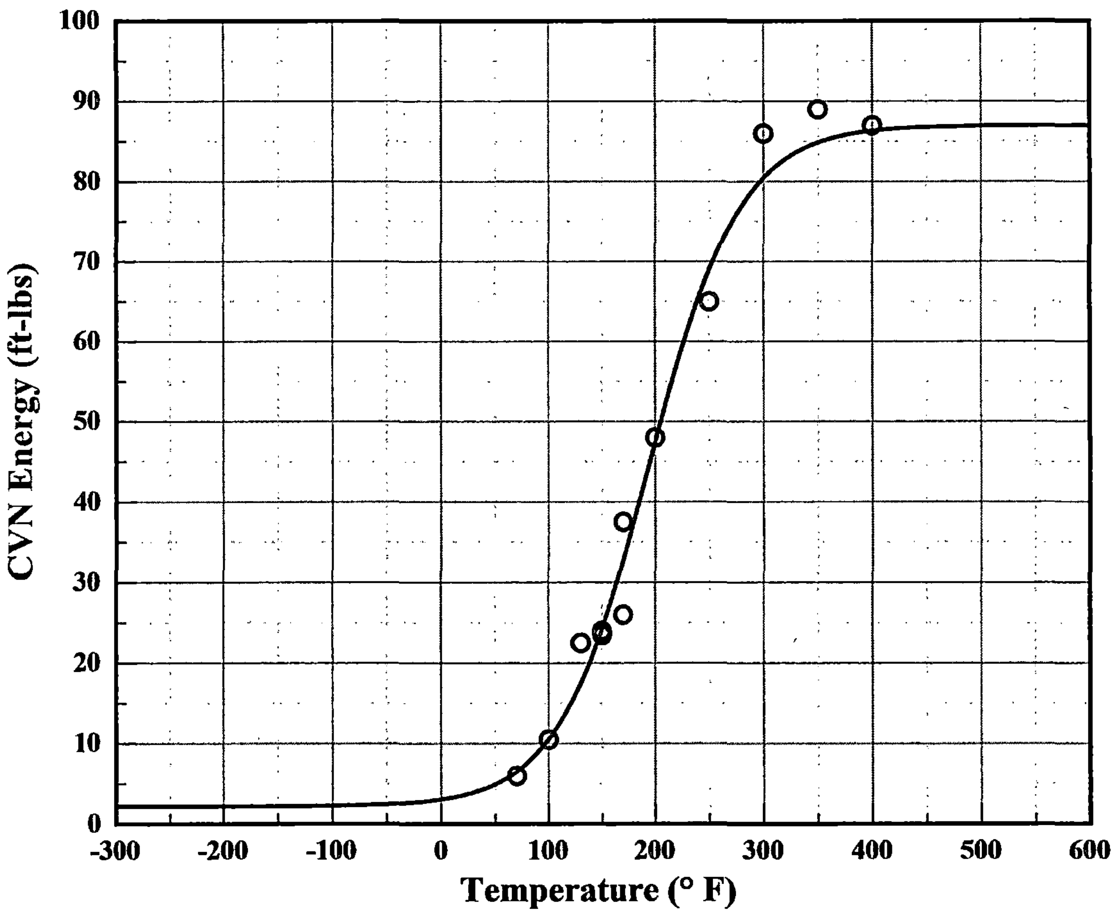
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf Energy = 87.00 (Fixed) Lower Shelf Energy = 2.20 (Fixed)

Temp@30 ft-lbs=163.80° F Temp@35 ft-lbs=174.80° F Temp@50 ft-lbs=205.30° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **HSST-01MY**

Orientation: **LT** Capsule: **104°**



CVGraph 6.02 05/09/2016 Page 1/2

Plant: **Arkansas 2**
Orientation: **LT**

Material: **SA533B CL1**
Capsule: **104°**

Heat: **HSST-01MY**

ANO UNIT 2 CAPSULE 104° (SRM)

Charpy V-Notch Data

Temperature (° F)	Input CVN	Computed CVN	Differential
70	6.0	6.5	-0.53
100	10.5	10.5	-0.03
130	22.5	17.5	4.98
150	24.0	24.3	-0.31
150	23.5	24.3	-0.81
170	26.0	32.8	-6.79
170	37.5	32.8	4.71
200	48.0	47.4	0.60
250	65.0	68.9	-3.94
300	86.0	80.5	5.54
350	89.0	84.9	4.14
400	87.0	86.3	0.67

CVGraph 6.02 05/09/2016 Page 2/2

ANO UNIT 2 CAPSULE 104° (SRM)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 5/9/2016 2:24 PM

A = 42.34 B = 41.34 C = 102.98 T0 = 199.36 D = 0.00

Correlation Coefficient = 0.996

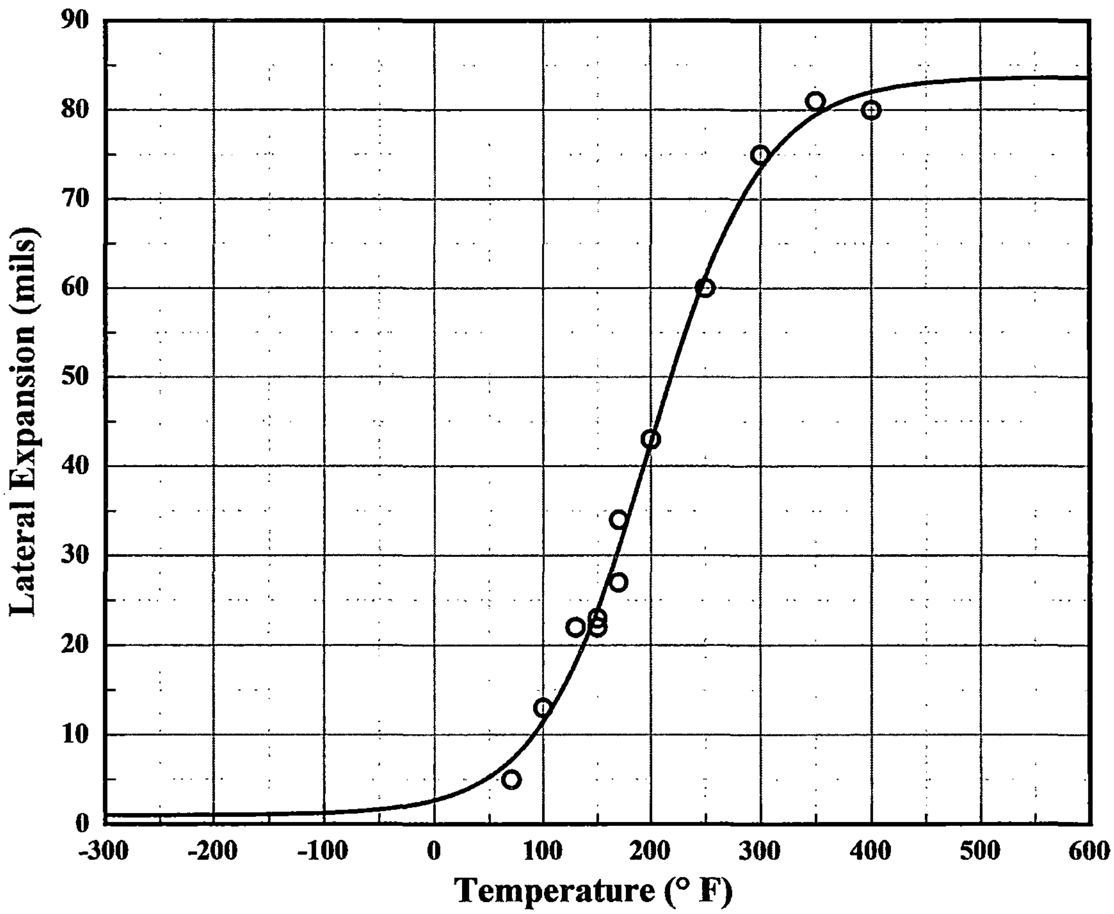
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf L.E. = 83.67 Lower Shelf L.E. = 1.00 (Fixed)

Temp@35 mils=180.90° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **HSST-01MY**

Orientation: **LT** Capsule: **104°**



CVGraph 6.02 05/09/2016 Page 1/2

Plant: **Arkansas 2**
Orientation: **LT**

Material: **SA533B CL1**
Capsule: **104°**

Heat: **HSST-01MY**

ANO UNIT 2 CAPSULE 104° (SRM)

Charpy V-Notch Data

Temperature (° F)	Input L. E.	Computed L. E.	Differential
70	5.0	7.2	-2.20
100	13.0	11.5	1.52
130	22.0	18.1	3.94
150	23.0	23.9	-0.91
150	22.0	23.9	-1.91
170	27.0	30.9	-3.86
170	34.0	30.9	3.14
200	43.0	42.6	0.41
250	60.0	61.2	-1.17
300	75.0	73.4	1.58
350	81.0	79.5	1.53
400	80.0	82.0	-2.03

CVGraph 6.02 05/09/2016 Page 2/2

ANO UNIT 2 CAPSULE 104° (SRM)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 5/9/2016 2:25 PM

A = 50.00 B = 50.00 C = 103.24 T0 = 178.47 D = 0.00

Correlation Coefficient = 0.984

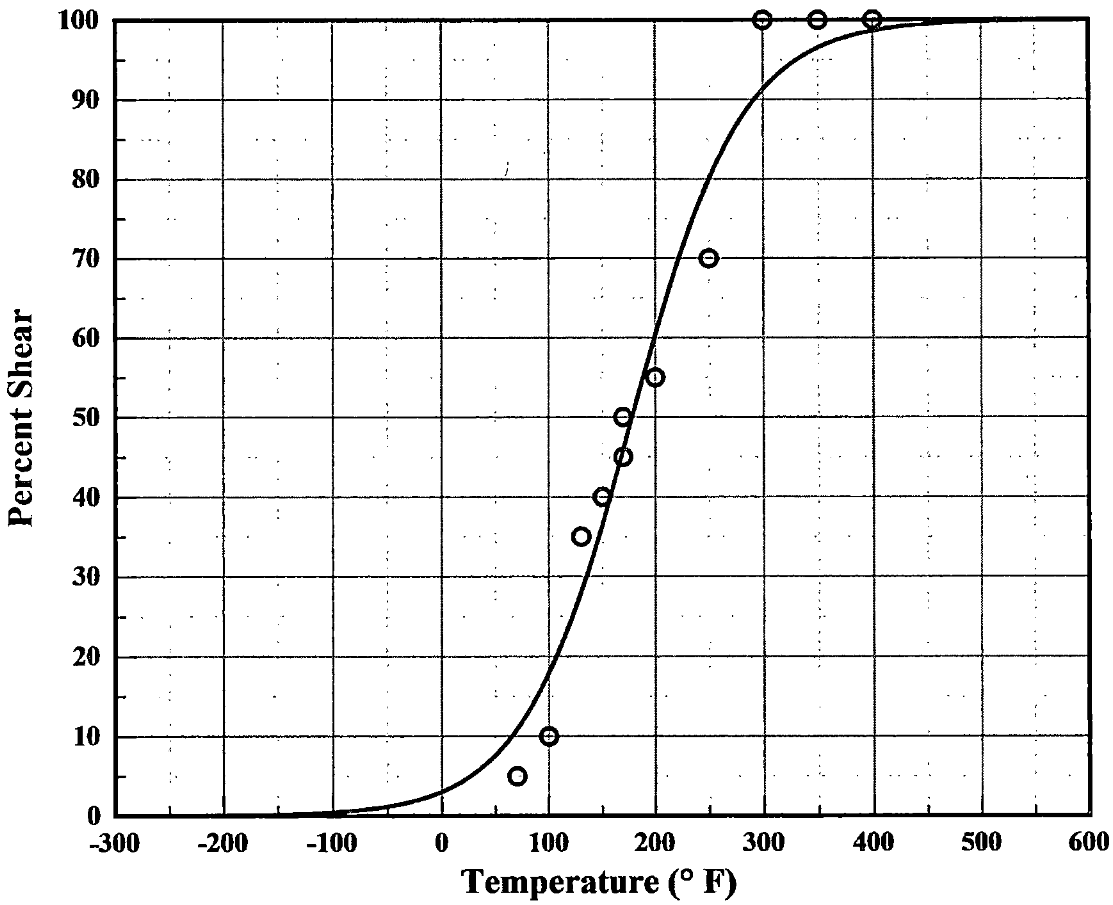
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf %Shear = 100.00 (Fixed) Lower Shelf %Shear = 0.00 (Fixed)

