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Analysis of Capsule 230° from Arizona Public Service Company Palo Verde Unit 2 Reactor Vessel Radiation Surveillance Program

Westinghouse

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February 2006

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PREFACE

This report has been technically reviewed and verified by:

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RECORD OF REVISIONS

Revision 0: Original Issue

TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES (cont.)

LIST OF FIGURES

LIST OF FIGURES (cont.)

EXECUTIVE SUMMARY

The purpose of this report is to document the results of the testing of surveillance capsule 230° from Palo Verde Unit 2. Capsule 230° was removed at 14.35 EFPY and post irradiation mechanical tests of the Charpy V-notch and tensile specimens were performed, along with a fluence evaluation based methodology and nuclear data including recently released neutron transport and dosimetry cross-section libraries derived from the ENDF/B-VI database. The calculated peak clad base/metal vessel fluence after 14.35 EFPY of plant operation was 7.14 x 10^{18} n/cm^2 and the surveillance capsule 230° calculated fluence was 9.92 x 10^{18} n/cm^2.

This evaluation led to the following conclusions: 1) The measured 30 ft-lb shift in transition temperature value of the Lower Shell Plate F-773-1 contained in capsule 230° (*Longitudinal*) is less than the Regulatory Guide 1.99, Revision 2 (Reference 1), Position 1.1 prediction. 2) The measured 30 ft-lb shift in transition temperature value of the Lower Shell Plate F-773-1 contained in capsule 230° (*Transverse*) is less than the Regulatory Guide 1.99, Revision 2, Position 1.1 prediction. 3) The measured 30 ft-lb shift in transition temperature value of the weld metal contained in capsule 230° is less than the Regulatory Guide 1.99, Revision 2, Position 1.1 prediction. 4) The measured percent decrease in upper shelf energy for these same Capsule 230° surveillance materials contained in the Palo Verde Unit 2 surveillance program is less than the Regulatory Guide 1.99, Revision 2 Position 1.2 prediction. 5) All beltline materials exhibit a more than adequate upper shelf energy level for continued safe plant operation and are predicted to maintain an upper shelf energy greater than 50 ft-lb throughout the current license (32 EFPY) as required by 10CFR50, Appendix G (Reference 2). 6) The Palo Verde Unit 2 lower shell surveillance plate and weld data was found to be “credible.” The credibility evaluation can be found in Appendix D.

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 230°, the second capsule to be removed from the Palo Verde Unit 2 reactor pressure vessel, led to the following conclusions:

- The capsule received an average fast neutron calculated fluence (E > 1.0 MeV) of 9.92×10^{18} n/cm^2 after 14.35 effective full power years (EFPY) of plant operation.

- Irradiation of the reactor vessel Lower Shell Plate F-773-1 Charpy specimens, oriented with the longitudinal axis of the specimen parallel to the major working direction of the plate (longitudinal orientation), to 9.92×10^{18} n/cm^2 (E > 1.0MeV) led to a 30 ft-lb transition temperature increase of 17.7°F and a 50 ft-lb transition temperature increase of 24.5°F. This results in an irradiated 30 ft-lb transition temperature of 18.5°F and an irradiated 50 ft-lb transition temperature of 61.6°F for the longitudinally oriented specimens.

- Irradiation of the reactor vessel Lower Shell Plate F-773-1 Charpy specimens, oriented with the longitudinal axis of the specimen normal to the major working direction of the plate (transverse orientation), to 9.92×10^{18} n/cm^2 (E > 1.0 MeV) led to a 30 ft-lb transition temperature increase of 19.3°F and a 50 ft-lb transition temperature increase of 20.8°F. This results in an irradiated 30 ft-lb transition temperature of 20.0°F and an irradiated 50 ft-lb transition temperature of 52.5°F for transversely oriented specimens.

- Irradiation of the weld metal Charpy specimens to 9.92×10^{18} n/cm^2 (E > 1.0 MeV) led to a 30 ft-lb transition temperature increase of 2.5°F and a 50 ft-lb transition temperature increase of 14.0°F. This results in an irradiated 30 ft-lb transition temperature of -37.6°F and an irradiated 50 ft-lb transition temperature of 4.1°F.

- Irradiation of the weld Heat-Affected-Zone (HAZ) metal Charpy specimens to 9.92×10^{18} n/cm^2 (E > 1.0 MeV) led to a 30 ft-lb transition temperature increase of 46.3°F and a 50 ft-lb transition temperature increase of 19.8°F. This results in an irradiated 30 ft-lb transition temperature of -35.0°F and an irradiated 50 ft-lb transition temperature of 79.0°F.

- Irradiation of the standard reference material Charpy specimens to 9.92×10^{18} n/cm^2 (E > 1.0 MeV) led to a 30 ft-lb transition temperature increase of 132.4°F and a 50 ft-lb transition temperature increase of 135.3°F. This results in an irradiated 30 ft-lb transition temperature of 138.7°F and an irradiated 50 ft-lb transition temperature of 170.3°F.

- The average upper shelf energy of the Lower Shell Plate F-773-1 (longitudinal orientation) had no energy decrease after irradiation to 9.92×10^{18} n/cm^2 (E > 1.0 MeV). The irradiated average upper shelf energy for the longitudinally oriented specimens is 140 ft-lb.

- The average upper shelf energy of the Lower Shell Plate F-773-1 (transverse orientation) had an average energy decrease of 13.5 ft-lb after irradiation to 9.92×10^{18} n/cm^2 (E > 1.0 MeV). This results in an irradiated average upper shelf energy of 123 ft-lb for the transversely oriented specimens.

- The average upper shelf energy of the weld metal Charpy specimens had an average energy decrease of 6 ft-lb after irradiation to 9.92×10^{18} n/cm^2 (E > 1.0 MeV). This results in an irradiated average upper shelf energy of 103 ft-lb for the weld metal specimens.

- The average upper shelf energy of the weld HAZ metal Charpy specimens had no energy decrease after irradiation to 9.92×10^{18} n/cm^2 (E > 1.0 MeV). The irradiated average upper shelf energy for the weld HAZ metal specimens is 90 ft-lb.

- The average upper shelf energy of the standard reference material Charpy specimens had an average energy decrease of 30 ft-lb after irradiation to 9.92×10^{18} n/cm^2 (E > 1.0 MeV). This results in an irradiated average upper shelf energy of 106 ft-lb for the standard reference material.

- A comparison of the Palo Verde Unit 2 reactor vessel beltline material test results with the Regulatory Guide 1.99, Revision 2 (Reference 1), predictions led to the following conclusions:

  – The measured 30 ft-lb shift in transition temperature values for the surveillance weld metal and lower shell plate F-773-1 (longitudinal & transverse) contained in capsule 230° are less than the Regulatory Guide 1.99, Revision 2, Position 1.1 predictions.

  – The measured percent decreases in upper shelf energy for the surveillance weld metal and lower shell plate F-773-1 (longitudinal & transverse) contained in capsule 230° are less than the Regulatory Guide 1.99, Revision 2, Position 1.2 predictions.

- All beltline materials exhibit a more than adequate upper shelf energy level for continued safe plant operation and are predicted to maintain an upper shelf energy greater than 50 ft-lb throughout the end of the current license (32 EFPY) as required by 10CFR50, Appendix G (Reference 2).

- The peak calculated and best estimate end-of-license (32 EFPY) neutron fluence (E > 1.0 MeV) at the core midplane for the Palo Verde Unit 2 reactor vessel using the Regulatory Guide 1.99, Revision 2 attenuation formula (i.e., Equation # 3 in the guide; $f_{(\text{depth } x)} = f_{\text{surface}} * e^{(-0.24x)}$) is as follows:

Calculated:	Vessel inner radius*	=	1.66×10^{19} n/cm^2
	Vessel 1/4 thickness	=	9.64×10^{18} n/cm^2
	Vessel 3/4 thickness	=	3.25×10^{18} n/cm^2

* Clad/Base Metal Interface

2 INTRODUCTION

This report presents the results of the examination of the capsule located at 230°, the second capsule removed from the reactor in the continuing surveillance program which monitors the effects of neutron irradiation on the Palo Verde Unit 2 reactor pressure vessel materials under actual operating conditions.

The surveillance program for the Arizona Public Service Company Palo Verde Unit 2 reactor pressure vessel materials was designed and recommended by Combustion Engineering. A description of the surveillance program and the pre-irradiation mechanical properties of the reactor vessel materials is presented in References 3 and 4. The surveillance program was planned to cover the 40-year design life of the reactor pressure vessel and was based on ASTM E185-82, "Standard Practice for conducting Surveillance Tests for light-water cooled Nuclear Power Reactor Vessels." Capsule 230° was removed from the reactor after 14.35 EFPY of exposure and shipped to the Westinghouse Science and Technology RMF, where the post-irradiation mechanical testing of the Charpy V-notch impact and tensile surveillance specimens was performed.

This report summarizes the testing of and the post-irradiation data obtained from the 230° surveillance capsule removed from the Palo Verde Unit 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 A533 Grade B Class 1 (base material of the Arizona Public Service Company Palo Verde Unit 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 (Reference 5). 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, per ASTM E-208 (Reference 6), 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 working 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_{Ia} curve) which appears in Appendix G to the ASME Code (Reference 5). The K_{Ia} curve is an intermediate bound of dynamic, crack arrest, and static fracture toughness results obtained from several heats of pressure vessel steel. When a given material is indexed to the K_{Ia} curve, allowable stress intensity factors can be obtained for this material as a function of temperature. Allowable operating limits can then be determined utilizing these allowable stress intensity factors. Note that the 1998 version of the ASME Code Section XI through the Summer of 2000 Addenda (originally established in Code Case N-640) now allows the use of the K_{Ic} curve as an alternative to the K_{Ia} curve.

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 surveillance program, such as the Palo Verde Unit 2 reactor vessel radiation surveillance program (Refs. 3, 4), in which a surveillance capsule is periodically removed from the operating nuclear reactor and the encapsulated specimens 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 obtain the adjusted RT_{NDT} (ART) for radiation embrittlement. This ART (RT_{NDT} initial + M + ΔRT_{NDT}) is used to index the material to the K_{Ia} 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 Palo Verde Unit 2 reactor pressure vessel core region (beltline) materials were inserted in the reactor vessel prior to initial plant start-up. The capsules were positioned in the reactor vessel between the core support barrel and the vessel wall at locations shown in Figure 4-1. The vertical center of the capsules is opposite the vertical center of the core.

Capsule 230° was removed after 14.35 effective full power years (EFPY) of plant operation. This capsule contained Charpy V-notch impact and tensile specimens made from reactor vessel lower shell course plate F-773-1, submerged arc weld metal (fabricated with Mill B-4 weld filler) representative of the beltline region welds, heat-affected-zone (HAZ) metal and standard reference material from HSST-01MY plate. All HAZ specimens are obtained within the heat-affected-zone of lower shell plate F-773-1.

Charpy V-notch impact specimens from lower shell plate F-773-1 were fabricated with either the longitudinal axis of the specimen parallel to the major working direction of the plate (longitudinal orientation) or the transverse axis of the specimen perpendicular to the major working direction of the plate (transverse orientation). The Charpy V-notch specimens from the weld metal were machined with the longitudinal axis of the specimen transverse to the weld direction with the notch oriented in the direction of the weld.

Tensile specimens from lower shell plate F-773-1 were machined with the longitudinal axis of the specimen perpendicular to the major working direction of the plate (transverse orientation). Tensile specimens from the weld metal were oriented with the longitudinal axis of the specimen transverse to the weld direction.

Capsule 230° contained flux monitor assemblies made from 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 capsule contained thermal monitors made from four low-melting-point eutectic alloys and sealed in glass capsules. These thermal monitors were 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:

80% Au, 20% Sn	Melting Point 536°F (280°C)
90% Pb, 5% Ag, 5% Sn	Melting Point 558°F (292°C)
97.5% Pb, 2.5% Ag	Melting Point 580°F (304°C)
97.5% Pb, 1.75% Ag, 0.75% Sn	Melting Point 590°F (310°C)

The chemical composition and heat treatment of the surveillance material is presented in Tables 4-1 and 4-2. The chemical analysis reported in Table 4-1 was obtained from TR-V-MCM-013 (Reference 4). The arrangement of the various mechanical test specimens, dosimeters and thermal monitors contained in capsule 230° is shown in Figure 4-2. A typical Palo Verde Unit 2 surveillance capsule Charpy impact compartment assembly is shown in Figure 4-3, while Figures 4-4 and 4-5 show the Tensile-Monitor Compartment and Charpy Flux & Compact Tension Compartment, respectively. Table 4-3 presents the compartment ID numbers, along with the specimen ID numbers contained within each compartment.

Table 4-1 Chemical Composition (wt %) of the Palo Verde Unit 2 Reactor Vessel Surveillance Materials

Element	Plate F-773-1	Weld Metal F-773-2/F-773-3
Si	0.21	0.47
S	0.009	0.011
P	0.006	0.010
Mn	1.54	1.46
C	0.24	0.12
Cr	0.03	0.10
Ni	0.68	0.09
Mo	0.52	0.51
V	0.003	0.005
Cb	<0.01	<0.01
B	<0.001	<0.001
Co	0.016	0.010
Cu	0.04	0.07
Al	0.015	0.005
W	0.010	0.010
Ti	<0.01	<0.01
As	0.021	0.010
Sn	0.003	0.004
Zr	<0.001	<0.001
N_2	0.014	0.011
Sb	0.0018	0.0114

Table 4-2 Heat Treatment of the Palo Verde Unit 2 Reactor Vessel Surveillance Material

Surveillance Program Material	Temperature (°F)	Time (hrs.)	Coolant
Test Plate F-773-1	Austenitizing: 1600 ± 25	4	Water-quenched
	Tempered: 1225 ± 25	4	Air Cooled
	Stress Relief: 1150 ± 25	40	Furnace Cooled to 600°F
Weld Metal	Stress Relief: 1125 ± 25	44 hr & 48 min.	Furnace Cooled to 600°F

Table 4-3 Arrangement of Encapsulated Test Specimens within the Palo Verde Unit 2 Capsule 230°

Compartment Position	Compartment Number	Specimen Numbers		
1	1B512 (Charpy Transverse Plate)	1B2AY	1B223	1B22K
		1B221	1B257	1B265
		1B26K	1B254	1B2AL
		1B27J	1B21M	1B26T
		1B225	1B27E	1B21D
2	1B522-1 (Pre-Cracked Charpy Longitudinal and Transverse Plate)	1B236	1B26A	1B23D
		1B2AD	1B25L	1B2AT
		1B24Y	1B22J	1B21L
		1B11A	1B154	1B12D
		1B11D	1B143	1B12Y
		1B13Y	1B11T	1B15B
3	1B532-4 (Charpy HAZ & Tensile Transverse Plate)	1B2JD	1B2J1	1B2KA
		1B41J	1B42E	1B443
		1B435	1B41U	1B454
		1B421	1B414	1B433
		1B415	1B424	1B44B
4	1B54D-3 (Charpy SRM & Tensile Weld)	1BD3L	1BD33	1BD45
		1BD3A	1BD3U	1BD34
		1BD2K	1BD2P	1BD2J
		1B3K6	1B3JM	1B3JD
5	1B553 (Charpy Weld)	1B313	1B36J	1B366
		1B354	1B347	1B36T
		1B35D	1B36P	1B35Y
		1B352	1B33K	1B321
		1B32T	1B372	1B351

Table 4-3 Arrangement of Encapsulated Test Specimens within the Palo Verde Unit 2 Capsule 230° (cont.)				
Compartment Position	**Compartment Number**	**Specimen Numbers**		
6	1B563-1 (Pre-Cracked Charpy Weld & Charpy Longitudinal Plate)	1B373	1B35C	1B35U
		1B3AJ	1B33B	1B356
		1B376	1B362	1B327
		1B133	1B13C	1B111
		1B12T	1B117	1B15L
		1B14T	1B115	1B14K

CODE: **Specimen ID** **Material**

Specimen ID	Material
1B1XX	Lower Shell Plate F-773-1 (Longitudinal Orientation)
1B2XX	Lower Shell Plate F-773-1 (Transverse Orientation)
1B3XX	Weld Metal
1B4XX	Heat-Affected-Zone
1BDXX	SRM HSST 01MY Material (Longitudinal Orientation)

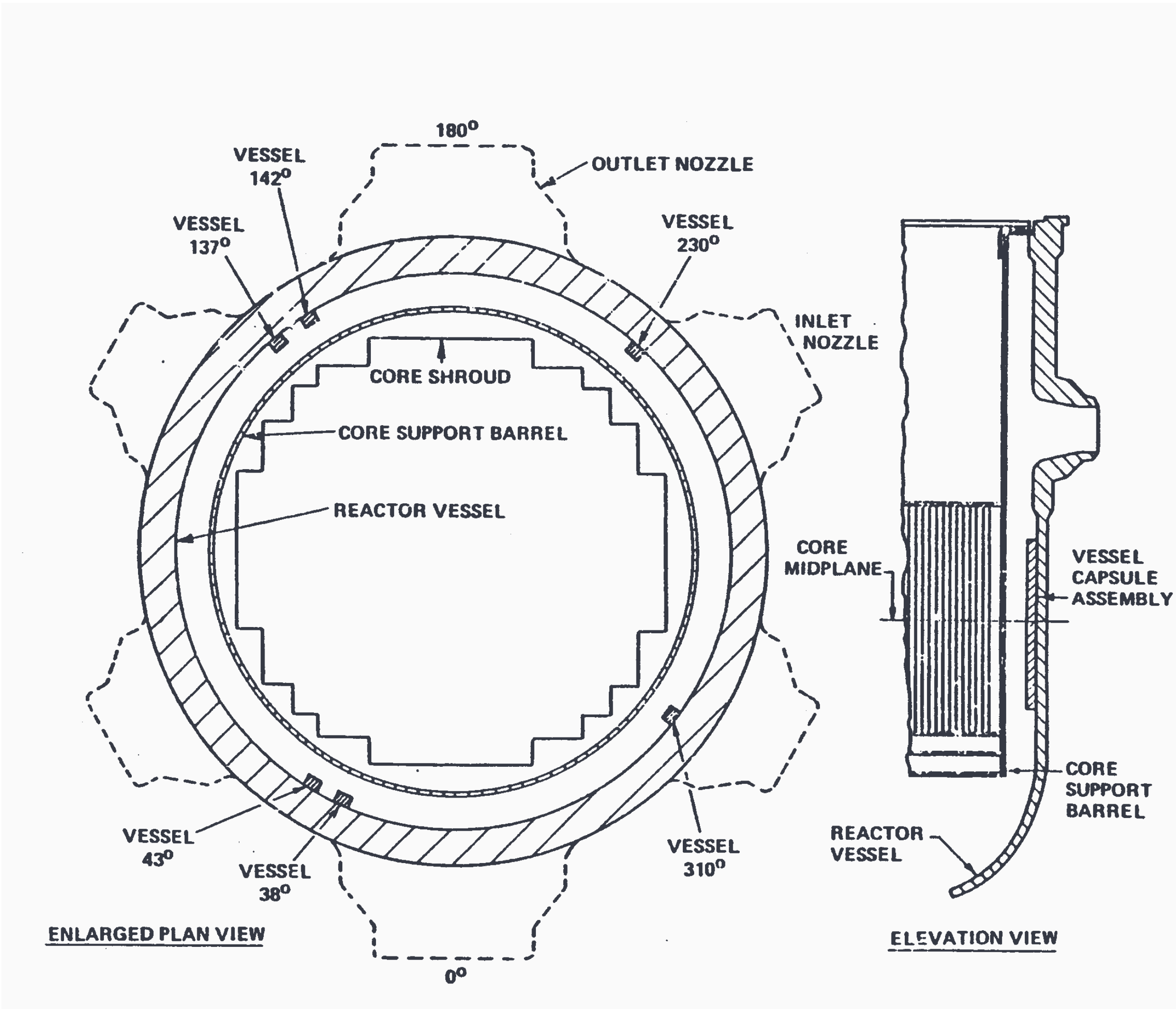


Figure 4-1 Arrangement of Surveillance Capsules in the Palo Verde Unit 2 Reactor Vessel

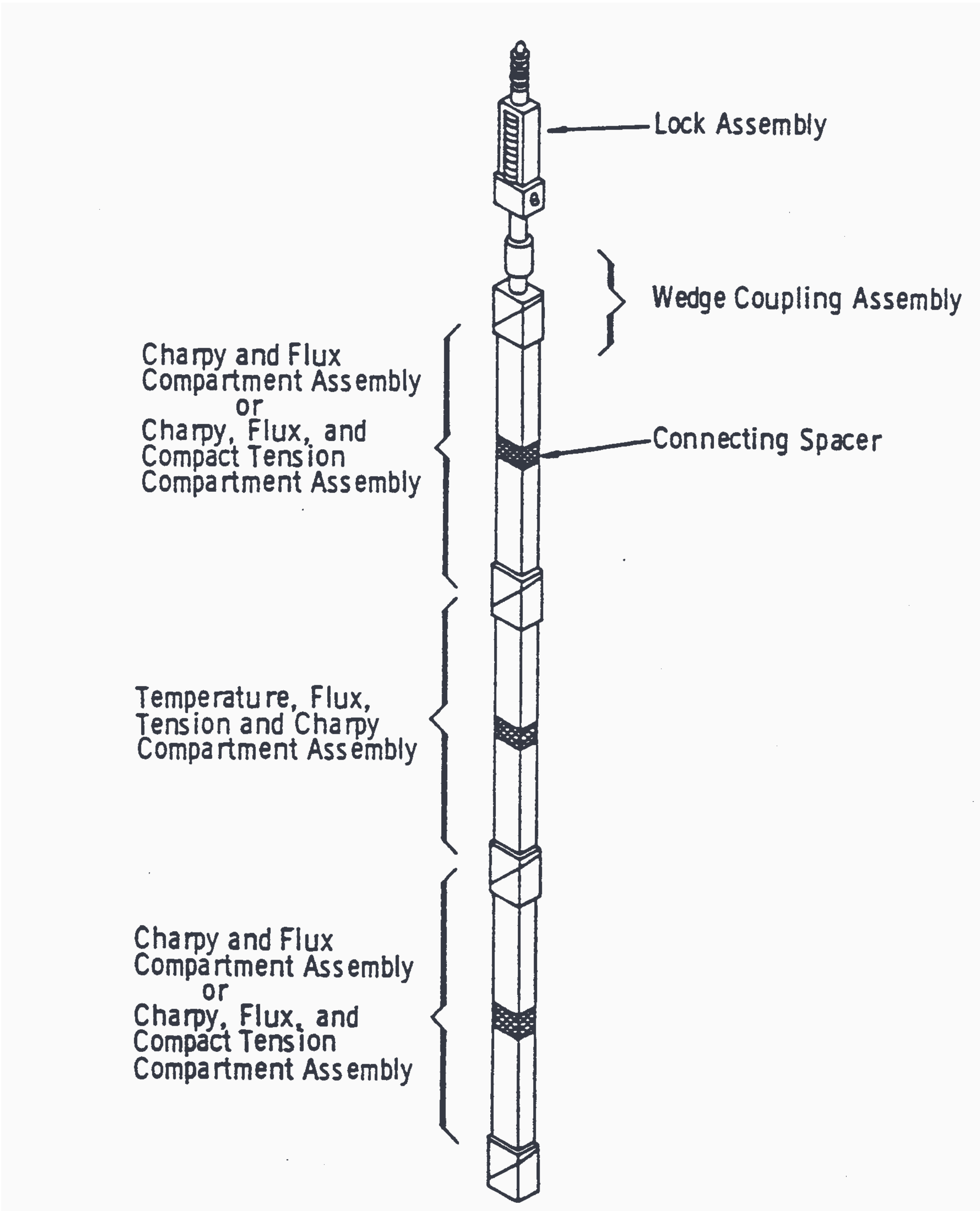


Figure 4-2 Typical Palo Verde Unit 2 Surveillance Capsule Assembly

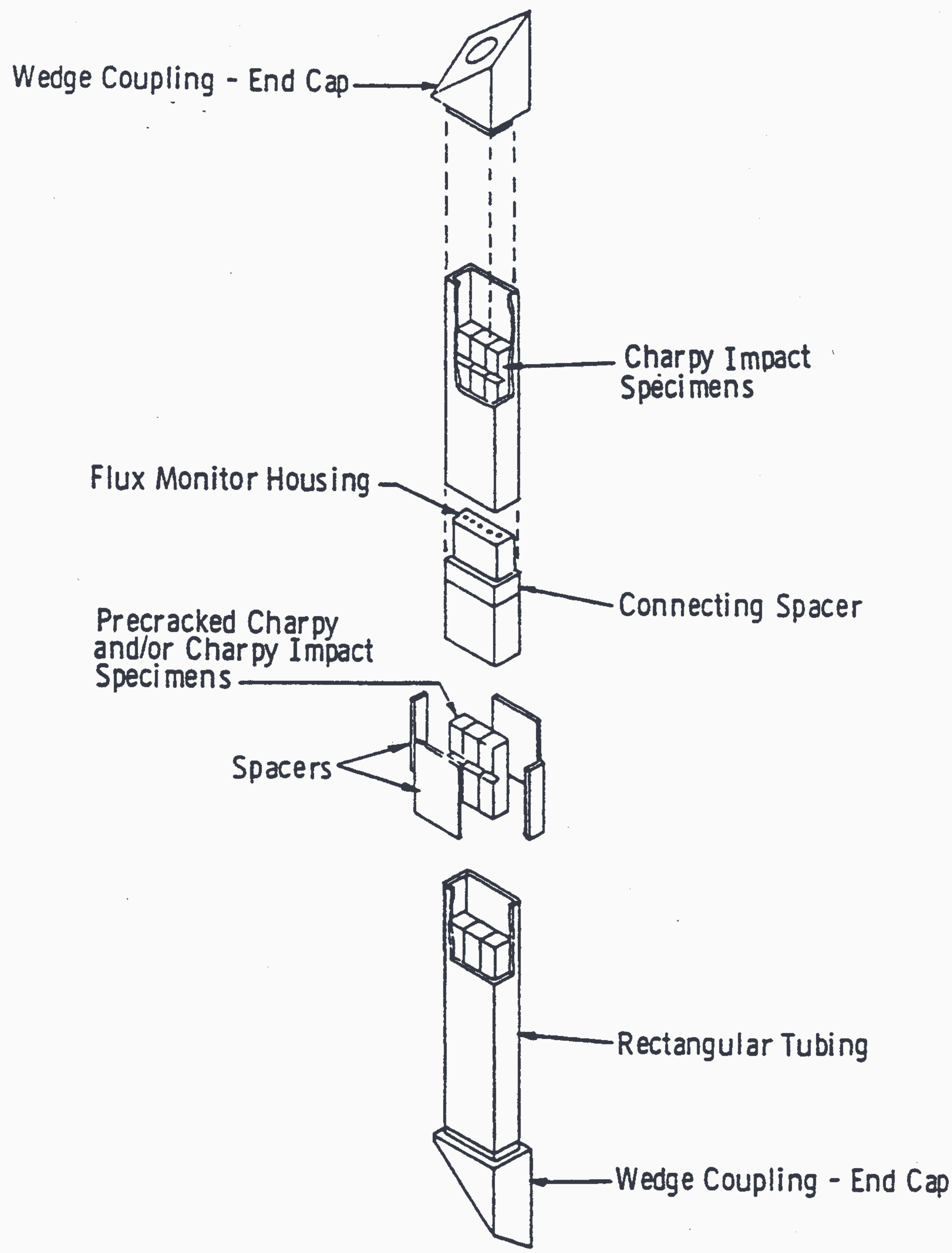


Figure 4-3 Typical Palo Verde Unit 2 Surveillance Capsule Charpy Impact Compartment Assembly

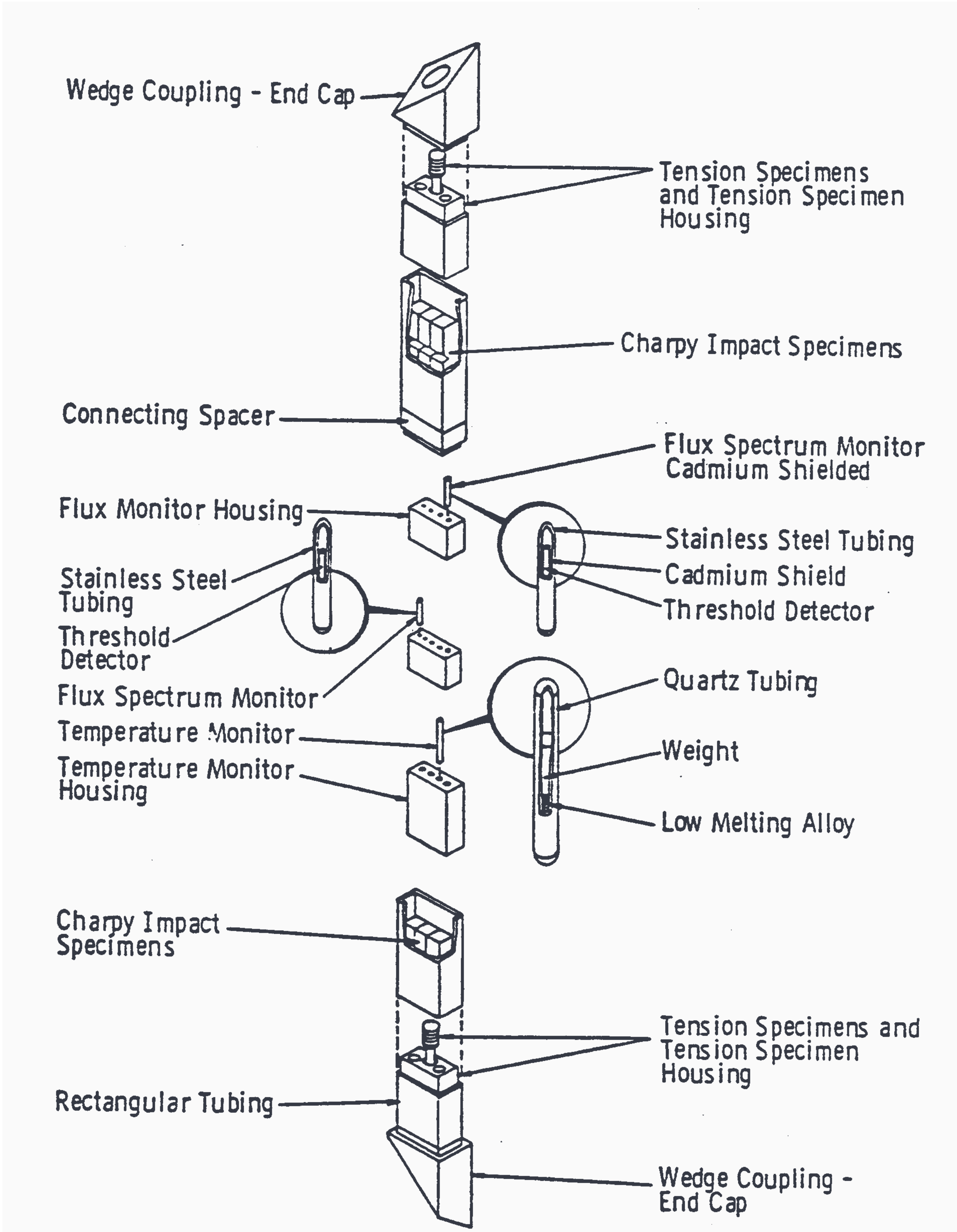


Figure 4-4 Typical Palo Verde Unit 2 Surveillance Capsule Tensile and Flux-Monitor Compartment Assembly

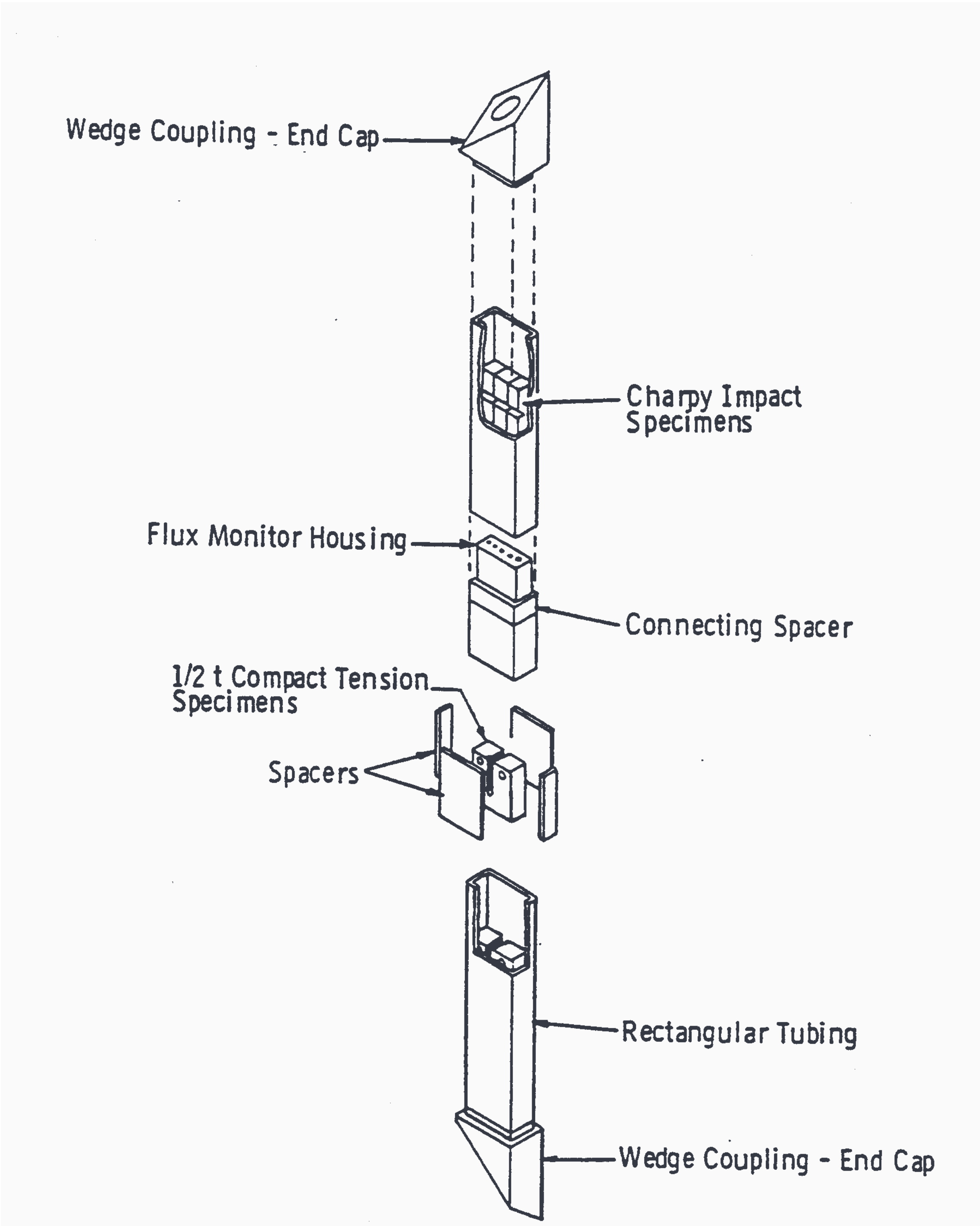


Figure 4-5 Typical Palo Verde Unit 2 Surveillance Capsule Charpy Flux and Compact Tension Compartment Assembly

5 TESTING OF SPECIMENS FROM CAPSULE 230°

5.1 OVERVIEW

The post-irradiation mechanical testing was done at the Remote Metallographic Facility at the Westinghouse Science and Technology Department (STD). The testing of the Charpy V-notch and tensile specimens was performed in accordance with ASTM Specification E185-82 (Reference 7) and Westinghouse Procedures RMF 8402 (Reference 8) as detailed by Westinghouse Procedures RMF 8102 (Reference 9) and RMF 8103 (Reference 10).

Upon receipt of the capsule at the hot cell laboratory the capsule was opened per Procedure RMF 8804 (Reference 11). The specimens and spacer blocks were carefully removed, inspected for identification number and checked against the master list in Reference 3. All items were in their proper locations.

Examination of the thermal monitors indicated that two of the lower melting point monitors melted. Based on this examination, the maximum temperature to which the specimens were exposed was less than 580°F (304°C).

The Charpy impact tests were performed per ASTM Specification E23-02a (Reference 12) and Procedure RMF 8103 on a Tinius-Olsen Model 74, 358J machine. The tup (striker) of the Charpy machine is instrumented with an Instron Impulse instrumentation system, feeding information into an IBM compatible computer. With this system, load-time and energy-time signals can be recorded in addition to the standard measurement of Charpy energy (E_D). From the load-time curve, the load of general yielding (P_{GY}), the time to general yielding (T_{GY}), the maximum load (P_M), and the time to maximum load (T_M) can be 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 fast fracture load (P_F). If the fast load drop terminates well above zero load, the termination load is identified as the arrest load (P_A).

The energy at maximum load (E_M) was determined by comparing the energy-time record and the load-time record. The energy at maximum load is approximately equivalent to the energy required to initiate a crack in the specimen. Therefore, the propagation energy for the crack (E_p) is the difference between the total energy to fracture (E_D) and the energy at maximum load (E_M).

The yield stress (σ_Y) was calculated from the three-point bend formula having the following expression:

$$\sigma_y = (P_{GY} * L) / [B * (W - a)^2 * C] \quad (1)$$

where:

L = distance between the specimen supports in the impact machine
B = the width of the specimen measured parallel to the notch
W = height of the specimen, measured perpendicularly to the notch
a = notch depth

The constant C is dependent on the notch flank angle (ϕ), notch root radius (ρ) and the type of loading (i.e., pure bending or three-point bending). In three-point bending, for a Charpy specimen in which $\phi = 45°$ and $\rho = 0.010$ inch, Equation 1 is valid with C = 1.21. Therefore, (for L = 4W),

$$\sigma_y = (P_{GY} * L) / [B * (W - \alpha)^2 * 1.21] = (3.305 * P_{GY} * W) / [B * (W - \alpha^2] \quad (2)$$

For the Charpy specimen, B = 0.394 inch, W = 0.394 inch and a = 0.079 inch. Equation 2 then reduces to:

$$\sigma_y = 33.3 * P_{GY} \quad (3)$$

where σ_y is in units of psi and P_{GY} is in units of lbs. The flow stress was calculated from the average of the yield and maximum loads, also using the three-point bend formula.

The symbol A in columns 4, 5, and 6 of Tables 5-6 through 5-10 is the cross-section area under the notch of the Charpy specimens:

$$A = B * (W - a) = 0.1241 \text{ sq. in.} \quad (4)$$

Percent shear was determined from post-fracture photographs using the ratio-of-areas methods in compliance with ASTM Specification E23-02a and A370-03a (Reference 13). The lateral expansion was measured using a dial gage rig similar to that shown in the same specification.

Tensile tests were performed on a 20,000-pound Instron, split-console test machine (Model 1115) per ASTM Specification E8-04 (Reference 14) and E21-03a (Reference 15), and Procedure RMF 8102. All pull rods, grips, and pins were made of Inconel 718. The upper pull rod was connected through a universal joint to improve axiality of loading. The tests were conducted at a constant crosshead speed of 0.05 inches per minute throughout the test.

Extension measurements were made with a linear variable displacement transducer extensometer. The extensometer knife-edges were spring-loaded to the specimen and operated through specimen failure. The extensometer gage length was 1.00 inch.

Elevated test temperatures were obtained with a three-zone electric resistance split-tube furnace with a 9-inch hot zone. All tests were conducted in air. Because of the difficulty in remotely attaching a thermocouple directly to the specimen, the following procedure was used to monitor specimen temperatures. Chromel-Alumel thermocouples were positioned at the center and at each end of the gage section of a dummy specimen and in each tensile machine griper. In the test configuration, with a slight load on the specimen, a plot of specimen temperature versus upper and lower tensile machine griper and controller temperatures was developed over the range from room temperature to 550°F. During the actual testing, the grip temperatures were used to obtain desired specimen temperatures. Experiments have indicated that this method is accurate to ± 2°F.

The yield load, ultimate load, fracture load, total elongation, and uniform elongation were determined directly from the load-extension curve. The yield strength, ultimate strength, and fracture strength were calculated using the original cross-sectional area. The final diameter and final gage length were determined from post-fracture photographs. The fracture area used to calculate the fracture stress (true stress at fracture) and percent reduction in area was computed using the final diameter measurement.

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 230°, which received a fluence of 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV) in 14.35 EFPY of operation, are presented in Tables 5-1 through 5-10 and are compared with unirradiated results as shown in Figures 5-1 through 5-15.

The analysis of the reactor vessel materials contained in surveillance capsule 230°, the second capsule to be removed from the Palo Verde Unit 2 reactor pressure vessel, led to the following conclusions:

- The capsule received an average fast neutron calculated fluence (E > 1.0 MeV) of 9.92 x 10^{18} n/cm^2 after 14.35 effective full power years (EFPY) of plant operation.

- Irradiation of the reactor vessel Lower Shell Plate F-773-1 Charpy specimens, oriented with the longitudinal axis of the specimen parallel to the major working direction of the plate (longitudinal orientation), to 9.92 x 10^{18} n/cm^2 (E > 1.0MeV) led to a 30 ft-lb transition temperature increase of 17.7°F and a 50 ft-lb transition temperature increase of 24.5°F. This results in an irradiated 30 ft-lb transition temperature of 18.5°F and an irradiated 50 ft-lb transition temperature of 61.6°F for the longitudinally oriented specimens.

- Irradiation of the reactor vessel Lower Shell Plate F-773-1 Charpy specimens, oriented with the longitudinal axis of the specimen normal to the major working direction of the plate (transverse orientation), to 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV) led to a 30 ft-lb transition temperature increase of 19.3°F and a 50 ft-lb transition temperature increase of 20.8°F. This results in an irradiated 30 ft-lb transition temperature of 20.0°F and an irradiated 50 ft-lb transition temperature of 52.5°F for transversely oriented specimens.

- Irradiation of the weld metal Charpy specimens to 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV) led to a 30 ft-lb transition temperature increase of 2.5°F and a 50 ft-lb transition temperature increase of 14.0°F. This results in an irradiated 30 ft-lb transition temperature of -37.6°F and an irradiated 50 ft-lb transition temperature of 4.1°F.

- Irradiation of the weld Heat-Affected-Zone (HAZ) metal Charpy specimens to 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV) led to a 30 ft-lb transition temperature increase of 46.3°F and a 50 ft-lb transition temperature increase of 19.8°F. This results in an irradiated 30 ft-lb transition temperature of -35.0°F and an irradiated 50 ft-lb transition temperature of 79.0°F.

- Irradiation of the standard reference material Charpy specimens to 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV) led to a 30 ft-lb transition temperature increase of 132.4°F and a 50 ft-lb transition temperature increase of 135.3°F. This results in an irradiated 30 ft-lb transition temperature of 138.7°F and an irradiated 50 ft-lb transition temperature of 170.3°F.

- The average upper shelf energy of the Lower Shell Plate F-773-1 (longitudinal orientation) had no energy decrease after irradiation to 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV). The irradiated average upper shelf energy for the longitudinally oriented specimens is 140 ft-lb.

- The average upper shelf energy of the Lower Shell Plate F-773-1 (transverse orientation) had an average energy decrease of 13.5 ft-lb after irradiation to 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV). This results in an irradiated average upper shelf energy of 123 ft-lb for the transversely oriented specimens.

- The average upper shelf energy of the weld metal Charpy specimens had an average energy decrease of 6 ft-lb after irradiation to 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV). This results in an irradiated average upper shelf energy of 103 ft-lb for the weld metal specimens.

- The average upper shelf energy of the weld HAZ metal Charpy specimens had no energy decrease after irradiation to 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV). The irradiated average upper shelf energy for the weld HAZ metal specimens is 90 ft-lb.

- The average upper shelf energy of the standard reference material Charpy specimens had an average energy decrease of 30 ft-lb after irradiation to 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV). This results in an irradiated average upper shelf energy of 106 ft-lb for the standard reference material.

- A comparison of the Palo Verde Unit 2 reactor vessel beltline material test results with the Regulatory Guide 1.99, Revision 2, predictions led to the following conclusions:

  – The measured 30 ft-lb shift in transition temperature values for the surveillance weld metal and lower shell plate F-773-1 (longitudinal & transverse) contained in capsule 230° are less than the Regulatory Guide 1.99, Revision 2, Position 1.1 predictions.

  – The measured percent decreases in upper shelf energy for the surveillance weld metal and lower shell plate F-773-1 (longitudinal & transverse) contained in Capsule 230° are less than the Regulatory Guide 1.99, Revision 2, Position 1.2 predictions.

- All beltline materials exhibit a more than adequate upper shelf energy level for continued safe plant operation and are predicted to maintain an upper shelf energy greater than 50 ft-lb throughout the end of the current license (32 EFPY) as required by 10CFR50, Appendix G.

- The fracture appearance of each irradiated Charpy specimen from the various surveillance Capsule 230° materials is shown in Figures 5-16 through 5-20 and shows an increasingly ductile or tougher appearance with increasing test temperature.

The load-time records for individual instrumented Charpy specimen tests are shown in Appendix B. The Charpy V-notch data presented in this report is based on a re-plot of all capsule data using CVGRAPH, Version 5.0.2, which is a hyperbolic tangent curve-fitting program. Appendix C presents the CVGRAPH, Version 5.0.2, Charpy V-notch plots and the program input data.

5.3 TENSILE TEST RESULTS

The results of the tensile tests performed on the various materials contained in Capsule 230° irradiated to 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV) are presented in Table 5-13 and are compared with unirradiated results as shown in Figures 5-21 and 5-22.

The results of the tensile tests performed on the Lower Shell Plate F-773-1 (*transverse orientation*) indicated that irradiation to 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV) caused an approximate increase of 1 to 4 ksi in the 0.2 percent offset yield strength and approximately a 2 to 3 ksi increase in the ultimate tensile strength when compared to unirradiated data (Figure 5-21).

The results of the tensile tests performed on the surveillance weld metal indicated that irradiation to 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV) caused a 0 to 10 ksi increase in the 0.2 percent offset yield strength and a 0 to 8 ksi increase in the ultimate tensile strength when compared to unirradiated data (Figure 5-22).

The fractured tensile specimens for the Lower Shell Plate F-773-1 material are shown in Figure 5-23, while the fractured tensile specimens for the surveillance weld metal are shown in Figure 5-24.

The engineering stress-strain curves for the tensile tests are shown in Figures 5-25 through 5-28.

Table 5-1 Charpy V-notch Data for the Palo Verde Unit 2 Lower Shell Plate F-773-1 Irradiated to a Fluence of 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV) (Longitudinal Orientation)							
Sample Number	**Temperature**		**Impact Energy**		**Lateral Expansion**		**Shear**
	°F	**°C**	**ft-lbs**	**Joules**	**mils**	**mm**	**%**
1B14T	-50	-46	8	11	7	0.18	5
1B13C	0	-18	26	35	30	0.76	20
1B14K	25	-4	19	26	21	0.53	15
1B115	50	10	43	58	41	1.04	40
1B117	75	24	75	102	64	1.63	60
1B111	125	52	89	121	73	1.85	80
1B133	175	79	92	125	75	1.91	85
1B12T	250	121	144	195	91	2.31	100
1B15L	325	163	135	183	89	2.26	100

Table 5-2 Charpy V-notch Data for the Palo Verde Unit 2 Lower Shell Plate F-773-1 Irradiated to a Fluence of 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV) (Transverse Orientation)

Sample Number	Temperature		Impact Energy		Lateral Expansion		Shear
	°F	°C	ft-lbs	Joules	mils	mm	%
1B221	-50	-46	7	9	7	0.18	5
1B2AL	0	-18	24	33	25	0.64	15
1B27E	25	-4	36	49	35	0.89	20
1B27J	40	4	34	46	33	0.84	20
1B257	50	10	47	64	41	1.04	25
1B21M	75	24	79	107	59	1.50	40
1B254	75	24	61	83	48	1.22	50
1B21D	100	38	75	102	62	1.57	60
1B2AY	125	52	104	141	74	1.88	70
1B26K	150	66	111	151	81	2.06	80
1B265	200	93	104	141	76	1.93	95
1B26T	200	93	123	167	82	2.08	90
1B22K	250	121	121	164	90	2.29	100
1B225	300	149	113	153	89	2.26	100
1B223	350	177	134	182	89	2.26	100

Table 5-3 Charpy V-notch Data for the Palo Verde Unit 2 Surveillance Weld Metal Irradiated to a Fluence of 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV)							
Sample Number	**Temperature**		**Impact Energy**		**Lateral Expansion**		**Shear**
	°F	**°C**	**ft-lbs**	**Joules**	**mils**	**mm**	**%**
1B36T	-75	-59	7	9	7	0.18	10
1B352	-25	-32	26	35	27	0.69	25
1B347	-10	-23	62	84	52	1.32	60
1B321	0	-18	72	98	62	1.57	55
1B36P	0	-18	44	60	41	1.04	55
1B33K	25	-4	42	57	43	1.09	55
1B35Y	25	-4	56	76	60	1.52	65
1B32T	50	10	68	92	63	1.60	60
1B351	75	24	80	108	67	1.70	70
1B313	125	52	108	146	89	2.26	98
1B366	150	66	100	136	86	2.18	98
1B372	200	93	90	122	83	2.11	98
1B35D	225	107	107	145	88	2.24	100
1B36J	250	121	102	138	86	2.18	100
1B354	300	149	111	151	90	2.29	100

Table 5-4 Charpy V-notch Data for the Palo Verde Unit 2 Heat Affected Zone Metal Irradiated to a Fluence of 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV)							
Sample Number	**Temperature**		**Impact Energy**		**Lateral Expansion**		**Shear**
	°F	**°C**	**ft-lbs**	**Joules**	**mils**	**mm**	**%**
1B435	-25	-32	9	12	14	0.36	15
1B44B	25	-4	24	33	23	0.58	25
1B415	50	10	33	45	30	0.76	30
1B454	75	24	66	89	54	1.37	45
1B414	80	27	56	76	47	1.19	40
1B41J	100	38	32	43	16	0.41	35
1B443	125	52	79	107	67	1.70	65
1B42E	150	66	83	113	74	1.88	80
1B433	200	93	70	95	62	1.57	75
1B424	250	121	99	134	81	2.06	100
1B421	300	149	83	113	70	1.78	100
1B41U	325	163	87	118	79	2.01	100

Table 5-5 Charpy V-notch Data for the Palo Verde Unit 2 Standard Reference Material Irradiated to a Fluence of 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV)							
Sample Number	**Temperature**		**Impact Energy**		**Lateral Expansion**		**Shear**
	°F	**°C**	**ft-lbs**	**Joules**	**mils**	**mm**	**%**
D45	0	-18	5	6	4	0.10	2
D2P	75	24	10	14	9	0.23	15
D34	100	38	26	35	22	0.56	20
D33	150	66	38	52	33	0.84	30
D2J	190	88	43	58	36	0.91	40
D2K	225	107	100	136	75	1.91	85
D3L	250	121	100	136	78	1.98	85
D3A	325	163	101	137	76	1.93	100
D3U	375	191	110	149	85	2.16	100

Table 5-6 Instrumented Charpy Impact Test Results for the Palo Verde Unit 2 Lower Shell Plate F-773-1 Irradiated to a Fluence of 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV) (Longitudinal Orientation)

Sample No.	Test Temp. (°F)	Charpy Energy E_D (ft-lb)	Normalized Energies (ft-lb/in^2)			Yield Load P_{GY} (lb)	Time to Yield t_{GY} (msec)	Max. Load P_M (lb)	Time to Max. T_m (msec)	Fast Fract. Load P_F (lb)	Arrest Load P_A (lb)	Yield Stress S_Y (ksi)	Flow Stress (ksi)
			Charpy E_D/A	Max. E_M/A	Prop. E_p/A								
1B14T	-50	8	64	33	32	2971	0.14	3117	0.16	3109	0	99	101
1B13C	0	26	209	132	78	1905	0.11	4068	0.39	4030	109	63	99
1B14K	25	19	153	75	78	1954	0.11	3425	0.28	3425	162	65	90
1B115	50	43	346	207	139	2119	0.13	3995	0.54	3970	1128	71	102
1B117	75	75	604	277	327	2159	0.12	4070	0.68	3828	1505	72	104
1B111	125	89	717	274	443	2429	0.14	3938	0.69	3760	2307	81	106
1B133	175	92	741	270	471	2051	0.13	3925	0.70	3731	2674	68	100
1B12T	250	144	1160	272	888	2587	0.14	3929	0.68	n/a	n/a	86	108
1B15L	325	135	1088	318	770	2272	0.14	3609	0.84	n/a	n/a	76	98

Table 5-7 Instrumented Charpy Impact Test Results for the Palo Verde Unit 2 Lower Shell Plate F-773-1 Irradiated to a Fluence of 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV) (Transverse Orientation)

Sample No.	Test Temp. (°F)	Charpy Energy E_D (ft-lb)	Normalized Energies (ft-lb/in^2)			Yield Load P_{GY} (lb)	Time to Yield t_{GY} (msec)	Max. Load P_M (lb)	Time to Max. T_m (msec)	Fast Fract. Load P_F (lb)	Arrest Load P_A (lb)	Yield Stress S_Y (ksi)	Flow Stress (ksi)
			Charpy E_D/A	Max. E_M/A	Prop. E_p/A								
1B221	-50	7	56	23	33	2212	0.13	2333	0.15	2333	0	74	76
1B2AL	0	24	193	112	81	2729	0.13	3846	0.36	3830	447	91	109
1B27E	25	36	290	208	82	2551	0.13	3987	0.53	3950	317	85	109
1B27J	40	34	274	171	103	1688	0.10	4047	0.47	4047	559	56	95
1B257	50	47	379	276	103	2430	0.13	4204	0.66	4184	814	81	110
1B21M	75	79	637	294	343	2989	0.21	4257	0.70	3986	1302	100	121
1B254	75	61	491	275	217	2061	0.12	4058	0.68	3858	1322	69	102
1B21D	100	75	604	276	328	2355	0.15	3982	0.69	3653	1442	78	106
1B2AY	125	104	838	291	547	2621	0.14	4164	0.70	3597	1957	87	113
1B26K	150	111	894	273	621	2179	0.14	4052	0.68	3456	1972	73	104
1B265	200	104	838	258	580	1971	0.14	3798	0.69	3311	3089	66	96
1B26T	200	123	991	349	642	3200	0.16	3955	0.83	2569	2103	107	119
1B22K	250	121	975	268	707	2723	0.14	3871	0.68	n/a	n/a	91	110
1B225	300	113	910	242	668	2395	0.16	3559	0.68	n/a	n/a	80	99
1B223	350	134	1080	265	815	2193	0.13	3685	0.73	n/a	n/a	73	98

Table 5-8 Instrumented Charpy Impact Test Results for the Palo Verde Unit 2 Surveillance Weld Metal Irradiated to a Fluence of 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV)

Sample No.	Test Temp. (°F)	Charpy Energy E_D (ft-lb)	Normalized Energies (ft-lb/in^2) Charpy E_D/A	Max. E_M/A	Prop. E_p/A	Yield Load P_{GY} (lb)	Time to Yield t_{GY} (msec)	Max. Load P_M (lb)	Time to Max. T_m (msec)	Fast Fract. Load P_F (lb)	Arrest Load P_A (lb)	Yield Stress S_Y (ksi)	Flow Stress (ksi)
1B36T	-75	7	56	32	24	2450	0.14	2717	0.17	2717	0	82	86
1B352	-25	26	209	119	91	2726	0.13	3837	0.35	3837	731	91	109
1B347	-10	62	500	287	213	2706	0.16	4071	0.69	3934	1446	90	113
1B321	0	72	580	282	298	2638	0.15	3989	0.68	3564	1219	88	110
1B36P	0	44	355	133	221	2225	0.13	3993	0.39	3955	2351	74	104
1B33K	25	42	338	180	158	2778	0.13	3786	0.48	3778	1889	93	109
1B35Y	25	56	451	183	268	2317	0.12	4015	0.48	3984	2593	77	105
1B32T	50	68	548	258	290	2090	0.13	3763	0.67	3475	1090	70	97
1B351	75	80	645	265	379	1842	0.11	3944	0.67	3582	2226	61	96
1B313	125	108	870	254	616	2274	0.14	3709	0.68	2466	2173	76	100
1B366	150	100	806	274	532	2478	0.15	3907	0.71	2810	2311	83	106
1B372	200	90	725	254	471	2155	0.13	3732	0.67	2809	2483	72	98
1B35D	225	107	862	260	602	2528	0.16	3844	0.68	n/a	n/a	84	106
1B36J	250	102	822	259	563	2436	0.15	3765	0.68	n/a	n/a	81	103
1B354	300	111	894	244	650	2435	0.14	3582	0.67	n/a	n/a	81	100

Table 5-9 Instrumented Charpy Impact Test Results for the Palo Verde Unit 2 Heat Affected Zone Material Irradiated to a Fluence of 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV)

Sample No.	Test Temp. (°F)	Charpy Energy E_D (ft-lb)	Normalized Energies (ft-lb/in^2) Charpy E_D/A	Max. E_M/A	Prop. E_p/A	Yield Load P_{GY} (lb)	Time to Yield t_{GY} (msec)	Max. Load P_M (lb)	Time to Max. T_m (msec)	Fast Fract. Load P_F (lb)	Arrest Load P_A (lb)	Yield Stress S_Y (ksi)	Flow Stress (ksi)
1B435	-25	9	73	31	41	2508	0.13	2871	0.16	2871	111	84	90
1B44B	25	24	193	87	106	2224	0.15	3483	0.33	3471	249	74	95
1B415	50	33	266	176	90	2291	0.12	3968	0.47	3952	842	76	104
1B454	75	66	532	284	248	2230	0.15	4210	0.68	3936	2442	74	107
1B414	80	56	451	287	164	2267	0.13	4168	0.68	4032	670	76	107
1B41J	100	32	258	80	178	2212	0.14	3554	0.38	3544	614	74	96
1B443	125	79	637	281	356	2632	0.15	4056	0.67	3498	1836	88	111
1B42E	150	83	669	275	394	2056	0.12	3968	0.70	3474	2048	68	100
1B433	200	70	564	252	312	2050	0.12	3719	0.67	3200	991	68	96
1B424	250	99	798	267	530	1893	0.11	3943	0.68	n/a	n/a	63	97
1B421	300	83	669	185	484	1419	0.09	3654	0.54	n/a	n/a	47	84
1B41U	325	87	701	186	515	2213	0.13	3618	0.53	n/a	n/a	74	97

Table 5-10 Instrumented Charpy Impact Test Results for the Palo Verde Unit 2 Standard Reference Material Irradiated to a Fluence of 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV)

Sample No.	Test Temp. (°F)	Charpy Energy E_D (ft-lb)	Normalized Energies (ft-lb/in^2) Charpy E_D/A	Max. E_M/A	Prop. E_p/A	Yield Load P_{GY} (lb)	Time to Yield t_{GY} (msec)	Max. Load P_M (lb)	Time to Max. T_m (msec)	Fast Fract. Load P_F (lb)	Arrest Load P_A (lb)	Yield Stress S_Y (ksi)	Flow Stress (ksi)
D45	0	5	4	36	30	7	812	0.06	2112	0.18	2112	0	27
D2P	75	10	4	81	33	48	2707	0.15	2743	0.17	2743	342	90
D34	100	26	18	209	149	61	2517	0.13	4278	0.40	4278	0	84
D33	150	38	27	306	217	89	1892	0.12	4304	0.54	4238	262	63
D2J	190	43	26	346	212	135	2257	0.13	4196	0.53	4176	905	75
D2K	225	100	37	806	296	510	2475	0.13	4412	0.67	3312	2165	82
D3L	250	100	36	806	288	518	1627	0.1	4386	0.67	1465	980	54
D3A	325	101	35	814	282	532	2450	0.14	4152	0.67	n/a	n/a	82
D3U	375	110	35	886	280	606	2570	0.13	4190	0.65	n/a	n/a	86

Table 5-11 Effect of Irradiation to 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV) on the Notch Toughness Properties of the Palo Verde Unit 2 Reactor Vessel Surveillance Materials

Material	Average 30 (ft-lb)[a] Transition Temperature (°F)			Average 35 mil Lateral[b] Expansion Temperature (°F)			Average 50 ft-lb[a] Transition Temperature (°F)			Average Energy Absorption[a] at Full Shear (ft-lb)		
	Unirradiated	Irradiated	ΔT	Unirradiated	Irradiated	ΔT	Unirradiated	Irradiated	ΔT	Unirradiated	Irradiated	ΔE
Lower Shell Plate F-773-1 (Longitudinal)	0.5	18.2	17.7	10.6	32.8	22.2	37.1	61.6	24.5	112	140	28
Lower Shell Plate F-773-1 (Transverse)	0.7	20.0	19.3	4.7	33.8	29.1	31.7	52.5	20.8	136.5	123	-13.5
Weld Metal (Heat #3P7317)	-40.1	-37.6	2.5	-37.5	-21.8	15.7	-9.9	4.1	14.0	109	103	-6
HAZ Metal	-11.3	35.0	46.3	-2.7	59.6	62.3	59.2	79.0	19.8	84	90	6
SRM	6.3	138.7	132.4	14.1	155.7	141.6	35.0	170.3	135.3	136	106	-30

Notes:

a. "Average" is defined as the value read from the curve fit through the data points of the Charpy tests (see Figures 5-1, 5-4, 5-7, 5-10 and 5-13).

b. "Average" is defined as the value read from the curve fit through the data points of the Charpy tests (see Figures 5-2, 5-5, 5-8, 5-11 and 5-14).

Table 5-12 Comparison of the Palo Verde Unit 2 Surveillance Material 30 ft-lb Transition Temperature Shifts and Upper Shelf Energy Decreases with Regulatory Guide 1.99, Revision 2, Predictions

Material	Capsule	Fluence (x 10^{19} n/cm^2)[a]	30 ft-lb Transition Temperature Shift		Upper Shelf Energy Decrease	
			Predicted (°F)[b]	Measured (°F) [c]	Predicted (%)[b]	Measured (%)[d]
Lower Shell Plate F-773-1 (Longitudinal)	137°	0.387	19.2	13.3	15	0
	230°	0.992	25.9	17.7	19	0
Lower Shell Plate F-773-1 (Transverse)	137°	0.387	19.2	9.5	15	16
	230°	0.992	25.9	19.3	19	10
Surveillance Program Weld Metal	137°	0.387	31.3	-0.1	17	1
	230°	0.992	42.3	2.5	21	6
Heat-Affected-Zone Material	137°	0.387	–	51.3	–	0
	230°	0.992	–	46.3	–	0
SRM HSST Plate 01MY (Longitudinal)	137°	0.387	–	116.0	–	23
	230°	0.992	–	132.4	–	22

Notes:

a. The fluence values presented here are the calculated values per Regulatory Guide 1.190.
b. Based on Regulatory Guide 1.99, Revision 2, Position 1 methodology using the mean weight percent values of copper and nickel of the surveillance material.
c. Calculated using measured Charpy data plotted using CVGRAPH, Version 5.0.2 (See Appendix C)
d. Values are based on the definition of upper shelf energy given in ASTM E185-82.

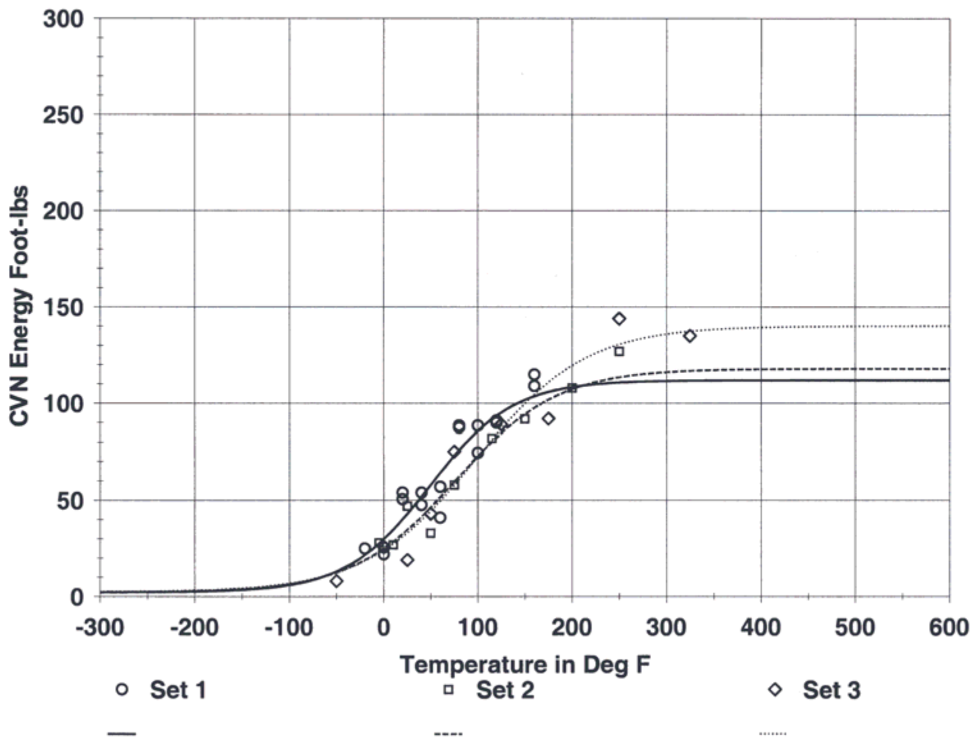
Table 5-13 Tensile Properties of the Palo Verde Unit 2 Capsule 230° Reactor Vessel Surveillance Materials Irradiated to 9.92 x 10^{18} n/cm^2 (E > 1.0 MeV)

Material	Sample Number	Test Temp. (°F)	0.2% Yield Strength (ksi)	Ultimate Strength (ksi)	Fracture Load (kip)	Fracture Stress (ksi)	Fracture Strength (ksi)	Uniform Elongation (%)	Total Elongation (%)	Reduction in Area (%)
Lower Shell Plate F-773-1 (Transverse)	1B2J1	75°F	65.4	85.6	2.75	186.0	56.0	11.7	27.5	70
	1B2JD	175°F	61.4	81.0	2.70	170.7	55.0	12.0	26.0	68
	1B2KA	550°F	56.4	85.6	2.95	180.6	60.1	11.3	22.8	67
Weld Metal Heat 3P7317	1B3K6	75°F	72.3	88.1	2.83	185.2	57.7	11.3	24.7	69
	1B3JM	150°F	68.8	83.7	2.65	167.6	54.0	11.0	24.5	68
	1B3JD	550°F	53.5	78.4	2.60	159.2	53.0	11.3	23.1	67

LOWER SHELL PLATE F-773-1 (LONGITUDINAL)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/29/2005 11:32 AM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALO VERDE 2	UNIRR	SA533B1	LT	F-773-1
2	PALO VERDE 2	137	SA533B1	LT	F-773-1
3	PALO VERDE 2	230	SA533B1	LT	F-773-1



Results

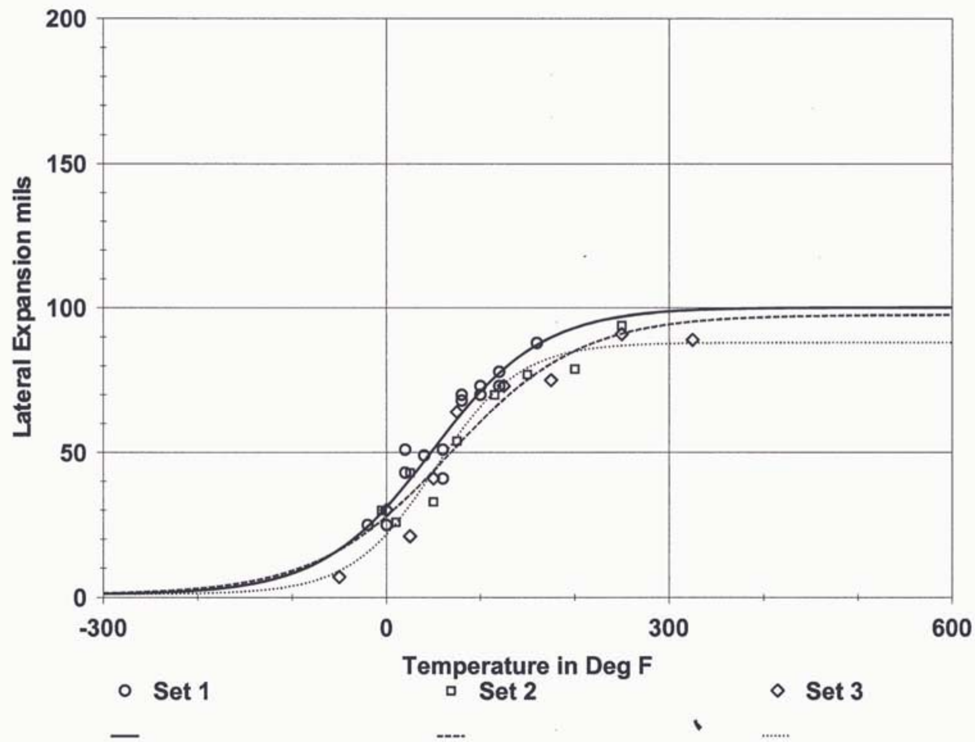
Curve	Fluence	LSE	USE	d-USE	T @30	d-T @30	T @50	d-T @50
1		2.2	112.0	.0	.5	.0	37.1	.0
2		2.2	118.0	6.0	13.8	13.3	57.1	20.0
3		2.2	140.0	28.0	18.2	17.7	61.6	24.5

Figure 5-1 Charpy V-Notch Impact Energy vs. Temperature for Palo Verde Unit 2 Reactor Vessel Lower Shell Plate F-773-1 (Longitudinal Orientation)

LOWER SHELL PLATE F-773-1 (LONGITUDINAL ORIENTATION)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 12/12/2005 03:30 PM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALO VERDE 2	UNIRR	SA533B1	LT	F-773-1
2	PALO VERDE 2	137	SA533B1	LT	F-773-1
3	PALO VERDE 2	230	SA533B1	LT	F-773-1



Results

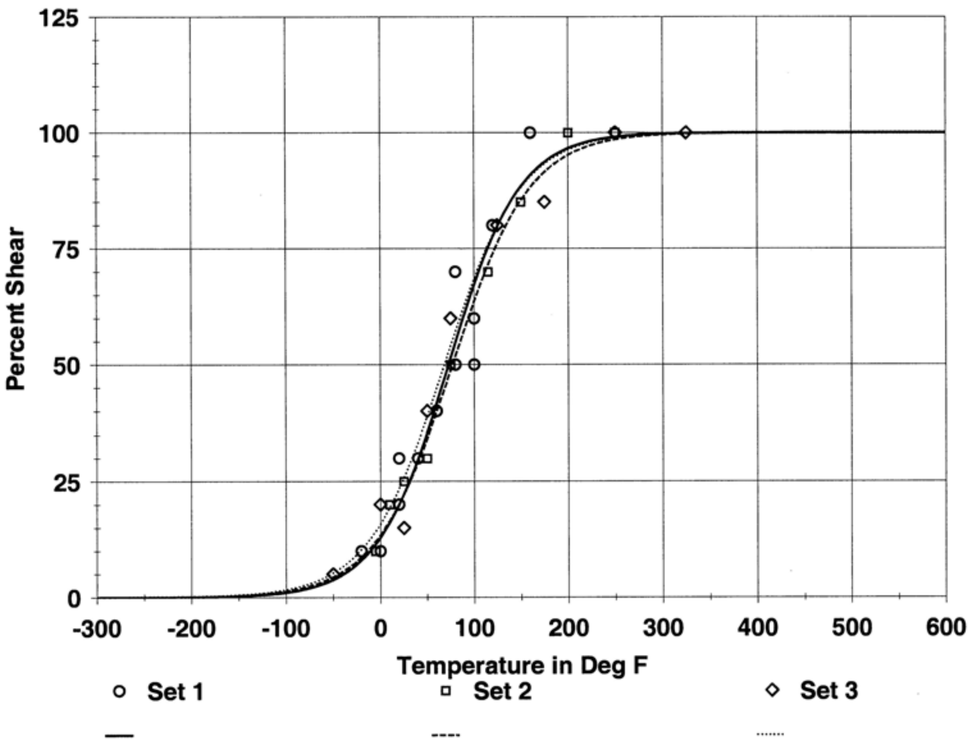
Curve	Fluence	LSE	USE	d-USE	T @35	d-T @35
1		1.0	100.1	.0	10.6	.0
2		1.0	97.7	-2.4	23.8	13.2
3		1.0	88.0	-12.2	32.8	22.2

Figure 5-2 Charpy V-Notch Lateral Expansion vs. Temperature for Palo Verde Unit 2 Reactor Vessel Lower Shell Plate F-773-1 (Longitudinal Orientation)

LOWER SHELL PLATE F-773-1 (LONGITUDINAL)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/29/2005 03:45 PM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALO VERDE 2	UNIRR	SA533B1	LT	F-773-1
2	PALO VERDE 2	137	SA533B1	LT	F-773-1
3	PALO VERDE 2	230	SA533B1	LT	F-773-1



Results

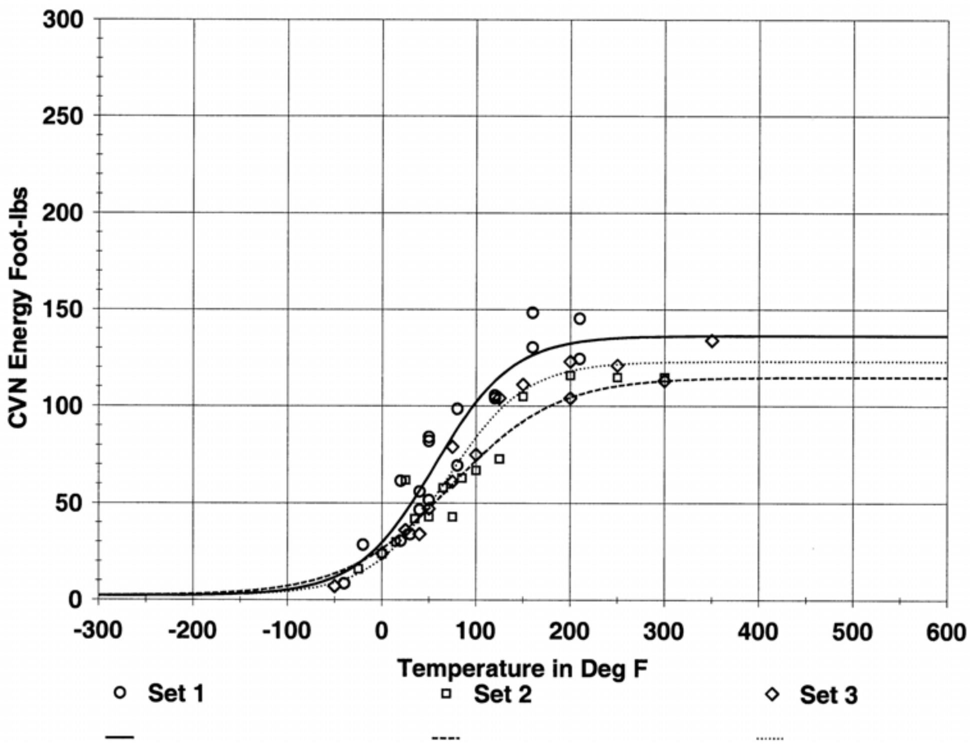
Curve	Fluence	LSE	USE	d-USE	T @50	d-T @50
1		.0	100.0	.0	72.8	.0
2		.0	100.0	.0	77.0	4.2
3		.0	100.0	.0	68.9	-3.9

Figure 5-3 Charpy V-Notch Percent Shear vs. Temperature for Palo Verde Unit 2 Reactor Vessel Lower Shell Plate F-773-1 (Longitudinal Orientation)

LOWER SHELL PLATE F-773-1 (TRANSVERSE)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/29/2005 04:03 PM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALO VERDE 2	UNIRR	SA533B1	TL	F-773-1
2	PALO VERDE 2	137	SA533B1	TL	F-773-1
3	PALO VERDE 2	230	SA533B1	TL	F-773-1



Results

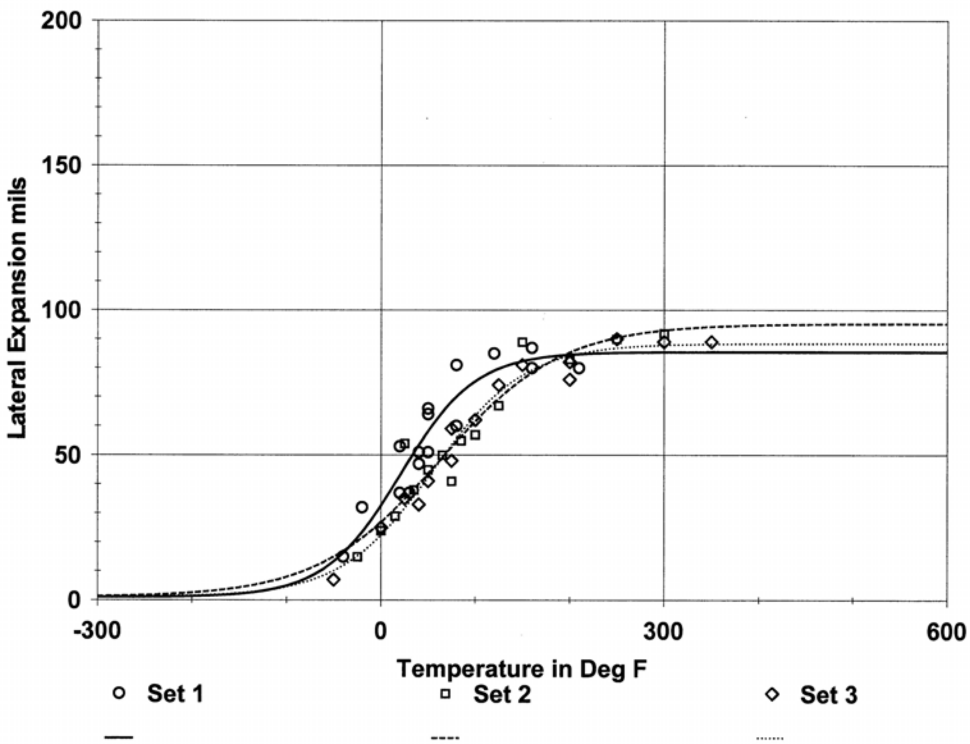
Curve	Fluence	LSE	USE	d-USE	T @30	d-T @30	T @50	d-T @50
1		2.2	136.5	.0	.7	.0	31.7	.0
2		2.2	115.0	-21.5	10.2	9.5	55.7	24.0
3		2.2	123.0	-13.5	20.0	19.3	52.5	20.8

Figure 5-4 Charpy V-Notch Impact Energy vs. Temperature for Palo Verde Unit 2 Reactor Vessel Lower Shell Plate F-773-1 (Transverse Orientation)

LOWER SHELL PLATE F-773-1 (TRANSVERSE ORIENTATION)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 12/12/2005 03:34 PM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALO VERDE 2	UNIRR	SA533B1	TL	F-773-1
2	PALO VERDE 2	137	SA533B1	TL	F-773-1
3	PALO VERDE 2	230	SA533B1	TL	F-773-1



Results

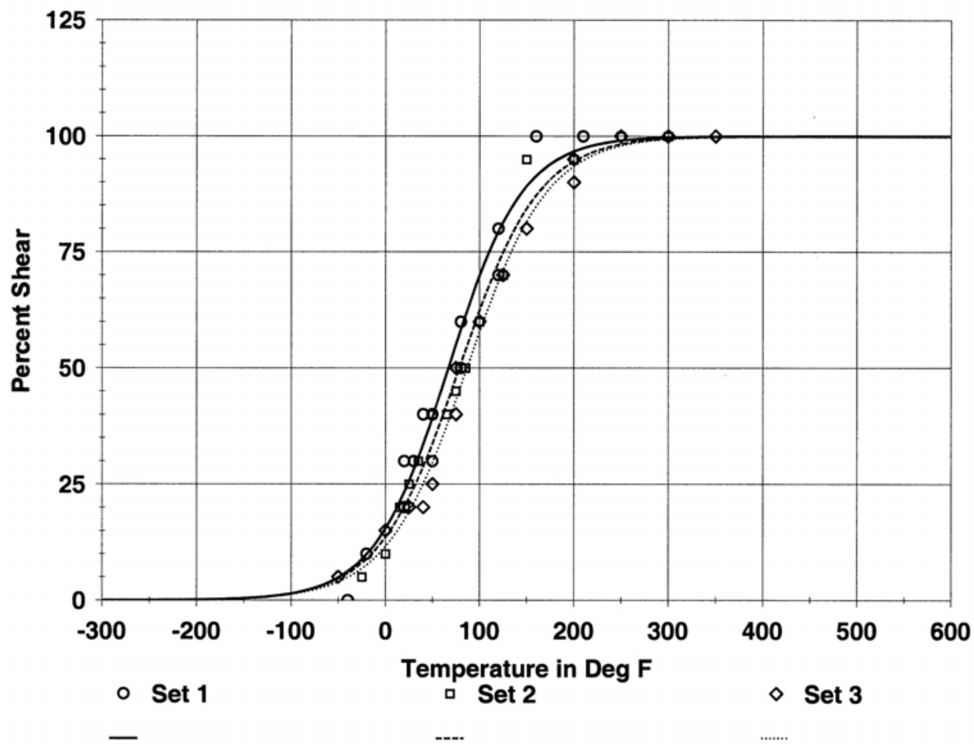
Curve	Fluence	LSE	USE	d-USE	T @35	d-T @35
1		1.0	85.5	.0	4.7	.0
2		1.0	95.3	9.8	25.6	20.9
3		1.0	88.3	2.8	33.8	29.1

Figure 5-5 Charpy V-Notch Lateral Expansion vs. Temperature for Palo Verde Unit 2 Reactor Vessel Lower Shell Plate F-773-1 (Transverse Orientation)

LOWER SHELL PLATE F-773-1 (TRANSVERSE)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/29/2005 07:17 PM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALO VERDE 2	UNIRR	SA533B1	TL	F-773-1
2	PALO VERDE 2	137	SA533B1	TL	F-773-1
3	PALO VERDE 2	230	SA533B1	TL	F-773-1



Results

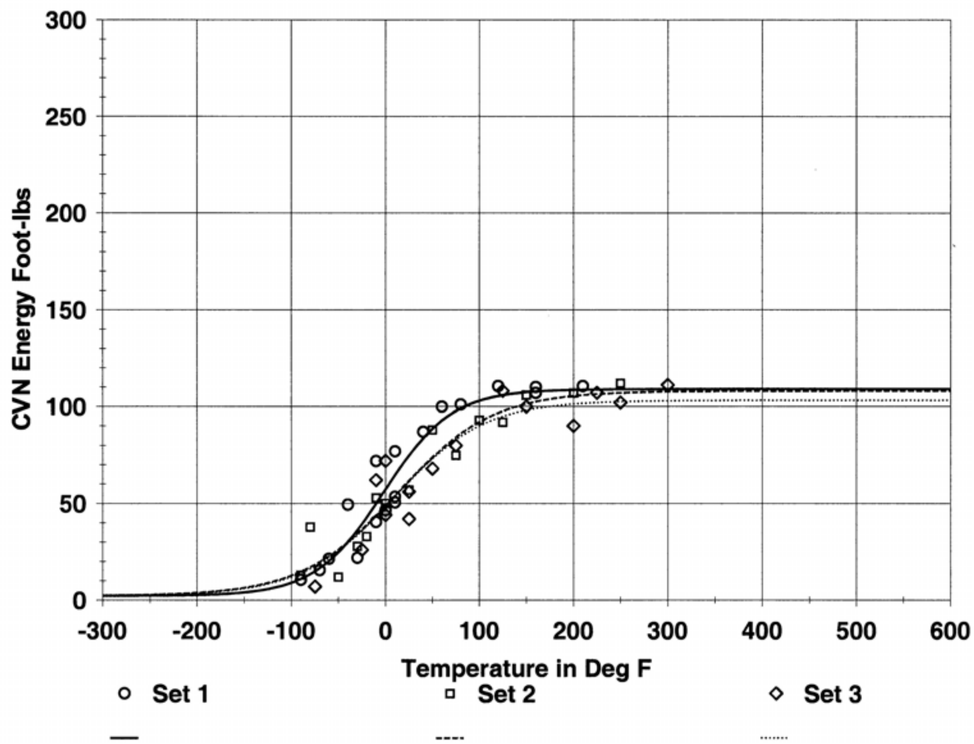
Curve	Fluence	LSE	USE	d-USE	T @50	d-T @50
1		.0	100.0	.0	67.0	.0
2		.0	100.0	.0	78.6	11.6
3		.0	100.0	.0	87.3	20.3

Figure 5-6 Charpy V-Notch Percent Shear vs. Temperature for Palo Verde Unit 2 Reactor Vessel Lower Shell Plate F-773-1 (Transverse Orientation)

SURVEILLANCE PROGRAM WELD METAL

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 03:09 PM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALO VERDE 2	UNIRR	SAW	NA	3P7317
2	PALO VERDE 2	137	SAW	NA	3P7317
3	PALO VERDE 2	230	SAW	NA	3P7317



Results

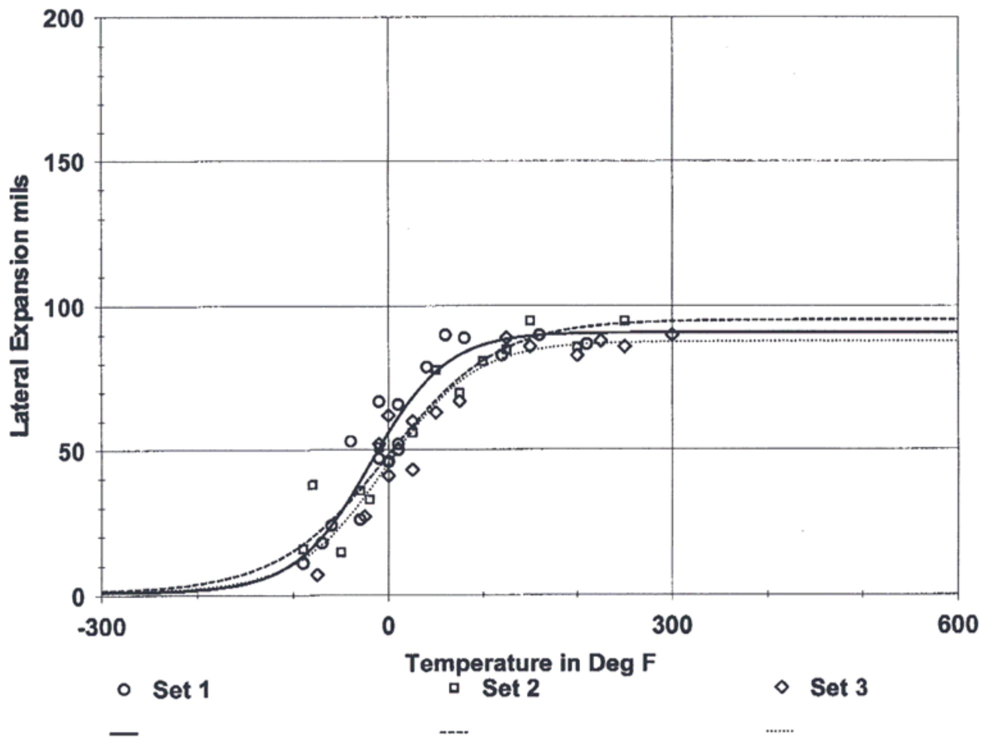
Curve	Fluence	LSE	USE	d-USE	T @30	d-T @30	T @50	d-T @50
1		2.2	109.0	.0	-40.1	.0	-9.9	.0
2		2.2	108.0	-1.0	-40.2	-.1	2.4	12.3
3		2.2	103.0	-6.0	-37.6	2.5	4.1	14.0

Figure 5-7 Charpy V-Notch Impact Energy vs. Temperature for Palo Verde Unit 2 Reactor Vessel Surveillance Weld Material

SURVEILLANCE PROGRAM WELD METAL

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 12/16/2005 07:33 AM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALO VERDE 2	UNIRR	SAW	NA	3P7317
2	PALO VERDE 2	137	SAW	NA	3P7317
3	PALO VERDE 2	230	SAW	NA	3P7317