Temperature at 50% Shear = 178.50

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **HSST-01MY**

Orientation: **LT** Capsule: **104°**



CVGraph 6.02 05/09/2016 Page 1/2

Plant: **Arkansas 2**
Orientation: **LT**

Material: **SA533B CL1**
Capsule: **104°**

Heat: **HSST-01MY**

ANO UNIT 2 CAPSULE 104° (SRM)

Charpy V-Notch Data

Temperature (° F)	Input %Shear	Computed %Shear	Differential
70	5.0	10.9	-5.90
100	10.0	17.9	-7.94
130	35.0	28.1	6.89
150	40.0	36.6	3.45
150	40.0	36.6	3.45
170	50.0	45.9	4.09
170	45.0	45.9	-0.91
200	55.0	60.3	-5.28
250	70.0	80.0	-9.99
300	100.0	91.3	8.67
350	100.0	96.5	3.48
400	100.0	98.7	1.35

CVGraph 6.02 05/09/2016 Page 2/2

ANO UNIT 2 CAPSULE 284° (LONGITUDINAL)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 1:39 PM

A = 62.10 B = 59.90 C = 88.76 T0 = 139.26 D = 0.00

Correlation Coefficient = 0.978

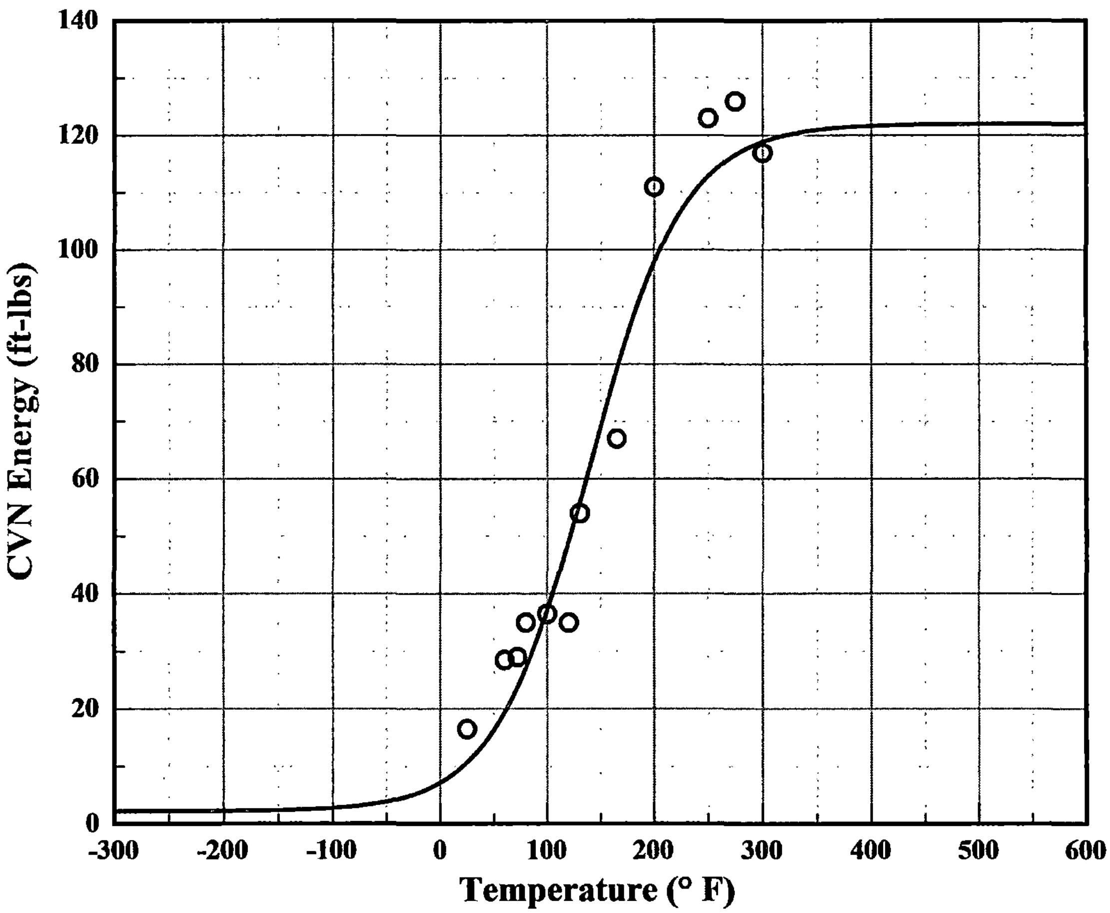
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf Energy = 122.00 (Fixed) Lower Shelf Energy = 2.20 (Fixed)

Temp@30 ft-lbs= 86.20° F Temp@35 ft-lbs= 96.00° F Temp@50 ft-lbs=121.10° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **LT** Capsule: **284°**



CVGraph 6.02 06/10/2016 Page 1/2

Plant: **Arkansas 2**
Orientation: **LT**
Material: **SA533B CL1**
Capsule: **284°**
Heat: **C8182-2**

ANO UNIT 2 CAPSULE 284° (LONGITUDINAL)

Charpy V-Notch Data

Temperature (° F)	Input CVN	Computed CVN	Differential
25	16.5	10.7	5.82
60	28.5	19.4	9.10
72	29.0	23.8	5.22
80	35.0	27.2	7.85
100	36.5	37.2	-0.71
120	35.0	49.3	-14.30
130	54.0	55.9	-1.87
165	67.0	79.0	-12.00
200	111.0	97.7	13.30
250	123.0	112.9	10.13
275	126.0	116.6	9.37
300	117.0	118.9	-1.88

CVGraph 6.02 06/10/2016 Page 2/2

ANO UNIT 2 CAPSULE 284° (LONGITUDINAL)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/20/2016 8:54 AM

A = 51.80 B = 50.80 C = 115.40 T0 = 143.85 D = 0.00

Correlation Coefficient = 0.981

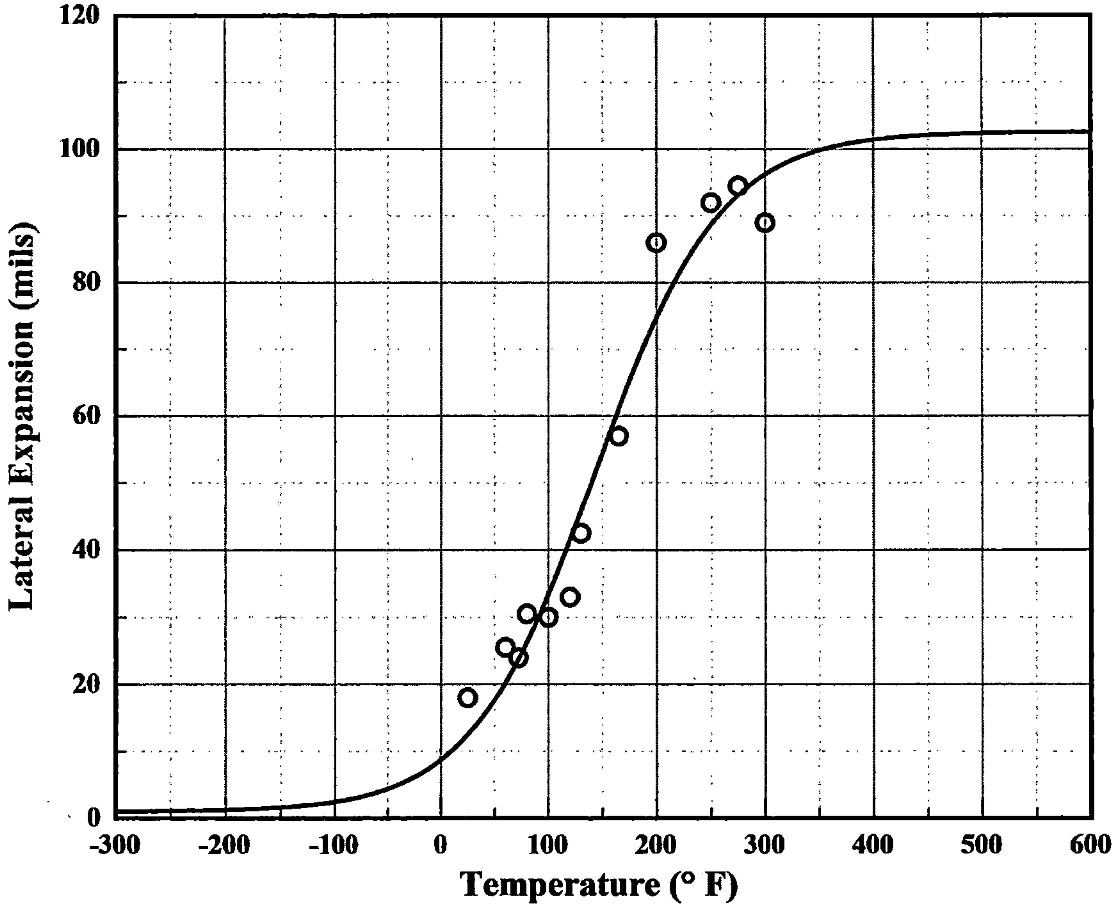
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf L.E. = 102.61* Lower Shelf L.E. = 1.00 (Fixed)

Temp@35 mils=104.20° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **LT** Capsule: **284°**



CVGraph 6.02 06/20/2016 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **LT** Capsule: **284°**

ANO UNIT 2 CAPSULE 284° (LONGITUDINAL)

Charpy V-Notch Data

Temperature (° F)	Input L. E.	Computed L. E.	Differential
25	18.0	12.5	5.51
60	25.5	20.3	5.24
72	24.0	23.7	0.29
80	30.5	26.3	4.25
100	30.0	33.4	-3.38
120	33.0	41.5	-8.45
130	42.5	45.7	-3.24
165	57.0	61.0	-4.01
200	86.0	74.7	11.26
250	92.0*	88.7	3.32
275	94.5*	93.1	1.38
300	89.0*	96.2	-7.24

* CVGraph 6.02 has calculated the upper-shelf LE value to be 102.61 mils. This plot reflects the CVGraph calculated value. However, no data appears near the calculated upper-shelf LE value. Therefore, the summary plot for the Intermediate Shell Plate C-8009-3 (Longitudinal), displaying all capsule results, contains a set value for Capsule 284° upper-shelf LE. The summary plot set value for the upper-shelf LE is the average of the three indicated points.

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ANO UNIT 2 CAPSULE 284° (LONGITUDINAL)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 1:51 PM

A = 50.00 B = 50.00 C = 96.27 T0 = 139.57 D = 0.00

Correlation Coefficient = 0.982

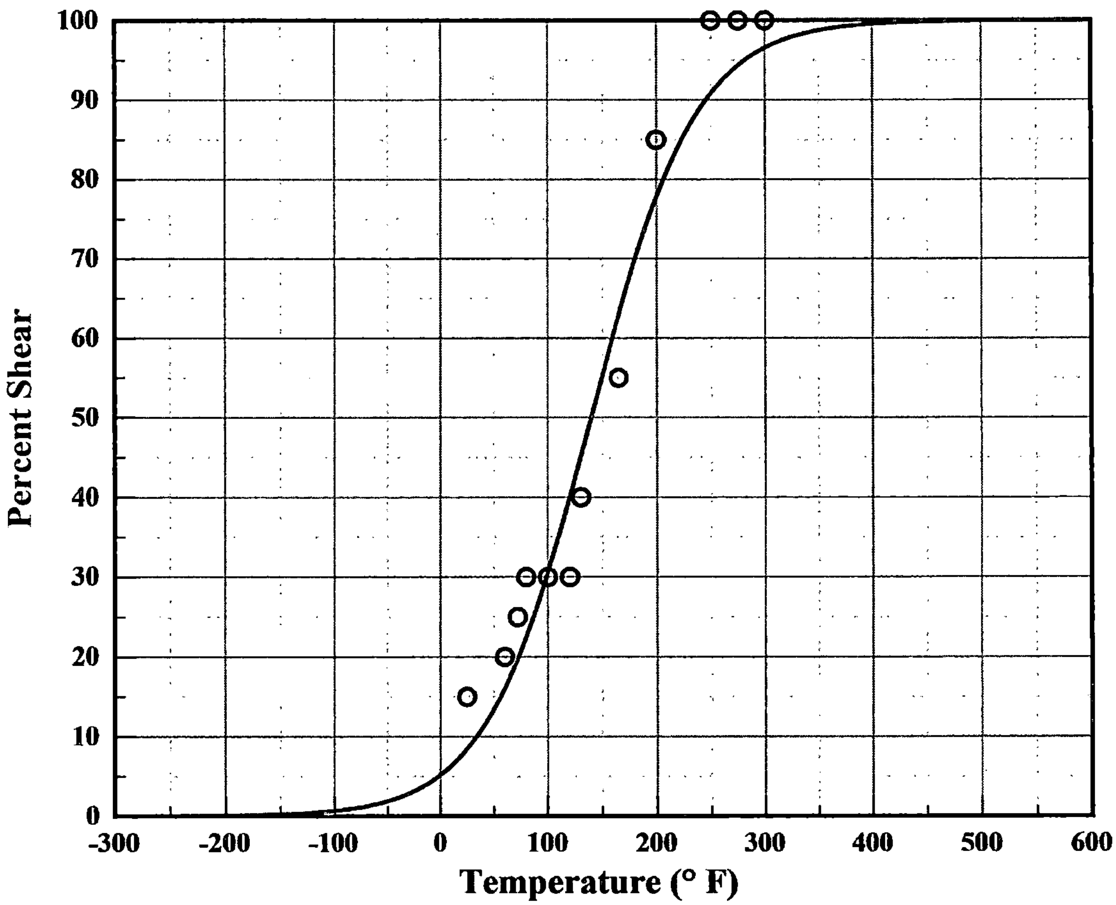
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf %Shear = 100.00 (Fixed) Lower Shelf %Shear = 0.00 (Fixed)

Temperature at 50% Shear = 139.60

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **LT** Capsule: **284°**



CVGraph 6.02 06/10/2016 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **LT** Capsule: **284°**

ANO UNIT 2 CAPSULE 284° (LONGITUDINAL)

Charpy V-Notch Data

Temperature (° F)	Input %Shear	Computed %Shear	Differential
25	15.0	8.5	6.53
60	20.0	16.1	3.93
72	25.0	19.7	5.28
80	30.0	22.5	7.51
100	30.0	30.5	-0.53
120	30.0	40.0	-9.97
130	40.0	45.0	-5.05
165	55.0	62.9	-7.91
200	85.0	77.8	7.18
250	100.0	90.8	9.16
275	100.0	94.3	5.66
300	100.0	96.6	3.45

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ANO UNIT 2 CAPSULE 284° (TRANSVERSE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 1:52 PM

A = 55.60 B = 53.40 C = 91.22 T0 = 148.10 D = 0.00

Correlation Coefficient = 0.979

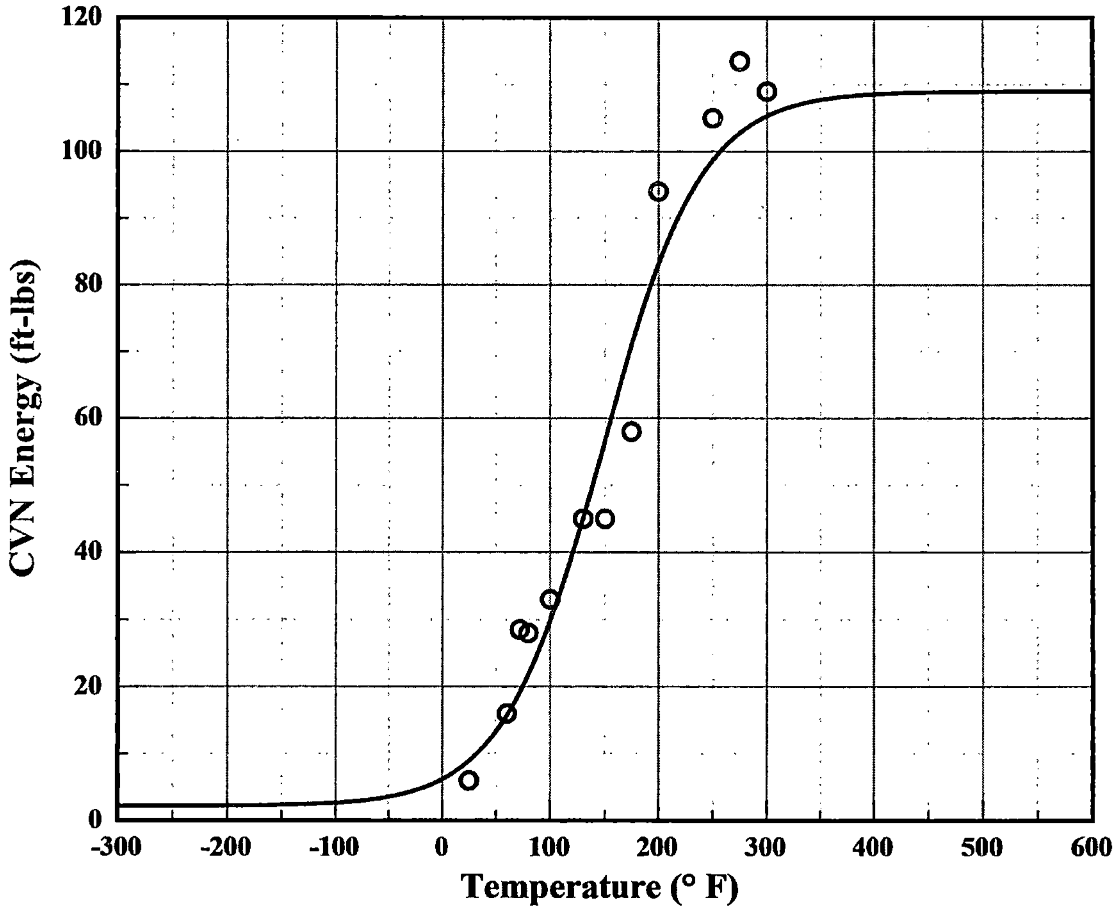
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf Energy = 109.00 (Fixed) Lower Shelf Energy = 2.20 (Fixed)

Temp@30 ft-lbs=100.50° F Temp@35 ft-lbs=111.00° F Temp@50 ft-lbs=138.50° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **TL** Capsule: **284°**



CVGraph 6.02 06/10/2016 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **TL** Capsule: **284°**

ANO UNIT 2 CAPSULE 284° (TRANSVERSE)

Charpy V-Notch Data

Temperature (° F)	Input CVN	Computed CVN	Differential
25	6.0	8.9	-2.93
60	16.0	15.7	0.28
72	28.5	19.1	9.36
80	28.0	21.8	6.21
100	33.0	29.8	3.21
130	45.0	45.1	-0.14
150	45.0	56.7	-11.71
175	58.0	70.9	-12.91
200	94.0	83.1	10.92
250	105.0	98.7	6.33
275	113.5	102.8	10.73
300	109.0	105.3	3.69

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ANO UNIT 2 CAPSULE 284° (TRANSVERSE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/20/2016 9:08 AM

A = 52.58 B = 51.58 C = 134.97 T0 = 164.28 D = 0.00

Correlation Coefficient = 0.988

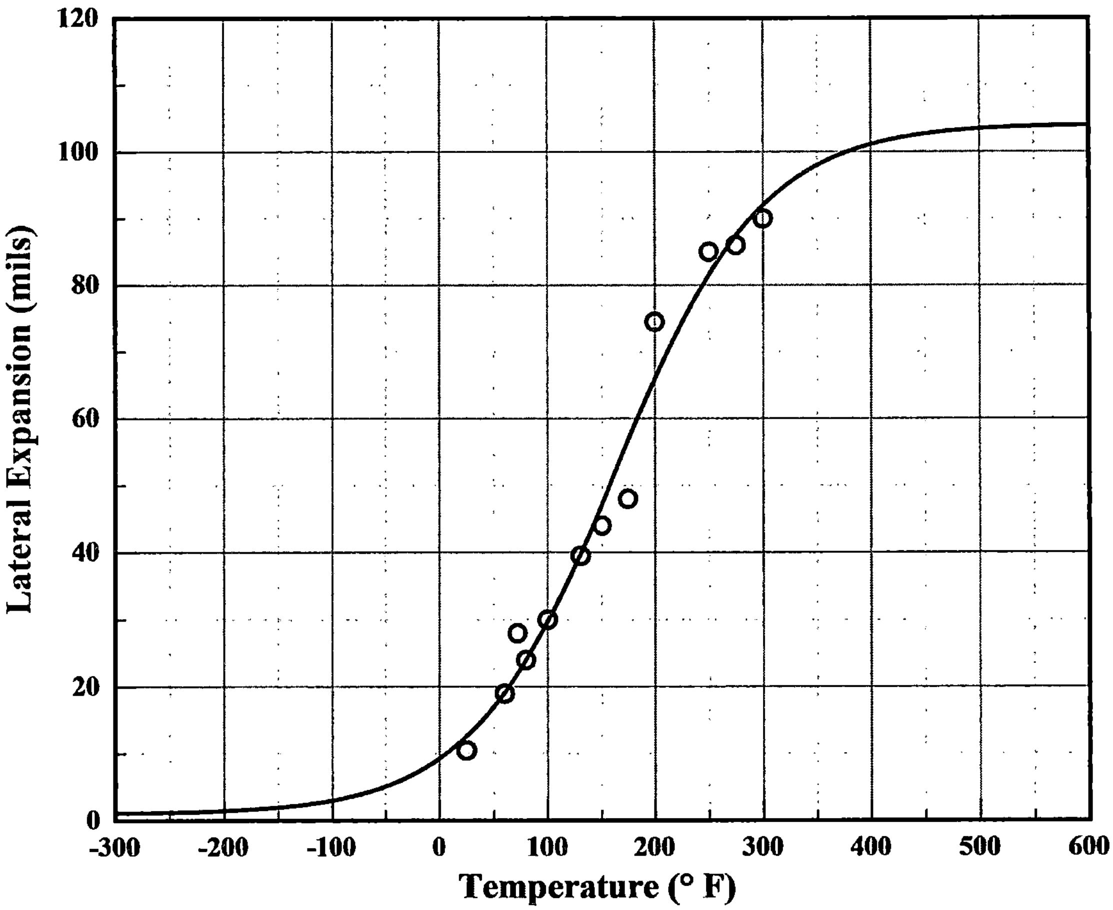
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf L.E. = 104.17* Lower Shelf L.E. = 1.00 (Fixed)