Results

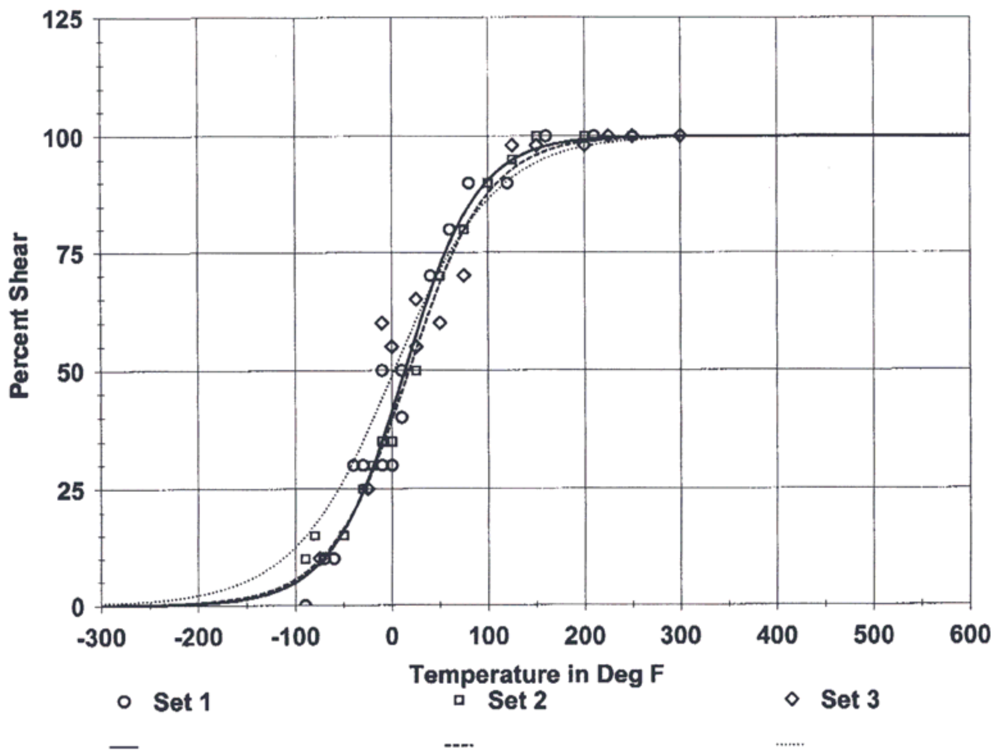
Curve	Fluence	LSE	USE	d-USE	T @35	d-T @35
1		1.0	90.9	.0	-37.5	.0
2		1.0	95.2	4.3	-33.3	4.2
3		1.0	87.7	-3.1	-21.8	15.7

Figure 5-8 Charpy V-Notch Lateral Expansion vs. Temperature for Palo Verde Unit 2 Reactor Vessel Surveillance Weld Metal

SURVEILLANCE PROGRAM WELD METAL

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 12/16/2005 07:33 AM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALO VERDE 2	UNIRR	SAW	NA	3P7317
2	PALO VERDE 2	137	SAW	NA	3P7317
3	PALO VERDE 2	230	SAW	NA	3P7317



Results

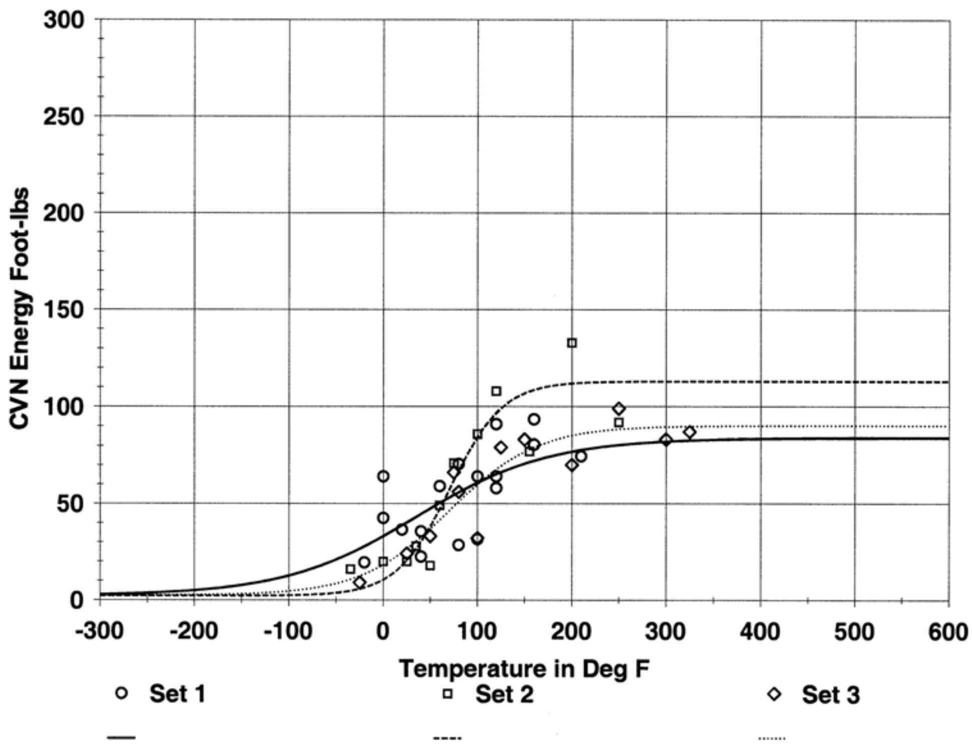
Curve	Fluence	LSE	USE	d-USE	T @50	d-T @50
1		.0	100.0	.0	13.6	.0
2		.0	100.0	.0	17.9	4.3
3		.0	100.0	.0	3.1	-10.5

Figure 5-9 Charpy V-Notch Percent Shear vs. Temperature for Palo Verde Unit 2 Reactor Vessel Surveillance Weld Metal

HEAT AFFECTED ZONE

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 03:34 PM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALO VERDE 2	UNIRR	SA533B1	NA	F-773-1
2	PALO VERDE 2	137	SA533B1	NA	F-773-1
3	PALO VERDE 2	230	SA533B1	NA	F-773-1



Results

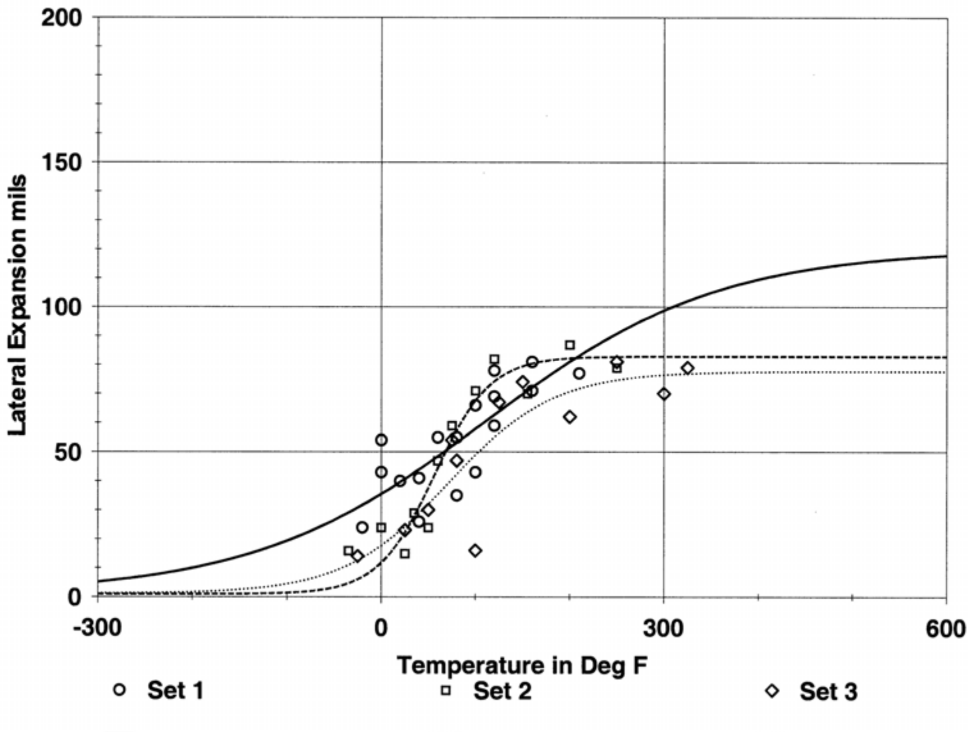
Curve	Fluence	LSE	USE	d-USE	T @30	d-T @30	T @50	d-T @50
1		2.2	84.0	.0	-11.3	.0	59.2	.0
2		2.2	113.0	29.0	40.0	51.3	63.0	3.8
3		2.2	90.0	6.0	35.0	46.3	79.0	19.8

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

HEAT AFFECTED ZONE

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 03:49 PM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALO VERDE 2	UNIRR	SA533B1	NA	F-773-1
2	PALO VERDE 2	137	SA533B1	NA	F-773-1
3	PALO VERDE 2	230	SA533B1	NA	F-773-1



Results

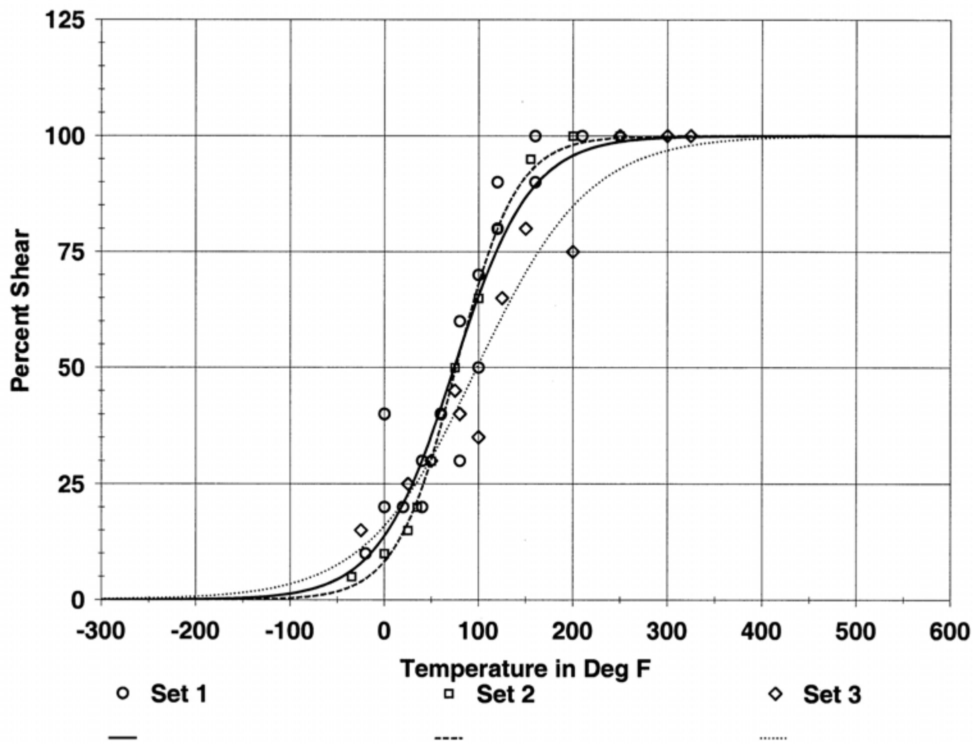
Curve	Fluence	LSE	USE	d-USE	T @35	d-T @35
1		1.0	120.1	.0	-2.7	.0
2		1.0	82.9	-37.2	46.1	48.8
3		1.0	77.6	-42.5	59.6	62.3

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

HEAT AFFECTED ZONE

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 03:39 PM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALO VERDE 2	UNIRR	SA533B1	NA	F-773-1
2	PALO VERDE 2	137	SA533B1	NA	F-773-1
3	PALO VERDE 2	230	SA533B1	NA	F-773-1



Results

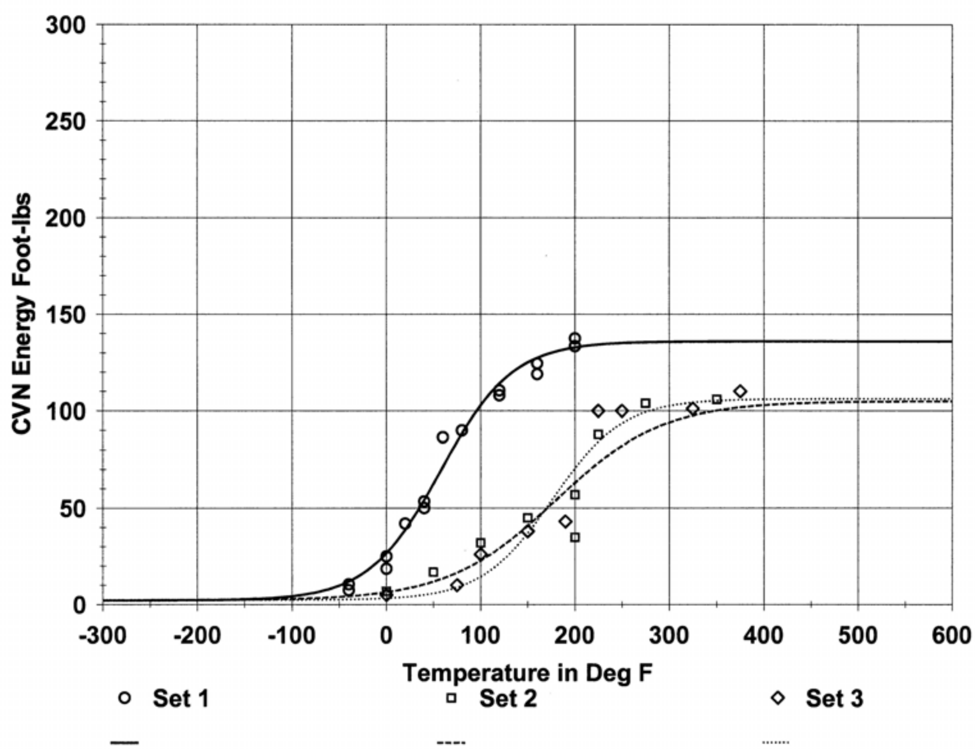
Curve	Fluence	LSE	USE	d-USE	T @50	d-T @50
1		. 0	100. 0	. 0	74. 2	. 0
2		. 0	100. 0	. 0	76. 2	2. 0
3		. 0	100. 0	. 0	99. 0	24. 8

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

STANDARD REFERENCE MATERIAL

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 12/12/2005 03:43 PM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALO VERDE 2	UNIRR	SA533B1	LT	A-1008
2	PALO VERDE 2	137	SA533B1	LT	A-1008
3	PALO VERDE 2	230	SA533B1	LT	A-1008



Results

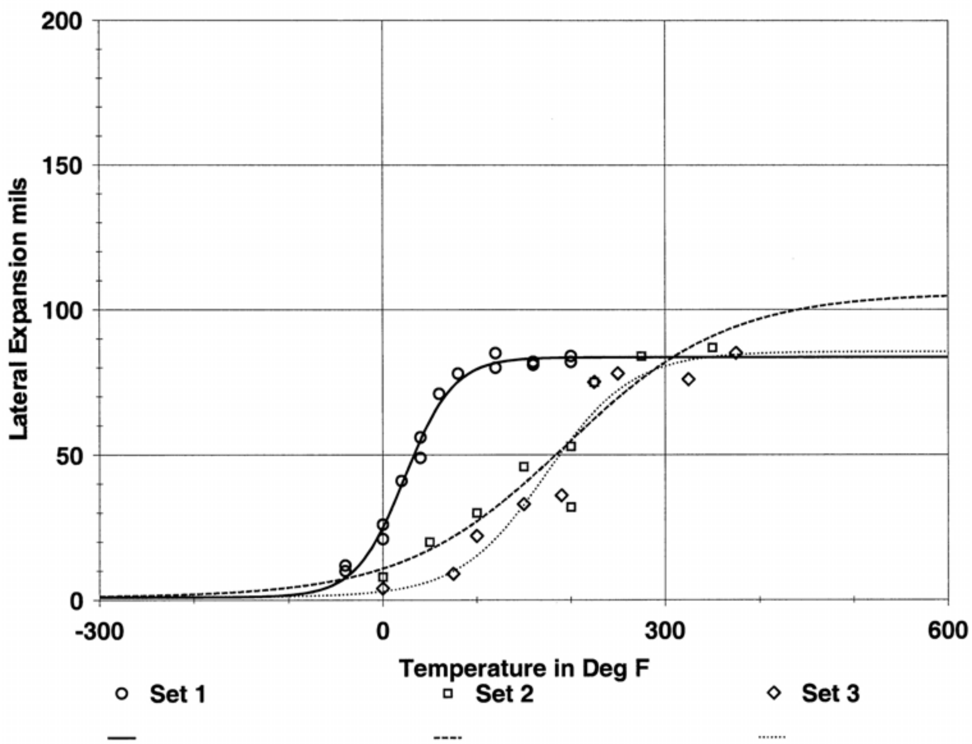
Curve	Fluence	LSE	USE	d-USE	T @30	d-T @30	T @50	d-T @50
1		2.2	136.0	.0	6.3	.0	35.0	.0
2		2.2	105.0	-31.0	122.3	116.0	170.8	135.8
3		2.2	106.0	-30.0	138.7	132.4	170.3	135.3

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

STANDARD REFERENCE MATERIAL

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 05:04 PM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALO VERDE 2	UNIRR	SA533B1	LT	A-1008
2	PALO VERDE 2	137	SA533B1	LT	A-1008
3	PALO VERDE 2	230	SA533B1	LT	A-1008



Results

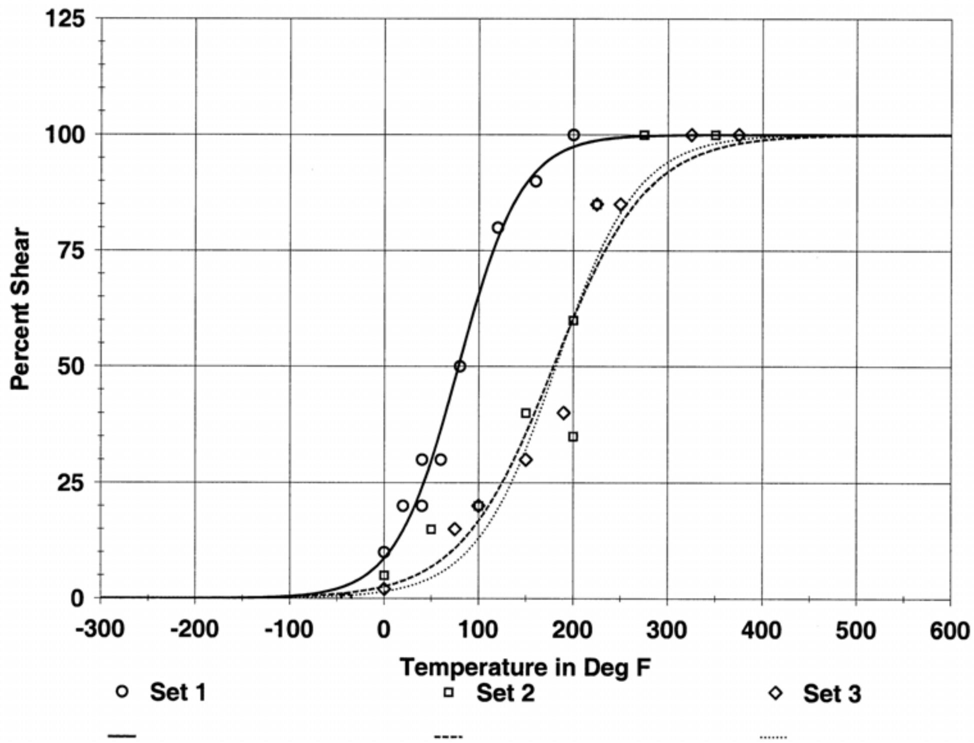
Curve	Fluence	LSE	USE	d-USE	T @35	d-T @35
1		1.0	83.6	.0	14.1	.0
2		1.0	105.6	22.0	131.8	117.7
3		1.0	85.4	1.8	155.7	141.6

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

STANDARD REFERENCE MATERIAL

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 04:52 PM
Data Set(s) Plotted

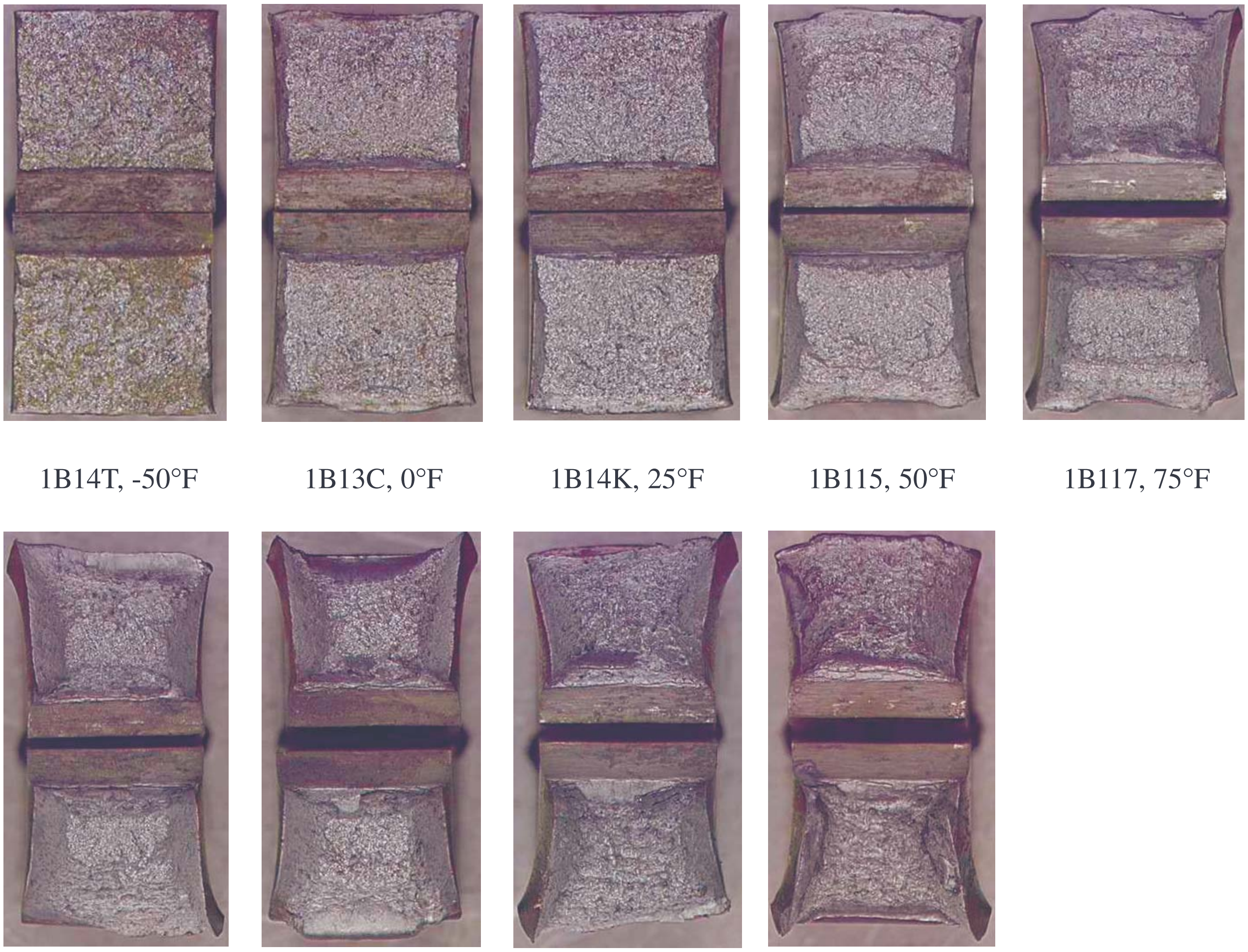
Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALO VERDE 2	UNIRR	SA533B1	LT	A-1008
2	PALO VERDE 2	137	SA533B1	LT	A-1008
3	PALO VERDE 2	230	SA533B1	LT	A-1008



Results

Curve	Fluence	LSE	USE	d-USE	T @50	d-T @50
1		. 0	100. 0	. 0	78. 6	. 0
2		. 0	100. 0	. 0	179. 1	100. 5
3		. 0	100. 0	. 0	182. 2	103. 6

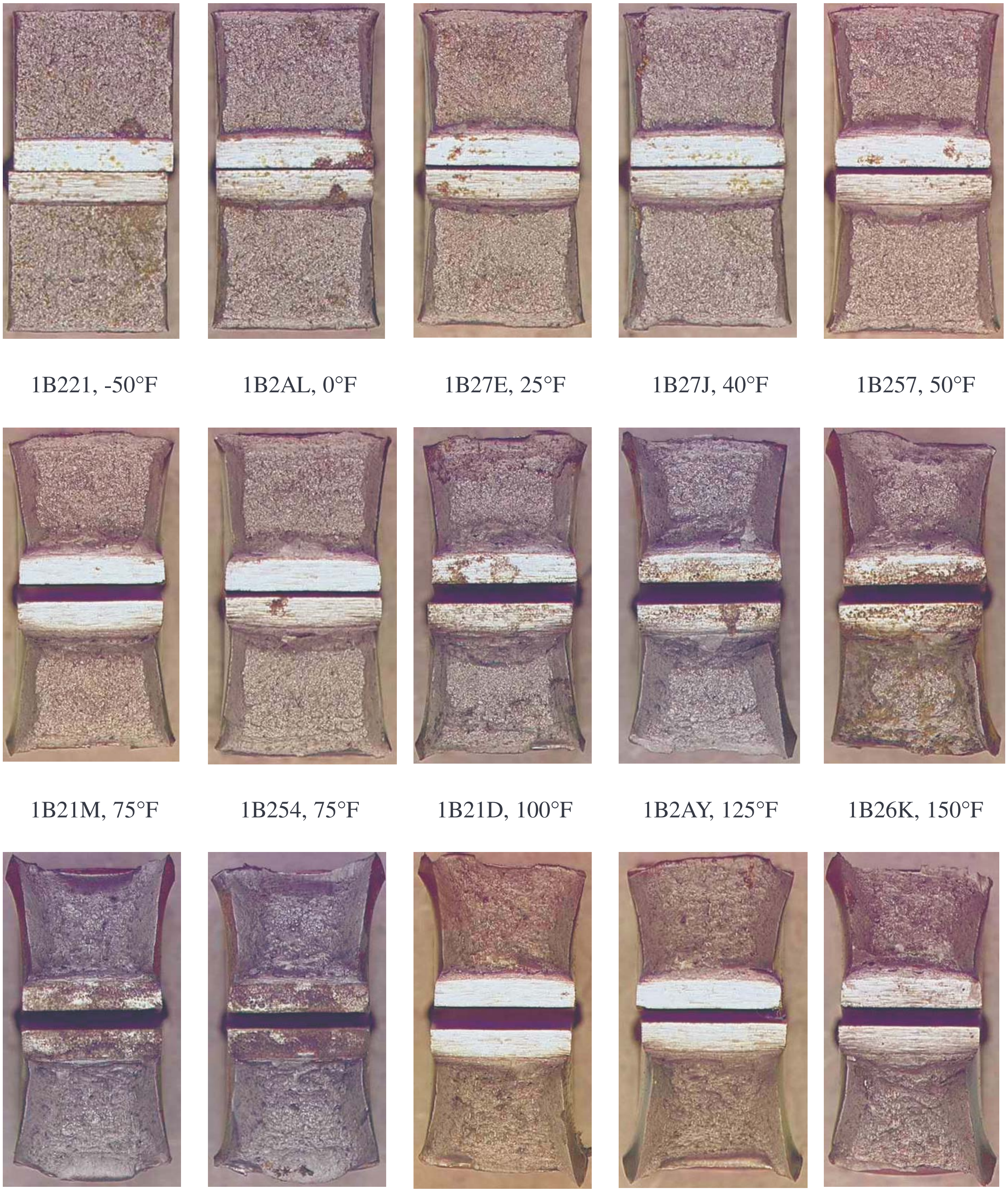
Figure 5-15 Charpy V-Notch Percent Shear vs. Temperature for Palo Verde Unit 2 Reactor Vessel Standard Reference Material



1B14T, -50°F | 1B13C, 0°F | 1B14K, 25°F | 1B115, 50°F | 1B117, 75°F

1B111, 125°F | 1B133, 175°F | 1B12T, 250°F | 1B15L, 325°F

Figure 5-16 Charpy Impact Specimen Fracture Surfaces of the Palo Verde Unit 2, 230° Capsule Reactor Vessel Lower Shell Plate F-773-1 (Longitudinal Orientation)



1B221, -50°F | 1B2AL, 0°F | 1B27E, 25°F | 1B27J, 40°F | 1B257, 50°F

1B21M, 75°F | 1B254, 75°F | 1B21D, 100°F | 1B2AY, 125°F | 1B26K, 150°F

1B265, 200°F | 1B26T, 200°F | 1B22K, 250°F | 1B225, 300°F | 1B223, 350°F

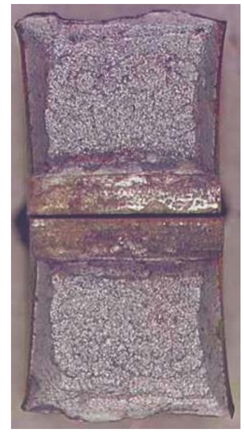
Figure 5-17 Charpy Impact Specimen Fracture Surfaces of the Palo Verde Unit 2, 230° Capsule Reactor Vessel Lower Shell Plate F-773-1 (Transverse Orientation)

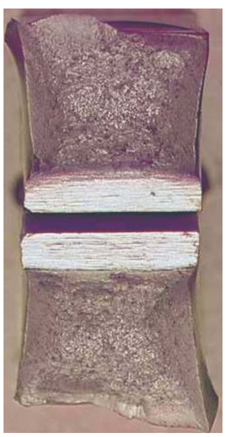

D45, 0°F

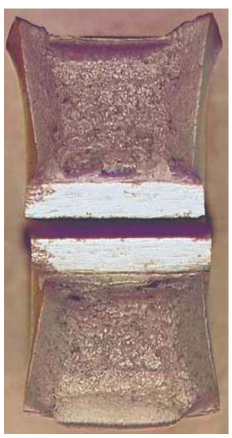

D2P, 75°F


D34, 100°F


D33, 150°F


D2J, 190°F


D2K, 225°F


D3L, 250°F


D3A, 325°F

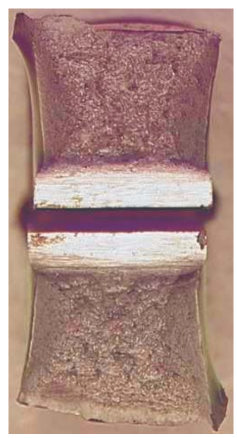

D3U, 375°F

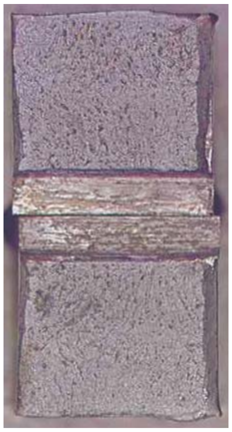
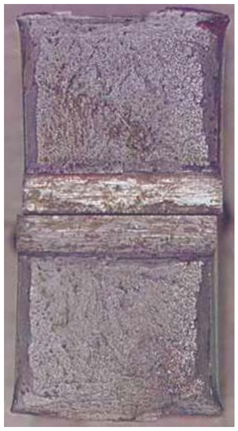
Figure 5-18 Charpy Impact Specimen Fracture Surfaces of the Palo Verde Unit 2, 230° Capsule Standard Reference Material

1B36T, -75°F | 1B352, -25°F | 1B347, -10°F | 1B321, 0°F | 1B36P, 0°F

1B33K, 25°F | 1B35Y, 25°F | 1B32T, 50°F | 1B351, 75°F | 1B313, 125°F

1B366, 150°F | 1B372, 200°F | 1B35D, 225°F | 1B36J, 250°F | 1B354, 300°F

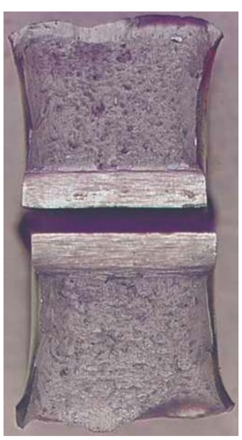
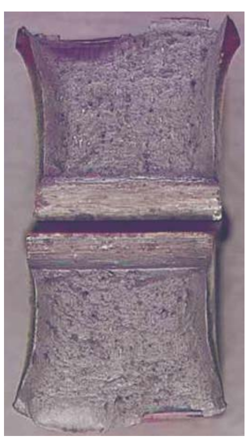
Figure 5-19 Charpy Impact Specimen Fracture Surfaces of the Palo Verde Unit 2, 230° Capsule Reactor Weld Metal Specimens

1B435, -25°F | 1B44B, 25°F | 1B415, 50°F | 1B454, 75°F | 1B414, 80°F

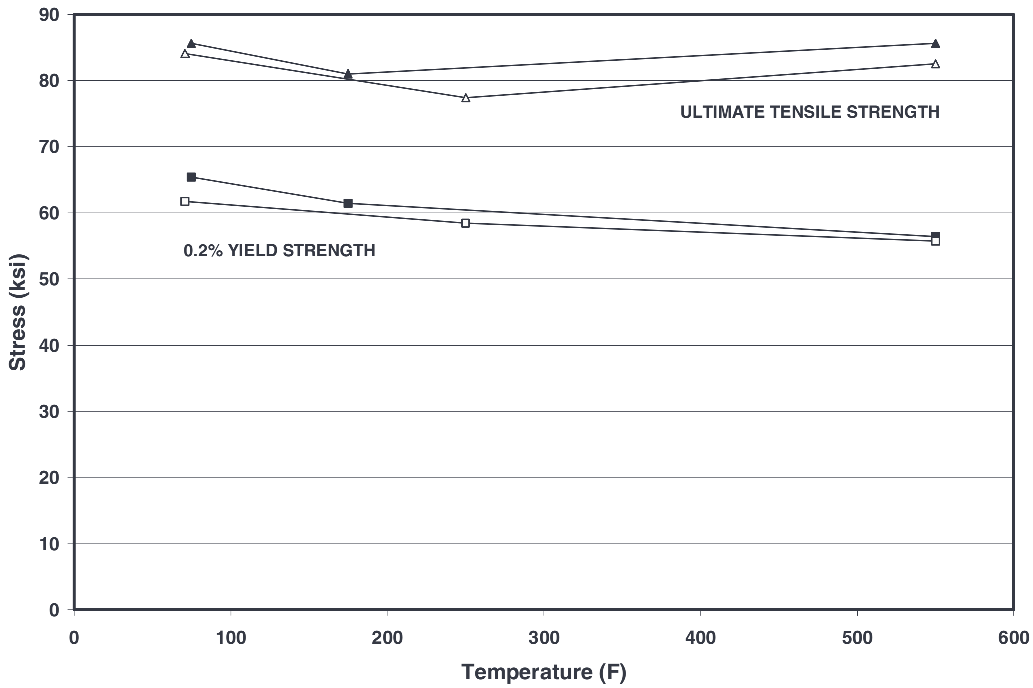
    

1B41J, 100°F | 1B443, 125°F | 1B42E, 150°F | 1B433, 200°F | 1B424, 250°F

1B421, 300°F | 1B41U, 325°F

Figure 5-20 Charpy Impact Specimen Fracture Surfaces of the Palo Verde Unit 2, 230° Capsule Reactor Vessel Heat Affected Zone (HAZ) Metal



Legend: Δ and ○ and □ are Unirradiated
▲and ● and ■ are Irradiated to 0.992 x 10^{19} n/cm^2 (E > 1.0 MeV)

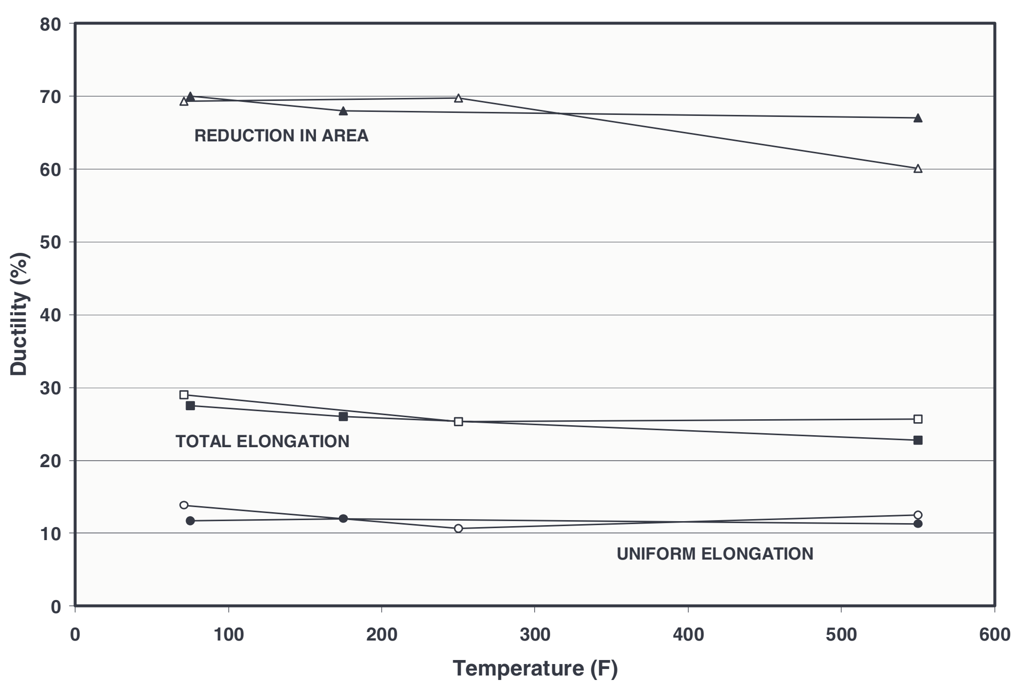
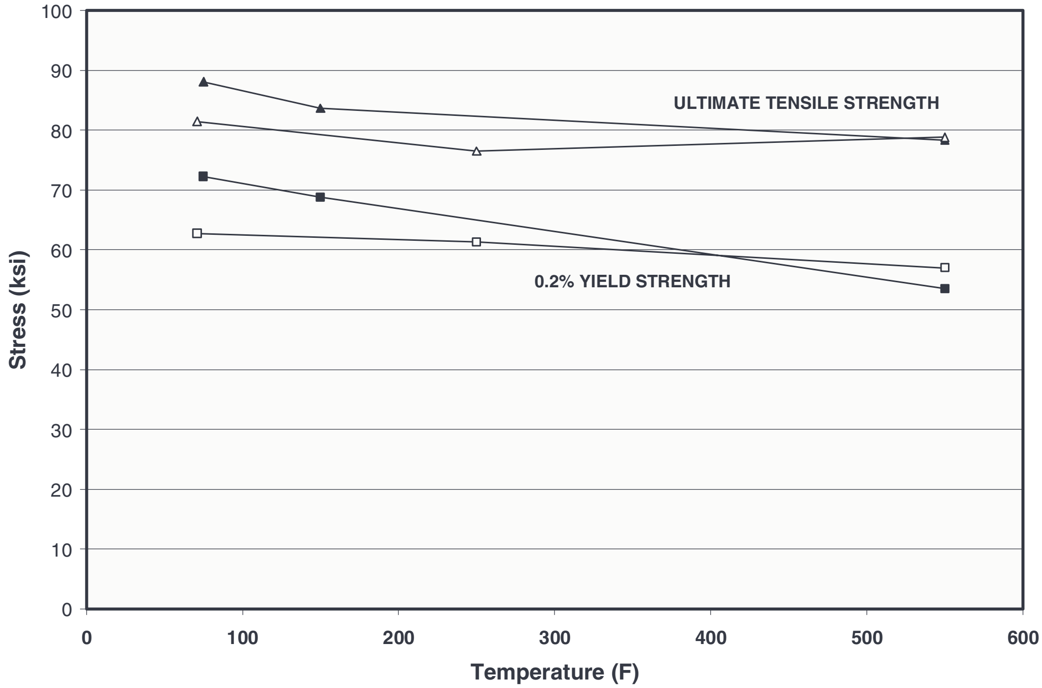


Figure 5-21 Tensile Properties for Palo Verde Unit 2 Reactor Vessel Lower Shell Plate F-773-1 (Transverse Orientation) – Unirradiated and Irradiated to 0.992 x 10^{19} n/cm^2 (E > 1.0 MeV)



Legend: Δ and ○ and □ are Unirradiated
▲ and ● and ■ are Irradiated to 0.992 x 10^{19} n/cm^2 (E > 1.0 MeV)

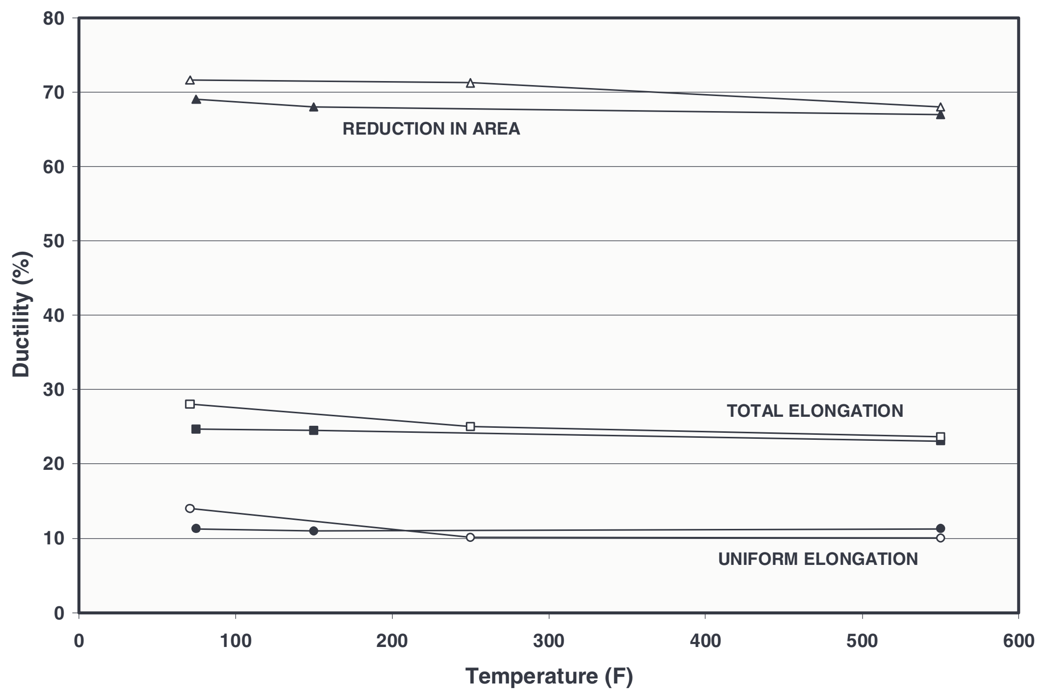
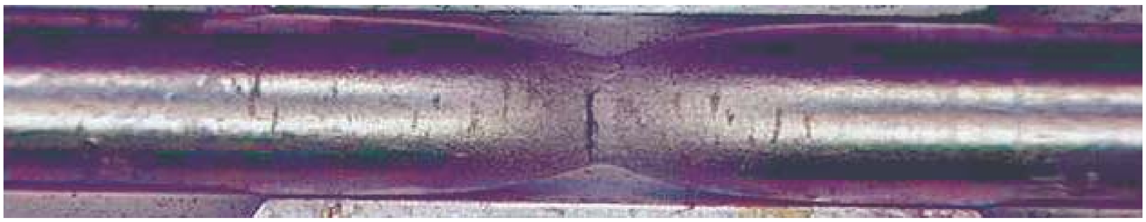
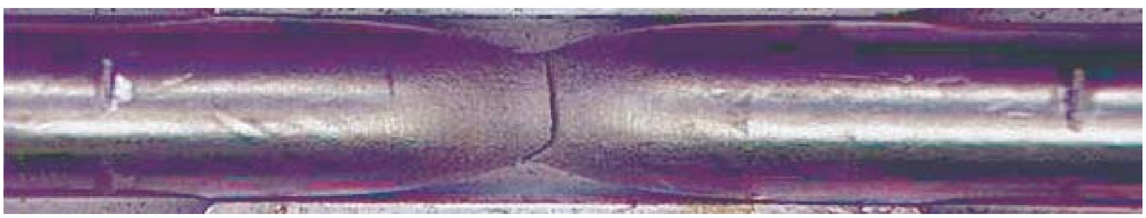


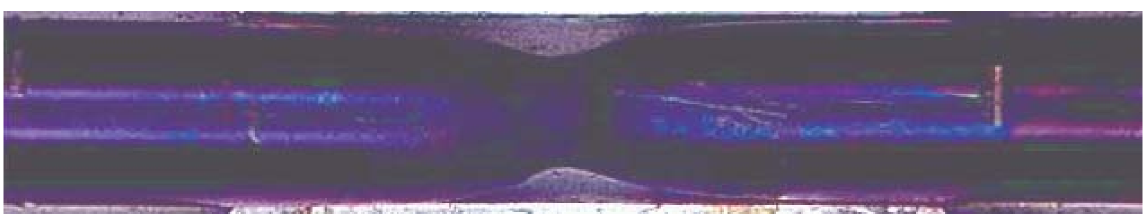
Figure 5-22 Tensile Properties for Palo Verde Unit 2 Reactor Vessel Weld Metal Heat 3P7317 – Unirradiated and Irradiated to 0.992 x 10^{19} n/cm^2 (E > 1.0 MeV)