Temp@35 mils=116.40° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **TL** Capsule: **284°**



CVGraph 6.02 06/20/2016 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **TL** Capsule: **284°**

ANO UNIT 2 CAPSULE 284° (TRANSVERSE)

Charpy V-Notch Data

Temperature (° F)	Input L. E.	Computed L. E.	Differential
25	10.5	12.6	-2.12
60	19.0	19.1	-0.13
72	28.0	21.9	6.05
80	24.0	24.0	0.00
100	30.0	29.7	0.28
130	39.5	39.8	-0.26
150	44.0	47.1	-3.15
175	48.0	56.7	-8.67
200	74.5	65.9	8.57
250	85.0*	81.6	3.45
275	86.0*	87.4	-1.42
300	90.0*	92.0	-1.99

* CVGraph 6.02 has calculated the upper-shelf LE value to be 104.17 mils. This plot reflects the CVGraph calculated value. However, no data appears near the calculated upper-shelf LE value. Therefore, the summary plot for the Intermediate Shell Plate C-8009-3 (Transverse), displaying all capsule results, contains a set value for Capsule 284° upper-shelf LE. The summary plot set value for the upper-shelf LE is the average of the three indicated points.

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ANO UNIT 2 CAPSULE 284° (TRANSVERSE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 1:53 PM

A = 50.00 B = 50.00 C = 101.89 T0 = 147.94 D = 0.00

Correlation Coefficient = 0.977

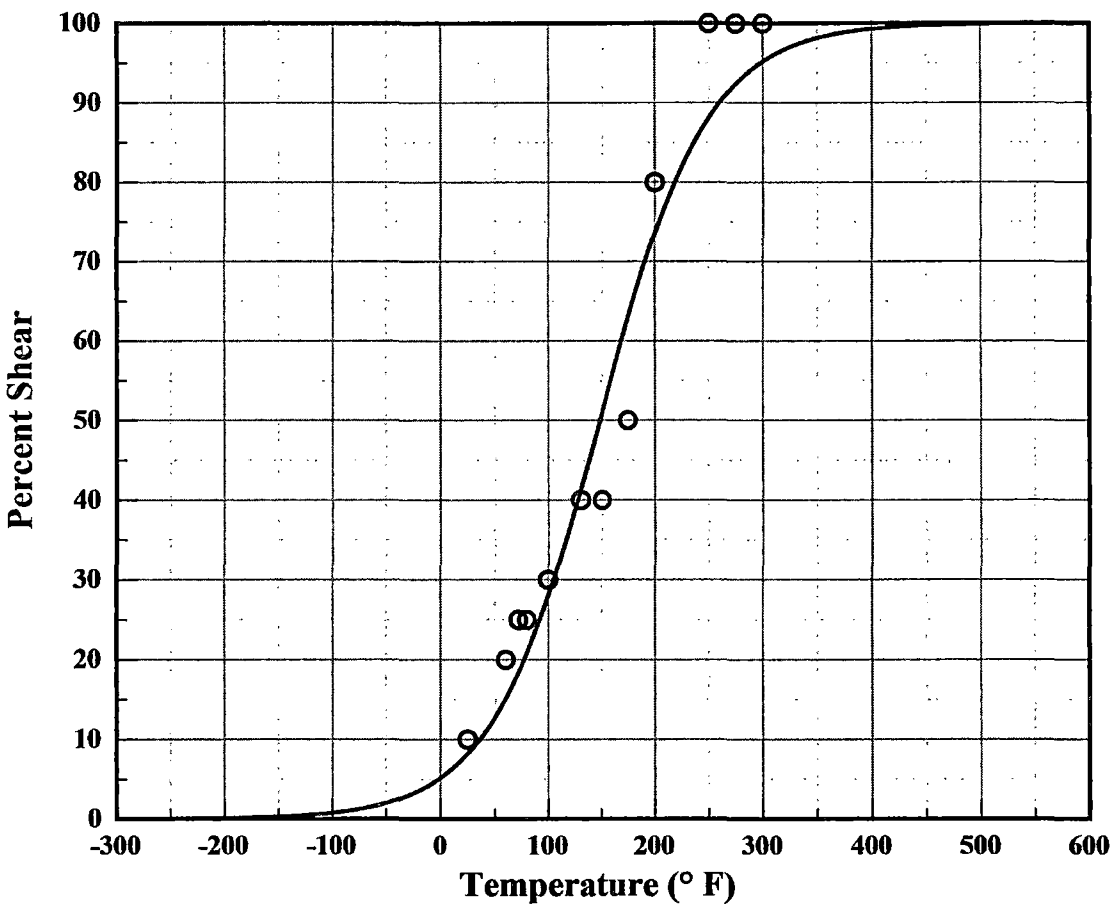
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf %Shear = 100.00 (Fixed)   Lower Shelf %Shear = 0.00 (Fixed)

Temperature at 50% Shear = 148.00

Plant: **Arkansas 2**   Material: **SA533B CL1**   Heat: **C8182-2**

Orientation: **TL**   Capsule: **284°**



CVGraph 6.02   06/10/2016   Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **TL** Capsule: **284°**

ANO UNIT 2 CAPSULE 284° (TRANSVERSE)

Charpy V-Notch Data

Temperature (° F)	Input %Shear	Computed %Shear	Differential
25	10.0	8.2	1.78
60	20.0	15.1	4.89
72	25.0	18.4	6.62
80	25.0	20.9	4.14
100	30.0	28.1	1.93
130	40.0	41.3	-1.29
150	40.0	51.0	-11.01
175	50.0	63.0	-12.98
200	80.0	73.5	6.47
250	100.0	88.1	11.88
275	100.0	92.4	7.63
300	100.0	95.2	4.81

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ANO UNIT 2 CAPSULE 284° (WELD)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 1:55 PM

A = 67.10 B = 64.90 C = 76.02 T0 = 57.59 D = 0.00

Correlation Coefficient = 0.907

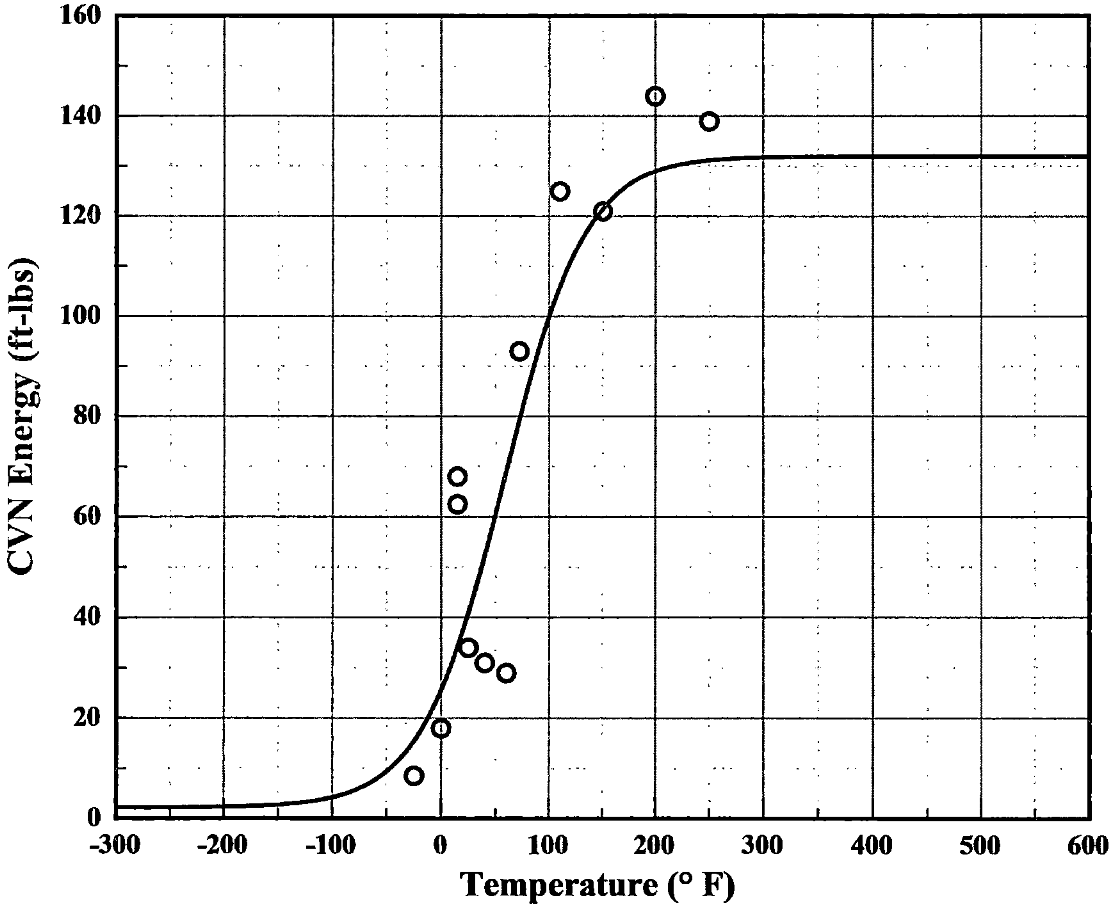
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf Energy = 132.00 (Fixed) Lower Shelf Energy = 2.20 (Fixed)

Temp@30 ft-lbs= 8.20° F Temp@35 ft-lbs= 16.40° F Temp@50 ft-lbs= 37.10° F

Plant: **Arkansas 2** Material: **WELD** Heat: **83650**

Orientation: **N/A** Capsule: **284°**



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Plant: **Arkansas 2** Material: **WELD** Heat: **83650**
Orientation: N/A Capsule: **284°**

ANO UNIT 2 CAPSULE 284° (WELD)

Charpy V-Notch Data

Temperature (° F)	Input CVN	Computed CVN	Differential
-25	8.5	15.5	-6.97
0	18.0	25.6	-7.59
15	62.5	34.1	28.38
15	68.0	34.1	33.88
25	34.0	40.9	-6.86
40	31.0	52.3	-21.34
60	29.0	69.2	-40.15
72	93.0	79.3	13.75
110	125.0	105.9	19.12
150	121.0	121.5	-0.51
200	144.0	129.0	14.99
250	139.0	131.2	7.82

CVGraph 6.02 06/10/2016 Page 2/2

ANO UNIT 2 CAPSULE 284° (WELD)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/20/2016 9:16 AM