Specimen 1B2J1 Tested at 75°F

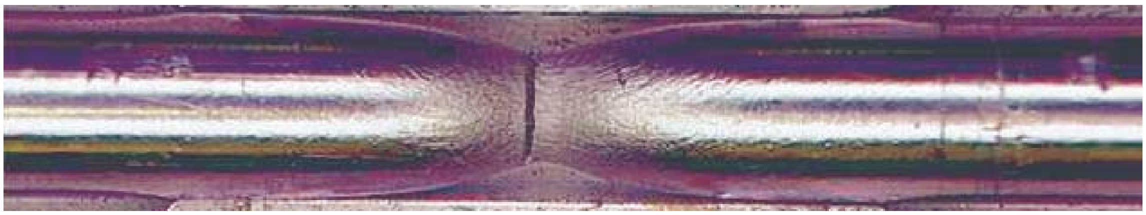


Specimen 1B2JD Tested at 175°F

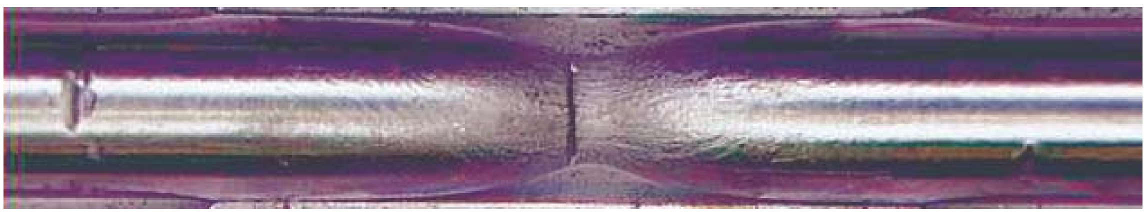


Specimen 1B2KA Tested at 550°F

Figure 5-23 Fractured Tensile Specimens from the Palo Verde Unit 2, 230° Capsule Reactor Vessel Lower Shell Plate F-773-1. (Transverse Orientation)



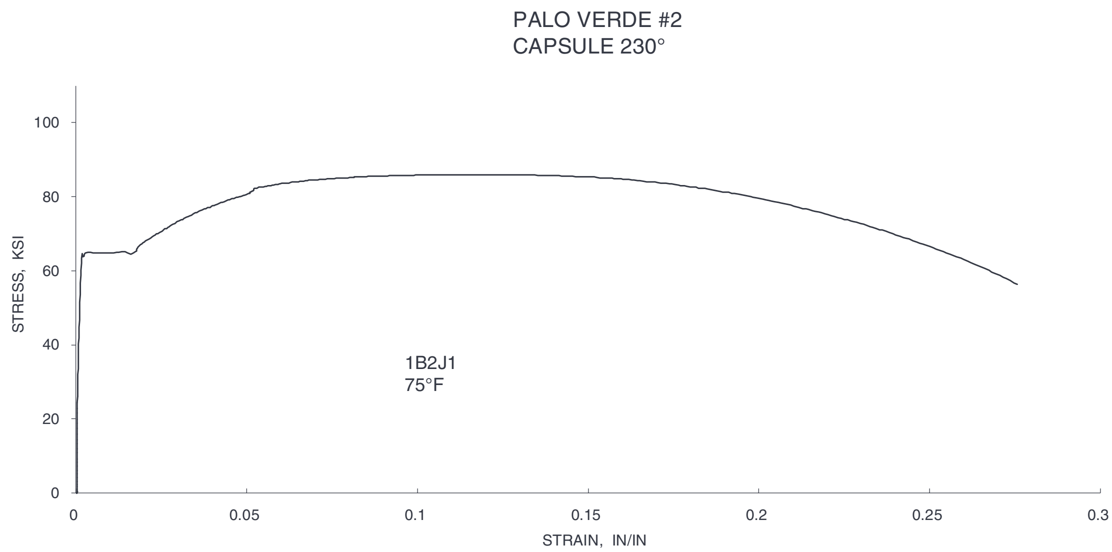
Specimen 1B3K6 Tested at 75°F



Specimen 1B3JM Tested at 150°F

Specimen 1B3JD Tested at 550°F

Figure 5-24 Fractured Tensile Specimens from the Palo Verde Unit 2, 230° Capsule Reactor Vessel Weld Metal Heat 3P7317



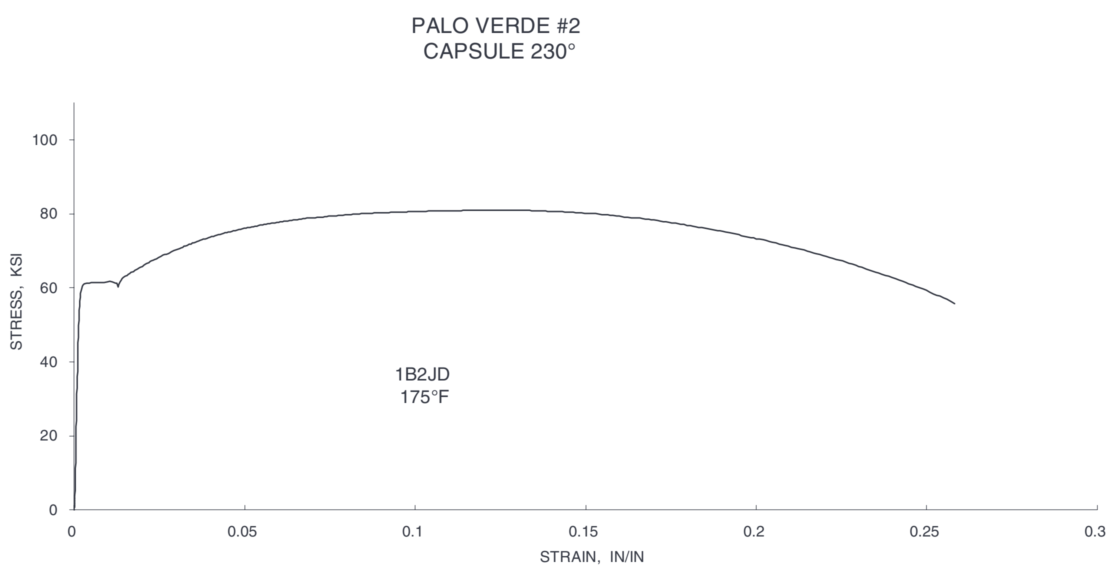


Figure 5-25 Engineering Stress-Strain Curves for Palo Verde Unit 2 Reactor Vessel Lower Shell Plate F-773-1, 230° Capsule, Transverse Tensile Specimens 1B2J1 and 1B2JD

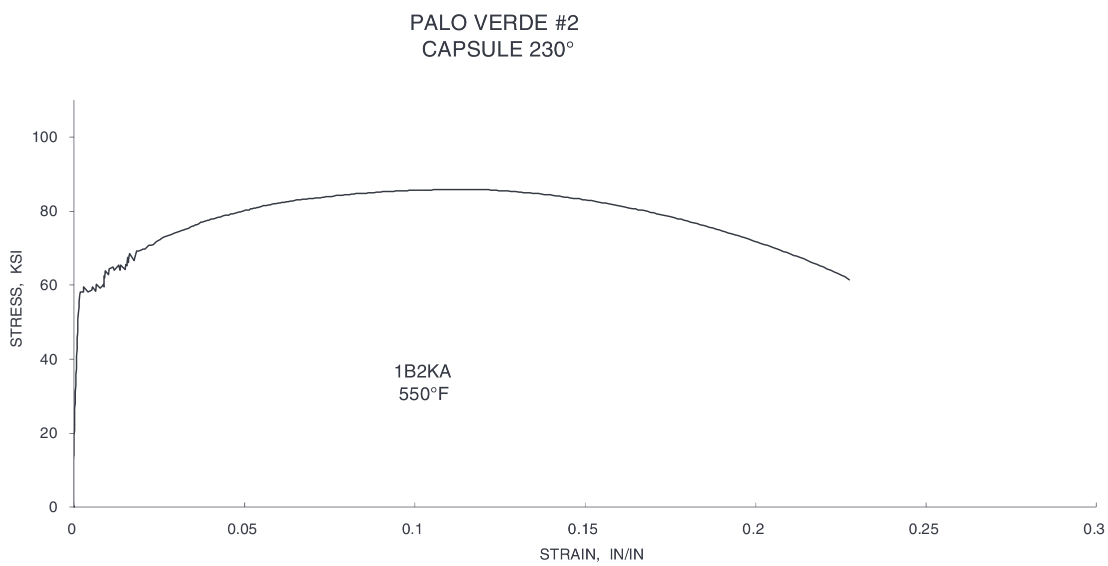
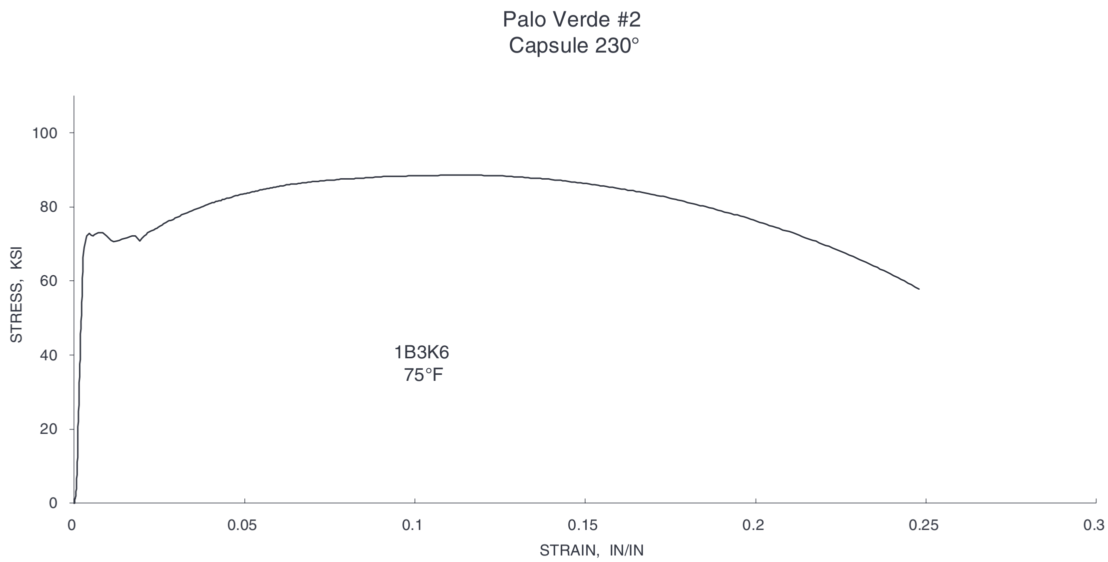


Figure 5-26 Engineering Stress-Strain Curve for Palo Verde Unit 2 Reactor Vessel Lower Shell Plate F-773-1, 230° Capsule, Transverse Tensile Specimen 1B2KA



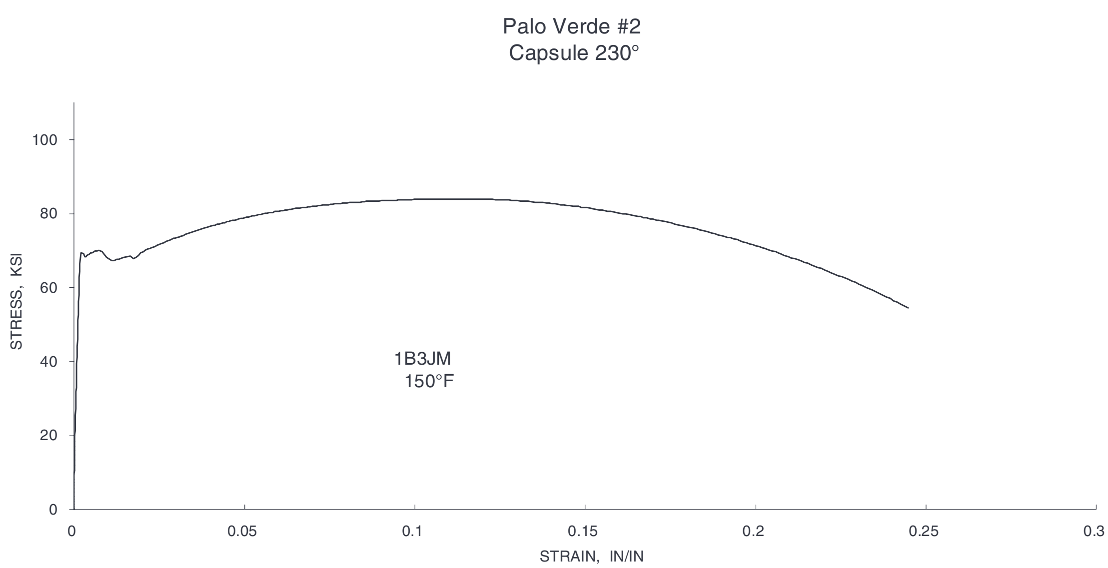


Figure 5-27 Engineering Stress-Strain Curves For Palo Verde Unit 2 Reactor Vessel Weld Material, 230° Capsule, Tensile Specimens 1B3K6 and 1B3JM

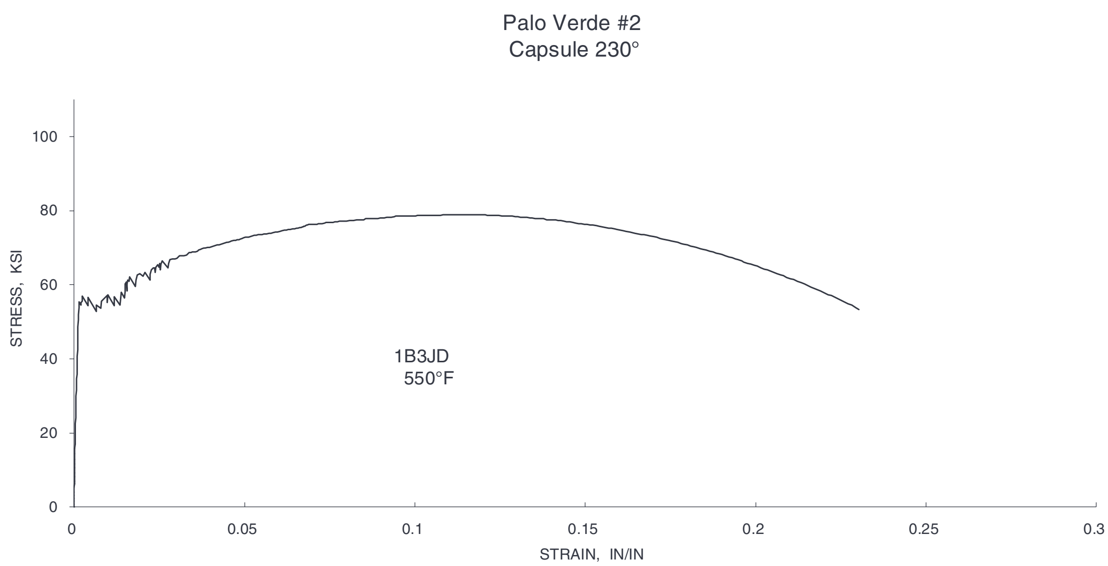


Figure 5-28 Engineering Stress-Strain Curve for Palo Verde Unit 2 Reactor Vessel Weld Material, 230° Capsule, Tensile Specimen 1B3JD

6 RADIATION ANALYSIS AND NEUTRON DOSIMETRY

6.1 INTRODUCTION

This section describes a discrete ordinates Sn transport analysis performed for the Palo Verde 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 fluence (E > 1.0 MeV) 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 W230, withdrawn at the end of the twelfth plant operating cycle, is provided. In addition, to provide an up-to-date data base applicable to the Palo Verde Unit 2 reactor, the sensor set from the previously withdrawn capsule (Capsule W137) was re-analyzed using the current dosimetry evaluation methodology. These dosimetry updates are presented in Appendix A of this report. Comparisons of the results from these dosimetry evaluations with the analytical predictions served to validate the plant specific neutron transport calculations. These validated calculations subsequently formed the basis for providing 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 fluence (E > 1.0 MeV) 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. In recent years, however, 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, "Analysis and Interpretation of Light-Water Reactor Surveillance Results," (Reference 16) recommends reporting displacements per iron atom (dpa) 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, "Characterizing Neutron Exposures in Iron and Low Alloy Steels in Terms of Displacements per Atom," (Reference 17). 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."

All of the calculations and dosimetry evaluations described in this section and in Appendix A were based on the latest available nuclear cross-section data derived from ENDF/B-VI and made use of the latest available calculational tools. 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," (Reference 18). Additionally, the methods used to develop the calculated pressure vessel fluence are consistent with the NRC approved methodology described in WCAP-14040-NP-A, "Methodology Used to Develop Cold Overpressure Mitigating System Setpoints and RCS Heatup and Cooldown Limit Curves," May 2004, (Reference 19).

6.2 DISCRETE ORDINATES ANALYSIS

A plan view of the Palo Verde Unit 2 reactor geometry at the core midplane is shown in Figure 4-1. Six irradiation capsules attached to the reactor vessel are included in the reactor design that constitutes the reactor vessel surveillance program. The capsules are located at azimuthal angles of 38° and 142° (38° from the core cardinal axes), 230° and 310° (40° from the core cardinal axes), and 43° and 137° (43° from the core cardinal axes). The stainless steel surveillance capsule holder containers are a 1.968-inch by 1.293-inch inner dimension with a 0.138-inch wall thickness. The stainless steel specimen containers are 1.50-inch by 0.75-inch and are approximately 96 inches in height. The containers are positioned axially such that the test specimens are centered on the core midplane, thus spanning the 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 marked effect on both the spatial distribution of neutron flux and the neutron energy spectrum in the water annulus between the core barrel and the reactor vessel. 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 Palo Verde Unit 2 reactor vessel and surveillance capsules, a series of fuel cycle specific forward transport calculations were carried out using the following three-dimensional flux synthesis technique:

$$\phi(r,\theta,z) = \phi(r,\theta) * \frac{\phi(r,z)}{\phi(r)}$$

where $\phi(r,\theta,z)$ is the synthesized three-dimensional neutron flux 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 Palo Verde Unit 2.

In performing the fast neutron exposure evaluations for Palo Verde Unit 2, two sets of transport calculations were carried out. The first set of calculations were based on a r,θ model that included surveillance capsules at 38°, 40°, and 43°, which is shown in Figure 6-1, and the second set of calculations were based on a r,θ model having no surveillance capsules present. The former set of calculations were used to perform surveillance capsule dosimetry evaluations and subsequent comparisons with calculated results, while the latter model was used to determine maximum neutron exposure levels at the pressure vessel wall. In developing these analytical models, nominal design dimensions were employed for the various structural components with two exceptions. Specifically, the radius to the center of the surveillance capsule holder as well as the pressure vessel inner radius (PVIR) were taken from the as-built drawings for the Palo Verde Unit 2 reactor to account for key differences between the nominal versus as-built dimensions. Likewise, water temperatures, and hence, coolant densities in the reactor core and bypass 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 models consisted of 151 radial by 78 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 flux convergence criterion utilized in the r,θ calculations was set at a value of 0.001.

The r,z model used for the Palo Verde Unit 2 calculations is shown in Figure 6-2 and extends radially from the centerline of the reactor core out to a location interior to the primary biological shield and over an axial span from an elevation 2-feet below the active fuel to 2-feet above the active fuel. As in the case of the r,θ models, nominal design dimensions (except for the PVIR as-built dimension) and full power coolant densities were employed in the calculations. In this case, the homogenous core region was treated as an equivalent cylinder with a volume equal to that of the active core zone. The stainless steel core shroud assembly girth rings located between the core shroud and core barrel regions were also explicitly included in the model. The r,z geometric mesh description of these reactor models consisted of 141 radial by 79 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 flux convergence criterion utilized in the r,z calculations was also set at a value of 0.001.

The one-dimensional radial models used in the synthesis procedure consisted of the same 141 radial mesh intervals included in the r,z models. Thus, radial synthesis factors could be determined on a meshwise basis throughout the entire geometry.

Data used in the transport analyses were taken from the appropriate Palo Verde Unit 2 cycle-specific fuel information provided by the Arizona Public Service Company. The extracted data represented cycle dependent fuel assembly enrichments, burnups, axial power distributions, and radial pin powers. 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 flux, 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 the 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 Version 3.2 (Reference 20) and the BUGLE-96 cross-section library (Reference 21). The BUGLE-96 library provides a 67 group coupled neutron-gamma ray 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 Tables 6-1 through 6-6. In Table 6-1, the calculated exposure rates and integrated exposures, expressed in terms of both neutron fluence ($E > 1.0$ MeV) and dpa, are given at the radial and azimuthal center of the three azimuthally symmetric surveillance capsule positions (38°, 40°, and 43°). These results, representative of the axial midplane of the active core, establish the calculated exposure of the surveillance capsules withdrawn to date as well as projected into the future. Similar information is provided in Table 6-2 for the reactor vessel inner radius at four azimuthal locations. The vessel data given in Table 6-2 were taken at the clad/base metal interface, and thus, represent maximum calculated exposure levels on the vessel.

Both calculated fluence (E > 1.0 MeV) and dpa data are provided in Table 6-1 and Table 6-2. These data tabulations include both plant and fuel cycle specific calculated neutron exposures at the end of the twelfth operating fuel cycle and future projections to 16, 32, 48, and 54 EFPY. The projections were based on the assumption that the core power distributions and associated plant operating characteristics from Cycle 12 were representative of future plant operation. The future projections are also based on the current reactor power level of 3990 MWt.

Radial gradient information applicable to fast (E > 1.0 MeV) neutron fluence and dpa are given in Tables 6-3 and 6-4, respectively. The data, based on the cumulative integrated exposures from Cycles 1 through 12, are presented on a relative basis for each exposure parameter at several azimuthal locations. Exposure distributions through the vessel wall may be obtained by multiplying the calculated exposure at the vessel inner radius by the gradient data listed in Tables 6-3 and 6-4.

The calculated fast neutron exposures for the two surveillance capsules withdrawn from the Palo Verde Unit 2 reactor are provided in Table 6-5. These assigned neutron exposure levels are based on the plant and fuel cycle specific neutron transport calculations performed for the Palo Verde Unit 2 reactor.

Updated lead factors for the Palo Verde Unit 2 surveillance capsules are provided in Table 6-6. The capsule lead factor is defined as the ratio of the calculated fluence (E > 1.0 MeV) at the geometric center of the surveillance capsule to the corresponding maximum calculated fluence at the pressure vessel clad/base metal interface. In Table 6-6, the lead factors for capsules that have been withdrawn from the reactor (Capsules W137 and W230) 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 (Capsules W38, W43, W142, and W230), the lead factor corresponds to the calculated fluence values at the end of Cycle 12, the latest completed operating fuel cycle for Palo Verde Unit 2.

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 via a least squares evaluation performed for each of the capsule dosimetry sets. However, since the neutron dosimetry measurement data merely serves 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, are documented in Appendix A.

The direct comparison of measured versus calculated fast neutron threshold reaction rates for the sensors from Capsule W230, that was withdrawn from Palo Verde Unit 2 at the end of the twelfth fuel cycle, is summarized below.

Reaction	Reaction Rates (rps/atom)		M/C Ratio
	Measured	Calculated	
^{46}Ti(n,p)^{46}Sc	5.23E-16	5.28E-16	0.99
^{54}Fe(n,p)^{54}Mn	2.88E-15	2.93E-15	0.98
^{58}Ni(n,p)^{58}Co (Cd)	3.59E-15	3.82E-15	0.94
		Average:	0.97
		% Standard Deviation:	2.8

The measured-to-calculated (M/C) reaction rate ratios for the Capsule W230 threshold reactions range from 0.94 to 0.99, and the average M/C ratio is 0.97 ± 2.8% (1σ). This direct comparison falls well within the ± 20% criterion specified in Regulatory Guide 1.190; furthermore, it is consistent with the full set of comparisons given in Appendix A for all measured dosimetry removed to date from the Palo Verde Unit 2 reactor. These comparisons validate the current analytical results described in Section 6.2; therefore, the calculations are deemed applicable for Palo Verde Unit 2.

6.4 CALCULATIONAL UNCERTAINTIES

The uncertainty associated with the calculated neutron exposure of the Palo Verde 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 Palo Verde 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 Palo Verde Unit 2 analysis was established from results of these three phases of the methods qualification.

The fourth phase of the uncertainty assessment (comparisons with Palo Verde 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 Palo Verde 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 19.

	Capsule	**Vessel IR**
PCA Comparisons	3%	3%
H. B. Robinson Comparisons	3%	3%
Analytical Sensitivity Studies	10%	11%
Additional Uncertainty for Factors not Explicitly Evaluated	5%	5%
Net Calculational Uncertainty	12%	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 Palo Verde Unit 2.

Table 6-1 Calculated Neutron Exposure Rates and Integrated Exposures at the Surveillance Capsule Center						
Cycle	Cycle Length [EFPS]	Cumulative Irradiation Time [EFPS]	Cumulative Irradiation Time [EFPY]	Neutron Flux (E > 1.0 MeV) [n/cm^2-s]		
				38°	40°	43°
1	3.63E+07	3.63E+07	1.15	3.52E+10	3.55E+10	3.51E+10
2	3.39E+07	7.02E+07	2.23	2.46E+10	2.46E+10	2.42E+10
3	3.74E+07	1.08E+08	3.41	2.43E+10	2.48E+10	2.48E+10
4	3.57E+07	1.43E+08	4.54	2.42E+10	2.41E+10	2.36E+10
5	3.10E+07	1.74E+08	5.52	2.39E+10	2.39E+10	2.33E+10
6	2.73E+07	2.02E+08	6.39	1.92E+10	1.97E+10	1.96E+10
7	4.14E+07	2.43E+08	7.70	2.09E+10	2.10E+10	2.07E+10
8	4.47E+07	2.88E+08	9.12	1.25E+10	1.25E+10	1.22E+10
9	4.35E+07	3.31E+08	10.50	1.79E+10	1.87E+10	1.91E+10
10	3.91E+07	3.70E+08	11.73	2.03E+10	2.10E+10	2.11E+10
11	4.43E+07	4.15E+08	13.14	1.74E+10	1.79E+10	1.80E+10
12	3.81E+07	4.53E+08	14.35	2.19E+10	2.29E+10	2.34E+10
Future	5.22E+07	5.05E+08	16.00	2.19E+10	2.29E+10	2.34E+10
Future	5.05E+08	1.01E+09	32.00	2.19E+10	2.29E+10	2.34E+10
Future	5.05E+08	1.51E+09	48.00	2.19E+10	2.29E+10	2.34E+10
Future	1.89E+08	1.70E+09	54.00	2.19E+10	2.29E+10	2.34E+10

Note:
Neutron exposure values reported for the surveillance capsules are centered at the core midplane.

Table 6-1 (cont.) Calculated Neutron Exposure Rates and Integrated Exposures at the Surveillance Capsule Center

Cycle	Cycle Length [EFPS]	Cumulative Irradiation Time [EFPS]	Cumulative Irradiation Time [EFPY]	Neutron Fluence (E > 1.0 MeV) [n/cm^2]		
				38°	40°	43°
1	3.63E+07	3.63E+07	1.15	1.28E+18	1.29E+18	1.28E+18
2	3.39E+07	7.02E+07	2.23	2.11E+18	2.13E+18	2.10E+18
3	3.74E+07	1.08E+08	3.41	3.02E+18	3.05E+18	3.03E+18
4	3.57E+07	1.43E+08	4.54	3.88E+18	3.91E+18	3.87E+18
5	3.10E+07	1.74E+08	5.52	4.62E+18	4.65E+18	4.59E+18
6	2.73E+07	2.02E+08	6.39	5.15E+18	5.19E+18	5.12E+18
7	4.14E+07	2.43E+08	7.70	6.01E+18	6.06E+18	5.98E+18
8	4.47E+07	2.88E+08	9.12	6.57E+18	6.62E+18	6.53E+18
9	4.35E+07	3.31E+08	10.50	7.35E+18	7.43E+18	7.36E+18
10	3.91E+07	3.70E+08	11.73	8.15E+18	8.25E+18	8.18E+18
11	4.43E+07	4.15E+08	13.14	8.92E+18	9.04E+18	8.98E+18
12	3.81E+07	4.53E+08	14.35	9.76E+18	9.92E+18	9.87E+18
Future	5.22E+07	5.05E+08	16.00	1.09E+19	1.11E+19	1.11E+19
Future	5.05E+08	1.01E+09	32.00	2.20E+19	2.27E+19	2.29E+19
Future	5.05E+08	1.51E+09	48.00	3.31E+19	3.42E+19	3.47E+19
Future	1.89E+08	1.70E+09	54.00	3.72E+19	3.86E+19	3.91E+19

Note:

Neutron exposure values reported for the surveillance capsules are centered at the core midplane.

Table 6-1 (cont.) Calculated Neutron Exposure Rates and Integrated Exposures at the Surveillance Capsule Center

Cycle	Cycle Length [EFPS]	Cumulative Irradiation Time [EFPS]	Cumulative Irradiation Time [EFPY]	Iron Atom Displacement Rate [dpa/s]		
				38°	40°	43°
1	3.63E+07	3.63E+07	1.15	5.11E-11	5.16E-11	5.10E-11
2	3.39E+07	7.02E+07	2.23	3.57E-11	3.58E-11	3.53E-11
3	3.74E+07	1.08E+08	3.41	3.53E-11	3.60E-11	3.61E-11
4	3.57E+07	1.43E+08	4.54	3.52E-11	3.51E-11	3.43E-11
5	3.10E+07	1.74E+08	5.52	3.48E-11	3.48E-11	3.39E-11
6	2.73E+07	2.02E+08	6.39	2.80E-11	2.86E-11	2.86E-11
7	4.14E+07	2.43E+08	7.70	3.04E-11	3.06E-11	3.01E-11
8	4.47E+07	2.88E+08	9.12	1.82E-11	1.82E-11	1.78E-11
9	4.35E+07	3.31E+08	10.50	2.61E-11	2.72E-11	2.78E-11
10	3.91E+07	3.70E+08	11.73	2.96E-11	3.05E-11	3.07E-11
11	4.43E+07	4.15E+08	13.14	2.54E-11	2.61E-11	2.62E-11
12	3.81E+07	4.53E+08	14.35	3.19E-11	3.33E-11	3.40E-11
Future	5.22E+07	5.05E+08	16.00	3.19E-11	3.33E-11	3.40E-11
Future	5.05E+08	1.01E+09	32.00	3.19E-11	3.33E-11	3.40E-11
Future	5.05E+08	1.51E+09	48.00	3.19E-11	3.33E-11	3.40E-11
Future	1.89E+08	1.70E+09	54.00	3.19E-11	3.33E-11	3.40E-11

Note:

Neutron exposure values reported for the surveillance capsules are centered at the core midplane.

Table 6-1 (cont.) Calculated Neutron Exposure Rates and Integrated Exposures at the Surveillance Capsule Center

Cycle	Cycle Length [EFPS]	Cumulative Irradiation Time [EFPS]	Cumulative Irradiation Time [EFPY]	Iron Atom Displacements [dpa]		
				38°	40°	43°
1	3.63E+07	3.63E+07	1.15	1.85E-03	1.87E-03	1.85E-03
2	3.39E+07	7.02E+07	2.23	3.07E-03	3.09E-03	3.05E-03
3	3.74E+07	1.08E+08	3.41	4.38E-03	4.43E-03	4.40E-03
4	3.57E+07	1.43E+08	4.54	5.64E-03	5.68E-03	5.62E-03
5	3.10E+07	1.74E+08	5.52	6.72E-03	6.76E-03	6.67E-03
6	2.73E+07	2.02E+08	6.39	7.48E-03	7.54E-03	7.45E-03
7	4.14E+07	2.43E+08	7.70	8.74E-03	8.81E-03	8.70E-03
8	4.47E+07	2.88E+08	9.12	9.55E-03	9.62E-03	9.49E-03
9	4.35E+07	3.31E+08	10.50	1.07E-02	1.08E-02	1.07E-02
10	3.91E+07	3.70E+08	11.73	1.19E-02	1.20E-02	1.19E-02
11	4.43E+07	4.15E+08	13.14	1.30E-02	1.32E-02	1.31E-02
12	3.81E+07	4.53E+08	14.35	1.42E-02	1.44E-02	1.44E-02
Future	5.22E+07	5.05E+08	16.00	1.59E-02	1.62E-02	1.61E-02
Future	5.05E+08	1.01E+09	32.00	3.20E-02	3.30E-02	3.33E-02
Future	5.05E+08	1.51E+09	48.00	4.81E-02	4.98E-02	5.04E-02
Future	1.89E+08	1.70E+09	54.00	5.41E-02	5.61E-02	5.69E-02

Note:

Neutron exposure values reported for the surveillance capsules are centered at the core midplane.

Table 6-2 Calculated Azimuthal Variation of Maximum Exposure Rates and Integrated Exposures at the Reactor Vessel Clad/Base Metal Interface

Cycle	Cycle Length [EFPS]	Cumulative Irradiation Time [EFPS]	Cumulative Irradiation Time [EFPY]	Neutron Flux (E > 1.0 MeV) [n/cm^2-s]			
				0°	15°	30°	45°
1	3.63E+07	3.63E+07	1.15	1.51E+10	2.14E+10	2.19E+10	2.53E+10
2	3.39E+07	7.02E+07	2.23	1.08E+10	1.51E+10	1.63E+10	1.77E+10
3	3.74E+07	1.08E+08	3.41	1.17E+10	1.55E+10	1.56E+10	1.82E+10
4	3.57E+07	1.43E+08	4.54	1.21E+10	1.57E+10	1.66E+10	1.73E+10
5	3.10E+07	1.74E+08	5.52	6.79E+09	1.02E+10	1.50E+10	1.68E+10
6	2.73E+07	2.02E+08	6.39	8.76E+09	1.15E+10	1.22E+10	1.45E+10
7	4.14E+07	2.43E+08	7.70	6.67E+09	9.71E+09	1.34E+10	1.52E+10
8	4.47E+07	2.88E+08	9.12	6.82E+09	9.32E+09	8.80E+09	8.94E+09
9	4.35E+07	3.31E+08	10.50	7.27E+09	9.44E+09	1.04E+10	1.41E+10
10	3.91E+07	3.70E+08	11.73	7.09E+09	1.01E+10	1.20E+10	1.52E+10
11	4.43E+07	4.15E+08	13.14	1.24E+10	1.27E+10	1.13E+10	1.32E+10
12	3.81E+07	4.53E+08	14.35	1.02E+10	1.21E+10	1.28E+10	1.69E+10
Future	5.22E+07	5.05E+08	16.00	1.02E+10	1.21E+10	1.28E+10	1.69E+10
Future	5.05E+08	1.01E+09	32.00	1.02E+10	1.21E+10	1.28E+10	1.69E+10
Future	5.05E+08	1.51E+09	48.00	1.02E+10	1.21E+10	1.28E+10	1.69E+10
Future	1.89E+08	1.70E+09	54.00	1.02E+10	1.21E+10	1.28E+10	1.69E+10

Table 6-2 (cont.)	Calculated Azimuthal Variation of Maximum Exposure Rates and Integrated Exposures at the Reactor Vessel Clad/Base Metal Interface						
Cycle	Cycle Length [EFPS]	Cumulative Irradiation Time [EFPS]	Cumulative Irradiation Time [EFPY]	Neutron Fluence (E > 1.0 MeV) [n/cm^2]			
				0°	15°	30°	45°
1	3.63E+07	3.63E+07	1.15	5.49E+17	7.78E+17	7.96E+17	9.20E+17
2	3.39E+07	7.02E+07	2.23	9.10E+17	1.28E+18	1.34E+18	1.51E+18
3	3.74E+07	1.08E+08	3.41	1.34E+18	1.86E+18	1.92E+18	2.18E+18
4	3.57E+07	1.43E+08	4.54	1.77E+18	2.41E+18	2.50E+18	2.79E+18
5	3.10E+07	1.74E+08	5.52	1.98E+18	2.73E+18	2.97E+18	3.32E+18
6	2.73E+07	2.02E+08	6.39	2.21E+18	3.03E+18	3.29E+18	3.70E+18
7	4.14E+07	2.43E+08	7.70	2.48E+18	3.43E+18	3.84E+18	4.32E+18
8	4.47E+07	2.88E+08	9.12	2.79E+18	3.84E+18	4.23E+18	4.72E+18
9	4.35E+07	3.31E+08	10.50	3.10E+18	4.25E+18	4.67E+18	5.32E+18
10	3.91E+07	3.70E+08	11.73	3.38E+18	4.64E+18	5.14E+18	5.92E+18
11	4.43E+07	4.15E+08	13.14	3.92E+18	5.20E+18	5.64E+18	6.50E+18
12	3.81E+07	4.53E+08	14.35	4.30E+18	5.66E+18	6.12E+18	7.14E+18
Future	5.22E+07	5.05E+08	16.00	4.83E+18	6.30E+18	6.79E+18	8.03E+18
Future	5.05E+08	1.01E+09	32.00	9.96E+18	1.24E+19	1.33E+19	1.66E+19
Future	5.05E+08	1.51E+09	48.00	1.51E+19	1.85E+19	1.97E+19	2.51E+19
Future	1.89E+08	1.70E+09	54.00	1.70E+19	2.08E+19	2.21E+19	2.83E+19

Table 6-2 (cont.) Calculated Azimuthal Variation of Fast Neutron Exposure Rates and Iron Atom Displacement Rates at the Reactor Vessel Clad/Base Metal Interface

Cycle	Cycle Length [EFPS]	Cumulative Irradiation Time [EFPS]	Cumulative Irradiation Time [EFPY]	Iron Atom Displacement Rate [dpa/s]			
				0°	15°	30°	45°
1	3.63E+07	3.63E+07	1.15	2.33E-11	3.27E-11	3.35E-11	3.86E-11
2	3.39E+07	7.02E+07	2.23	1.66E-11	2.31E-11	2.50E-11	2.70E-11
3	3.74E+07	1.08E+08	3.41	1.80E-11	2.37E-11	2.38E-11	2.78E-11
4	3.57E+07	1.43E+08	4.54	1.86E-11	2.40E-11	2.54E-11	2.65E-11
5	3.10E+07	1.74E+08	5.52	1.05E-11	1.57E-11	2.29E-11	2.57E-11
6	2.73E+07	2.02E+08	6.39	1.35E-11	1.76E-11	1.87E-11	2.21E-11
7	4.14E+07	2.43E+08	7.70	1.03E-11	1.49E-11	2.05E-11	2.33E-11
8	4.47E+07	2.88E+08	9.12	1.06E-11	1.43E-11	1.35E-11	1.37E-11
9	4.35E+07	3.31E+08	10.50	1.12E-11	1.45E-11	1.60E-11	2.15E-11
10	3.91E+07	3.70E+08	11.73	1.10E-11	1.56E-11	1.85E-11	2.32E-11
11	4.43E+07	4.15E+08	13.14	1.90E-11	1.95E-11	1.73E-11	2.02E-11
12	3.81E+07	4.53E+08	14.35	1.57E-11	1.86E-11	1.97E-11	2.58E-11
Future	5.22E+07	5.05E+08	16.00	1.57E-11	1.86E-11	1.97E-11	2.58E-11
Future	5.05E+08	1.01E+09	32.00	1.57E-11	1.86E-11	1.97E-11	2.58E-11
Future	5.05E+08	1.51E+09	48.00	1.57E-11	1.86E-11	1.97E-11	2.58E-11
Future	1.89E+08	1.70E+09	54.00	1.57E-11	1.86E-11	1.97E-11	2.58E-11

Table 6-2 (cont.) Calculated Azimuthal Variation of Maximum Exposure Rates and Integrated Exposures at the Reactor Vessel Clad/Base Metal Interface

Cycle	Cycle Length [EFPS]	Cumulative Irradiation Time [EFPS]	Cumulative Irradiation Time [EFPY]	Iron Atom Displacements [dpa]			
				0°	15°	30°	45°
1	3.63E+07	3.63E+07	1.15	8.47E-04	1.19E-03	1.22E-03	1.40E-03
2	3.39E+07	7.02E+07	2.23	1.40E-03	1.96E-03	2.05E-03	2.31E-03
3	3.74E+07	1.08E+08	3.41	2.07E-03	2.84E-03	2.94E-03	3.33E-03
4	3.57E+07	1.43E+08	4.54	2.73E-03	3.68E-03	3.83E-03	4.27E-03
5	3.10E+07	1.74E+08	5.52	3.05E-03	4.17E-03	4.54E-03	5.07E-03
6	2.73E+07	2.02E+08	6.39	3.42E-03	4.64E-03	5.04E-03	5.66E-03
7	4.14E+07	2.43E+08	7.70	3.84E-03	5.25E-03	5.88E-03	6.61E-03
8	4.47E+07	2.88E+08	9.12	4.31E-03	5.88E-03	6.48E-03	7.21E-03
9	4.35E+07	3.31E+08	10.50	4.79E-03	6.50E-03	7.16E-03	8.14E-03
10	3.91E+07	3.70E+08	11.73	5.22E-03	7.11E-03	7.89E-03	9.05E-03
11	4.43E+07	4.15E+08	13.14	6.05E-03	7.96E-03	8.64E-03	9.93E-03
12	3.81E+07	4.53E+08	14.35	6.65E-03	8.67E-03	9.39E-03	1.09E-02
Future	5.22E+07	5.05E+08	16.00	7.46E-03	9.64E-03	1.04E-02	1.23E-02
Future	5.05E+08	1.01E+09	32.00	1.54E-02	1.90E-02	2.04E-02	2.53E-02
Future	5.05E+08	1.51E+09	48.00	2.33E-02	2.84E-02	3.03E-02	3.84E-02
Future	1.89E+08	1.70E+09	54.00	2.62E-02	3.19E-02	3.40E-02	4.33E-02

Table 6-3 Relative Radial Distribution of Neutron Fluence (E > 1.0 MeV) Within the Reactor Vessel Wall

Radius (cm)	Azimuthal Angle			
	0°	15°	30°	45°
233.72	1.000	1.000	1.000	1.000
239.37	0.557	0.552	0.554	0.552
245.03	0.268	0.265	0.266	0.263
250.68	0.122	0.118	0.119	0.119
256.33	0.048	0.044	0.044	0.043

Notes:

Base Metal Inner Radius = 233.72 cm
Base Metal 1/4T = 239.37 cm
Base Metal 1/2T = 245.03 cm
Base Metal 3/4T = 250.68 cm
Base Metal Outer Radius = 256.33 cm

Table 6-4 Relative Radial Distribution of Iron Atom Displacements (dpa) Within the Reactor Vessel Wall

Radius (cm)	Azimuthal Angle			
	0°	15°	30°	45°
233.72	1.000	1.000	1.000	1.000
239.37	0.628	0.621	0.625	0.622
245.03	0.370	0.363	0.367	0.362
250.68	0.212	0.202	0.205	0.201
256.33	0.100	0.089	0.089	0.084

Notes:

Base Metal Inner Radius = 233.72 cm
Base Metal 1/4T = 239.37 cm
Base Metal 1/2T = 245.03 cm
Base Metal 3/4T = 250.68 cm
Base Metal Outer Radius = 256.33 cm

Table 6-5 Calculated Fast Neutron Exposure of Surveillance Capsules Withdrawn from Palo Verde Unit 2

Capsule	Irradiation Time [EFPY]	Fluence (E > 1.0 MeV) [n/cm^2]	Iron Displacements [dpa]
W137	4.54	3.87E+18	5.62E-03
W230	14.35	9.92E+18	1.44E-02

Table 6-6 Calculated Surveillance Capsule Lead Factors

Capsule ID	Status	Lead Factor(1)
W137	Withdrawn EOC 4	1.38
W230	Withdrawn EOC 12	1.39
W38	In Reactor	1.37
W43	In Reactor	1.38
W142	In Reactor	1.37
W310	In Reactor	1.39

Note:

1. Lead factors for the capsules remaining in the reactor are based on cycle specific exposure calculations through the most recently completed operating fuel cycle, i.e., Cycle 12.

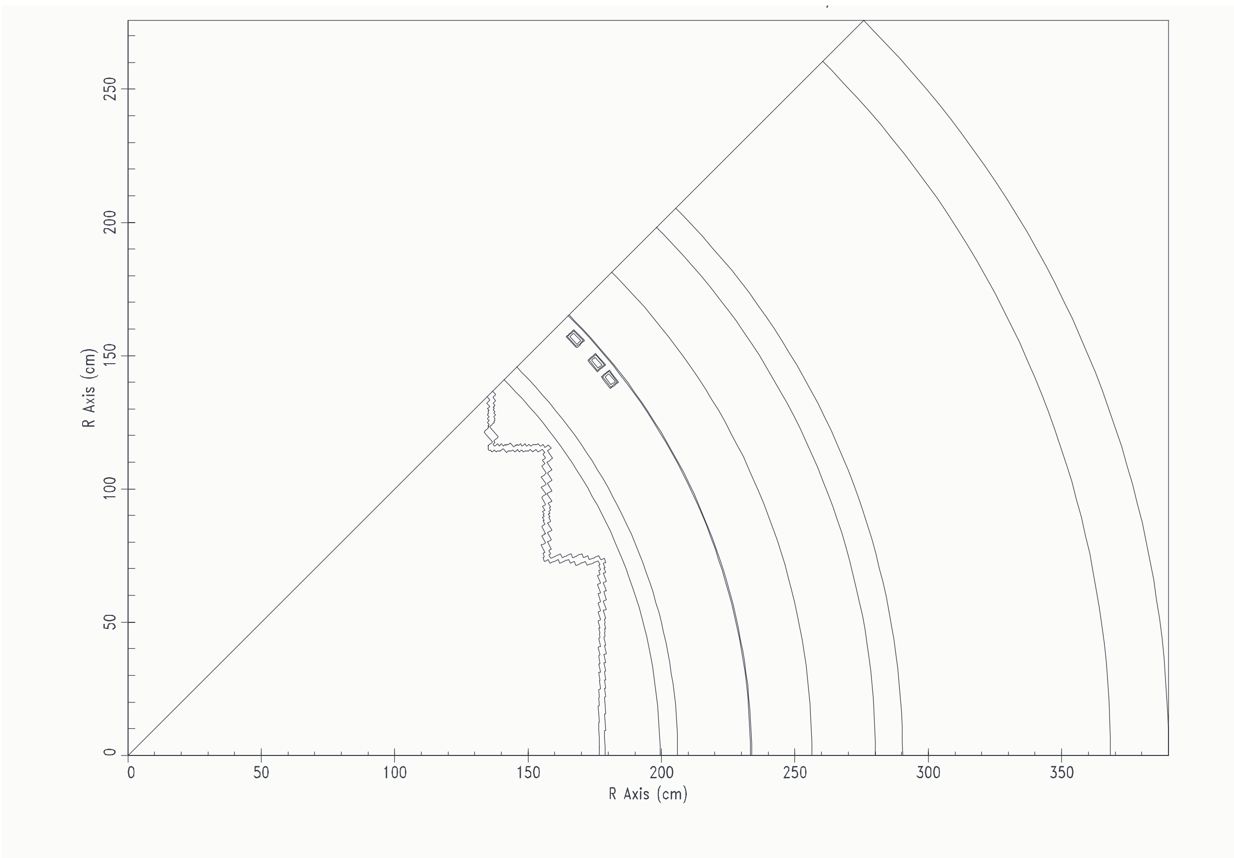


Figure 6-1 Palo Verde Unit 2 r,θ Reactor Geometry at the Core Midplane

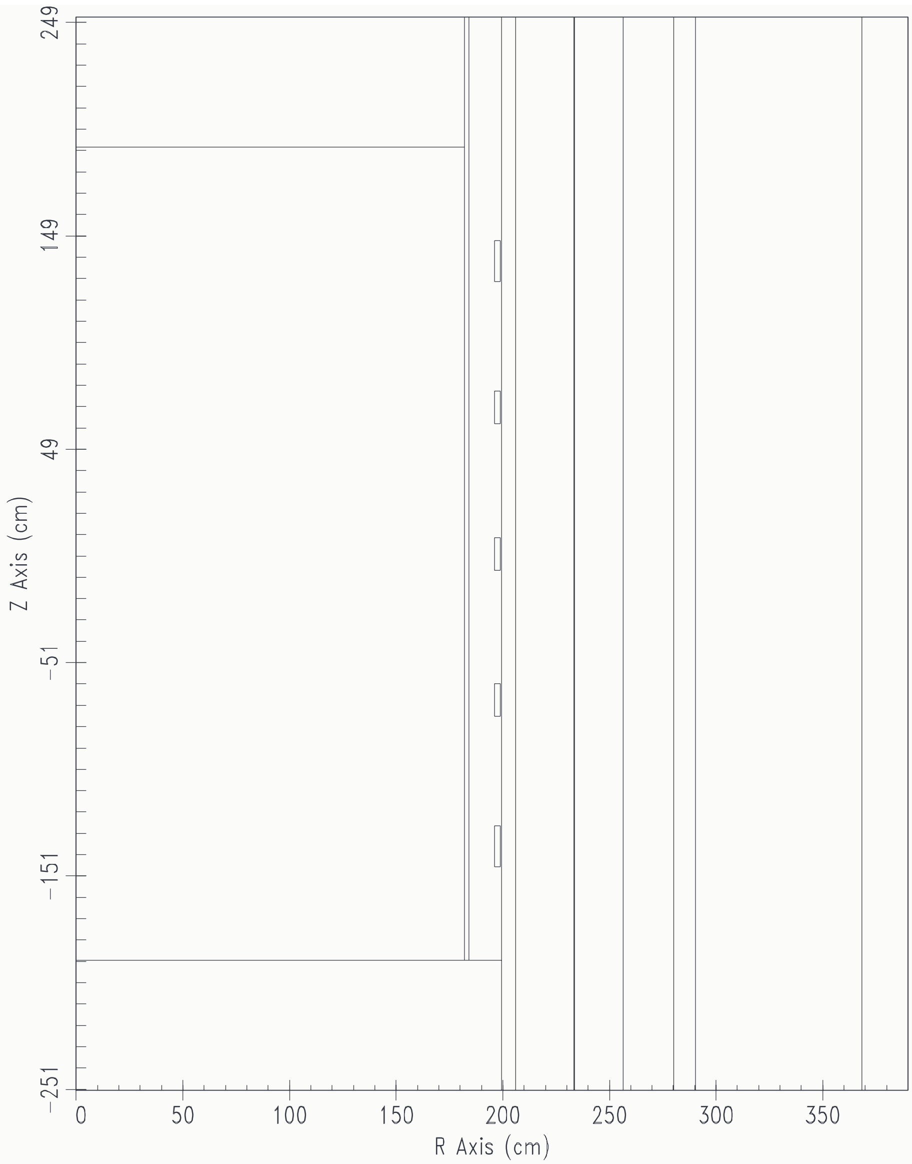


Figure 6-2 Palo Verde Unit 2 r,z Reactor Geometry

7 SURVEILLANCE CAPSULE REMOVAL SCHEDULE

The following surveillance capsule removal schedule meets the intent of ASTM E185-82 and is recommended for future capsules to be removed from the Palo Verde Unit 2 reactor vessel. This recommended removal schedule is applicable to 32 EFPY of operation.

Table 7-1 Palo Verde Unit 2 Reactor Vessel Surveillance Capsule Withdrawal Schedule

Capsule Location	Lead Factor[a]	Withdrawal EFPY[b]	Fluence (n/cm^2)[a]
137°	1.38	4.54	3.87×10^{18} [c]
230°	1.39	14.35	9.92×10^{18} [c]
310°	1.39	23.4	1.66×10^{19} [d]
38°	1.37	Standby	[e]
43°	1.38	Standby	[e]
142°	1.37	Standby	[e]

Notes:

a. Updated in Capsule 230° dosimetry analysis (see Table 6-6).
b. Effective full-power years (EFPY) from plant startup.
c. Plant-specific evaluation.
d. This fluence is equal to the peak EOL (@ 32 EFPY) vessel fluence. If EOL is greater than 32 EFPY, then the removal EFPY should be increased as necessary to accumulate sufficient fluence. If license renewal is achieved prior to this capsule's removal, then it need not be removed until 39.3 EFPY, which would be equivalent to when the capsule accumulates a fluence equal to 54 EFPY.
e. Capsules could be removed anytime after 39.3 EFPY but not to exceed 72 EFPY (i.e., a possible second license renewal). If all capsules are removed, then alternative fluence capabilities must be implemented.

8 REFERENCES

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

2. Code of Federal Regulations, 10CFR50, Appendix G, "Fracture Toughness Requirements," and Appendix H, "Reactor Vessel Material Surveillance Program Requirements," U.S. Nuclear Regulatory Commission, Washington, D.C.

3. TR-V-MCM-004, "Summary Report on Manufacture of Test Specimens and Assembly of Capsules for Irradiation Surveillance of Palo Verde Unit 2 Reactor Vessel Materials," A. D. Emery, May 26, 1983.

4. TR-V-MCM-013, "Arizona Public Service Company Palo Verde Unit 2 Evaluation and Baseline Specimens – Reactor Vessel Materials Irradiation Surveillance Program," B. C. Chang, November 4, 1992.

5. Section XI of the ASME Boiler and Pressure Vessel Code, Appendix G, "Fracture Toughness Criteria for Protection Against Failure."

6. ASTM E208-95a, "Standard Test Method for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels," American Society for Testing and Materials.

7. ASTM E185-82, "Standard Practice for Conducting Surveillance Tests for Light-Water Cooled Nuclear Power Reactor Vessels," American Society for Testing and Materials.

8. Procedure RMF 8402, "Surveillance Capsule Testing Program," Revision 2.

9. Procedure RMF 8102, "Tensile Testing," Revision 3.

10. Procedure RMF 8103, "Charpy Impact Testing," Revision 2.

11. Procedure RMF 8804, "Opening of Westinghouse Surveillance Capsules," Revision 2.

12. ASTM E23-02a, "Standard Test Method for Notched Bar Impact Testing of Metallic Materials," American Society for Testing and Materials.

13. ASTM E370-03a, "Standard Test Methods and Definitions for Mechanical Testing of Steel Products," American Society for Testing and Materials.

14. ASTM E8-04, "Standard Test Methods for Tension Testing of Metallic Materials," American Society for Testing and Materials.

15. ASTM E21-03a, "Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials," American Society for Testing and Materials.

16. ASTM E853-01, "Standard Practice for Analysis and Interpretation of Light-Water Reactor Surveillance Results, E706(IA)," American Society for Testing and Materials.

17. ASTM E693-01, "Standard Practice for Characterizing Neutron Exposures in Iron and Low Alloy Steels in Terms of Displacements Per Atom (DPA), E706(ID)," American Society for Testing and Materials.

18. Regulatory Guide RG-1.190, "Calculational and Dosimetry Methods for Determining Pressure Vessel Neutron Fluence," U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, March 2001.

19. WCAP-14040-NP-A, Revision 4, "Methodology Used to Develop Cold Overpressure Mitigating System Setpoints and RCS Heatup and Cooldown Limit Curves," May 2004.

20. RSICC Computer Code Collection CCC-650, DOORS 3.2, "One, Two- and Three-Dimensional Discrete Ordinates Neutron/Photon Transport Code System," April 1998.

21. RSIC Data Library Collection DLC-185, "BUGLE-96, Coupled 47 Neutron, 20 Gamma-Ray Group Cross Section Library Derived from ENDF/B-VI for LWR Shielding and Pressure Vessel Dosimetry Applications," March 1996.

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 all surveillance capsules withdrawn from service to date at Palo Verde Unit 2 are described herein. The sensor sets from these capsules 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," (Reference A-1). One of the main purposes for presenting 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. This information may also be useful in the future, in particular, as least squares adjustment techniques become accepted in the regulatory environment.

A.1.1 Sensor Reaction Rate Determinations

In this section, the results of the evaluations of the two neutron sensor sets withdrawn to date as part of the Palo Verde 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 ID	Azimuthal Location	Withdrawal Time	Irradiation Time [EFPY]
W137	137°	End of Cycle 4	4.54
W230	230°	End of Cycle 12	14.35

The azimuthal locations included in the above tabulation represent the first octant equivalent azimuthal angle of the geometric center of the respective surveillance capsules.

The passive neutron sensors included in the evaluations of Surveillance Capsules W137 and W230 are summarized as follows:

Sensor Material	Reaction of Interest	Capsule W137	Capsule W230
Copper	$^{63}Cu(n,\alpha)^{60}Co$	X	X
Iron	$^{54}Fe(n,p)^{54}Mn$	X	X
Nickel	$^{58}Ni(n,p)^{58}Co$	X	X
Titanium	$^{46}Ti(n,p)^{46}Sc$	X	X
Uranium-238*	$^{238}U(n,f)^{137}Cs$	X	X
Cobalt-Aluminum*	$^{59}Co(n,\gamma)^{60}Co$	X	X
* The uranium and cobalt-aluminum measurements for this plant include both bare and cadmium-covered sensors.			

In regards to the neutron sensors listed above, it should be recognized that both of these capsules also contained sulfur sensors as well. The reaction of interest in these sensors is $^{32}S(n,p)^{32}P$; however, due to the short half-life of ^{32}P (14.28 days), this reaction was not measured for Capsule W230 as part of this evaluation, nor for Capsule W137 as reported in Reference A-2. Further note that the bare uranium sensor measurements for Capsules W137 and W230 were excluded from this assessment. The bare $^{238}U(n,f)$ measurement is dominated by contributions from thermal neutron reactions in ^{235}U impurities. These thermal contributions add significant uncertainty to the determination of the $^{238}U(n,f)$ reaction rate. The cadmium-covered ^{238}U sensor provides greater accuracy for the measurement of the fast neutron reaction of interest.

Since all of the dosimetry monitors were accommodated within the dosimeter block centered at the radial, azimuthal, and axial center of the material test specimen array, gradient corrections were not required for these reaction rates. Pertinent physical and nuclear characteristics of the passive neutron sensors are listed in Table A-1.

The use of passive monitors such as those listed above does not yield a direct measure of the energy dependent neutron flux 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 flux has on the target material over the course of the irradiation period. An accurate assessment of the average neutron flux 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.

Results from the radiometric counting of the neutron sensors from Capsule W137 are documented in Reference A-2. The radiometric counting of the sensors from Capsule W230 was carried out by Pace Analytical Services, Inc., located at the Westinghouse Waltz Mill Site. In all cases, the radiometric counting followed established ASTM procedures. Following sample preparation and weighing, the specific activity of each sensor was determined by means of a high-resolution gamma spectrometer. For the copper, iron, nickel, titanium, and cobalt-aluminum sensors, these analyses were performed by direct counting of each of the individual samples. In the case of the uranium fission sensors, the analyses were carried out by direct counting preceded by dissolution and chemical separation of cesium, zirconium, and ruthenium from the sensor material.

The irradiation history of the reactor over the irradiation periods experienced by Capsules W137 and W230 was based on the reported monthly power generation of Palo Verde Unit 2 for Cycles 1 through 12. 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 W137 and W230 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:

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

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/gm).
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.
Pj	=	Average core power level during irradiation period j (MWt).
P_{ref}	=	Maximum or reference power level of the reactor (MWt).
C_j	=	Calculated ratio of $\phi(E > 1.0 \text{ MeV})$ during irradiation period j to the time weighted average $\phi(E > 1.0 \text{ MeV})$ over the entire irradiation period.
λ	=	Decay constant of the product isotope (1/sec).
t_j	=	Length of irradiation period j (sec).
t_d	=	Decay time following irradiation period j (sec).

and 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 flux 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, particularly those employing low leakage fuel management, the additional C_j term should be employed. The impact of changing flux 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 flux values along with the computed values for C_j are listed in Table A-3. These flux values represent the cycle dependent results at the radial and azimuthal center of the respective capsules at the axial elevation of the active fuel 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 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 capsule irradiations. The correction factors applied to the Palo Verde Unit 2 fission sensor reaction rates are summarized as follows:

Correction	Capsule W137	Capsule W230
^{235}U Impurity/Pu Build-in	0.869	0.846
$^{238}U(\gamma,f)$	0.867	0.867
Net ^{238}U Correction	0.754	0.734

These factors were applied in a multiplicative fashion to the decay corrected uranium fission sensor reaction rates.

Results of the sensor reaction rate determinations for Capsules W137 and W230 are given in Table A-4. In Table A-4, the measured specific activities, decay corrected saturated specific activities, and computed reaction rates for each sensor indexed to the radial center of the capsule are listed. The fission sensor reaction rates are listed both with and without the applied corrections for 238U impurities, plutonium build-in, and gamma ray induced fission effects.

Examination of the Table A-4 results revealed that the copper as well as the uranium fission monitor reaction rates for Capsule W230 were inconsistent with measurement data obtained from comparable reactors. Similar observations were also determined for the bare and cadmium covered cobalt-aluminum reaction rates obtained from Capsules W137 and W230, although it is recognized that non-threshold reactions are involved in these sensors. As a result of these observations, the aforementioned measurements were not utilized in the least squares adjustment calculations for these capsules.

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 $\phi(E > 1.0\ \text{MeV})$ or dpa/s along with their uncertainties are then easily obtained from the adjusted spectrum. In general, the least squares methods, as applied to surveillance capsule 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,

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

relates a set of measured reaction rates, R_i, to a single neutron spectrum, ϕ_g, through the multigroup dosimeter reaction cross-section, 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 Palo Verde Unit 2 surveillance capsule dosimetry, the FERRET code (Reference A-3) was employed to combine the results of the plant specific neutron transport calculations and sensor set reaction rate measurements to determine best-estimate values of exposure parameters ($\phi(E > 1.0\ \text{MeV})$ and dpa) along with associated uncertainties for the two in-vessel capsules withdrawn to date.

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 Palo Verde 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 (Reference A-4). The SNLRML library is an evaluated dosimetry reaction cross-section compilation recommended for use in LWR evaluations by ASTM Standard E 1018, “Application of ASTM Evaluated Cross-Section Data File, Matrix E 706 (IIB),” (Reference A-5).

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 E 944, “Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance, E 706 (IIA),” (Reference A-6).

The following provides a summary of the uncertainties associated with the least squares evaluation of the Palo Verde 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 assured 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%
$^{46}Ti(n,p)^{46}Sc$	5%
$^{54}Fe(n,p)^{54}Mn$	5%
$^{58}Ni(n,p)^{58}Co$	5%
$^{238}U(n,f)^{137}Cs$	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 the most recent cross-section evaluations and they have been tested with respect to their 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 Palo Verde 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%
$^{46}Ti(n,p)^{46}Sc$	4.51-4.87%
$^{54}Fe(n,p)^{54}Mn$	3.05-3.11%
$^{58}Ni(n,p)^{58}Co$	4.49-4.56%
$^{238}U(n,f)^{137}Cs$	0.54-0.64%

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

Calculated Neutron Spectrum

The neutron spectra input 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 Palo Verde Unit 2 calculated spectra was as follows:

Flux Normalization Uncertainty (R_n)	15%
Flux Group Uncertainties (R_g, $R_{g'}$)	
(E > 0.0055 MeV)	15%
(0.68 eV < E < 0.0055 MeV)	29%
(E < 0.68 eV)	52%

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
Flux 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 the Palo Verde Unit 2 surveillance capsules withdrawn to date are provided in Tables A-5 and A-6. In Table A-5, measured, calculated, and best-estimate values for sensor reaction rates are given for each capsule. Also provided in this tabulation 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. In Table A-6, comparison of the calculated and best estimate values of neutron flux (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 Tables A-5 and A-6 show that the adjustments to the calculated spectra are relatively small and well 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, it may be noted that the uncertainty associated with the unadjusted calculation of neutron fluence (E > 1.0 MeV) and iron atom displacements at the surveillance capsule locations is specified as 12% at the 1σ level. From Table A-6, it is noted that the corresponding uncertainties associated with the least squares adjusted exposure parameters have been reduced to 7% for neutron flux (E > 1.0 MeV) and 6% for iron atom displacement rate. Again, the uncertainties from the least squares evaluation are at the 1σ level.

Further comparisons of the measurement results with calculations are given in Tables A-7 and A-8. These comparisons are given on two levels. In Table A-7, 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-8, calculations of fast neutron exposure rates in terms of ϕ(E > 1.0 MeV) and dpa/s are compared with the best estimate results obtained from the least squares evaluation of the capsule dosimetry results. These two levels of comparison yield consistent and similar results with all measurement-to-calculation comparisons falling well within the 20% limits specified as the acceptance criteria in Regulatory Guide 1.190.

In the case of the direct comparison of measured and calculated sensor reaction rates, the M/C comparisons for fast neutron reactions range from 0.94–1.16 for the 8 samples included in the data set. The overall average M/C ratio for the entire set of Palo Verde Unit 2 data is 1.03 with an associated standard deviation of 7.6%.

In the comparisons of best estimate and calculated fast neutron exposure parameters, the corresponding BE/C comparisons for the capsule data sets range from 0.96–1.01 for neutron flux (E > 1.0 MeV) and from 0.96-1.00 for iron atom displacement rate. The overall average BE/C ratios for neutron flux (E > 1.0 MeV) and iron atom displacement rate are 0.98 with a standard deviation of 3.0% and 0.99 with a standard deviation of 3.4%, respectively.

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 Palo Verde Unit 2 reactor pressure vessel.

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

Monitor Material	Reaction of Interest	Target Atom Fraction	90% Response Range (MeV)	Product Half-life	Fission Yield (%)
Copper	$^{63}Cu\ (n,\alpha)$	0.6917	5.1 – 12.1	5.271 y	
Titanium	$^{46}Ti\ (n,p)$	0.0825	4.1 – 10.6	83.79 d	
Iron	$^{54}Fe\ (n,p)$	0.0585	2.4 – 8.9	312.1 d	
Nickel	$^{58}Ni\ (n,p)$	0.6808	2.1 – 8.9	70.82 d	
Uranium-238	$^{238}U\ (n,f)\ ^{137}Cs$	0.9996	1.5 – 8.2	30.07 y	6.02
Uranium-238	$^{238}U\ (n,f)\ ^{95}Zr$	0.9996	1.5 – 8.2	64.02 d	5.15
Uranium-238	$^{238}U\ (n,f)\ ^{103}Ru$	0.9996	1.5 – 8.2	39.26 d	6.26
Cobalt-Aluminum	$^{59}Co\ (n,\gamma)$	0.0017	non-threshold	5.271 y	

Note:

The 90% response range is defined such that, in the neutron spectrum characteristic of the Palo Verde Unit 2 surveillance capsules, approximately 90% of the sensor response is due to neutrons in the energy range specified with approximately 5% of the total response due to neutrons with energies below the lower limit and 5% of the total response due to neutrons with energies above the upper limit.

Table A-2 Monthly Thermal Generation During the First Twelve Fuel Cycles of the Palo Verde Unit 2 Reactor (Reactor Power of 3800 MWt for Cycles 1 through 6, 3876 MWt for Cycles 7 through 11, and 3990 MWt for Cycle 12)

Year	Month	Thermal Generation (MWt-hr)	Year	Month	Thermal Generation (MWt-hr)	Year	Month	Thermal Generation (MWt-hr)
1986	5	178458	1989	5	0	1992	5	2824993
1986	6	748794	1989	6	20794	1992	6	2735197
1986	7	179055	1989	7	1657660	1992	7	2826315
1986	8	789746	1989	8	2576391	1992	8	2823534
1986	9	441921	1989	9	1206913	1992	9	2701162
1986	10	1785522	1989	10	1205545	1992	10	2797104
1986	11	2573938	1989	11	0	1992	11	2490116
1986	12	2217984	1989	12	2546733	1992	12	2819640
1987	1	816605	1990	1	2806069	1993	1	2825987
1987	2	0	1990	2	2064631	1993	2	2549505
1987	3	843281	1990	3	0	1993	3	1182454
1987	4	2523504	1990	4	0	1993	4	0
1987	5	2217619	1990	5	0	1993	5	0
1987	6	2370470	1990	6	0	1993	6	0
1987	7	2667944	1990	7	558801	1993	7	0
1987	8	2807364	1990	8	2659419	1993	8	22326
1987	9	2670655	1990	9	2724764	1993	9	2262024
1987	10	2794687	1990	10	2746944	1993	10	2392778
1987	11	2400712	1990	11	2722657	1993	11	2159716
1987	12	2799320	1990	12	2809763	1993	12	2403758
1988	1	2796621	1991	1	2810976	1994	1	534792
1988	2	1711979	1991	2	2550144	1994	2	0
1988	3	0	1991	3	2797277	1994	3	411841
1988	4	0	1991	4	2733538	1994	4	2333826
1988	5	0	1991	5	2826434	1994	5	2059615
1988	6	510519	1991	6	2734422	1994	6	2048644
1988	7	2794833	1991	7	2825239	1994	7	2560704
1988	8	2713036	1991	8	1760151	1994	8	2636172
1988	9	2702001	1991	9	2731841	1994	9	1479547

Table A-2 (cont.) Monthly Thermal Generation During the First Twelve Fuel Cycles of the Palo Verde Unit 2 Reactor (Reactor Power of 3800 MWt for Cycles 1 through 6, 3876 MWt for Cycles 7 through 11, and 3990 MWt for Cycle 12)

Year	Month	Thermal Generation (MWt-hr)	Year	Month	Thermal Generation (MWt-hr)	Year	Month	Thermal Generation (MWt-hr)
1988	10	2814560	1991	10	1454795	1994	10	802515
1988	11	1909336	1991	11	0	1994	11	2724190
1988	12	2766725	1991	12	0	1994	12	2817816
1989	1	2800843	1992	1	1548257	1995	1	2820387
1989	2	1383148	1992	2	2642730	1995	2	268987
1989	3	1303549	1992	3	2150742	1995	3	53416
1989	4	0	1992	4	2730948	1995	4	2599884
1995	5	2742603	1998	5	2883335	2001	5	2865539
1995	6	2734778	1998	6	2790394	2001	6	2772636
1995	7	2633500	1998	7	2882767	2001	7	2607267
1995	8	2822403	1998	8	2883121	2001	8	2848637
1995	9	2734249	1998	9	2790367	2001	9	2721733
1995	10	2825987	1998	10	2883279	2001	10	862314
1995	11	2718234	1998	11	2790460	2001	11	1945485
1995	12	2826324	1998	12	2883363	2001	12	2835372
1996	1	2563541	1999	1	2883363	2002	1	2836627
1996	2	269352	1999	2	2604346	2002	2	2564095
1996	3	1299310	1999	3	2378679	2002	3	1368020
1996	4	0	1999	4	0	2002	4	1089162
1996	5	2317819	1999	5	2595552	2002	5	2814543
1996	6	2789129	1999	6	2606579	2002	6	2727352
1996	7	2882058	1999	7	2883316	2002	7	2823102
1996	8	2880178	1999	8	2883279	2002	8	2824460
1996	9	2789909	1999	9	2790329	2002	9	2733408
1996	10	2882872	1999	10	2883307	2002	10	2827613
1996	11	2787475	1999	11	2790348	2002	11	2739566
1996	12	2883225	1999	12	2882572	2002	12	2831167
1997	1	2883246	2000	1	2110352	2003	1	2832332

Table A-2 (cont.) Monthly Thermal Generation During the First Twelve Fuel Cycles of the Palo Verde Unit 2 Reactor (Reactor Power of 3800 MWt for Cycles 1 through 6, 3876 MWt for Cycles 7 through 11, and 3990 MWt for Cycle 12)

Year	Month	Thermal Generation (MWt-hr)	Year	Month	Thermal Generation (MWt-hr)	Year	Month	Thermal Generation (MWt-hr)
1997	2	2604205	2000	2	2697361	2003	2	2558653
1997	3	2882766	2000	3	2883018	2003	3	2835381
1997	4	2790155	2000	4	2782832	2003	4	2745241
1997	5	2883228	2000	5	2831790	2003	5	2835995
1997	6	2716753	2000	6	2788553	2003	6	2744971
1997	7	2873371	2000	7	2880767	2003	7	2624533
1997	8	2381061	2000	8	2612588	2003	8	2726031
1997	9	323147	2000	9	2709277	2003	9	2365421
1997	10	675309	2000	10	243286	2003	10	0
1997	11	2780202	2000	11	1940564	2003	11	0
1997	12	2883152	2000	12	2862628	2003	12	1315809
1998	1	2883214	2001	1	2871865	2004	1	2958888
1998	2	2603598	2001	2	2593797	2004	2	1792388
1998	3	2883379	2001	3	2855781	2004	3	2102614
1998	4	2790387	2001	4	2765092	2004	4	2868596
						2004	5	2964854
						2004	6	2315860
						2004	7	2603801
						2004	8	2967564
						2004	9	2871881
						2004	10	2967775
						2004	11	2870167
						2004	12	2967641
						2005	1	2967104
						2005	2	2680351
						2005	3	2965726
						2005	4	92588

Table A-3 Calculated C_j Factors at the Surveillance Capsule Center Core Midplane Elevation

Fuel Cycle	$\phi(E > 1.0\ MeV)$ [n/cm²-s]	
	Capsule W137	Capsule W230
1	3.51E+10	3.55E+10
2	2.42E+10	2.46E+10
3	2.48E+10	2.48E+10
4	2.36E+10	2.41E+10
5		2.39E+10
6		1.97E+10
7		2.10E+10
8		1.25E+10
9		1.87E+10
10		2.10E+10
11		1.79E+10
12		2.29E+10
Average	2.70E+10	2.19E+10

Fuel Cycle	C_j	
	Capsule W137	Capsule W230
1	1.301	1.621
2	0.898	1.125
3	0.920	1.131
4	0.873	1.100
5		1.091
6		0.897
7		0.960
8		0.569
9		0.855
10		0.956
11		0.818
12		1.045
Average	1.000	1.000

Table A-4 Measured Sensor Activities And Reaction Rates Surveillance Capsule W137					
Reaction	**Location**	**Measured Activity (dps/g)**	**Saturated Activity (dps/g)**	**Radially Adjusted Reaction Rate (rps/atom)**	**Average Radially Adjusted Reaction Rate (rps/atom)**
^{63}Cu (n,α) ^{60}Co (Cd)	Top	1.22E+05	3.23E+05	4.93E-17	
	Middle	1.19E+05	3.15E+05	4.80E-17	
	Bottom	1.19E+05	3.15E+05	4.80E-17	4.84E-17
^{46}Ti (n,p) ^{46}Sc	Top	2.01E+05	8.06E+05	7.45E-16	
	Middle	1.95E+05	7.82E+05	7.23E-16	
	Bottom	1.90E+05	7.62E+05	7.05E-16	7.24E-16
54Fe (n,p) ^{54}Mn	Top	1.29E+06	2.41E+06	3.81E-15	
	Middle	1.28E+06	2.39E+06	3.78E-15	
	Bottom	1.24E+06	2.31E+06	3.67E-15	3.75E-15
^{58}Ni (n,p) ^{58}Co (Cd)	Middle	6.81E+06	3.39E+07	4.85E-15	4.85E-15
^{238}U (n,f) ^{137}Cs (Cd)	Top	2.50E+05	2.60E+06	1.71E-14	
	Middle	2.08E+05	2.17E+06	1.42E-14	
	Bottom	2.16E+05	2.25E+06	1.48E-14	1.54E-14
	Including ^{235}U, ^{239}Pu, and γ, fission corrections:				1.16E-14
^{59}Co (n,γ) ^{60}Co	Middle	6.67E+07	1.77E+08	1.02E-11	1.02E-11
^{59}Co (n,γ) ^{60}Co (Cd)	Middle	7.98E+06	2.11E+11	1.22E-12	1.22E-12

Notes:

1. Measured specific activities are indexed to a counting date of August 8, 1993.
2. Reaction rates referenced to the Cycles 1-4 Average Rated Reactor Power of 3800 MWt.
3. The average ^{238}U (n,f) cadmium covered reaction rates includes a correction factor of 0.869 to account for plutonium build-in and an additional correction factor of 0.867 to account for photo-fission effects in these sensors.

Table A-4 Measured Sensor Activities And Reaction Rates Surveillance Capsule W230 (cont.)

Reaction	Location	Measured Activity (dps/g)	Saturated Activity (dps/g)	Radially Adjusted Reaction Rate (rps/atom)	Average Radially Adjusted Reaction Rate (rps/atom)
^{63}Cu (n,α) ^{60}Co (Cd)	Top	2.16E+05	3.24E+05	4.95E-17	
	Middle	1.92E+05	2.88E+05	4.40E-17	
	Bottom	1.90E+05	2.85E+05	4.35E-17	4.56E-17
^{46}Ti (n,p) ^{46}Sc	Top	1.46E+05	5.95E+05	5.50E-16	
	Middle	1.37E+05	5.58E+05	5.16E-16	
	Bottom	1.33E+05	5.42E+05	5.01E-16	5.23E-16
^{54}Fe (n,p) ^{54}Mn	Top	1.17E+06	1.92E+06	3.05E-15	
	Middle	1.09E+06	1.79E+06	2.84E-15	
	Bottom	1.06E+06	1.74E+06	2.76E-15	2.88E-15
^{58}Ni (n,p) ^{58}Co (Cd)	Middle	4.76E+06	2.51E+07	3.59E-15	3.59E-15
^{238}U (n,f) ^{137}Cs (Cd)	Top	2.39E+05	9.02E+05	5.92E-15	
	Middle	3.57E+05	1.35E+06	8.85E-15	
	Bottom	2.66E+05	1.00E+06	6.59E-15	7.12E-15
	Including ^{235}U, ^{239}Pu, and γ, fission corrections:				5.25E-15
^{238}U (n,f) ^{95}Zr (Cd)	Top	1.30E+05	8.18E+05	6.28E-15	
	Middle	1.95E+05	1.23E+06	9.42E-15	
	Bottom	1.44E+05	9.06E+05	6.96E-15	7.55E-15
	Including ^{235}U, ^{239}Pu, and γ, fission corrections:				5.57E-15
^{238}U (n,f) ^{103}Ru (Cd)	Top	3.86E+04	8.00E+05	5.05E-15	
	Middle	6.03E+04	1.25E+06	7.89E-15	
	Bottom	5.06E+04	1.05E+06	6.62E-15	6.52E-15
	Including ^{235}U, ^{239}Pu, and γ, fission corrections:				4.81E-15
^{59}Co (n,γ) ^{60}Co	Middle	8.32E+07	1.25E+08	7.19E-12	7.19E-12
^{59}Co (n,γ) ^{60}Co (Cd)	Middle	9.58E+06	1.44E+07	8.28E-13	8.28E-13

Notes:

1. Measured specific activities are indexed to a counting date of September 24, 2005.
2. Reaction rates referenced to the Cycles 1-12 Average Rated Reactor Power of 3852 MWt.
3. The average ^{238}U (n,f) cadmium covered reaction rates includes a correction factor of 0.846 to account for plutonium build-in and an additional correction factor of 0.867 to account for photo-fission effects in these sensors.

Table A-5 Comparison of Measured, Calculated, and Best Estimate Reaction Rates at the Surveillance Capsule Center

Capsule W137					
	Reaction Rate [rps/atom]				
Reaction	Measured	Calculated	Best Estimate	M/C	M/BE
$^{63}Cu(n,\alpha)^{60}Co$ (Cd)	4.84E-17	4.18E-17	4.72E-17	1.16	1.03
$^{46}Ti(n,p)^{46}Sc$	7.24E-16	6.44E-16	7.10E-16	1.12	1.02
$^{54}Fe(n,p)^{54}Mn$	3.75E-15	3.60E-15	3.80E-15	1.04	0.99
$^{58}Ni(n,p)^{58}Co$ (Cd)	4.85E-15	4.69E-15	4.92E-15	1.03	0.99
$^{238}U(n,f)^{137}Cs$ (Cd)	1.16E-14	1.21E-14	1.24E-14	0.96	0.94

Capsule W230					
	Reaction Rate [rps/atom]				
Reaction	Measured	Calculated	Best Estimate	M/C	M/BE
$^{46}Ti(n,p)^{46}Sc$	5.23E-16	5.28E-16	5.17E-16	0.99	1.01
$^{54}Fe(n,p)^{54}Mn$	2.88E-15	2.93E-15	2.85E-15	0.98	1.01
$^{58}Ni(n,p)^{58}Co$ (Cd)	3.59E-15	3.82E-15	3.67E-15	0.94	0.98

Table A-6 Comparison of Calculated and Best Estimate Exposure Rates at the Surveillance Capsule Center

Capsule ID	$\phi(E > 1.0\ MeV)\ [n/cm^2\text{-}s]$			
	Calculated	**Best Estimate**	**Uncertainty (1σ)**	**BE/C**
W137	2.70E+10	2.72E+10	6%	1.007
W230	2.19E+10	2.11E+10	7%	0.965

Note:

Calculated results are based on the synthesized transport calculations taken at the core midplane following the completion of each respective capsules irradiation period.

Capsule ID	Iron Atom Displacement Rate [dpa/s]			
	Calculated	**Best Estimate**	**Uncertainty (1σ)**	**BE/C**
W137	3.92E-11	3.93E-11	6%	1.002
W230	3.19E-11	3.04E-11	6%	0.955

Note:

Calculated results are based on the synthesized transport calculations taken at the core midplane following the completion of each respective capsules irradiation period.

Table A-7 Comparison of Measured/Calculated (M/C) Sensor Reaction Rate Ratios Including all Fast Neutron Threshold Reactions		
	M/C Ratio	
Reaction	**Capsule W137**	**Capsule W230**
$^{63}Cu(n,\alpha)^{60}Co$ (Cd)	1.16	--
$^{46}Ti(n,p)^{46}Sc$	1.12	0.99
$^{54}Fe(n,p)^{54}Mn$	1.04	0.98
$^{58}Ni(n,p)^{58}Co$ (Cd)	1.03	0.94
$^{238}U(n,f)^{137}Cs$ (Cd)	0.96	--
Average	1.06	0.97
% Standard Deviation	7.4	2.8

Note:
The overall average M/C ratio for the set of 8 sensor measurements is 1.03 with an associated standard deviation of 7.6%.

Table A-8 Comparison of Best Estimate/Calculated (BE/C) Exposure Rate Ratios		
	BE/C Ratio	
Capsule ID	**ϕ(E > 1.0 MeV)**	**dpa/s**
W137	1.01	1.00
W230	0.96	0.96
Average	0.99	0.98
% Standard Deviation	3.0	3.4

Appendix A References

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

A-2 WCAP-13935, "Analysis of the 137° Capsule from the Arizona Public Service Company Palo Verde Unit No. 2 Reactor Vessel Radiation Surveillance Program," February 1994.

A-3 A. Schmittroth, FERRET Data Analysis Core, HEDL-TME 79-40, Hanford Engineering Development Laboratory, Richland, WA, September 1979.

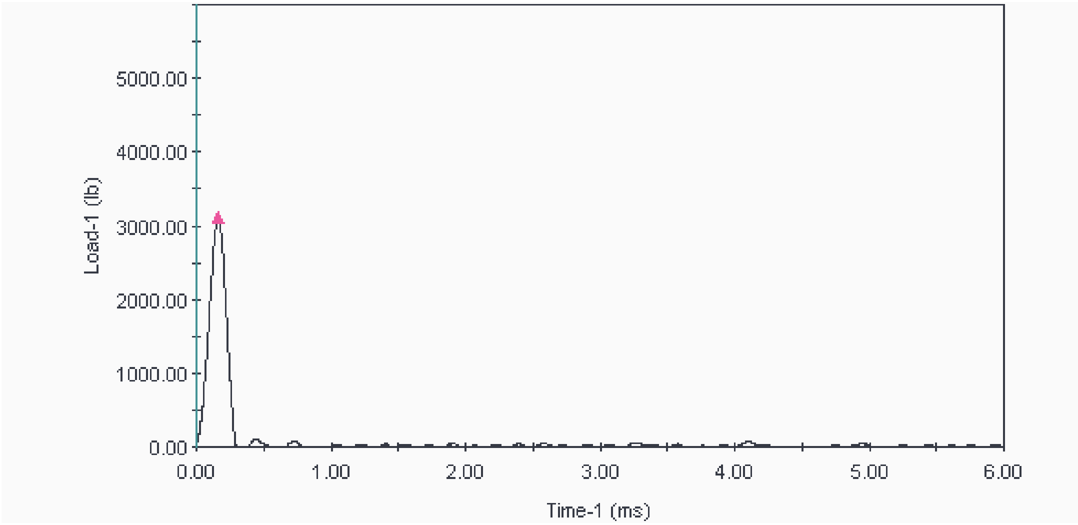
A-4 RSIC Data Library Collection DLC-178, "SNLRML Recommended Dosimetry Cross-Section Compendium," July 1994.

A-5 ASTM E1018-01, "Application of ASTM Evaluated Cross-Section Data File, Matrix E 706 (IIB)," American Society for Testing and Materials.

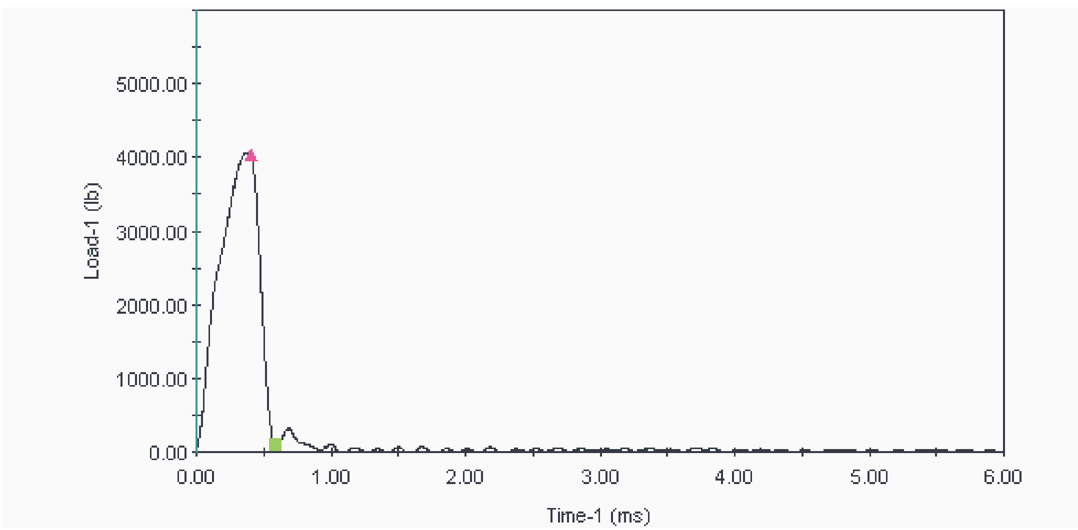
A-6 ASTM Standard E944-02, "Application of Neutron Spectrum Adjustment Methods in Reactor Surveillance, E 706 (IIA)," American Society for Testing and Materials.