A = 51.85 B = 50.85 C = 92.44 T0 = 49.55 D = 0.00

Correlation Coefficient = 0.913

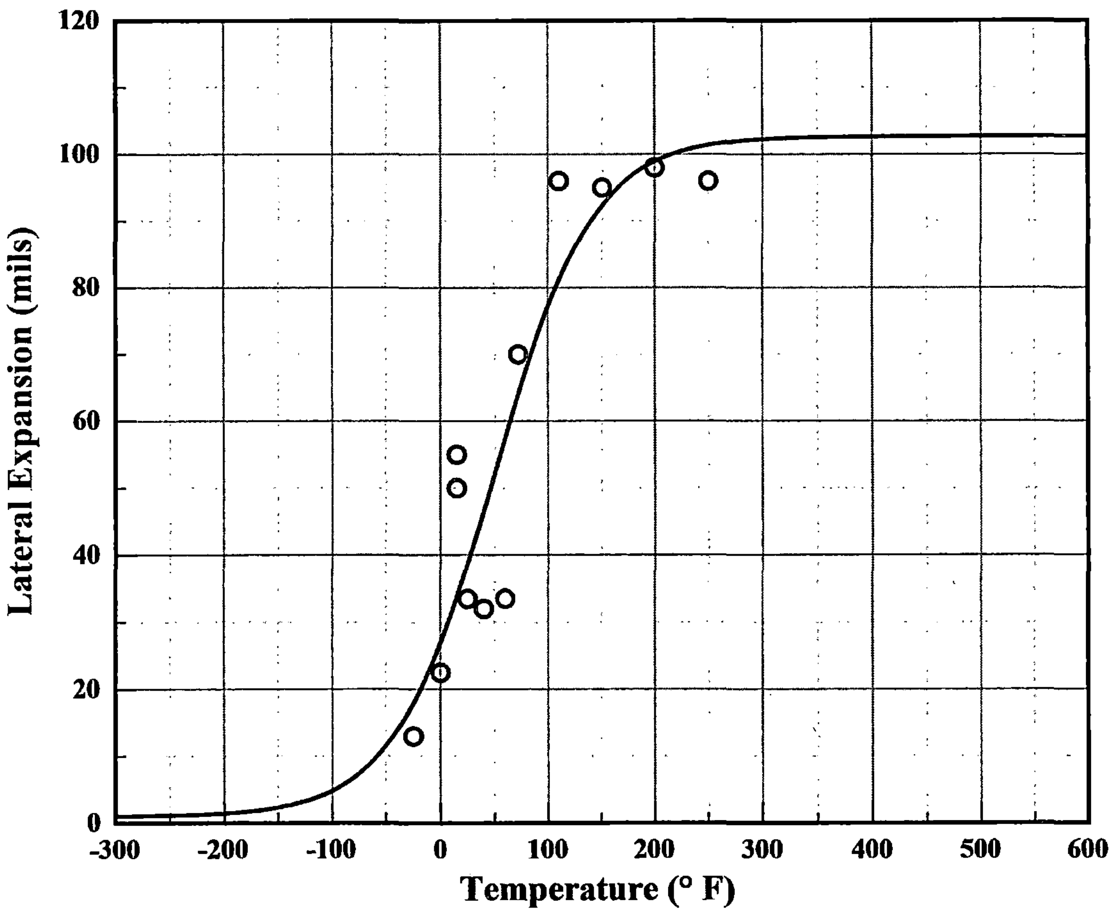
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf L.E. = 102.70* Lower Shelf L.E. = 1.00 (Fixed)

Temp@35 mils= 17.80° F

Plant: **Arkansas 2** Material: **WELD** Heat: **83650**

Orientation: **N/A** Capsule: **284°**



CVGraph 6.02 06/20/2016 Page 1/2

Plant: **Arkansas 2** Material: **WELD** Heat: **83650**
Orientation: N/A Capsule: **284°**

ANO UNIT 2 CAPSULE 284° (WELD)

Charpy V-Notch Data

Temperature (° F)	Input L. E.	Computed L. E.	Differential
-25	13.0	17.9	-4.90
0	22.5	26.9	-4.43
15	50.0	33.7	16.32
15	55.0	33.7	21.32
25	33.5	38.7	-5.15
40	32.0	46.6	-14.62
60	33.5	57.6	-24.07
72	70.0	64.0	6.04
110	96.0*	81.1	14.94
150	95.0*	92.3	2.69
200	98.0*	98.9	-0.92
250	96.0*	101.4	-5.39

* CVGraph 6.02 has calculated the upper-shelf LE value to be 102.70 mils. This plot reflects the CVGraph calculated value. However, no data appears near the calculated upper-shelf LE value. Therefore, the summary plot for the Surveillance Program Weld Metal, displaying all capsule results, contains a set value for Capsule 284° upper-shelf LE. The summary plot set value for the upper-shelf LE is the average of the four indicated points.

CVGraph 6.02 06/20/2016 Page 2/2

ANO UNIT 2 CAPSULE 284° (WELD)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 1:57 PM

A = 50.00 B = 50.00 C = 86.91 T0 = 29.45 D = 0.00

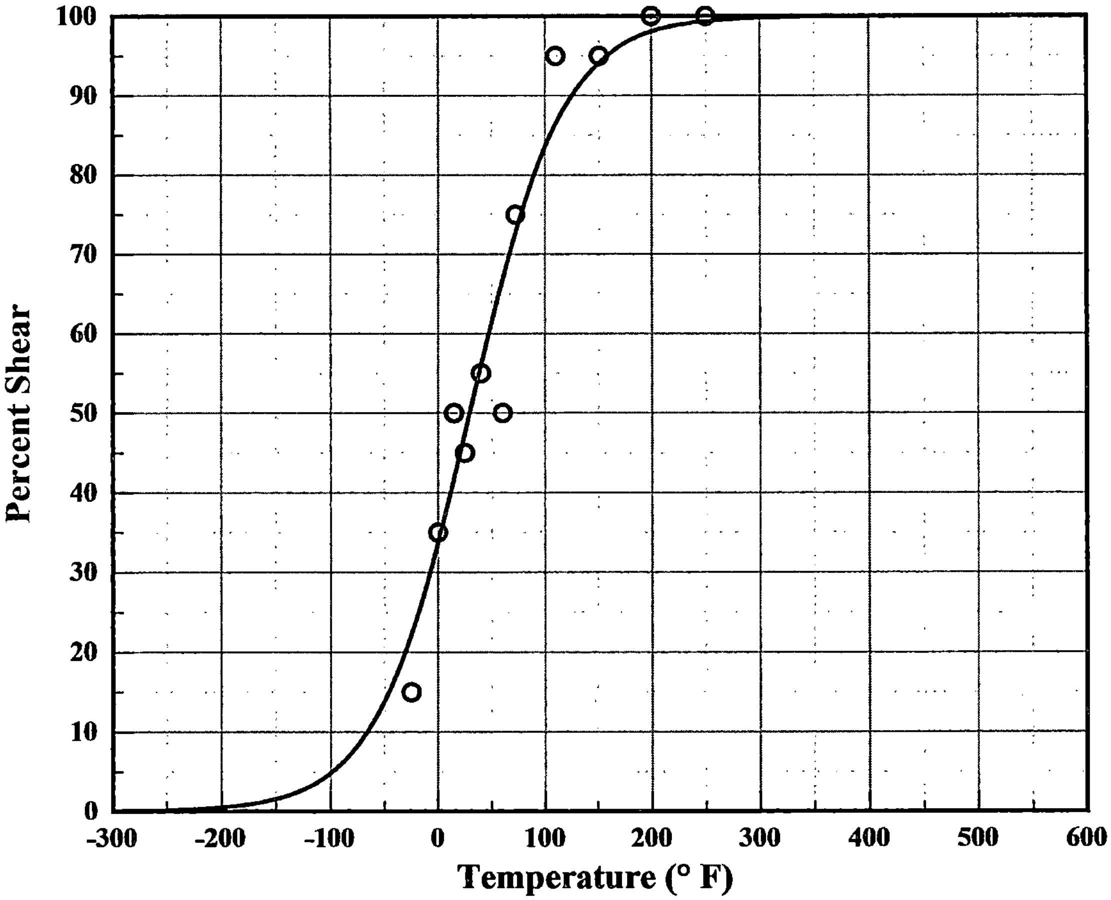
Correlation Coefficient = 0.968

Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf %Shear = 100.00 (Fixed) Lower Shelf %Shear = 0.00 (Fixed)

Temperature at 50% Shear = 29.50

Plant: **Arkansas 2** Material: **WELD** Heat: **83650**
Orientation: **N/A** Capsule: **284°**



CVGraph 6.02 06/10/2016 Page 1/2

Plant: **Arkansas 2** Material: **WELD** Heat: **83650**
Orientation: N/A Capsule: **284°**

ANO UNIT 2 CAPSULE 284° (WELD)

Charpy V-Notch Data

Temperature (° F)	Input %Shear	Computed %Shear	Differential
-25	15.0	22.2	-7.22
0	35.0	33.7	1.33
15	50.0	41.8	8.24
15	50.0	41.8	8.24
25	45.0	47.4	-2.44
40	55.0	56.0	-1.04
60	50.0	66.9	-16.89
72	75.0	72.7	2.31
110	95.0	86.5	8.54
150	95.0	94.1	0.87
200	100.0	98.1	1.94
250	100.0	99.4	0.62

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ANO UNIT 2 CAPSULE 284° (HEAT-AFFECTED ZONE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 1:58 PM

A = 72.10 B = 69.90 C = 104.33 T0 = 16.28 D = 0.00

Correlation Coefficient = 0.957

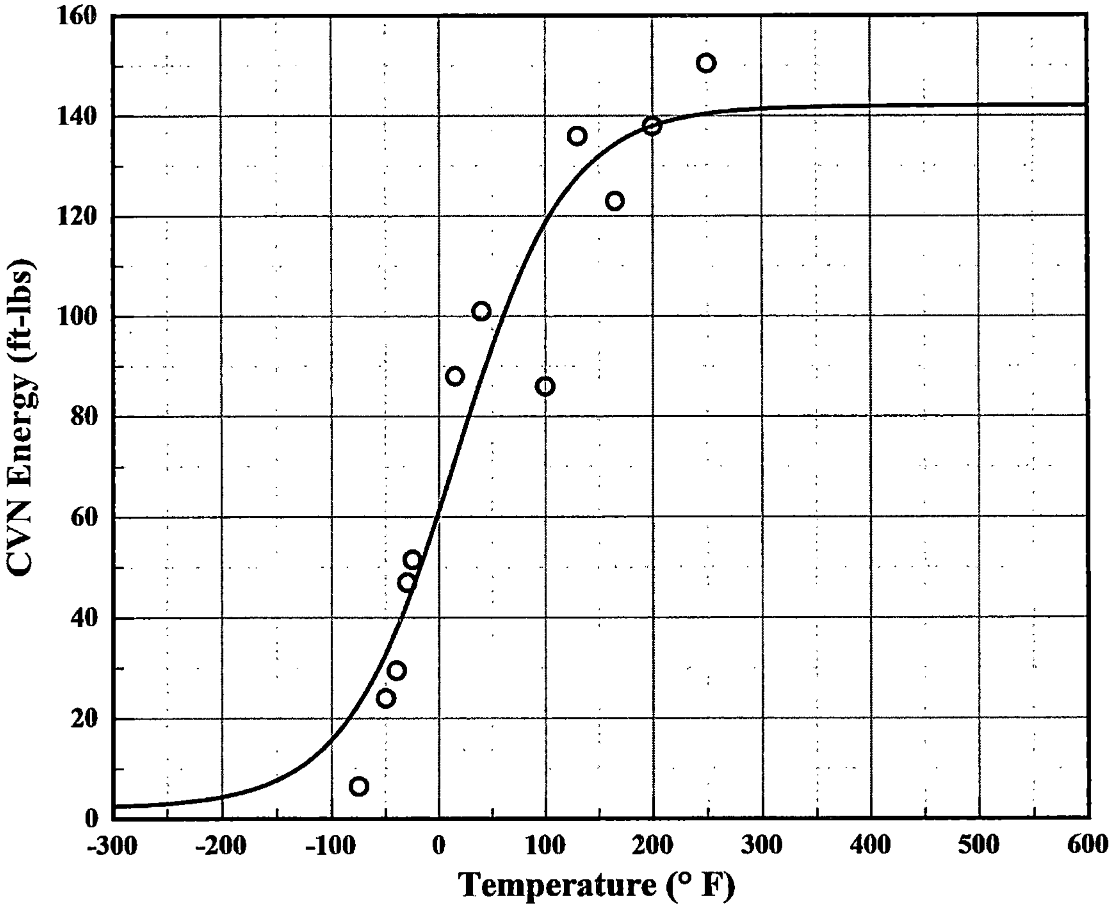
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf Energy = 142.00 (Fixed) Lower Shelf Energy = 2.20 (Fixed)