APPENDIX B
LOAD-TIME RECORDS FOR CHARPY SPECIMEN TESTS

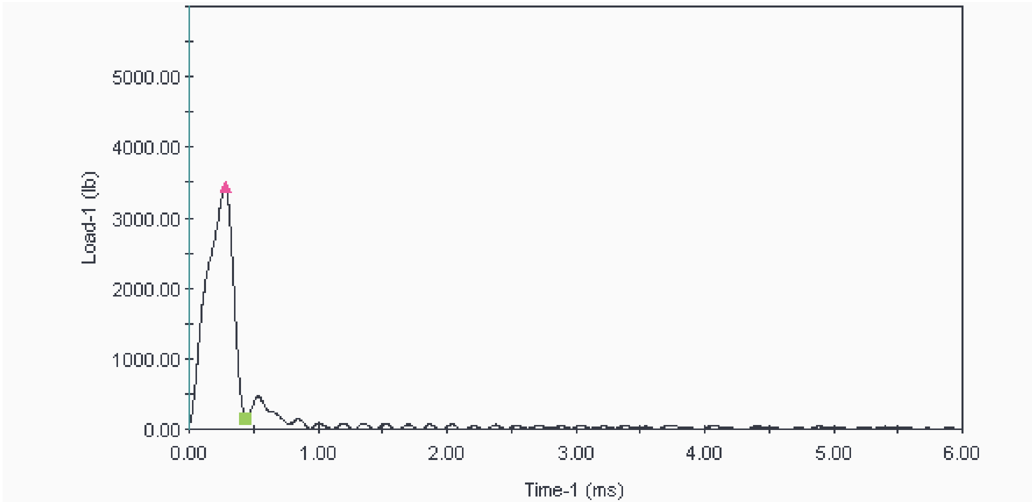
- Specimen prefix "1B1" denotes Lower Plate, Longitudinal Orientation
- Specimen prefix "1B2" denotes Lower Plate, Transverse Orientation
- Specimen prefix "1B3" denotes weld material
- Specimen prefix "1B4" denotes Heat-Affected Zone material
- Specimen prefix "D" denotes Standard Reference Material Plate, Longitudinal Orientation



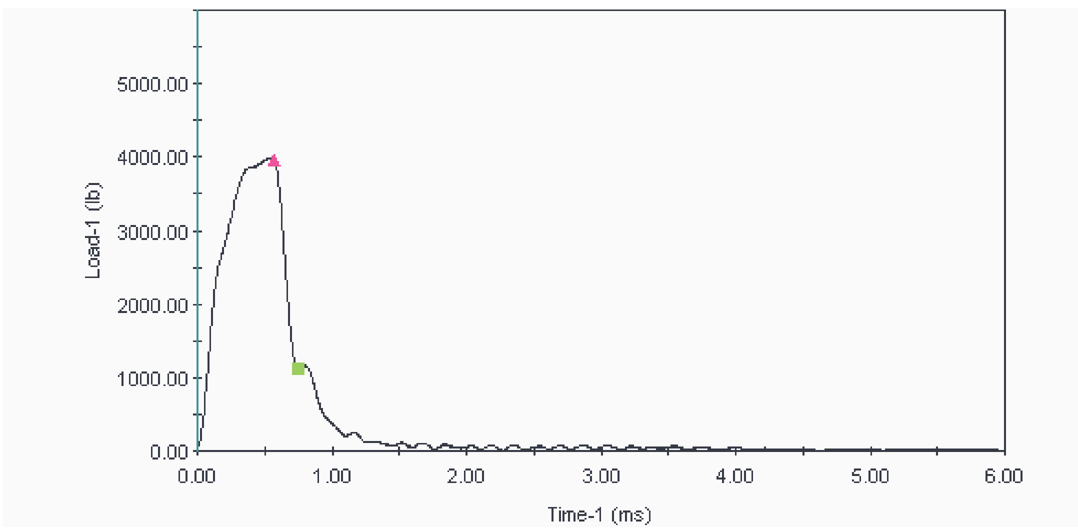
1B14T, -50°F



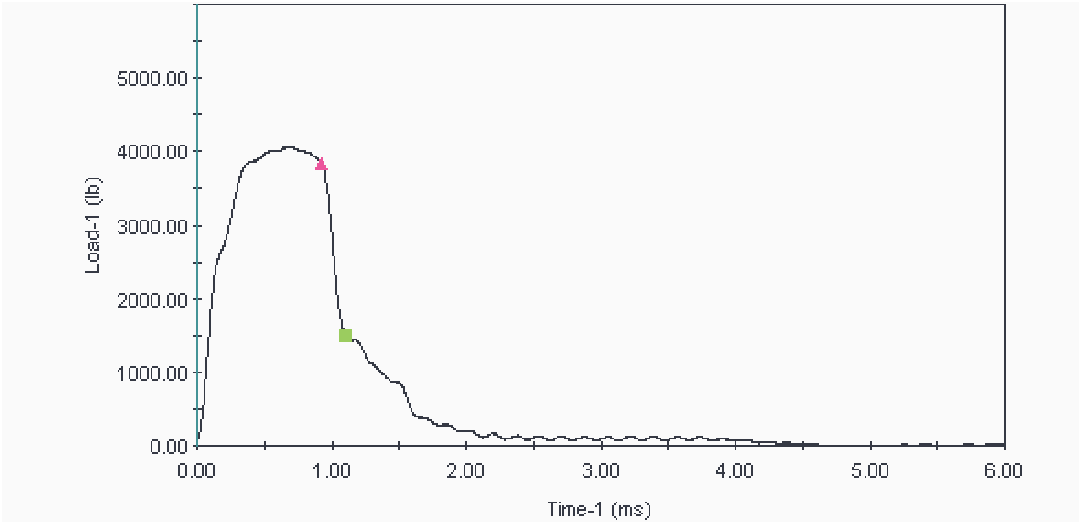
1B13C, 0°F



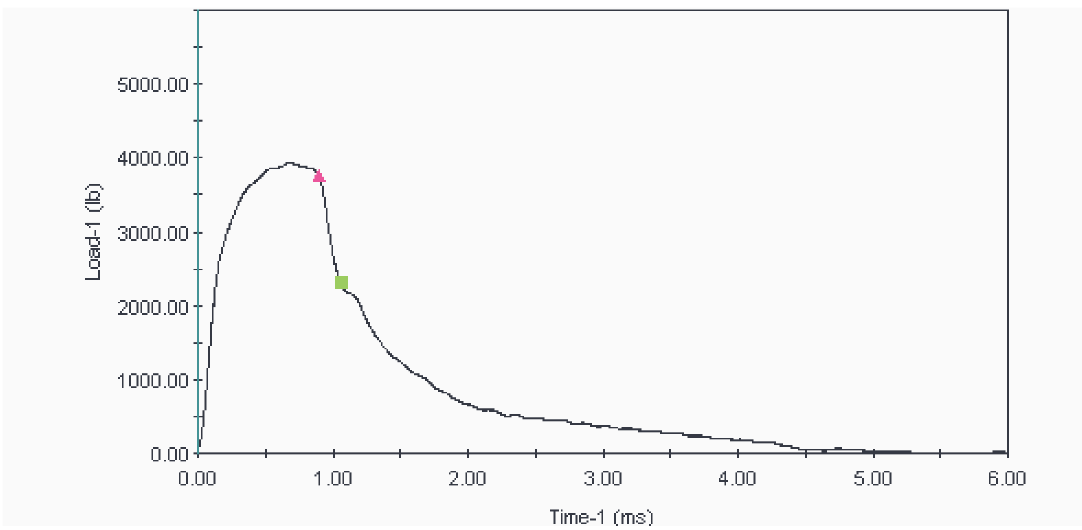
1B14K, 25°F



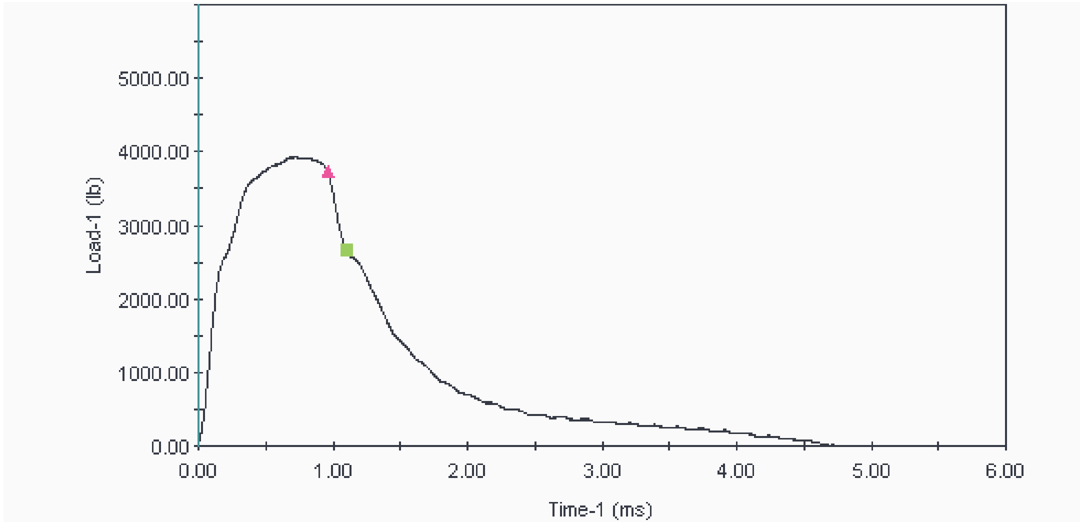
1B115, 50°F



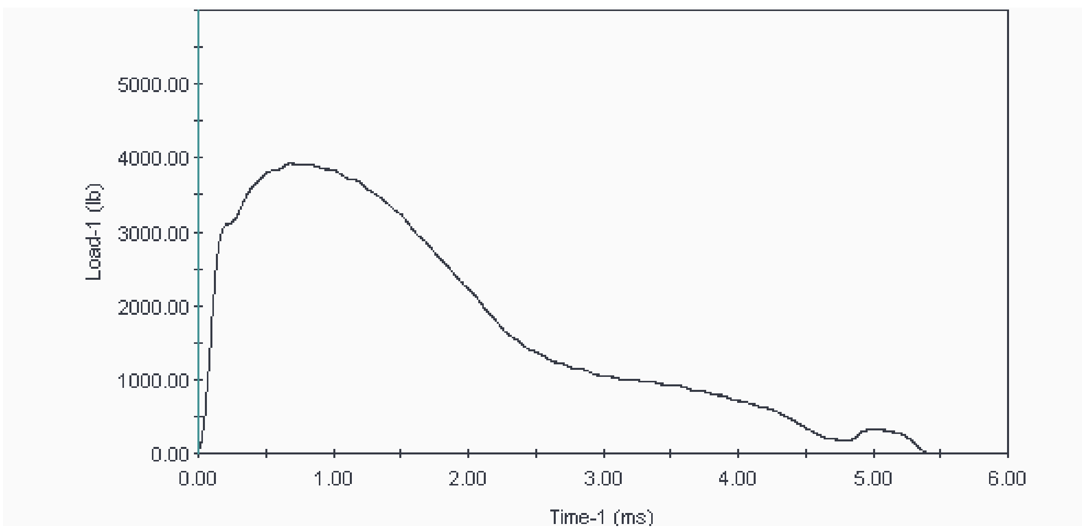
1B117, 75°F



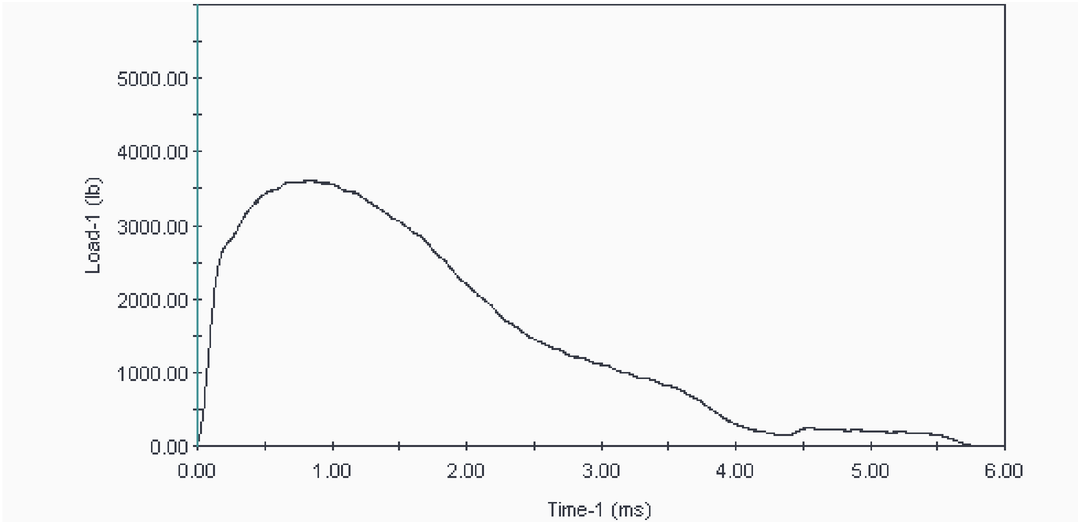
1B111, 125°F



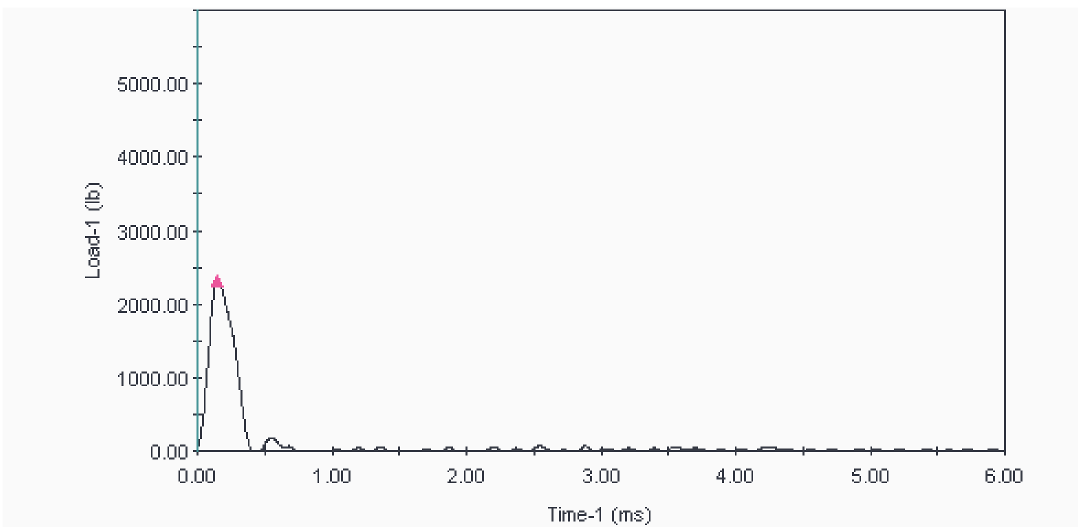
1B133, 175°F



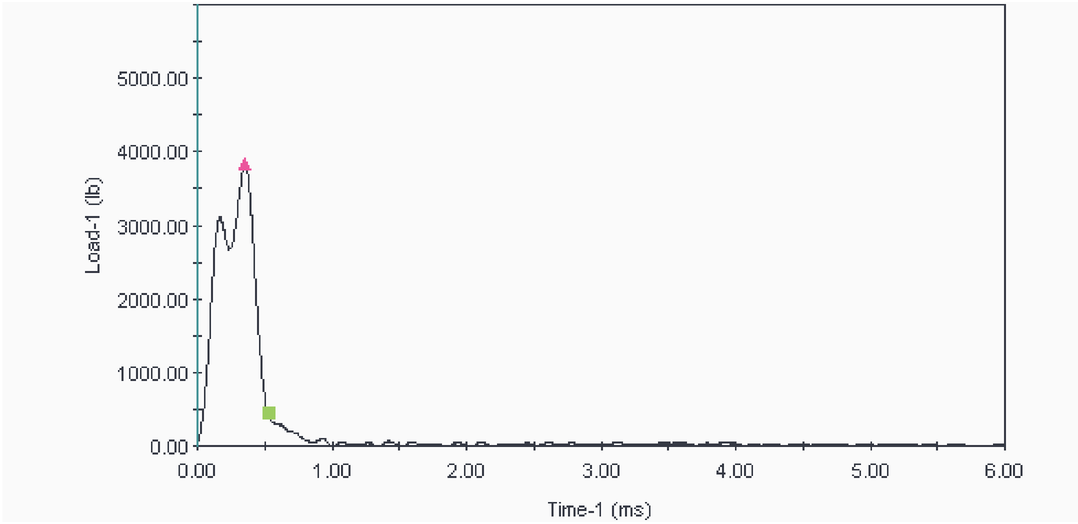
1B12T, 250°F



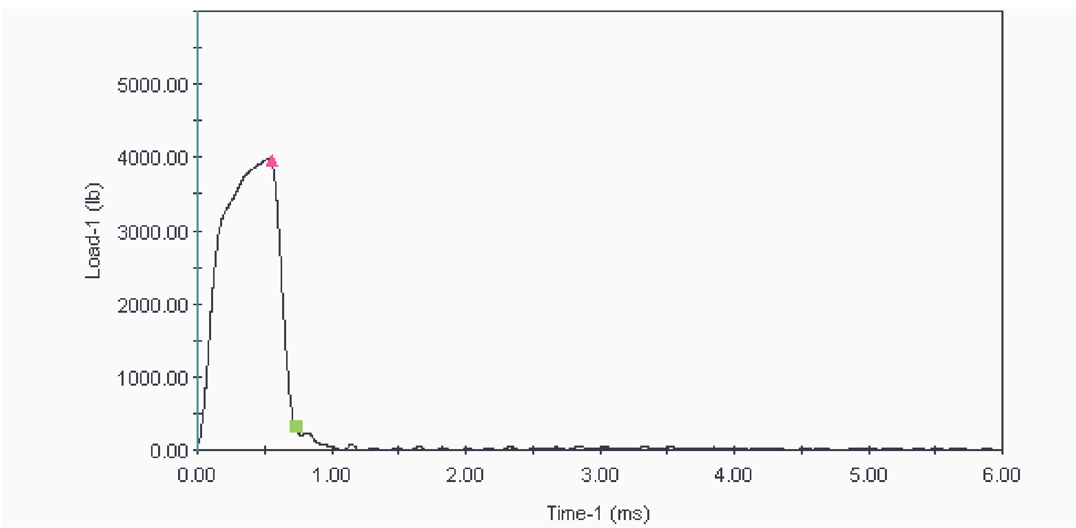
1B15L, 325°F



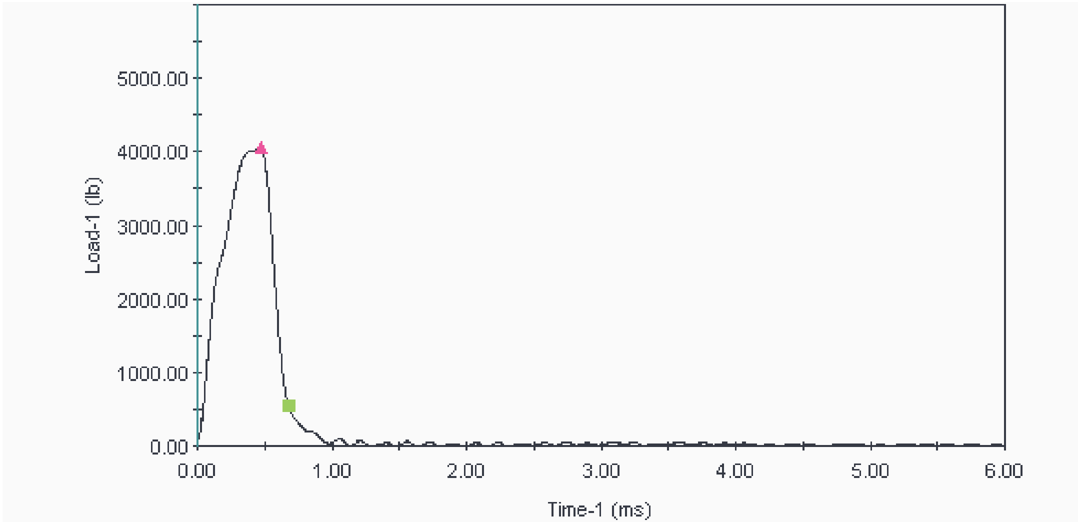
1B221, -50°F



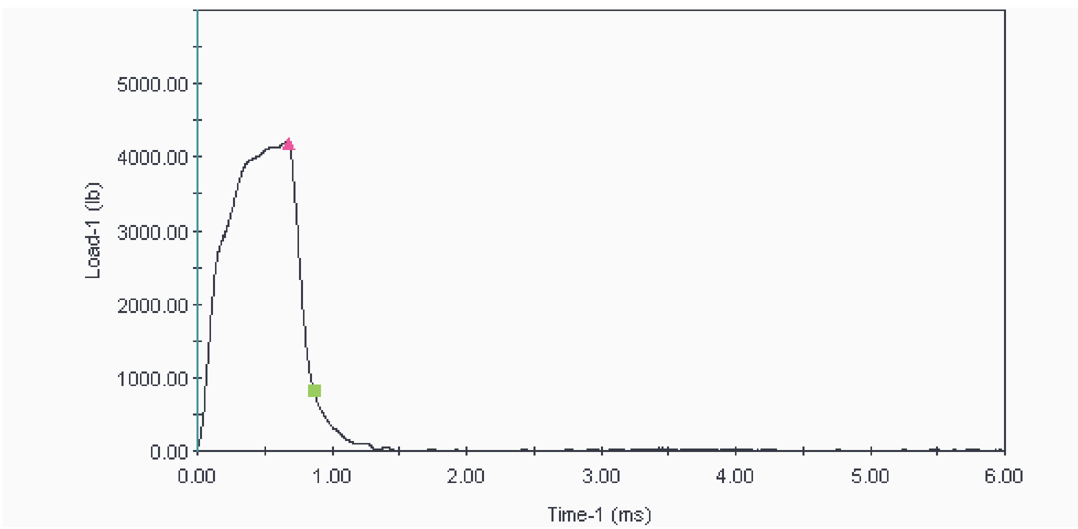
1B2AL, 0°F



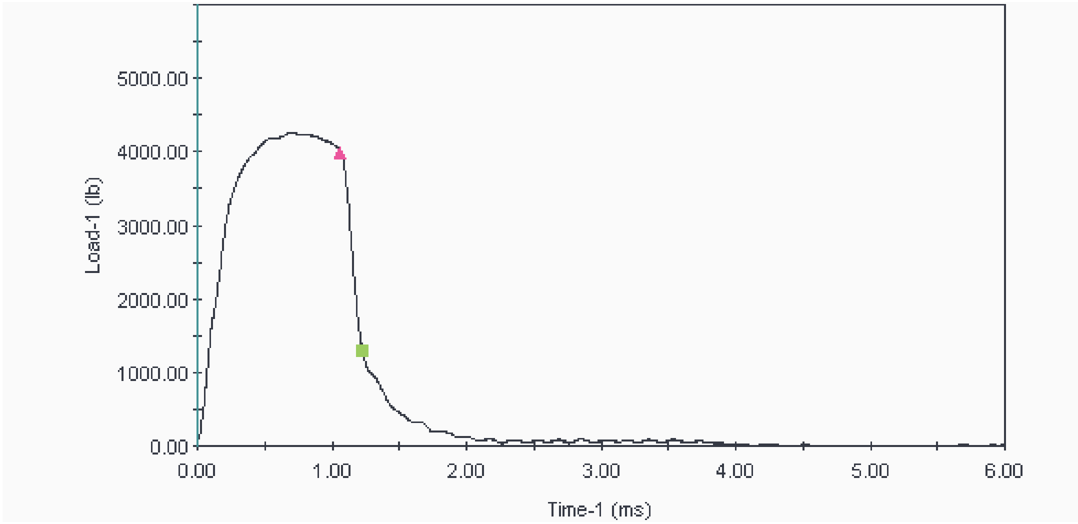
1B27E, 25°F



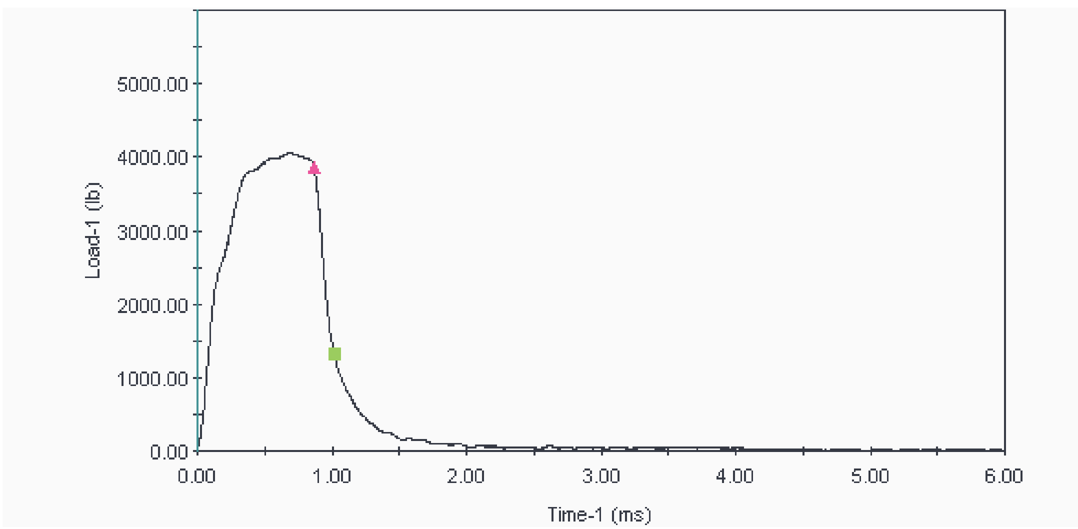
1B27J, 40°F



1B257, 50°F



1B21M, 75°F



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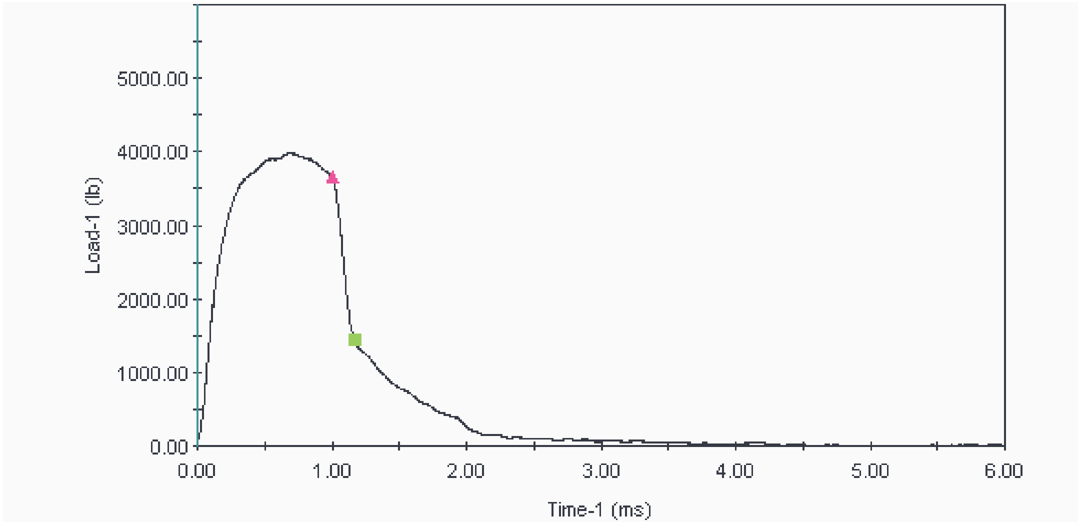
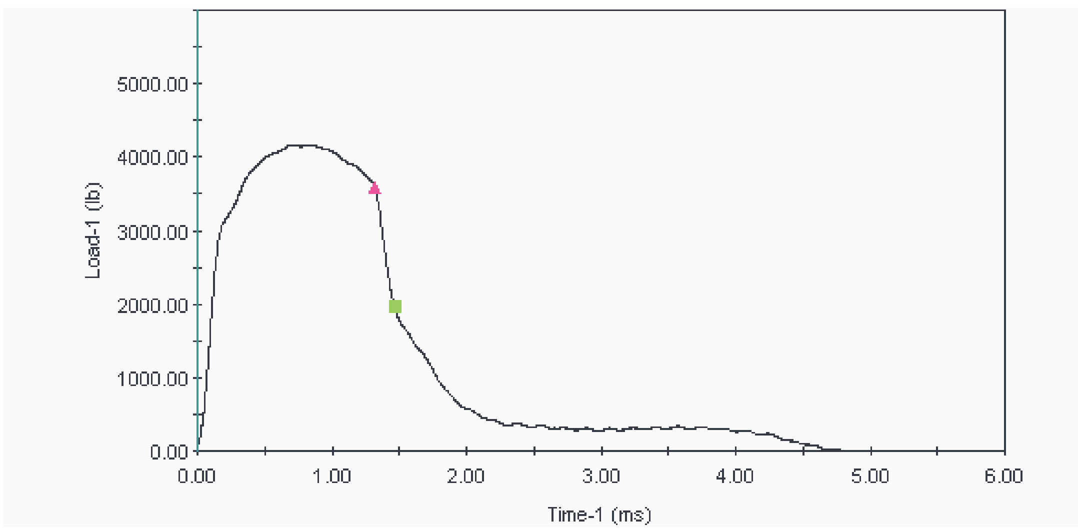
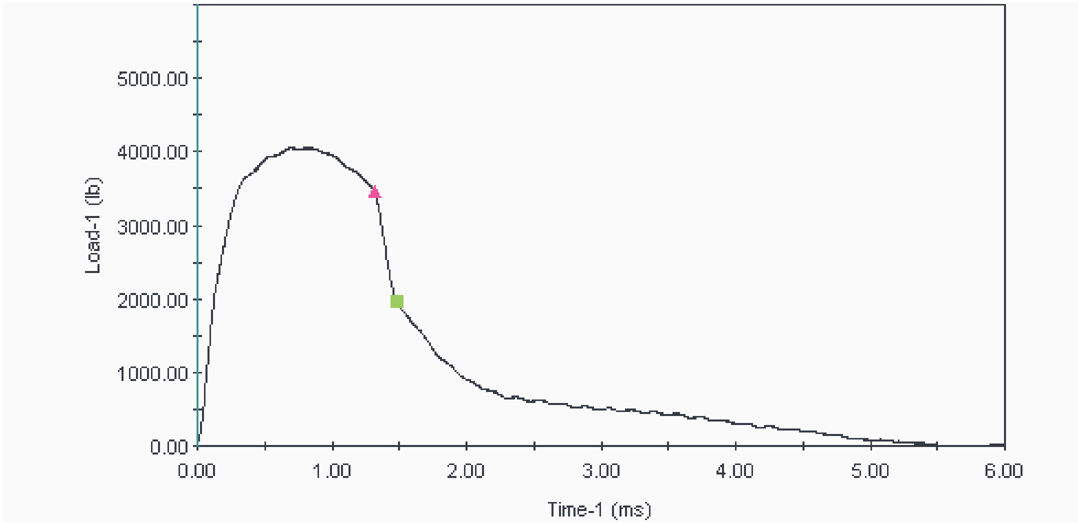


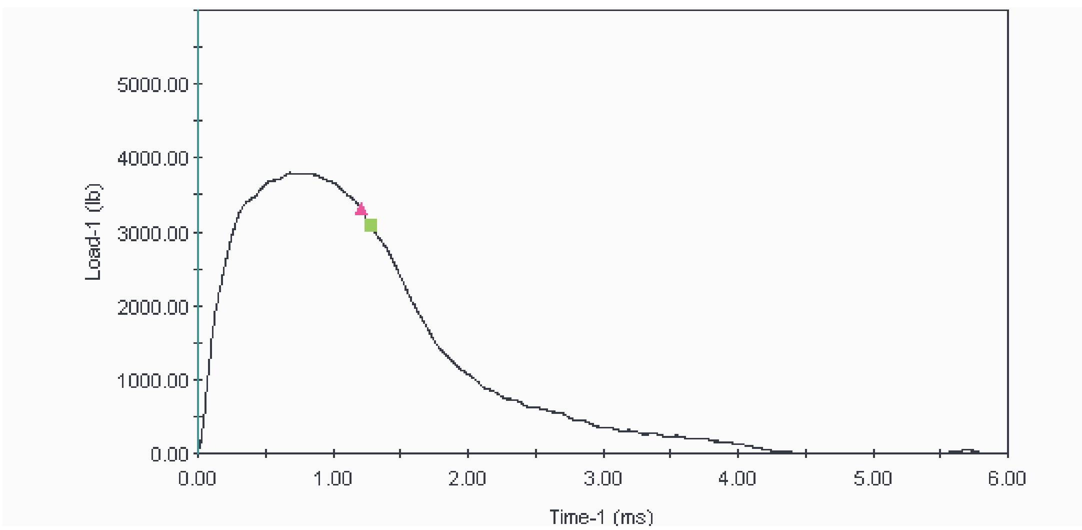
1B21D, 100°F



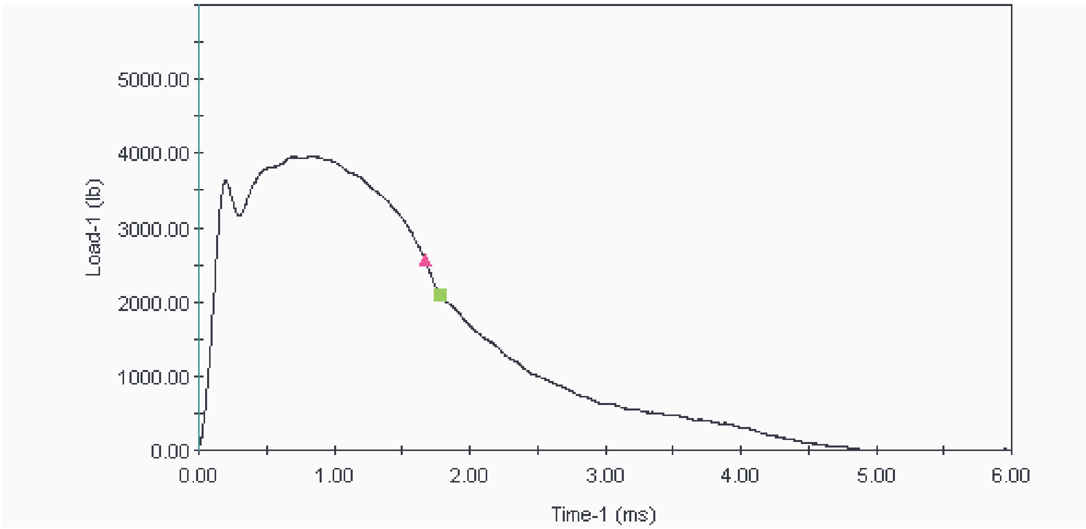
1B2AY, 125°F



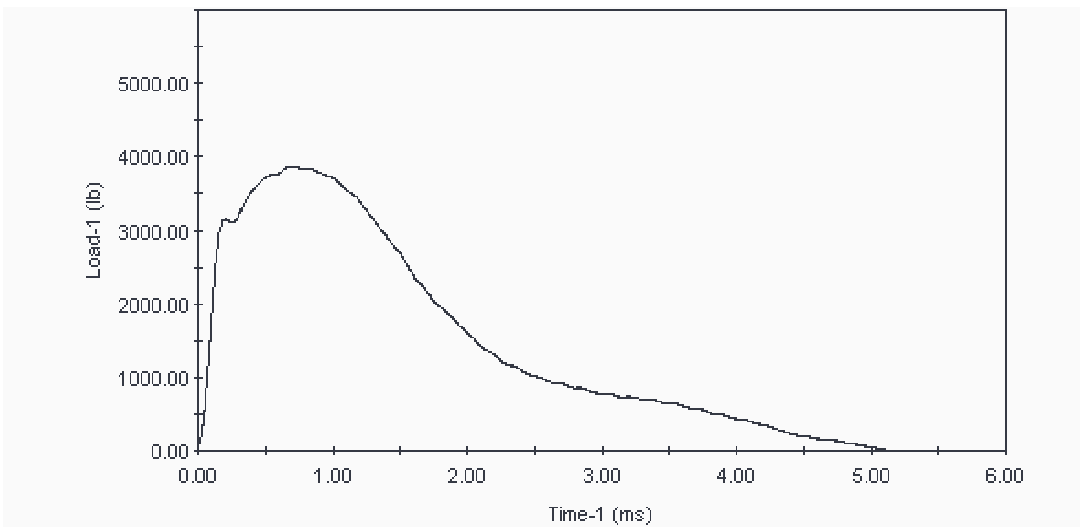
1B26K, 150°F



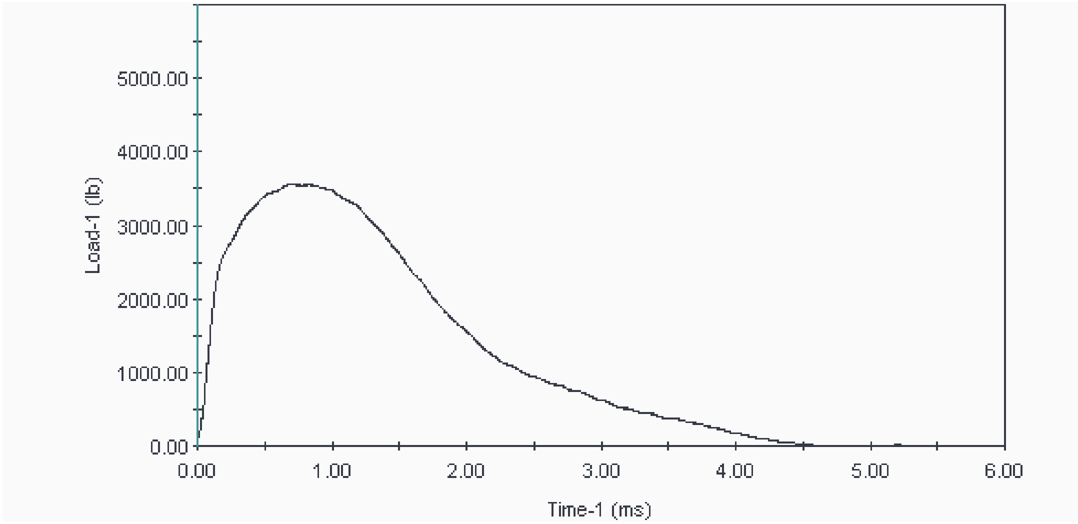
1B265, 200°F



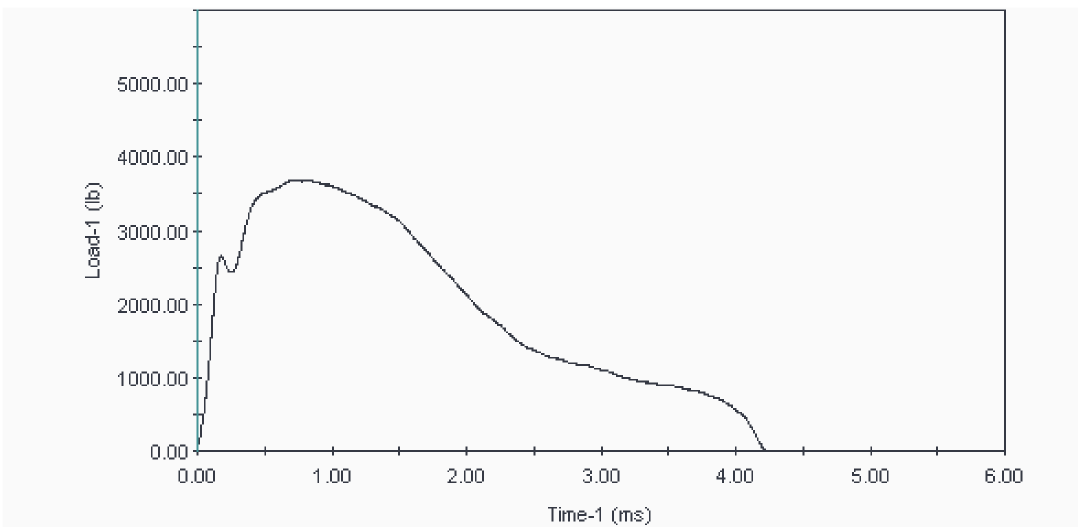
1B26T, 200°F



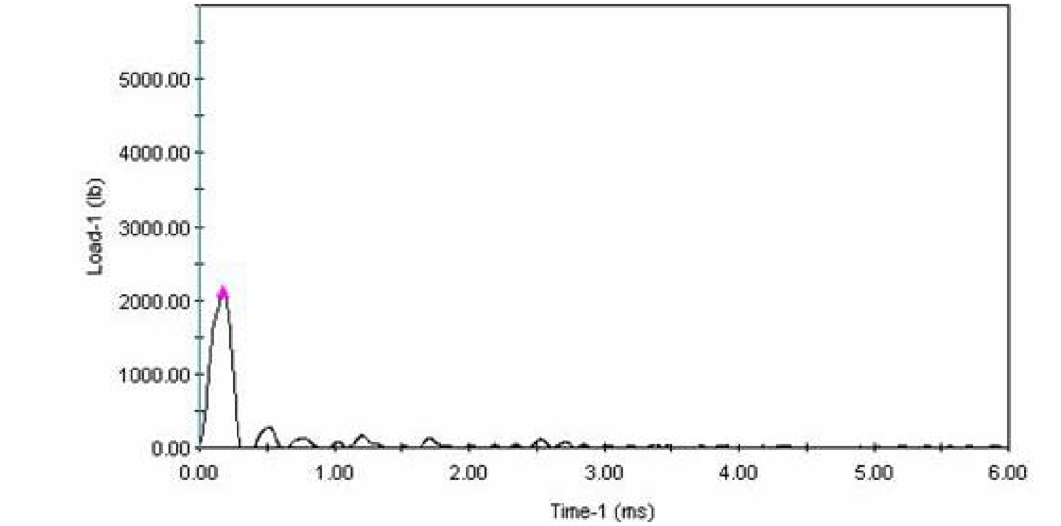
1B22K, 250°F



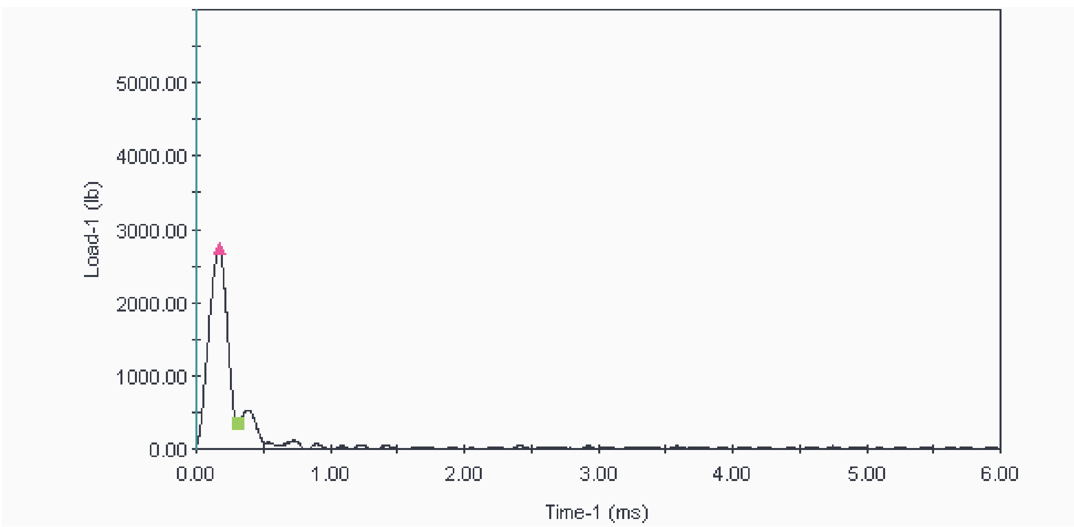
1B225, 300°F



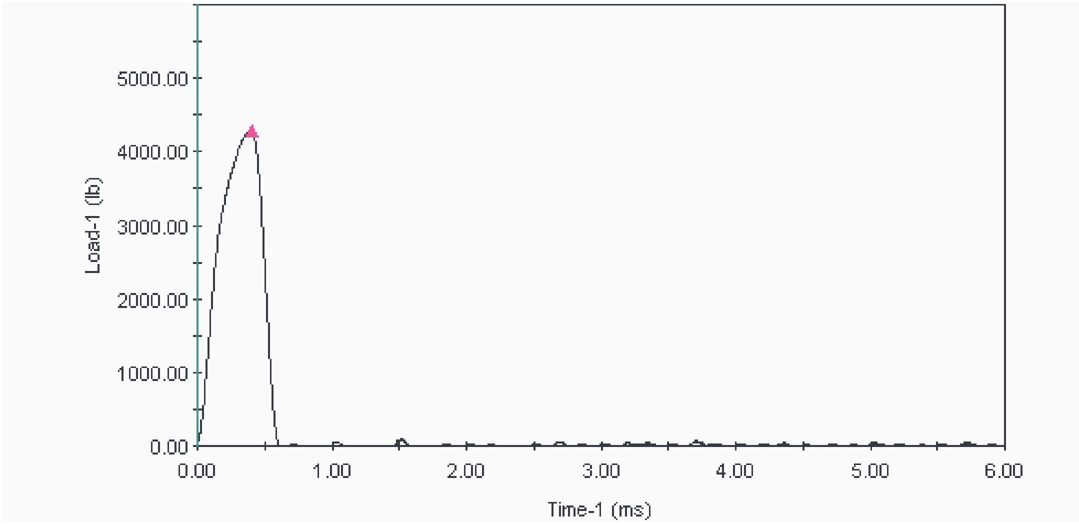
1B223, 350°F



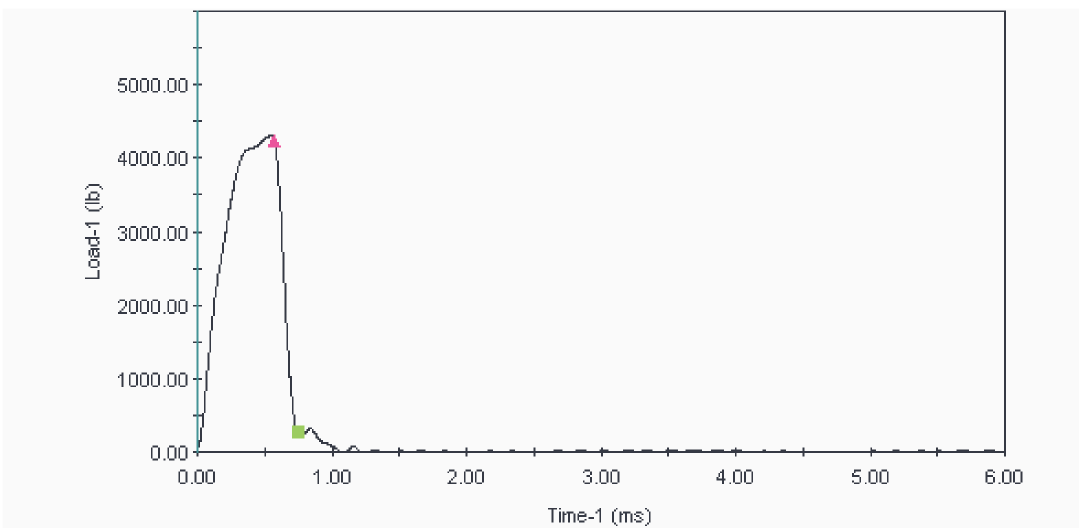
D45, 0°F



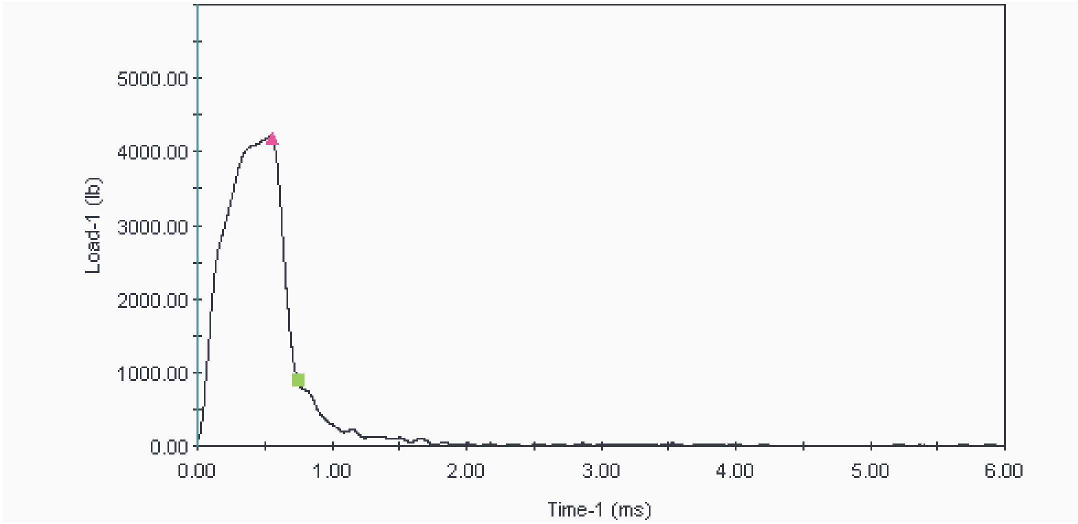
D2P, 75°F



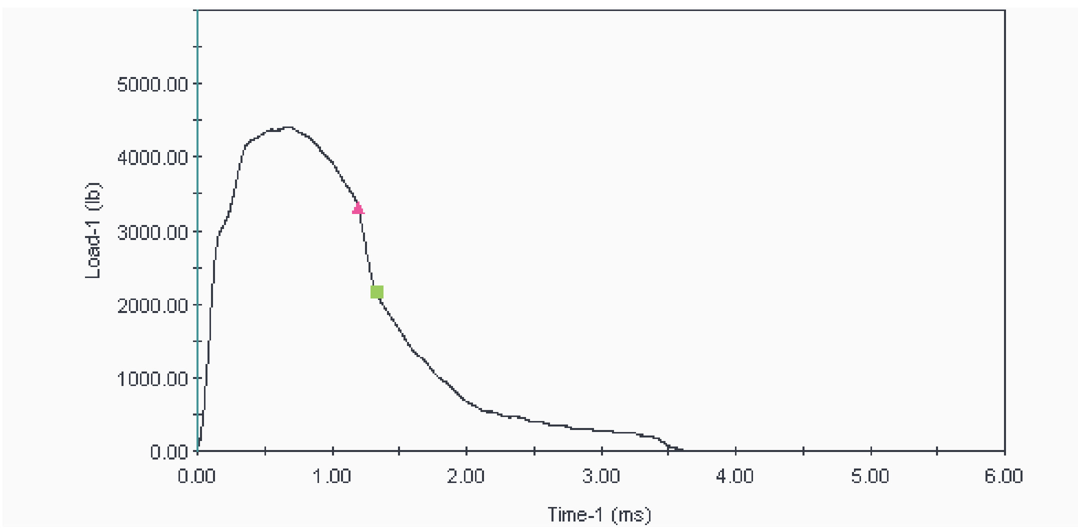
D34, 100°F



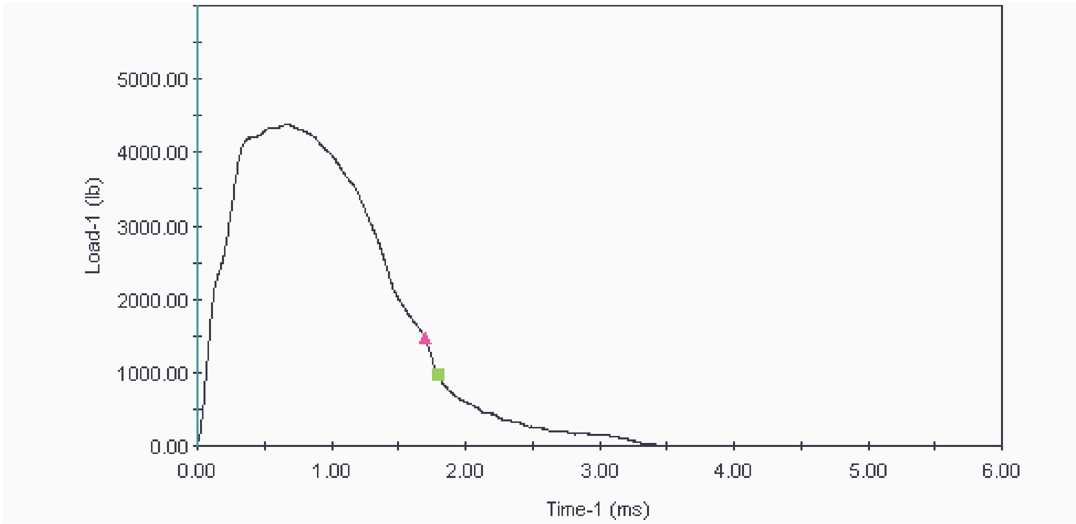
D33, 150°F



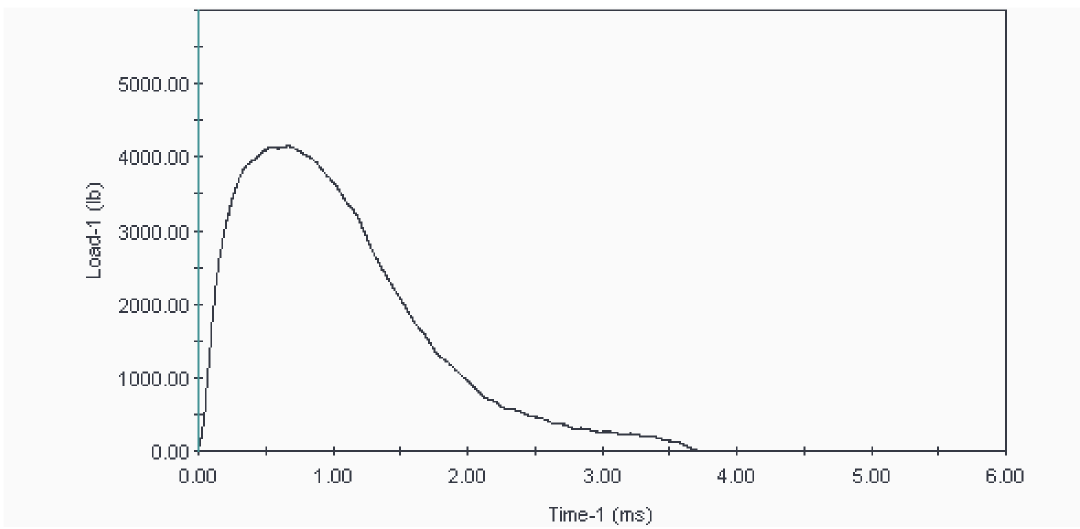
D2J, 190°F



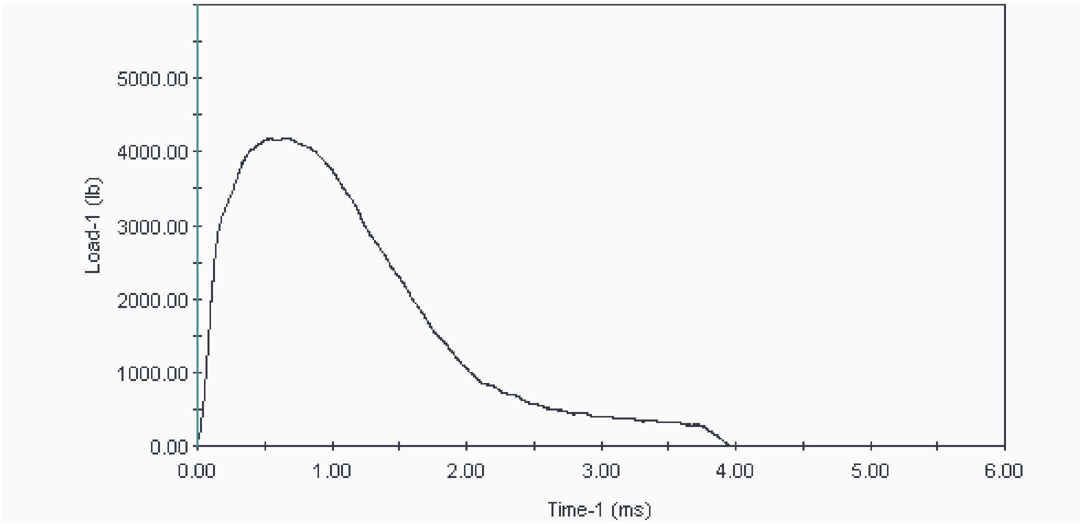
D2K, 225°F



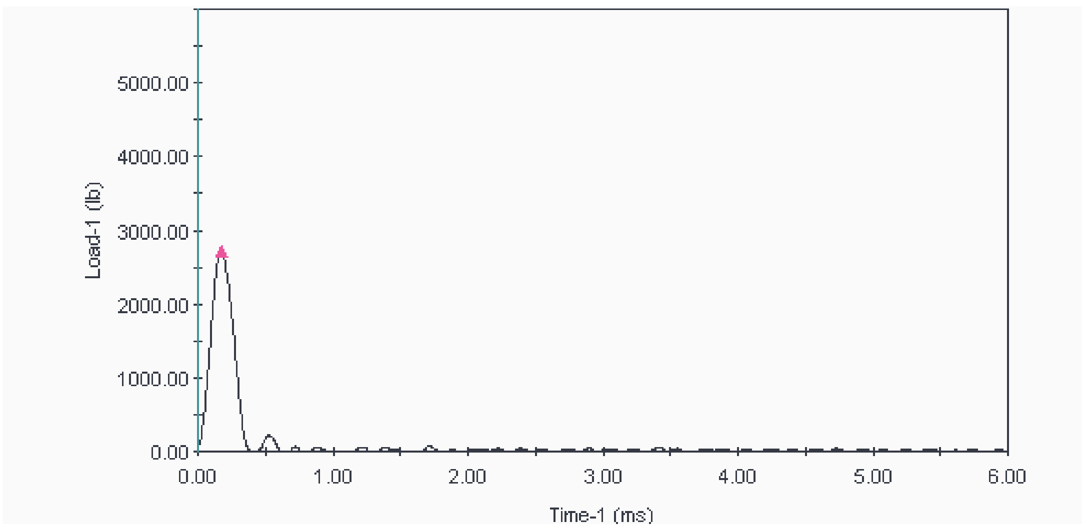
D3L, 250°F



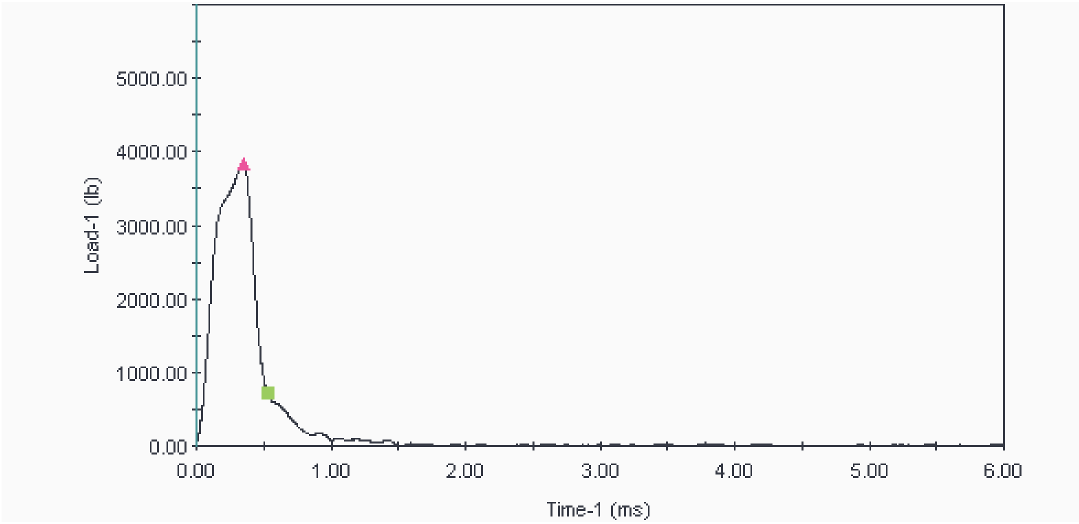
D3A, 325°F



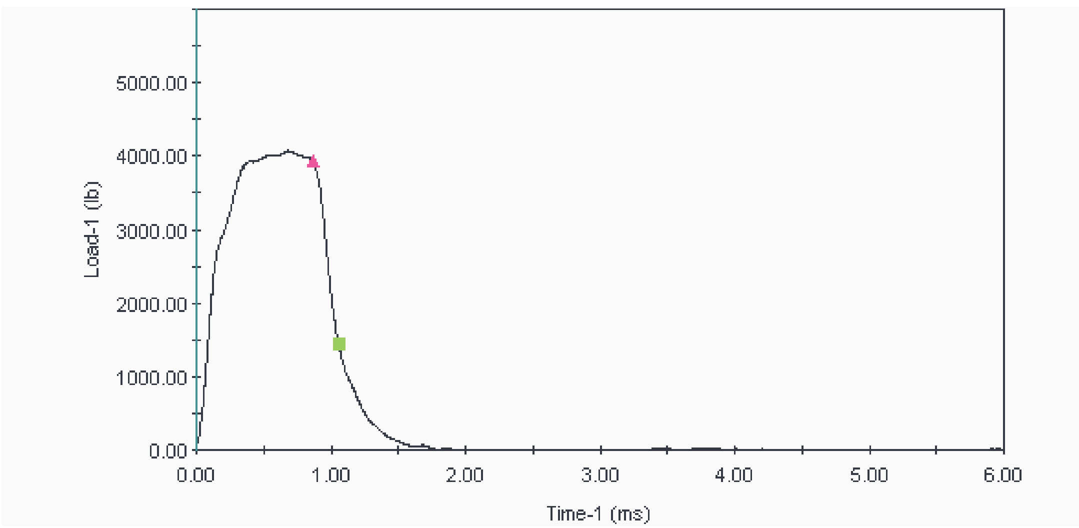
D3U, 375°F



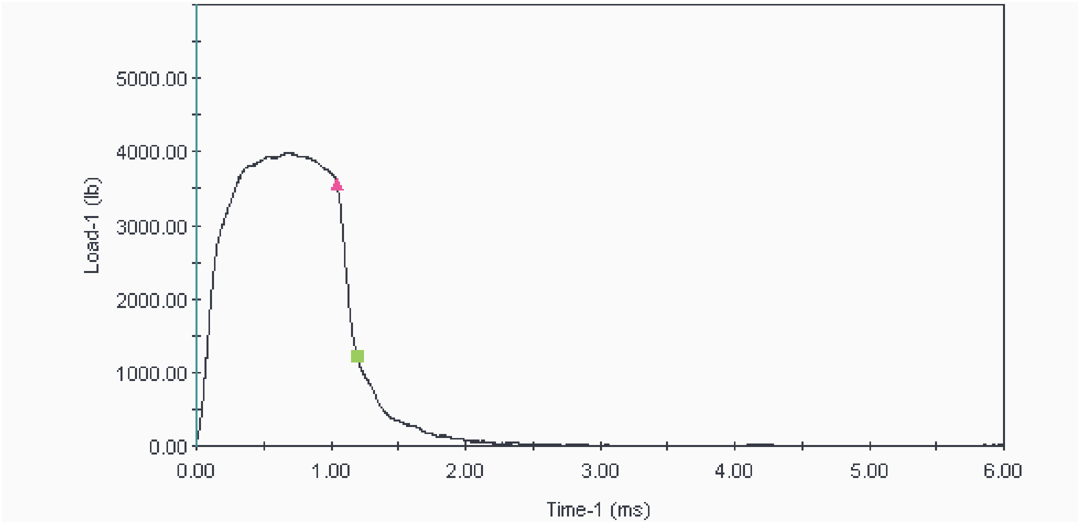
1B36T, -75°F



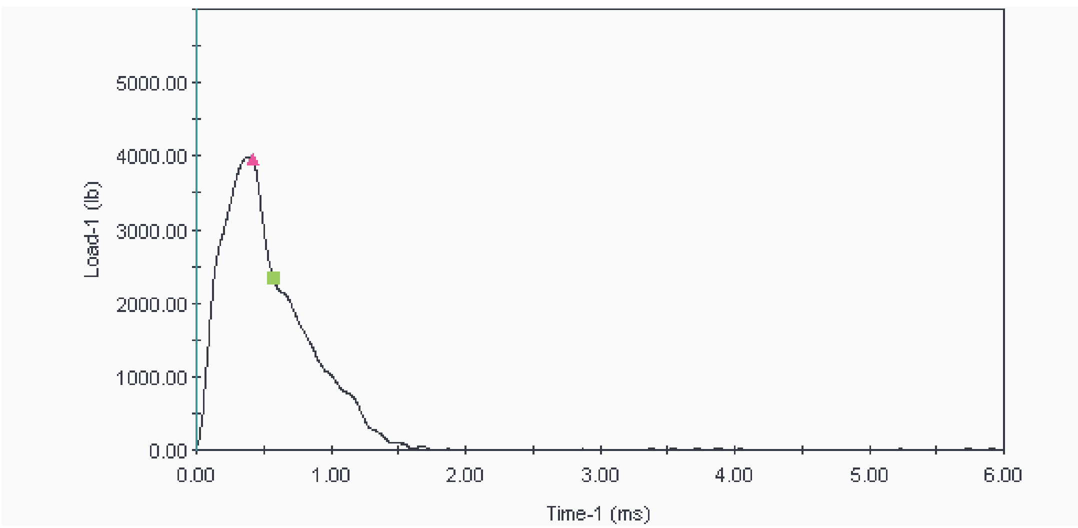
1B352, -25°F



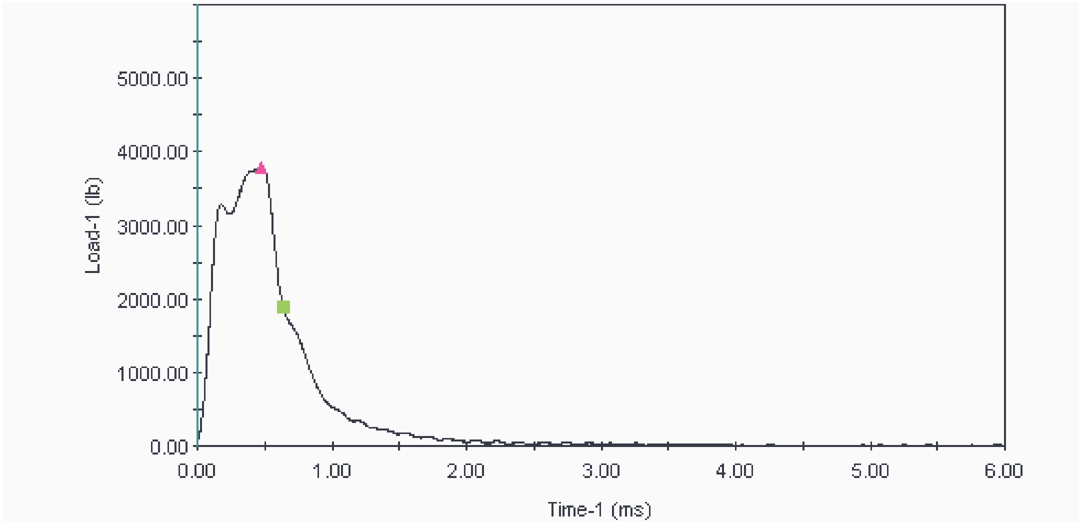
1B347, -10°F



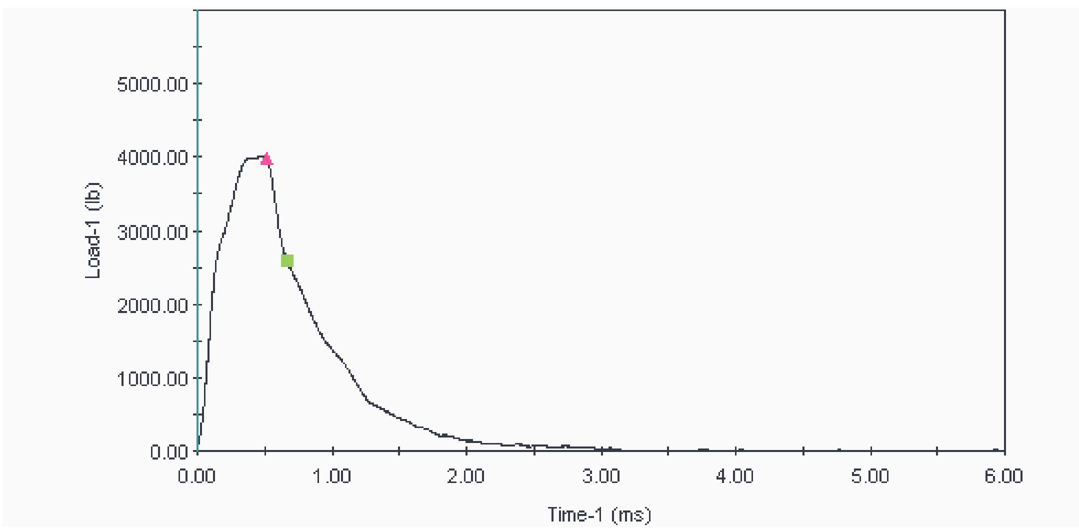
1B321, 0°F



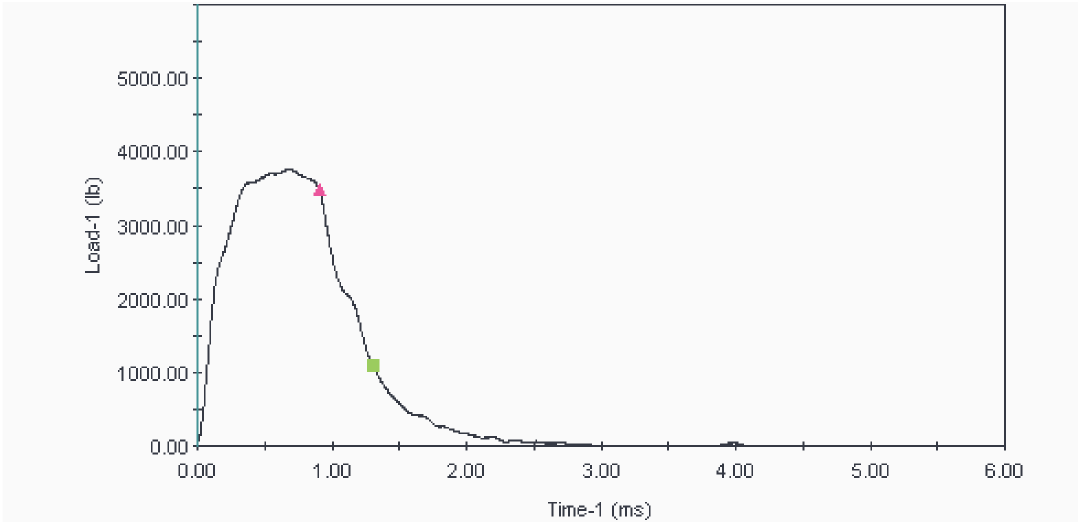
1B36P, 0°F



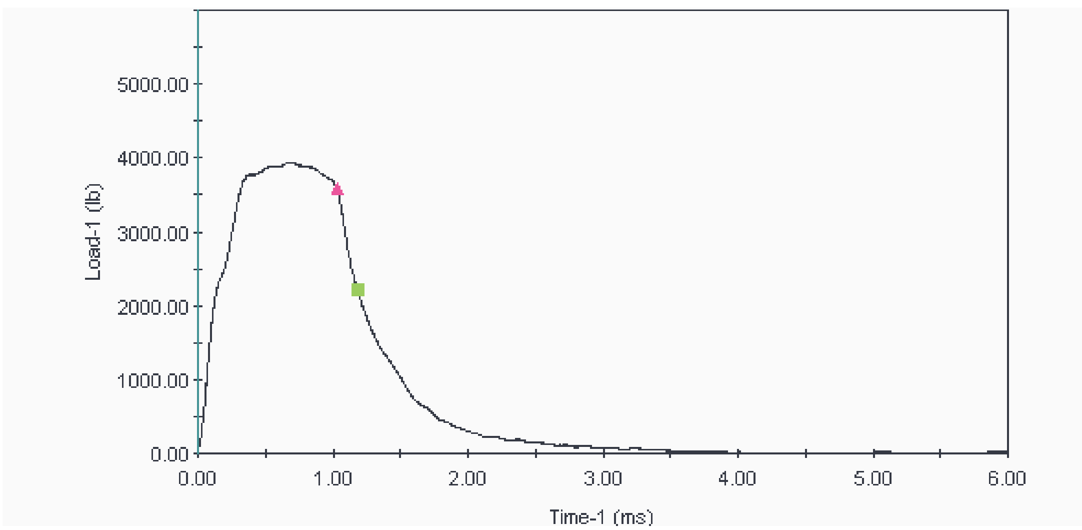
1B33K, 25°F



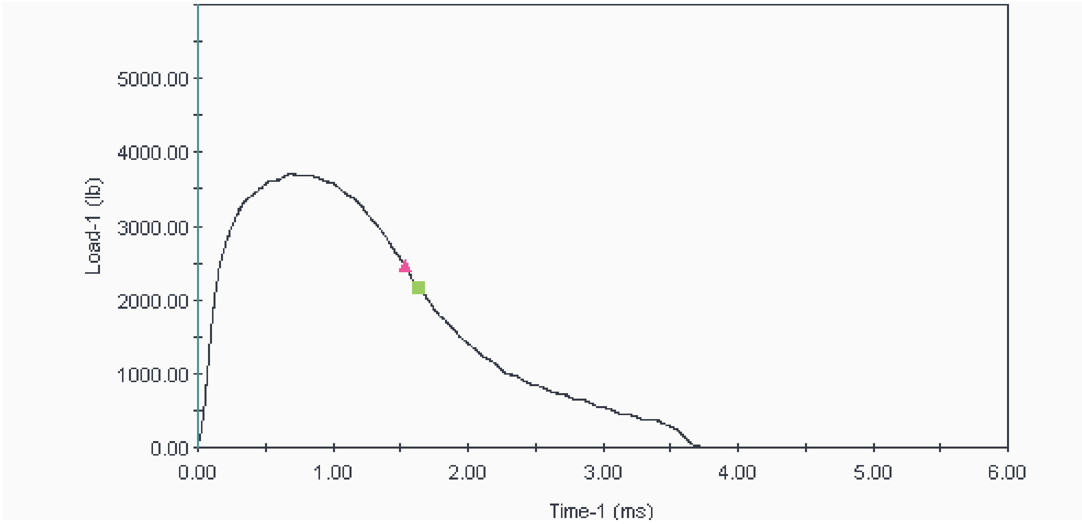
1B35Y, 25°F



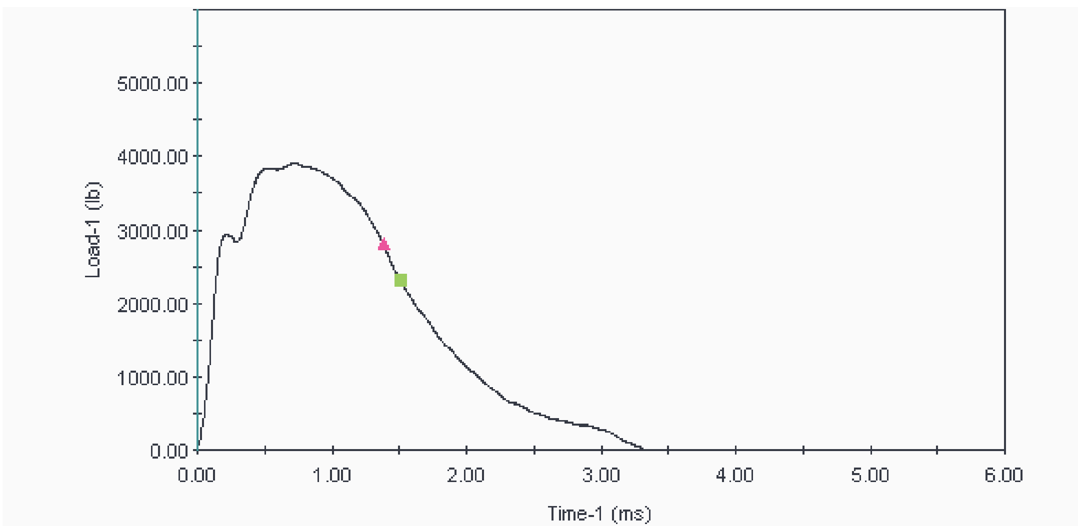
1B32T, 50°F



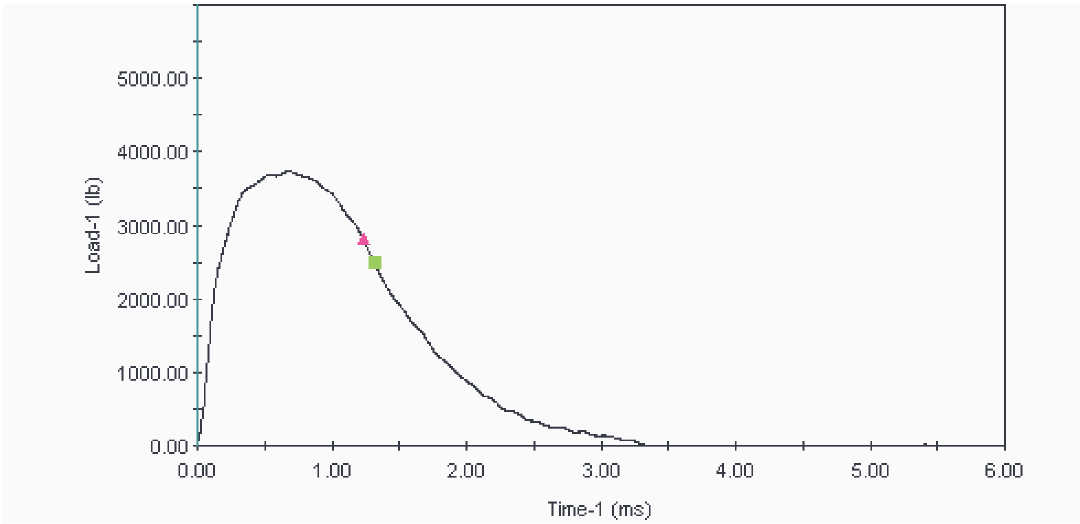
1B351, 75°F



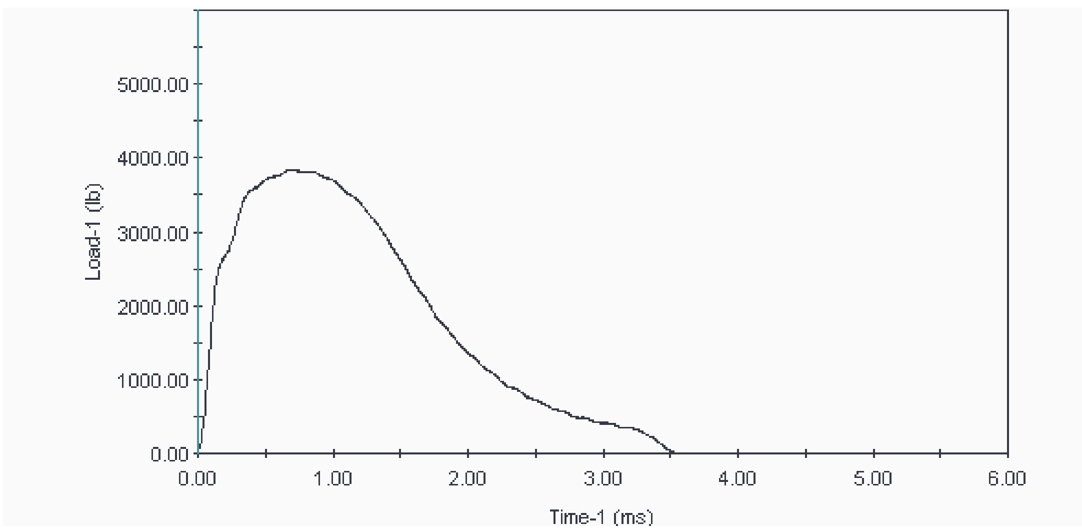
1B313, 125°F



1B366, 150°F



1B372, 200°F



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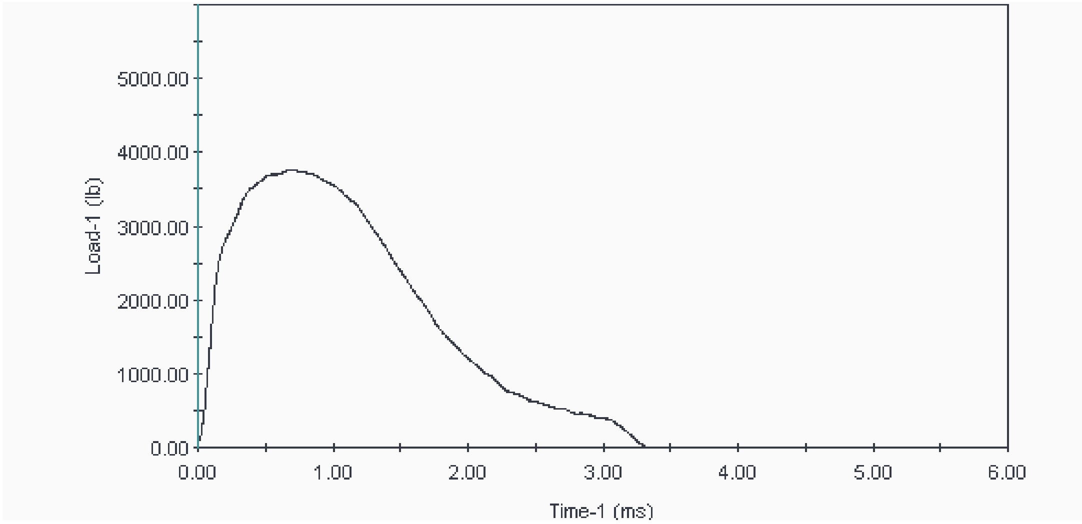
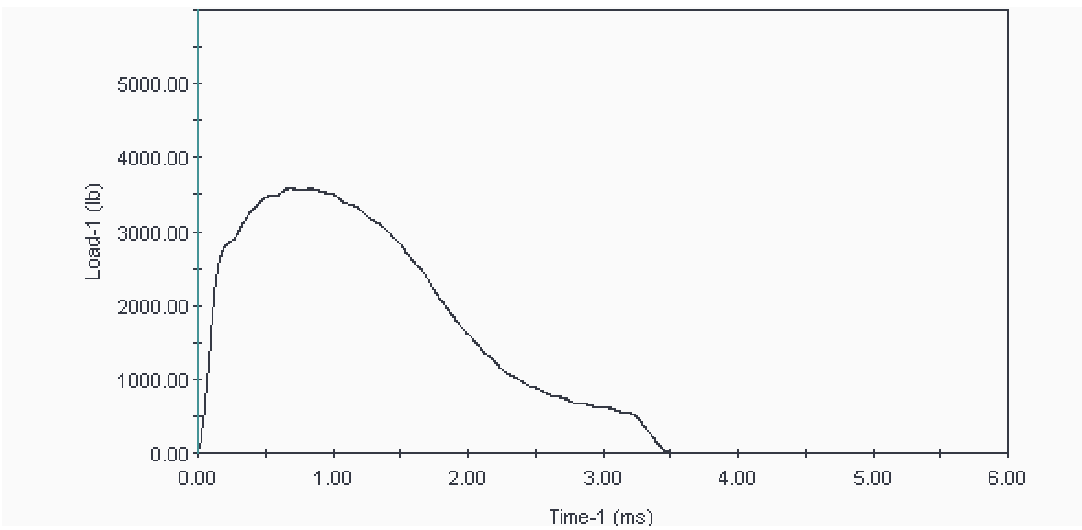
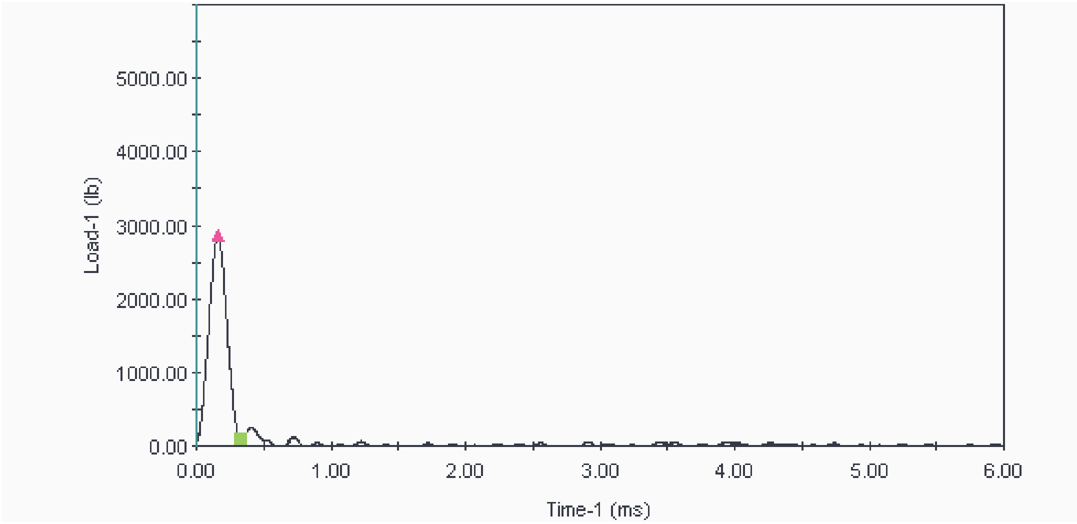


1B36J, 250°F



1B354, 300°F



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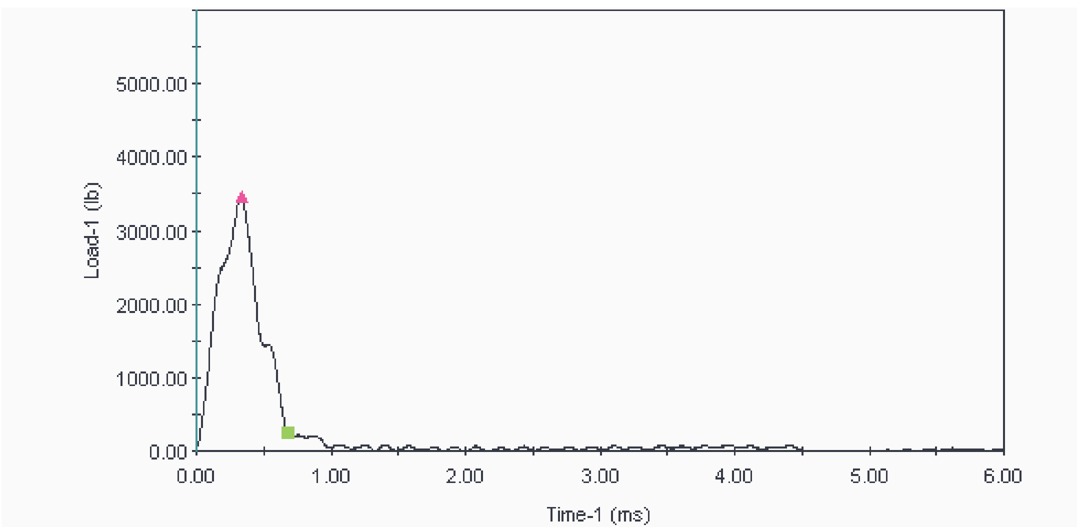

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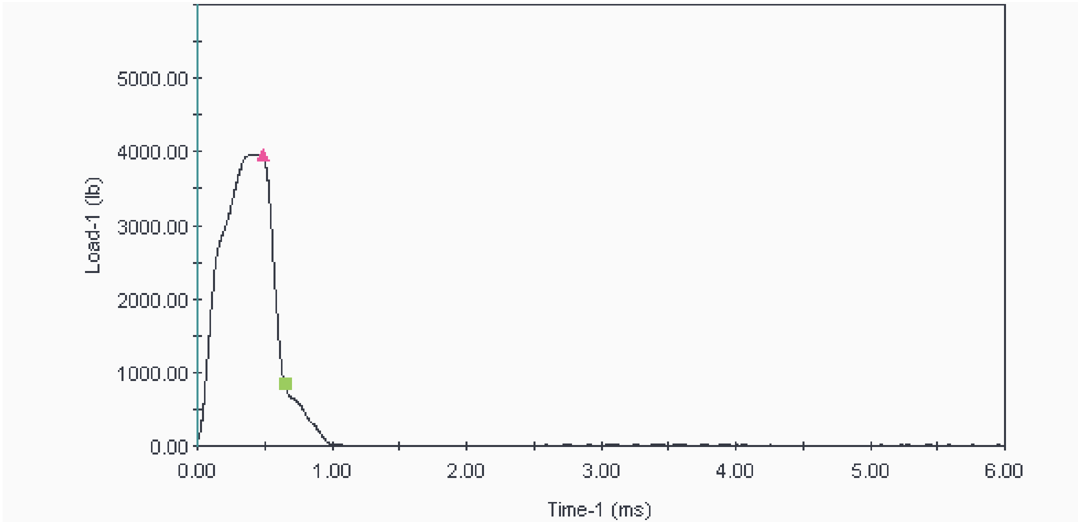
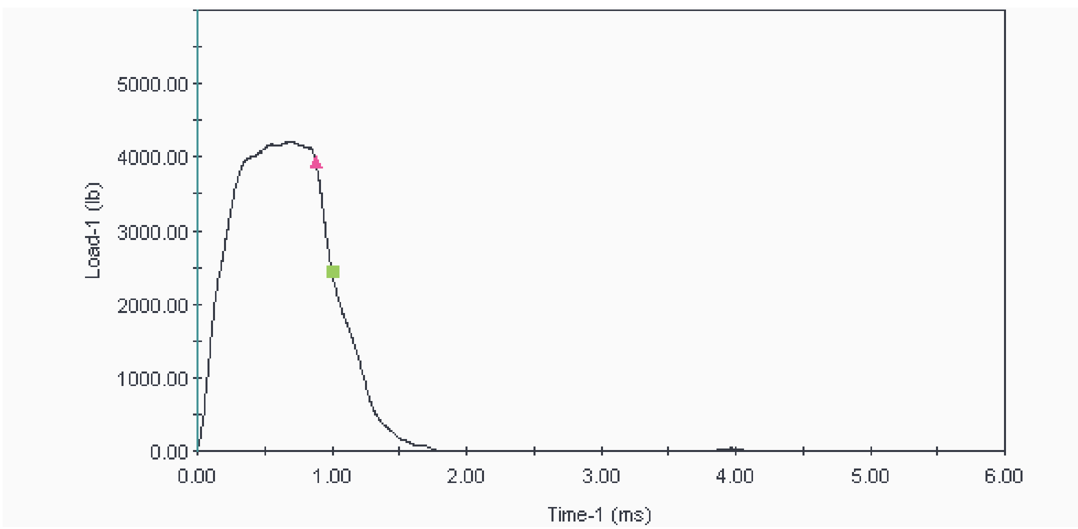
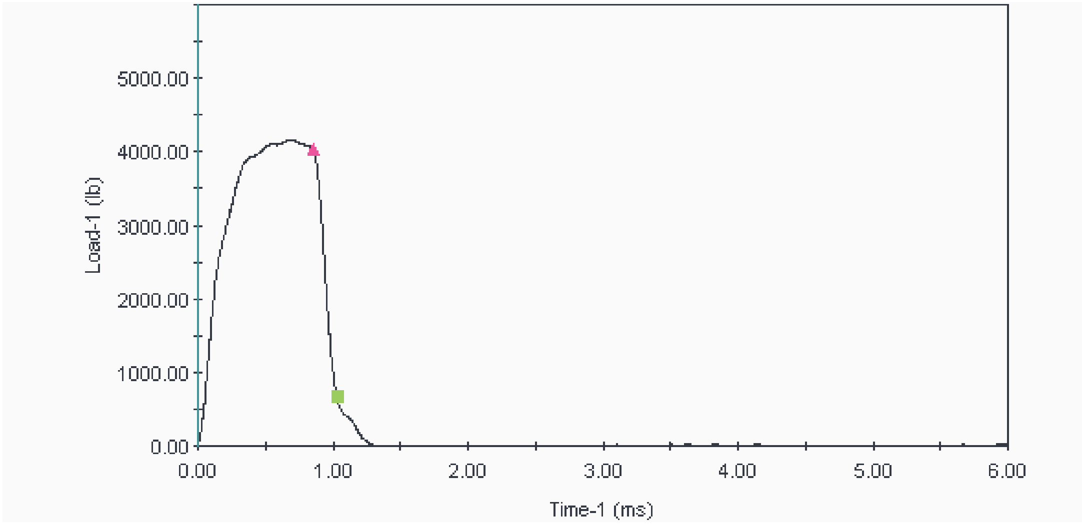