Temp@30 ft-lbs=-56.40° F Temp@35 ft-lbs=-45.30° F Temp@50 ft-lbs=-17.80° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **N/A** Capsule: **284°**



CVGraph 6.02 06/10/2016 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **N/A** Capsule: **284°**

ANO UNIT 2 CAPSULE 284° (HEAT-AFFECTED ZONE)

Charpy V-Notch Data

Temperature (° F)	Input CVN	Computed CVN	Differential
-75	6.5	22.9	-16.40
-50	24.0	32.8	-8.84
-40	29.5	37.7	-8.17
-30	47.0	43.0	4.02
-25	51.5	45.8	5.70
15	88.0	71.2	16.76
40	101.0	87.7	13.28
100	86.0	118.6	-32.61
130	136.0	127.8	8.20
165	123.0	134.4	-11.36
200	138.0	138.0	0.01
250	150.5	140.4	10.07

CVGraph 6.02 06/10/2016 Page 2/2

ANO UNIT 2 CAPSULE 284° (HEAT-AFFECTED ZONE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 1:59 PM

A = 42.04 B = 41.04 C = 46.91 T0 = -18.13 D = 0.00

Correlation Coefficient = 0.943

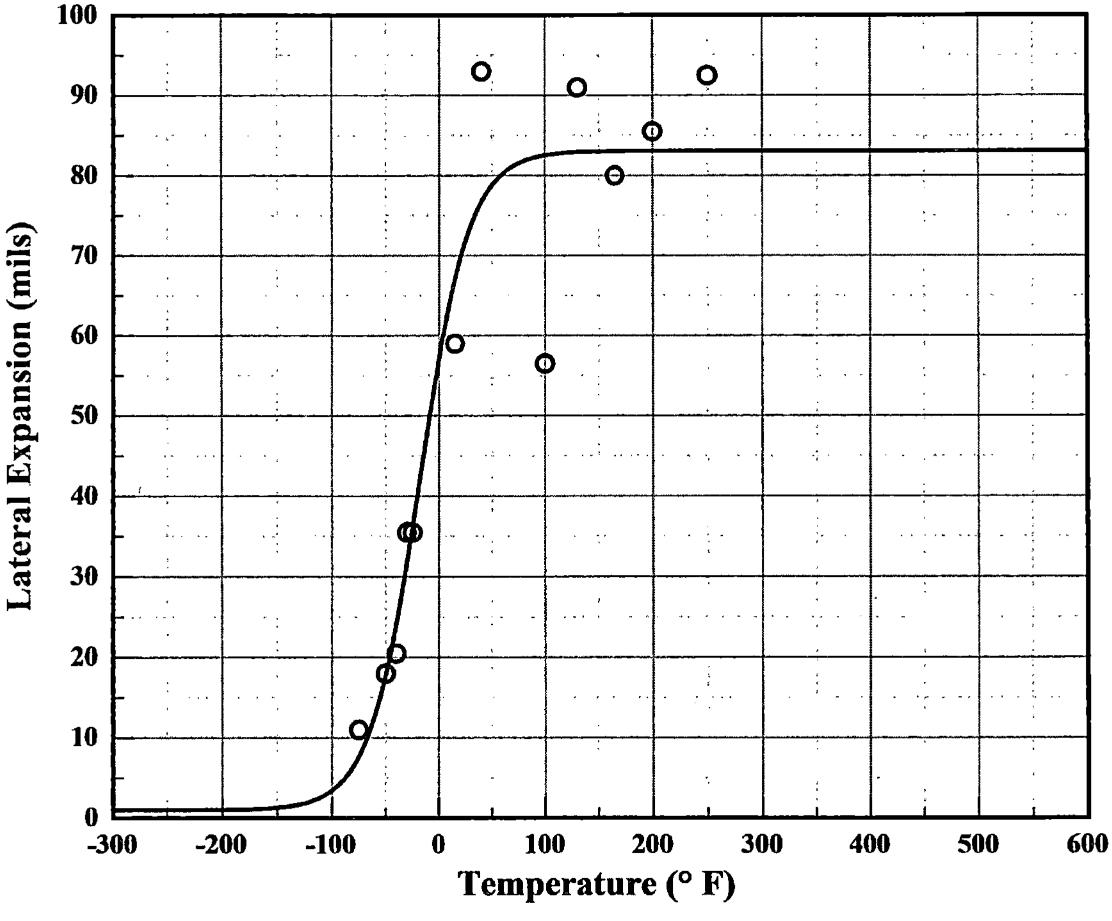
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf L.E. = 83.07 Lower Shelf L.E. = 1.00 (Fixed)

Temp@35 mils=-26.20° F

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **N/A** Capsule: **284°**



CVGraph 6.02 06/10/2016 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **N/A** Capsule: **284°**

ANO UNIT 2 CAPSULE 284° (HEAT-AFFECTED ZONE)

Charpy V-Notch Data

Temperature (° F)	Input L. E.	Computed L. E.	Differential
-75	11.0	7.7	3.33
-50	18.0	17.8	0.22
-40	20.5	24.2	-3.68
-30	35.5	31.9	3.63
-25	35.5	36.1	-0.57
15	59.0	67.0	-8.00
40	93.0	76.7	16.28
100	56.5	82.5	-26.04
130	91.0	82.9	8.08
165	80.0	83.0	-3.04
200	85.5	83.1	2.44
250	92.5	83.1	9.43

CVGraph 6.02 06/10/2016 Page 2/2

ANO UNIT 2 CAPSULE 284° (HEAT-AFFECTED ZONE)

CVGraph 6.02: Hyperbolic Tangent Curve Printed on 6/10/2016 2:00 PM

A = 50.00 **B** = 50.00 **C** = 93.17 **T0** = -7.56 **D** = 0.00

Correlation Coefficient = 0.942

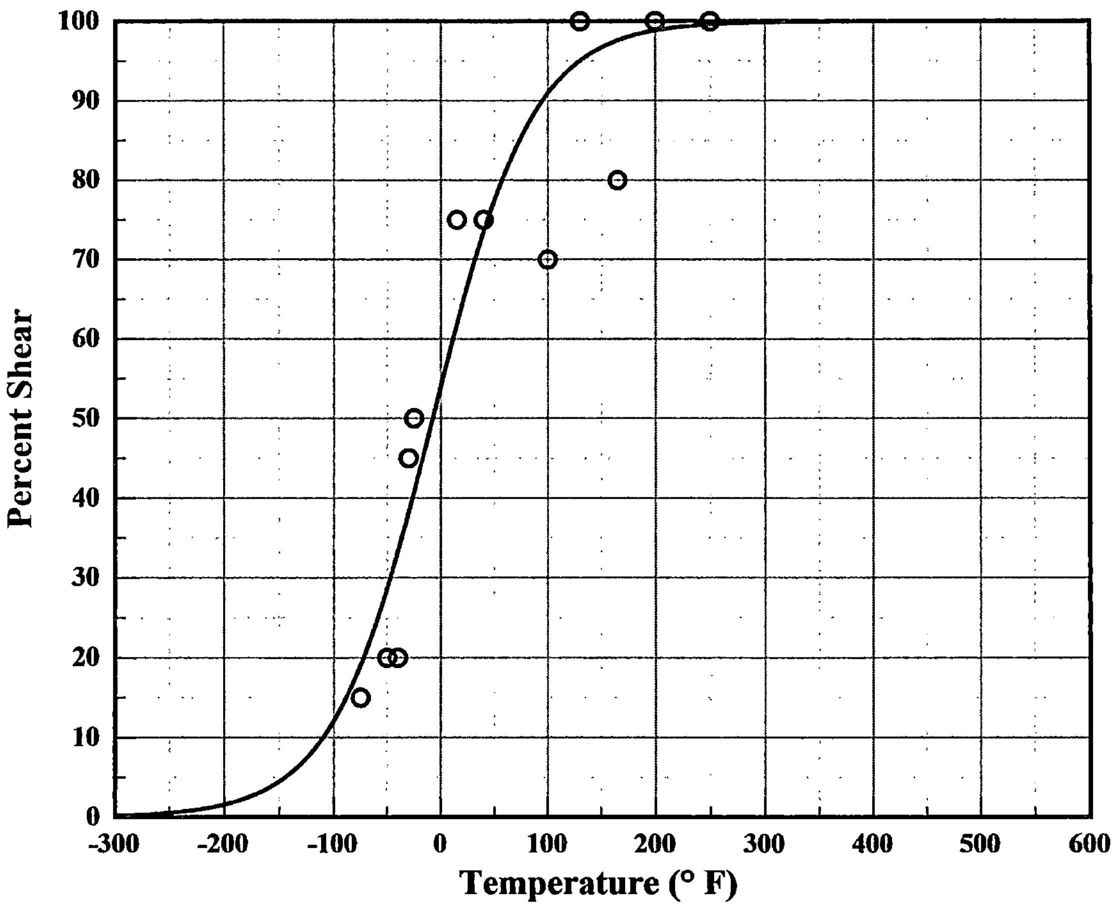
Equation is A + B * [Tanh((T-T0)/(C+DT))]

Upper Shelf %Shear = 100.00 (Fixed) Lower Shelf %Shear = 0.00 (Fixed)

Temperature at 50% Shear = -7.50

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**

Orientation: **N/A** Capsule: **284°**



CVGraph 6.02 06/10/2016 Page 1/2

Plant: **Arkansas 2** Material: **SA533B CL1** Heat: **C8182-2**
Orientation: **N/A** Capsule: **284°**

ANO UNIT 2 CAPSULE 284° (HEAT-AFFECTED ZONE)

Charpy V-Notch Data

Temperature (° F)	Input %Shear	Computed %Shear	Differential
-75	15.0	19.0	-4.04
-50	20.0	28.7	-8.68
-40	20.0	33.3	-13.26
-30	45.0	38.2	6.82
-25	50.0	40.7	9.25
15	75.0	61.9	13.13
40	75.0	73.5	1.49
100	70.0	91.0	-20.96
130	100.0	95.0	4.96
165	80.0	97.6	-17.60
200	100.0	98.9	1.15
250	100.0	99.6	0.40

CVGraph 6.02 06/10/2016 Page 2/2

APPENDIX D ARKANSAS NUCLEAR ONE UNIT 2 SURVEILLANCE PROGRAM CREDIBILITY EVALUATION

D.1 INTRODUCTION

Regulatory Guide 1.99, Revision 2 [Ref. D-1] describes general procedures acceptable to the NRC staff for calculating the effects of neutron radiation embrittlement of the low-alloy steels currently used for light-water-cooled reactor vessels. Position C.2 of Regulatory Guide 1.99, Revision 2, describes the method for calculating the adjusted reference temperature and Charpy upper-shelf energy of reactor vessel beltline materials using surveillance capsule data. The methods of Position C.2 can only be applied when two or more credible surveillance data sets become available from the reactor in question.

To date there have been three surveillance capsules removed and tested from the Arkansas Nuclear One Unit 2 (ANO-2) reactor vessel. To use these surveillance data sets, they must be shown to be credible. In accordance with Regulatory Guide 1.99, Revision 2, the credibility of the surveillance data will be judged based on five criteria.

The purpose of this evaluation is to apply the credibility requirements of Regulatory Guide 1.99, Revision 2, to the ANO-2 reactor vessel surveillance data and determine if that surveillance data is credible.

D.2 EVALUATION

Criterion 1: Materials in the capsules should be those judged most likely to be controlling with regard to radiation embrittlement.

The beltline region of the reactor vessel is defined in Appendix G to 10 CFR Part 50, "Fracture Toughness Requirements" [Ref. D-2], as follows:

> *"the region of the reactor vessel (shell material including welds, heat affected zones, and plates or forgings) that directly surrounds the effective height of the active core and adjacent regions of the reactor vessel that are predicted to experience sufficient neutron radiation damage to be considered in the selection of the most limiting material with regard to radiation damage."*

The ANO-2 reactor vessel beltline region traditionally consists of the following materials:

1. Intermediate Shell Plates C-8009-1, C-8009-2, and C-8009-3
2. Lower Shell Plates C-8010-1, C-8010-2, and C-8010-3
3. Intermediate Shell Longitudinal Welds 2-203A, B, & C (Multiple Heat #'s)
4. Lower Shell Longitudinal Welds 3-203A, B, & C (Heat # 10120, Flux Type Linde 0091)
5. Intermediate to Lower Shell Circumferential Weld 9-203 (Heat # 83650, Flux Type Linde 0091)

Per BAW-2399, Revision 1 [Ref. D-3], the ANO-2 surveillance program was developed to the requirements of ASTM E185-73. At the time of the surveillance program development, all of the beltline plates were considered in terms of irradiation embrittlement through end of life. Of the beltline plates, Intermediate Shell Plate C-8009-3 was foreseen to be the most limiting plate. As determined in CEN-15(A)-P [Ref. D-4], Intermediate Shell Plate C-8009-3 has the highest estimated initial and end of life RT_{NDT} and the lowest initial upper-shelf energy value of the ANO-2 beltline plates. The chemistry values (Cu and Ni weight percent) for the beltline plates are relatively consistent and no plate is clearly differentiated from the rest by its high copper or nickel content. Therefore, Intermediate Shell Plate C-8009-3 was selected as the plate material for the surveillance program.

The beltline welds all have low copper content. Since Intermediate to Lower Shell Circumferential Weld 9-203 (Heat # 83650, Flux Type Linde 0091) has the highest projected fluence in comparison to the other beltline welds, it was selected for the surveillance program. Lastly, selection of the beltline circumferential weld is consistent with the general practice for Combustion Engineering surveillance programs because it was considered representative material.

Based on the discussion above, Criterion 1 is met for the ANO-2 surveillance program.

Criterion 2: Scatter in the plots of Charpy energy versus temperature for the irradiated and unirradiated conditions should be small enough to permit the determination of the 30 ft-lb temperature and upper-shelf energy unambiguously.

Based on engineering judgment, the scatter in the data presented in these plots, as documented in Appendix C, is small enough to permit the determination of the 30 ft-lb temperature and the upper-shelf energy of the ANO-2 surveillance materials unambiguously.

Hence, the ANO-2 surveillance program meets Criterion 2.

Criterion 3: When there are two or more sets of surveillance data from one reactor, the scatter of ΔRT_{NDT} values about a best-fit line drawn as described in Regulatory Position 2.1 normally should be less than 28°F for welds and 17°F for base metal. Even if the fluence range is large (two or more orders of magnitude), the scatter should not exceed twice those values. Even if the data fail this criterion for use in shift calculations, they may be credible for determining decrease in upper-shelf energy if the upper shelf can be clearly determined, following the definition given in ASTM E185-82 [Ref. D-5].

The functional form of the least squares method as described in Regulatory Position 2.1 will be utilized to determine a best-fit line for this data and to determine if the scatter of these ΔRT_{NDT} values about this line is less than 28°F for welds and less than 17°F for the plate.

Following is the calculation of the best-fit line as described in Regulatory Position 2.1 of Regulatory Guide 1.99, Revision 2. In addition, the recommended NRC methods for determining credibility will be followed. The NRC methods were presented to industry at a meeting held by the NRC on February 12 and 13, 1998 [Ref. D-6]. At this meeting, the NRC presented five cases. Of the five cases, Case 1 ("Surveillance data available from plant and no other source") most closely represents the situation for the ANO-2 surveillance plate and weld material.

Case 1: Intermediate Shell Plate C-8009-3 and Weld Heat # 83650

Following the NRC Case 1 guidelines, the ANO-2 surveillance plate and weld metal (Heat # 83650) will be evaluated using the ANO-2 data. This evaluation is contained in Table D-1. Note that when evaluating the credibility of the surveillance weld data, the measured ΔRT_{NDT} values for the surveillance weld material do not include the adjustment ratio procedure of Regulatory Guide 1.99, Revision 2, Position 2.1, since this calculation is based on the actual surveillance weld material measured shift values. In addition, only ANO-2 data is being considered; therefore, no temperature adjustment is required.

Table D-1 Calculation of Interim Chemistry Factors for the Credibility Evaluation Using ANO-2 Surveillance Capsule Data

Material	Capsule	Capsule Fluence (x 10^{19} n/cm^2, E > 1.0 MeV)	FF[(a)]	ΔRT_{NDT}[(b)] (°F)	FF*ΔRT_{NDT} (°F)	FF^2
Intermediate Shell Plate C-8009-3 (Longitudinal)	97°	0.303	0.673	23.5	15.81	0.45
	284°	3.67	1.337	85.7	114.60	1.79
Intermediate Shell Plate C-8009-3 (Transverse)	97°	0.303	0.673	33.4	22.47	0.45
	104°	2.15	1.208	52.9	63.90	1.46
	284°	3.67	1.337	85.6	114.47	1.79
				SUM:	331.26	5.94
	$CF_{C\text{-}8009\text{-}3} = \Sigma(FF * \Delta RT_{NDT}) \div \Sigma(FF^2) = (331.26) \div (5.94) =$ **55.8°F**					
Surveillance Weld Material (Heat #83650)	97°	0.303	0.673	13.2	8.88	0.45
	104°	2.15	1.208	16.1	19.45	1.46
	284°	3.67	1.337	12.0	16.05	1.79
				SUM:	44.38	3.70
	$CF_{Surv.\ Weld} = \Sigma(FF * \Delta RT_{NDT}) \div \Sigma(FF^2) = (44.38) \div (3.70) =$ **12.0°F**					

Notes:

(a) FF = fluence factor = $f^{(0.28 - 0.10*\log(f))}$ per Regulatory Guide 1.99, Revision 2 [Ref. D-1].

(b) ΔRT_{NDT} values are the measured 30 ft-lb shift values taken from Table 5-10.

The scatter of ΔRT_{NDT} values about the functional form of a best-fit line drawn as described in Regulatory Position 2.1 is presented in Table D-2.

Table D-2 ANO-2 Surveillance Capsule Data Scatter about the Best-Fit Line

Material	Capsule	CF ($Slope_{best-fit}$) (°F)	Capsule Fluence (x 10^{19} n/cm^2)	FF	Measured ΔRT_{NDT} (°F)	Predicted ΔRT_{NDT} (°F)	Scatter ΔRT_{NDT} (°F)	<17°F (Base Metal) <28°F (Weld)
Intermediate Shell Plate C-8009-3 (Longitudinal)	97°	55.8	0.303	0.673	23.5	37.5	14.0	Yes
	284°	55.8	3.67	1.337	85.7	74.6	11.1	Yes
Intermediate Shell Plate C-8009-3 (Transverse)	97°	55.8	0.303	0.673	33.4	37.5	4.1	Yes
	104°	55.8	2.15	1.208	52.9	67.4	14.5	Yes
	284°	55.8	3.67	1.337	85.6	74.6	11.0	Yes
Surveillance Weld Material (Heat # 83650)	97°	12.0	0.303	0.673	13.2	8.1	5.1	Yes
	104°	12.0	2.15	1.208	16.1	14.5	1.6	Yes
	284°	12.0	3.67	1.337	12.0	16.0	4.0	Yes

From a statistical point of view, +/- 1σ would be expected to encompass 68% of the data. Table D-2 indicates that all five of the five surveillance data points fall inside the +/- 1σ of 17°F scatter band for surveillance base metal; therefore, the plate data is deemed "credible" per the third criterion.

Table D-2 indicates that all three of the three surveillance data points fall inside the +/- 1σ of 28°F scatter band for surveillance weld material; therefore, the surveillance weld data is deemed "credible" per the third criterion.

Criterion 4: The irradiation temperature of the Charpy specimens in the capsule should match the vessel wall temperature at the cladding/base metal interface within +/- 25°F.

The surveillance materials are contained in capsules positioned near the reactor vessel inside wall so that the irradiation conditions (fluence, flux spectrum, temperature) of the test specimens resemble, as closely as possible, the irradiation conditions of the reactor vessel. The capsules are bisected by the midplane of the core and are placed in capsule holders positioned circumferentially about the core at locations near the regions of maximum flux. The location of the specimens with respect to the reactor vessel beltline provides assurance that the reactor vessel wall and the specimens experience equivalent operating conditions such that the temperatures will not differ by more than 25°F.

Hence, Criterion 4 is met for the ANO-2 surveillance program.

Criterion 5: The surveillance data for the correlation monitor material in the capsule should fall within the scatter band of the database for that material.

The ANO-2 surveillance program does contain Standard Reference Material (SRM). The material was obtained from an A533 Grade B, Class 1 plate (HSST Plate 01). NUREG/CR-6413, ORNL/TM-13133 [Ref. D-7] contains a plot of Residual vs. Fast Fluence for the SRM (Figure 11 in the report). This Figure shows a 2σ uncertainty of 50°F. The data used for this plot is contained in Table 14 in the report. However, the NUREG Report does not consider the recalculated fluence and ΔRT_{NDT} values for Capsule 104°. Thus, Table D-3 contains an updated calculation of Residual vs. Fast Fluence, considering the recalculated capsule fluence and ΔRT_{NDT} values for Capsule 104°.

Table D-3 Calculation of Residual vs. Fast Fluence for ANO-2

Capsule	Capsule fluence (x 10^{19} n/cm^2, E > 1.0 MeV)	FF	Measured Shift[(a)] (°F)	RG 1.99, Rev. 2[(b)] Shift (°F)	Residual[(c)] (°F)
104°	2.15	1.208	132.3	164.4	32.1

Notes:

(a) The measured ΔT_{30} value for the SRM was taken from Section 5.

(b) Per NUREG/CR-6413, ORNL/TM-13133, the Cu and Ni values for the SRM (HSST Plate 01) are 0.18 and 0.66, respectively. This equates to a chemistry factor value of 136.1°F based on Regulatory Guide 1.99, Revision 2, Position 1.1. The calculated shift is thus equal to CF * FF.

(c) Residual = Absolute Value [Measured Shift – RG 1.99 Shift].

Table D-3 shows a 2σ uncertainty of less than 50°F, which is the allowable scatter in NUREG/CR-6413, ORNL/TM-13133 [Ref. D-7].

Hence, Criterion 5 is met for the ANO-2 surveillance program.

D.3 CONCLUSION

Based on the preceding responses to all five criteria of Regulatory Guide 1.99, Revision 2, Section B:

- The ANO-2 surveillance plate data are deemed "credible"
- The ANO-2 surveillance weld data are deemed "credible"

D.4 REFERENCES

D-1 U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Regulatory Guide 1.99, Revision 2, *Radiation Embrittlement of Reactor Vessel Materials,* May 1988.

D-2 Code of Federal Regulations, 10 CFR 50, Appendix G, *Fracture Toughness Requirements,* Federal Register, Volume 60, No. 243, December 19, 1995.

D-3 AREVA, NP Inc. Report BAW-2399, Revision 1, *Analysis of Capsule W-104 Entergy Operations, Inc. Arkansas Nuclear One Unit 2 Power Plant Reactor Vessel Material Surveillance Program,* February 2005.

D-4 Combustion Engineering Report CEN-15(A)-P, *Summary Report on Manufacture of Test Specimens and Assembly of Capsules for Irradiation Surveillance of Arkansas Nuclear One – Unit 2 Reactor Vessel Materials,* May 1975.

D-5 ASTM E185-82, *Standard Practice for Conducting Surveillance Tests for Light-Water Cooled Nuclear Power Reactor Vessels, E706 (IF),* 1982.

D-6 K. Wichman, M. Mitchell, and A. Hiser, USNRC, Generic Letter 92-01 and RPV Integrity Workshop Handouts, *NRC/Industry Workshop on RPV Integrity Issues,* February 12, 1998, Agencywide Document Access and Management System (ADAMS) Accession Number ML110070570.

D-7 NUREG/CR-6413; ORNL/TM-13133, *Analysis of the Irradiation Data for A302B and A533B Correlation Monitor Materials,* April 1996.

APPENDIX E ARKANSAS NUCLEAR ONE UNIT 2 UPPER-SHELF ENERGY EVALUATION

E.1 EVALUATION

Per U.S. Regulatory Guide 1.99, Revision 2 [Ref. E-1], the Charpy upper-shelf energy (USE) is assumed to decrease as a function of fluence and copper content as indicated in Figure 2 of the Guide (Figure E-1 of this appendix) when surveillance data is not used. Linear interpolation is permitted. In addition, if surveillance data is to be used, the decrease in USE may be obtained by plotting the reduced plant surveillance data on Figure 2 of the Guide (Figure E-1 of this appendix) and fitting the data with a line drawn parallel to the existing lines as the upper bound of all the data. This line should be used in preference to the existing graph.

The end-of-license (32 effective full-power years [EFPY]) USE of the vessel materials can be predicted using the corresponding quarter-thickness (1/4T) fluence projection, the copper content of the beltline materials and/or the results of the capsules tested to date using Figure 2 in Regulatory Guide 1.99, Revision 2 [Ref. E-1].

The ANO-2 reactor vessel beltline region thickness is 7.875 inches per Reference E-2. Calculation of the 1/4T vessel fluence values at 32 EFPY for the beltline materials is shown in Table E-1. The following pages present the ANO-2 USE evaluation. Figure E-1, as indicated above, is used in making predictions in accordance with Regulatory Guide 1.99, Revision 2 [Ref. E-1]. Table E-2 provides the predicted USE values for 32 EFPY (end-of-license).

Table E-1 ANO-2 Beltline 1/4T Fast Neutron Fluence Calculation

Material	32 EFPY Fluence (x 10^{19} n/cm^2, E > 1.0 MeV)	
	Surface	1/4T[(a)]
Intermediate Shell Plate C-8009-1	3.02	1.88
Intermediate Shell Plate C-8009-2	3.02	1.88
Intermediate Shell Plate C-8009-3	3.02	1.88
Lower Shell Plate C-8010-1	3.02	1.88
Lower Shell Plate C-8010-2	3.02	1.88
Lower Shell Plate C-8010-3	3.02	1.88
Intermediate Shell Longitudinal Welds 2-203A, B, & C (Heat # Multiple)	2.89	1.80
Lower Shell Longitudinal Welds 3-203A, B, & C (Heat # 10120)	2.89	1.80
Intermediate to Lower Shell Girth Weld 9-203 (Heat # 83650)	3.00	1.87

Note:

(a) 1/4T fluence values were calculated from the surface fluence, the reactor vessel beltline thickness (7.875 inches) and equation $f = f_{surf} * e^{-0.24\,(x)}$ from Regulatory Guide 1.99, Revision 2, where x = the depth into the vessel wall (inches).

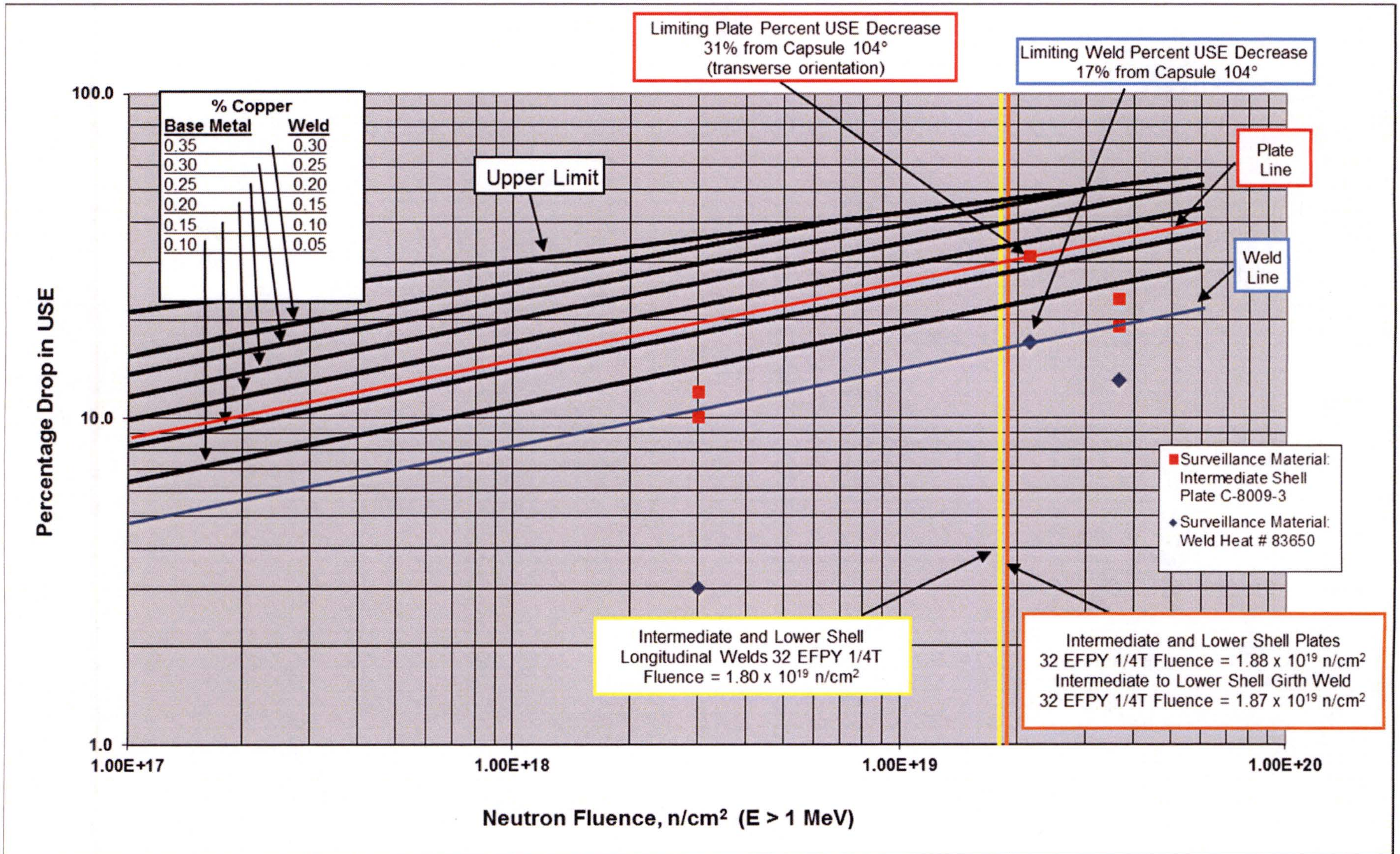


Figure E-1 **Regulatory Guide 1.99, Revision 2 Predicted Decrease in Upper-Shelf Energy as a Function of Copper and Fluence**

Table E-2 Predicted Positions 1.2 and 2.2 Upper-Shelf Energy Values at 32 EFPY

Material	Weight % Cu	1/4T EOLE Fluence (x 10^{19} n/cm^2, E > 1.0 MeV)	Unirradiated USE (ft-lb)	Projected USE Decrease (%)	Projected EOL USE[b] (ft-lb)
Position 1.2[a]					
Intermediate Shell Plate C-8009-1	0.098	1.88	95	22.0	74
Intermediate Shell Plate C-8009-2	0.085	1.88	93	22.0	73
Intermediate Shell Plate C-8009-3	0.096	1.88	134	22.0	105
Lower Shell Plate C-8010-1	0.085	1.88	89	22.0	69
Lower Shell Plate C-8010-2	0.083	1.88	94	22.0	73
Lower Shell Plate C-8010-3	0.080	1.88	97	22.0	76
Intermediate Shell Longitudinal Weld 2-203A, B, & C[c] (Heat # Multiple)	0.050	1.80	110	22.0	86
Lower Shell Longitudinal Weld 3-203A, B, & C (Heat # 10120)	0.046	1.80	125	22.0	98
Intermediate to Lower Shell Girth Weld 9-203 (Heat # 83650)	0.045	1.87	136	22.0	106
Position 2.2[d]					
Intermediate Shell Plate C-8009-3	0.096	1.88	134	30.0	94
Intermediate to Lower Shell Girth Weld 9-203 (Heat # 83650)	0.045	1.87	136	17.0	113

Notes:

(a) Calculated using the Cu wt. % values and 1/4T fluence value for each material and Regulatory Guide 1.99, Revision 2, Position 1.2. In calculating Position 1.2 percent USE decreases, the base metal and weld Cu weight percentages were conservatively rounded up to the nearest line in Regulatory Guide 1.99, Revision 2, Figure 2.

(b) The initial USE values for the beltline materials have been updated from those documented in previous analyses using all available Certified Material Test Report (CMTR) data and the USE calculation methodology described in Appendix C.

(c) A review of the ANO-2 fabrication records indicated that the intermediate shell longitudinal welds were fabricated using multiple different weld heats. The material properties used herein for these welds represent the limiting values considering all of the applicable intermediate shell longitudinal weld heats.

(d) Calculated using surveillance capsule measured percent decrease in USE from Table 5-10 and Regulatory Guide 1.99, Revision 2, Position 2.2; see Figure E-1.

USE Conclusion

As shown in Table E-2, all of the ANO-2 reactor vessel beltline materials are projected to remain above the USE screening criterion of 50 ft-lbs (per 10 CFR 50, Appendix G [Ref. E-3]) at 32 EFPY.

E.2 REFERENCES

E-1 U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Regulatory Guide 1.99, Revision 2, *Radiation Embrittlement of Reactor Vessel Materials*, May 1988.

E-2 AREVA NP, Inc. Report BAW-2405, Revision 3, *Appendix G Pressure-Temperature Limits for 32 EFPY, using ASME Code Cases, for Arkansas Nuclear One Unit 2 Power Plant,* May 2005.

E-3 Code of Federal Regulations, 10 CFR 50, Appendix G, *Fracture Toughness Requirements*, Federal Register, Volume 60, No. 243, December 19, 1995.