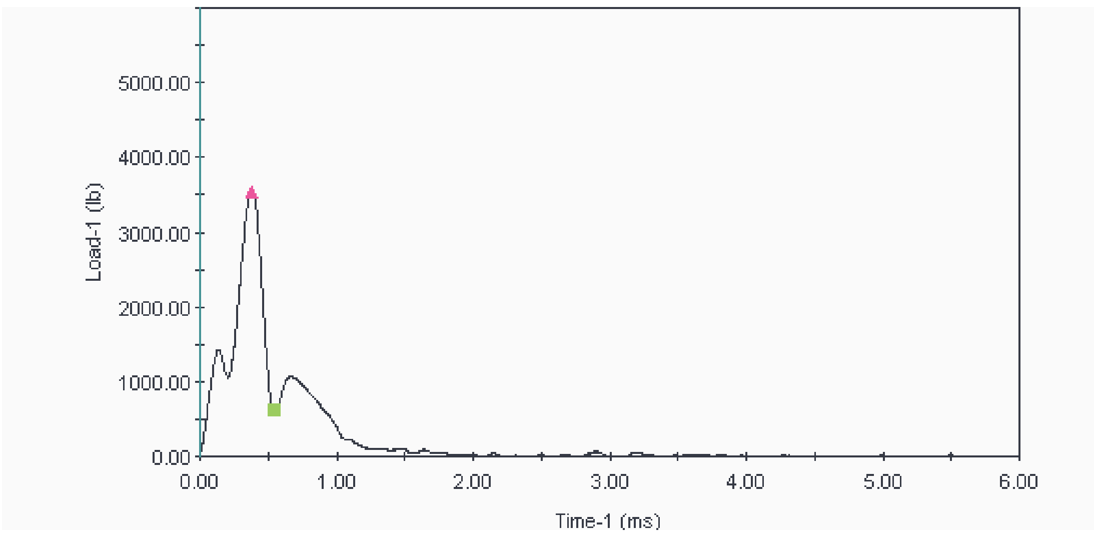
1B415, 50°F



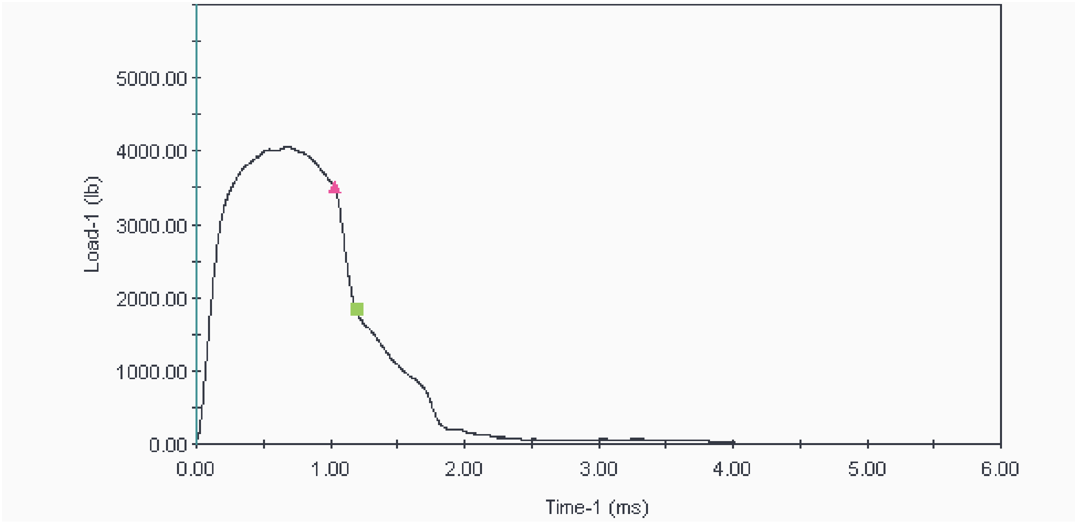
1B454, 75°F



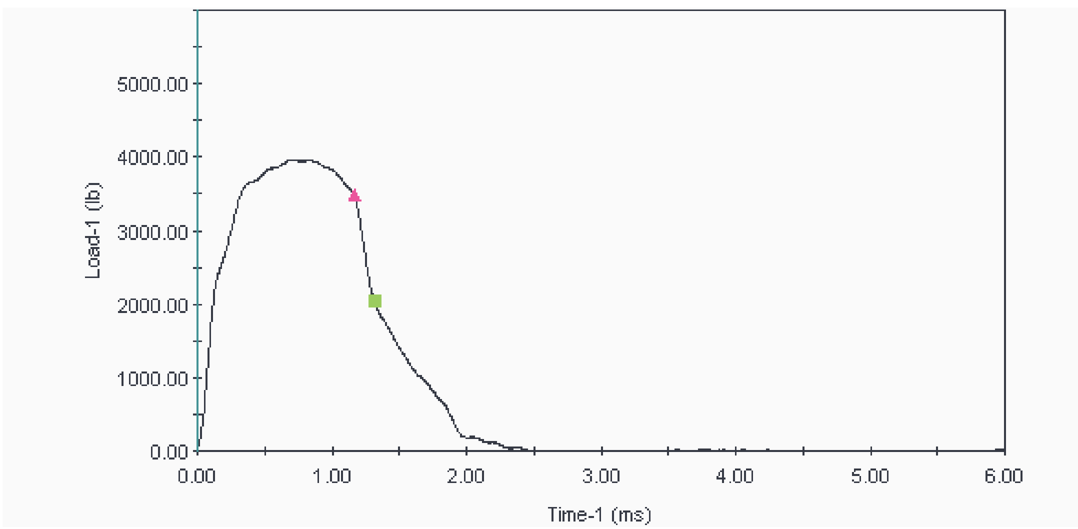
1B414, 80°F



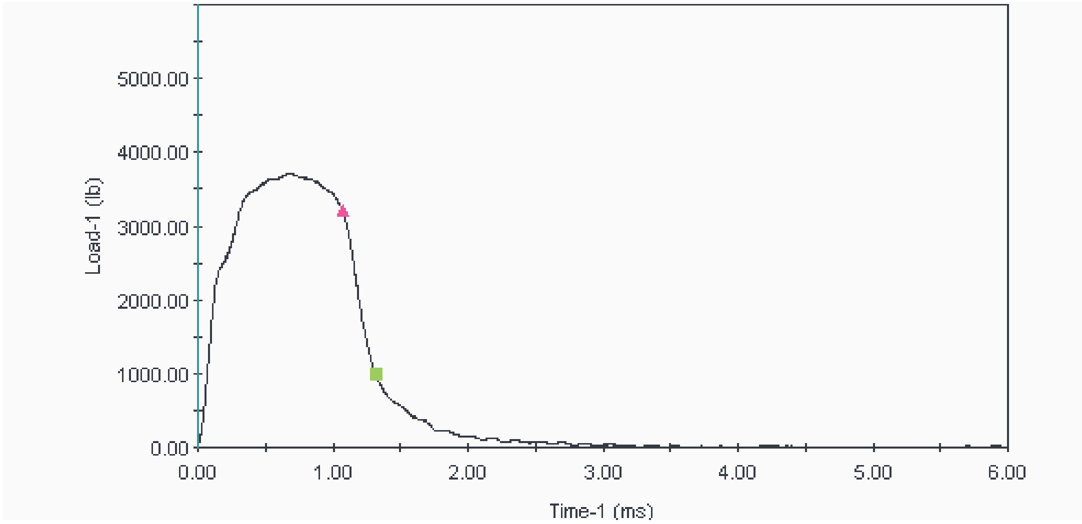
1B41J, 100°F



1B443, 125°F



1B42E, 150°F



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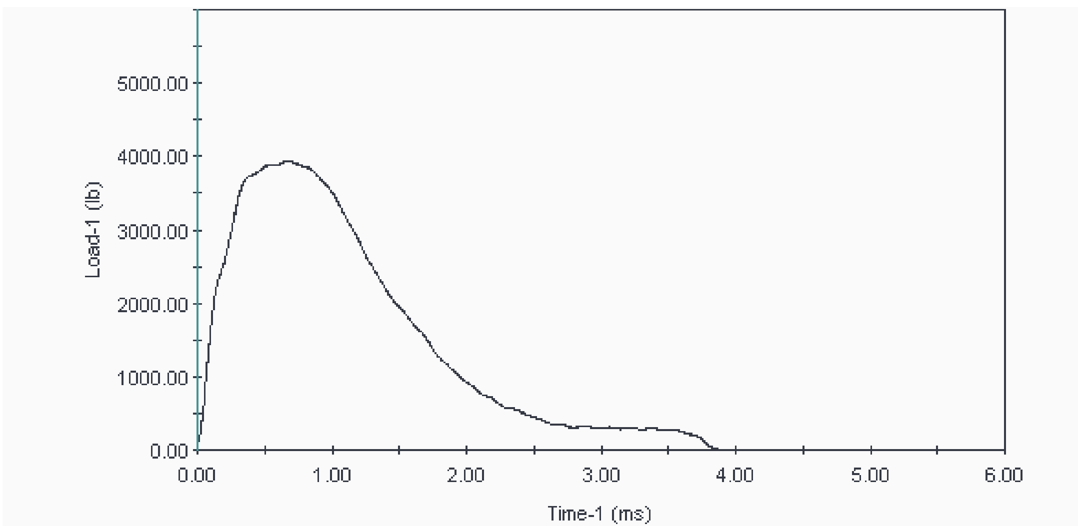
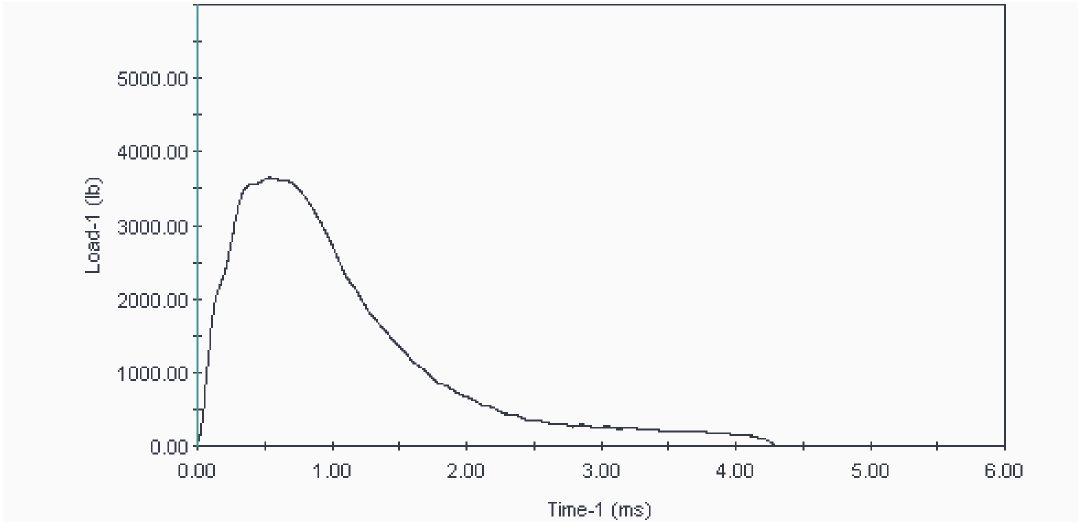
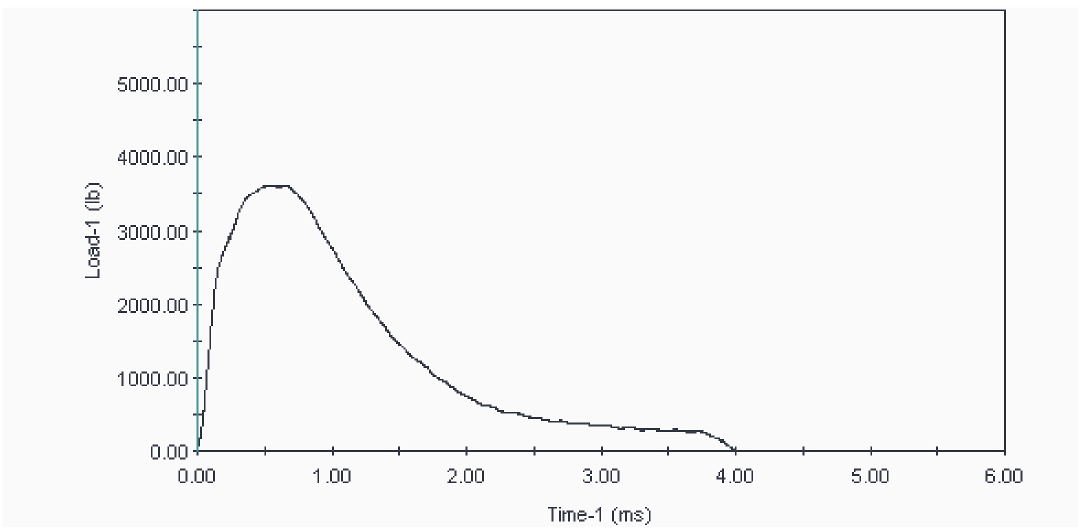


1B424, 250°F



1B421, 300°F

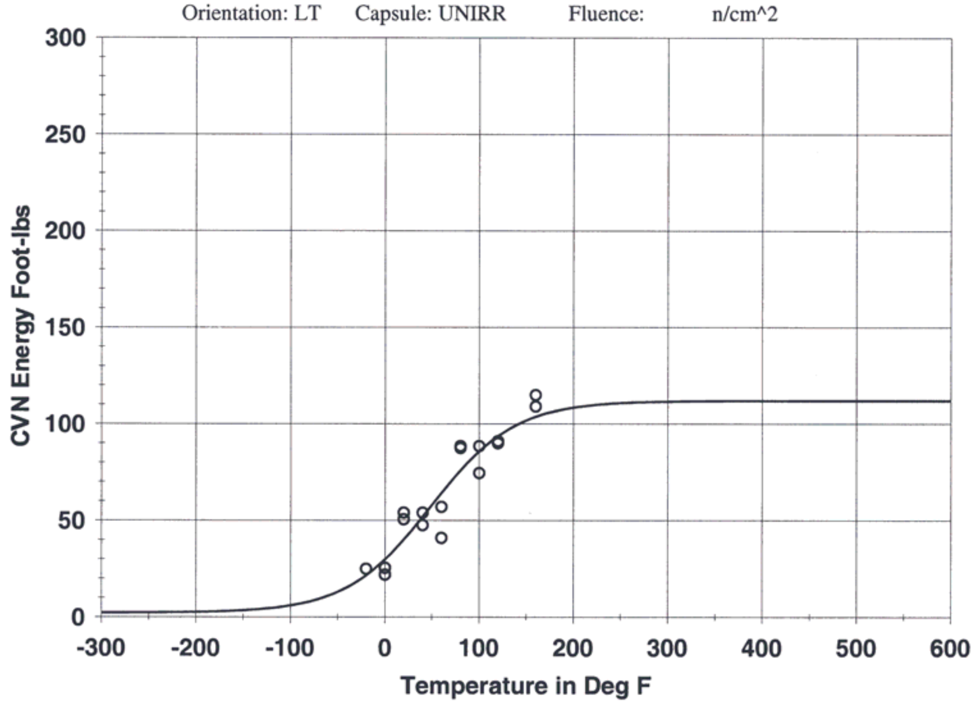


1B41U, 325°F

APPENDIX C
CHARPY V-NOTCH PLOTS FOR EACH CAPSULE USING HYPERBOLIC TANGENT CURVE-FITTING METHOD (REFERENCE C-1)

UNIRRADIATED LOWER SHELL PLATE F-773-1 (LONGITUDINAL)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/29/2005 11:30 AM
Page 1
Coefficients of Curve 1
A = 57.1 B = 54.9 C = 89.09 T0 = 48.59 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Upper Shelf Energy=112.0(Fixed) Lower Shelf Energy=2.2(Fixed)
Temp@30 ft-lbs=.5 Deg F Temp@50 ft-lbs=37.1 Deg F
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: LT Capsule: UNIRR Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
-20.00	25.00	21.58	3.42
.00	22.00	29.81	-7.81
.00	25.50	29.81	-4.31
20.00	50.50	40.06	10.44
20.00	54.00	40.06	13.94
40.00	47.50	51.82	-4.32
40.00	54.00	51.82	2.18
60.00	41.00	64.09	-23.09
60.00	57.00	64.09	-7.09

UNIRRADIATED LOWER SHELL PLATE F-773-1 (LONGITUDINAL)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: LT Capsule: UNIRR Fluence: n/cm^2

Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
80.00	87.50	75.69	11.81
80.00	88.50	75.69	12.81
100.00	74.50	85.68	-11.18
100.00	88.50	85.68	2.82
120.00	90.00	93.60	-3.60
120.00	91.00	93.60	-2.60
160.00	109.00	103.68	5.32
160.00	115.00	103.68	11.32

Correlation Coefficient = .940

CAPSULE 137 LOWER SHELL PLATE F-773-1 (LONGITUDINAL)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/29/2005 11:30 AM
Page 1
Coefficients of Curve 2

A = 60.1 B = 57.9 C = 108.33 T0 = 76.17 D = 0.00E+00

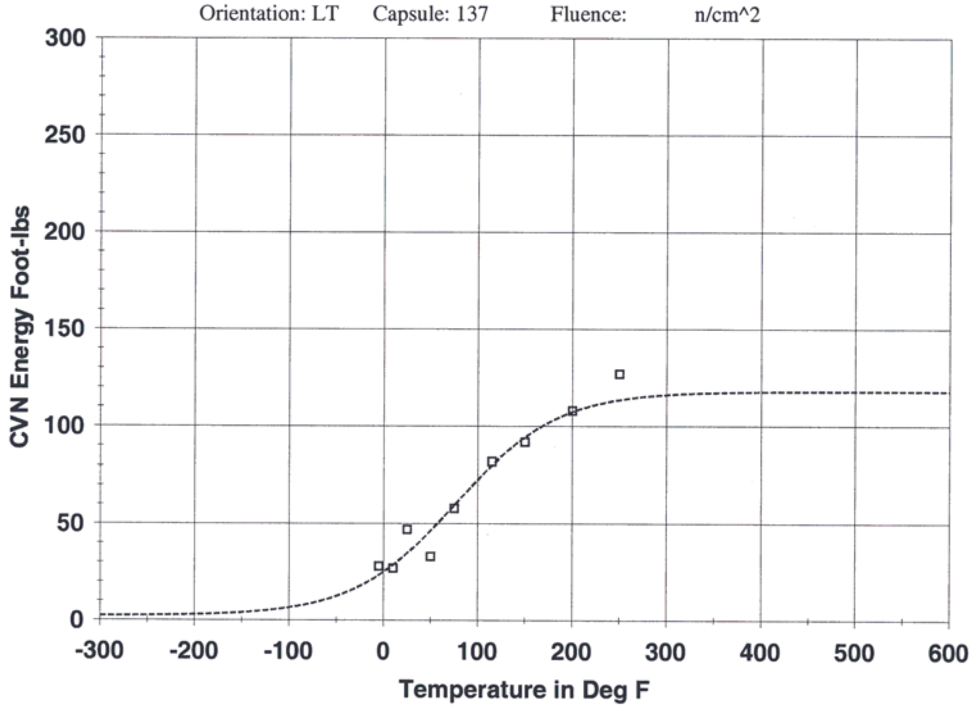
Equation is A + B * [Tanh((T-To)/(C+DT))]

Upper Shelf Energy=118.0(Fixed) Lower Shelf Energy=2.2(Fixed)

Temp@30 ft-lbs=13.8 Deg F Temp@50 ft-lbs=57.1 Deg F

Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1

Orientation: LT Capsule: 137 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
-5.00	28.00	23.35	4.65
10.00	27.00	28.56	-1.56
25.00	47.00	34.62	12.38
50.00	33.00	46.38	-13.38
75.00	58.00	59.47	-1.47
115.00	82.00	80.01	1.99
150.00	92.00	94.41	-2.41
200.00	108.00	107.31	.69
250.00	127.00	113.50	13.50

Correlation Coefficient = .976

CAPSULE 230 LOWER SHELL PLATE F-773-1 (LONGITUDINAL)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/29/2005 11:31 AM

Page 1

Coefficients of Curve 3

A = 71.1 B = 68.9 C = 116.99 T0 = 98.6 D = 0.00E+00

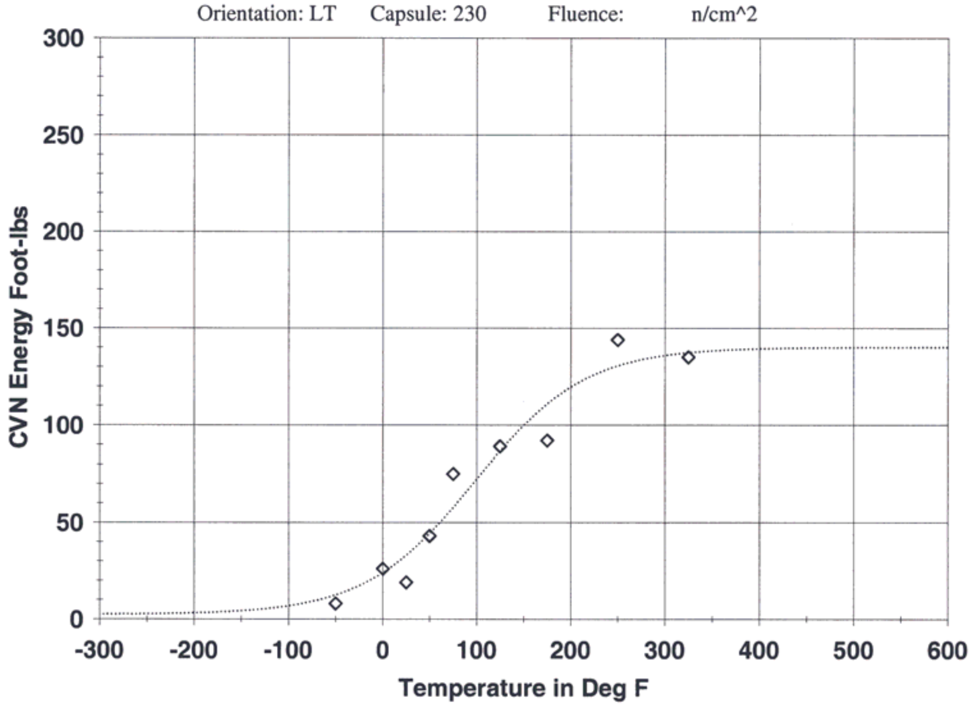
Equation is A + B * [Tanh((T-To)/(C+DT))]

Upper Shelf Energy=140.0(Fixed) Lower Shelf Energy=2.2(Fixed)

Temp@30 ft-lbs=18.2 Deg F Temp@50 ft-lbs=61.6 Deg F

Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1

Orientation: LT Capsule: 230 Fluence: n/cm^2



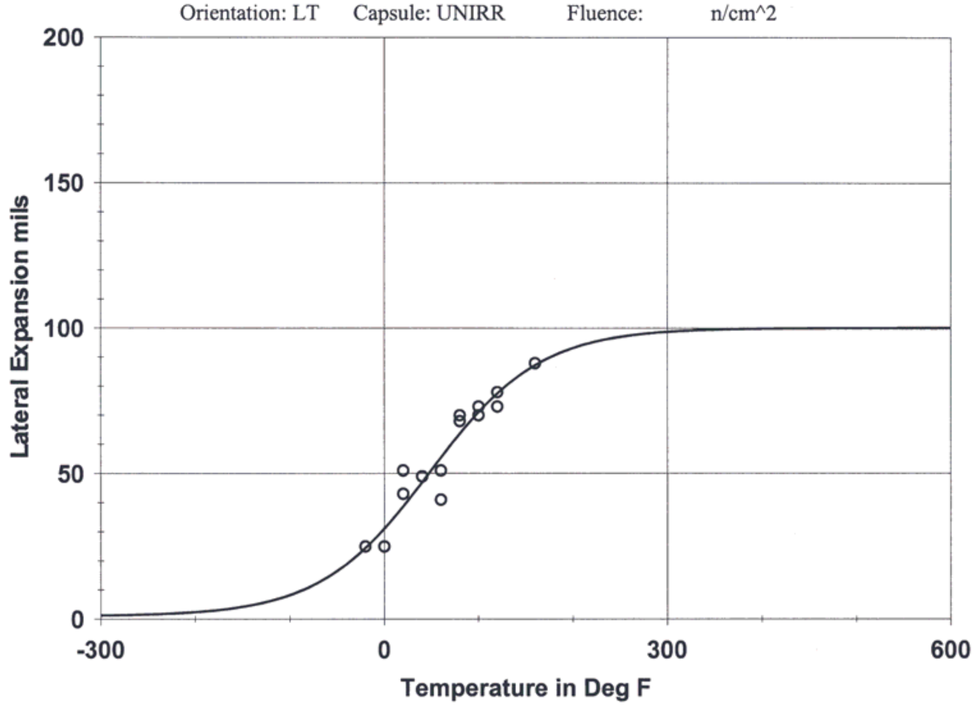
Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
-50.00	8.00	12.27	-4.27
.00	26.00	23.75	2.25
25.00	19.00	32.69	-13.69
50.00	43.00	44.02	-1.02
75.00	75.00	57.39	17.61
125.00	89.00	86.39	2.61
175.00	92.00	110.63	-18.63
250.00	144.00	130.37	13.63
325.00	135.00	137.19	-2.19

Correlation Coefficient = .973

UNIRRADIATED LOWER SHELL PLATE F-773-1 (LONGITUDINAL)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 12/12/2005 03:29 PM
Page 1
Coefficients of Curve 1
A = 50.56 B = 49.56 C = 116.98 T0 = 48.59 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Upper Shelf L.E.=100.1 Lower Shelf L.E.=1.0(Fixed)
Temp.@L.E. 35 mils=10.6 Deg F
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: LT Capsule: UNIRR Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
-20.00	25.00	24.43	.57
.00	25.00	31.08	-6.08
.00	25.00	31.08	-6.08
20.00	43.00	38.69	4.31
20.00	51.00	38.69	12.31
40.00	49.00	46.93	2.07
40.00	49.00	46.93	2.07
60.00	41.00	55.38	-14.38
60.00	51.00	55.38	-4.38

UNIRRADIATED LOWER SHELL PLATE F-773-1 (LONGITUDINAL)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: LT Capsule: UNIRR Fluence: n/cm^2

Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
80.00	70.00	63.56	6.44
80.00	68.00	63.56	4.44
100.00	73.00	71.04	1.96
100.00	70.00	71.04	-1.04
120.00	78.00	77.55	.45
120.00	73.00	77.55	-4.55
160.00	88.00	87.28	.72
160.00	88.00	87.28	.72

Correlation Coefficient = .959

CAPSULE 137 LOWER SHELL PLATE F-773-1 (LONGITUDINAL)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/29/2005 03:50 PM
Page 1
Coefficients of Curve 2

A = 49.34 B = 48.34 C = 139.78 T0 = 66.5 D = 0.00E+00

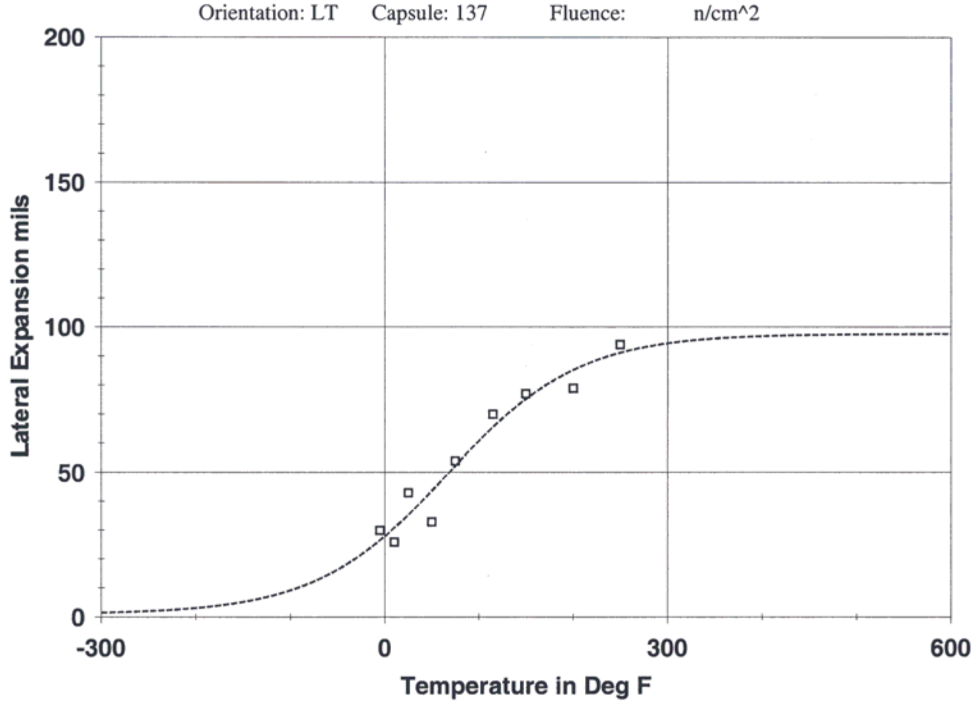
Equation is A + B * [Tanh((T-To)/(C+DT))]

Upper Shelf L.E.=97.7 Lower Shelf L.E.=1.0(Fixed)

Temp.@L.E. 35 mils=23.8 Deg F

Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1

Orientation: LT Capsule: 137 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
-5.00	30.00	26.56	3.44
10.00	26.00	30.80	-4.80
25.00	43.00	35.39	7.61
50.00	33.00	43.66	-10.66
75.00	54.00	52.27	1.73
115.00	70.00	65.47	4.53
150.00	77.00	75.21	1.79
200.00	79.00	85.21	-6.21
250.00	94.00	91.15	2.85

Correlation Coefficient = .971

CAPSULE 230 LOWER SHELL PLATE 773-1 (LONGITUDINAL)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/29/2005 03:50 PM
Page 1
Coefficients of Curve 3

A = 44.48 B = 43.48 C = 89.28 T0 = 52.49 D = 0.00E+00

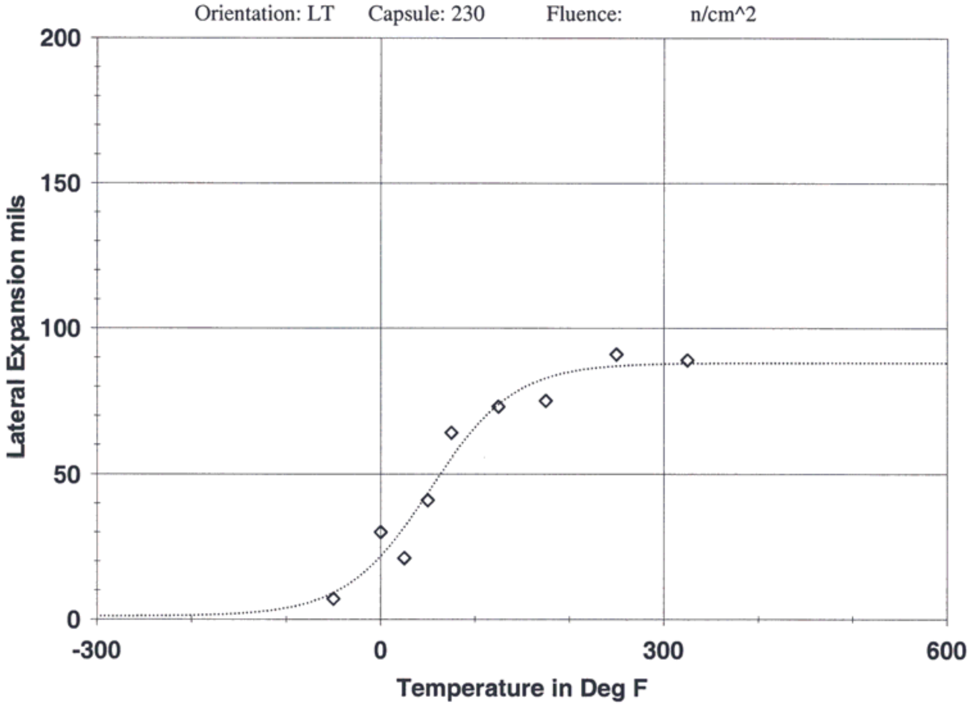
Equation is A + B * [Tanh((T-To)/(C+DT))]

Upper Shelf L.E.=88.0 Lower Shelf L.E.=1.0(Fixed)

Temp.@L.E. 35 mils=32.8 Deg F

Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1

Orientation: LT Capsule: 230 Fluence: n/cm^2



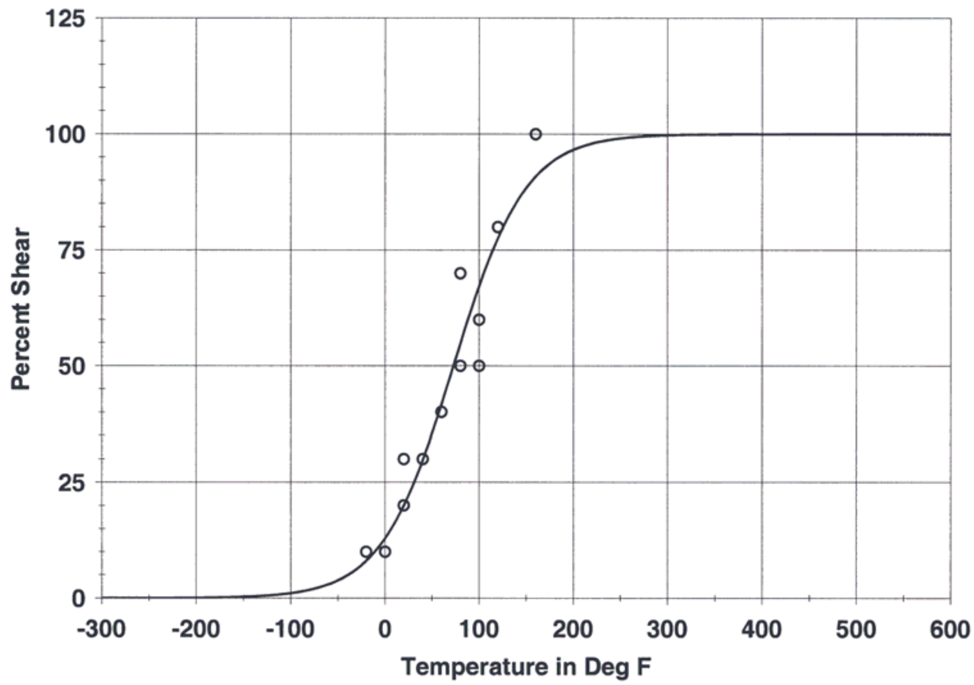
Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
-50.00	7.00	8.95	-1.95
.00	30.00	21.50	8.50
25.00	21.00	31.50	-10.50
50.00	41.00	43.26	-2.26
75.00	64.00	55.21	8.79
125.00	73.00	73.64	-.64
175.00	75.00	82.70	-7.70
250.00	91.00	86.93	4.07
325.00	89.00	87.76	1.24

Correlation Coefficient = .977

UNIRRADIATED LOWER SHELL PLATE F-773-1 (LONGITUDINAL)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/29/2005 03:44 PM
Page 1
Coefficients of Curve 1
A = 50. B = 50. C = 76.06 T0 = 72.76 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Temperature at 50% Shear = 72.8
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: LT Capsule: UNIRR Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
-20.00	10.00	8.02	1.98
.00	10.00	12.86	-2.86
.00	10.00	12.86	-2.86
20.00	20.00	19.98	.02
20.00	30.00	19.98	10.02
40.00	30.00	29.71	.29
40.00	30.00	29.71	.29
60.00	40.00	41.69	-1.69
60.00	40.00	41.69	-1.69

UNIRRADIATED LOWER SHELL PLATE F-773-1 (LONGITUDINAL)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: LT Capsule: UNIRR Fluence: n/cm^2

Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
80.00	70.00	54.75	15.25
80.00	50.00	54.75	-4.75
100.00	60.00	67.18	-7.18
100.00	50.00	67.18	-17.18
120.00	80.00	77.60	2.40
120.00	80.00	77.60	2.40
160.00	100.00	90.84	9.16
160.00	100.00	90.84	9.16

Correlation Coefficient = .969

CAPSULE 137 LOWER SHELL PLATE F-773-1 (LONGITUDINAL)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/29/2005 03:44 PM
Page 1
Coefficients of Curve 2

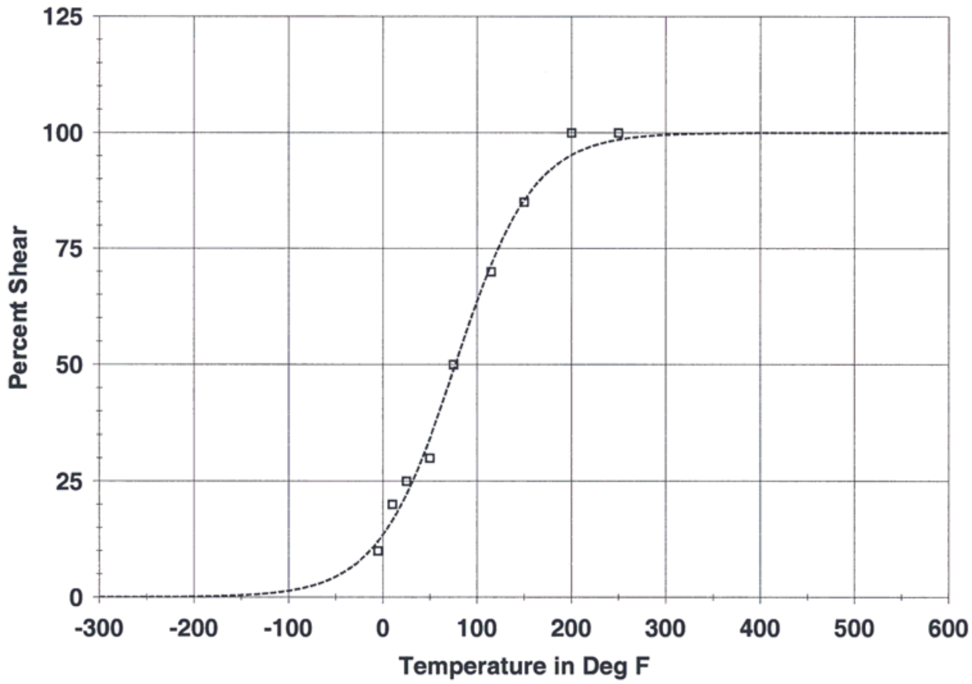
A = 50. B = 50. C = 82.55 T0 = 76.99 D = 0.00E+00

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

Temperature at 50% Shear = 77.0

Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1

Orientation: LT Capsule: 137 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
-5.00	10.00	12.06	-2.06
10.00	20.00	16.48	3.52
25.00	25.00	22.10	2.90
50.00	30.00	34.21	-4.21
75.00	50.00	48.79	1.21
115.00	70.00	71.52	-1.52
150.00	85.00	85.43	-.43
200.00	100.00	95.17	4.83
250.00	100.00	98.51	1.49

Correlation Coefficient = .997

CAPSULE 230 LOWER SHELL PLATE F-773-1 (LONGITUDINAL)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/29/2005 03:44 PM

Page 1

Coefficients of Curve 3

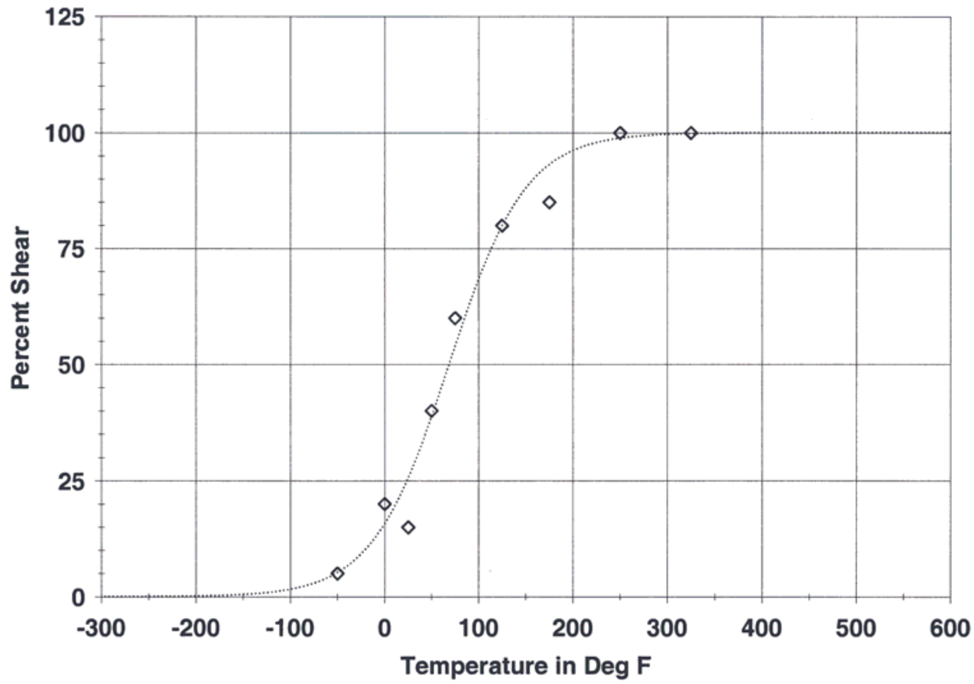
A = 50. B = 50. C = 81.6 T0 = 68.89 D = 0.00E+00

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

Temperature at 50% Shear = 68.9

Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1

Orientation: LT Capsule: 230 Fluence: n/cm^2



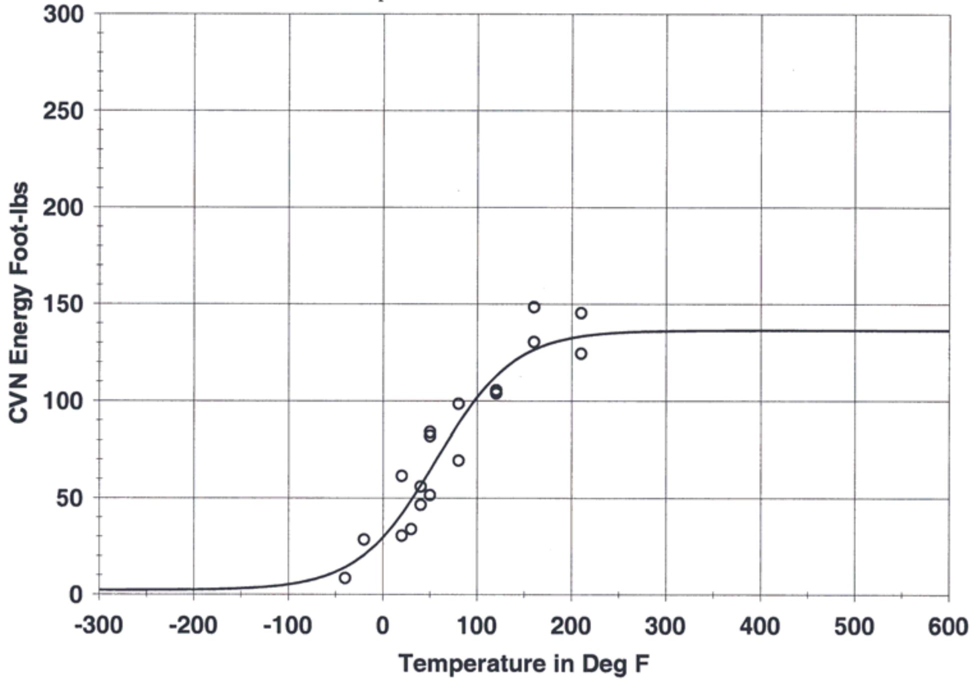
Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
-50.00	5.00	5.15	-.15
.00	20.00	15.60	4.40
25.00	15.00	25.43	-10.43
50.00	40.00	38.63	1.37
75.00	60.00	53.74	6.26
125.00	80.00	79.82	.18
175.00	85.00	93.09	-8.09
250.00	100.00	98.83	1.17
325.00	100.00	99.81	.19

Correlation Coefficient = .990

UNIRRADIATED LOWER SHELL PLATE F-773-1 (TRANSVERSE)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/29/2005 04:06 PM
Page 1
Coefficients of Curve 1
A = 69.35 B = 67.15 C = 82.58 T0 = 56.1 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Upper Shelf Energy=136.5(Fixed) Lower Shelf Energy=2.2(Fixed)
Temp@30 ft-lbs=.7 Deg F Temp@50 ft-lbs=31.7 Deg F
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: TL Capsule: UNIRR Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
-40.00	8.50	14.14	-5.64
-20.00	28.50	20.56	7.94
20.00	30.50	41.73	-11.23
20.00	61.50	41.73	19.77
30.00	34.00	48.81	-14.81
40.00	46.50	56.42	-9.92
40.00	56.00	56.42	-.42
50.00	51.50	64.40	-12.90
50.00	82.00	64.40	17.60

UNIRRADIATED LOWER SHELL PLATE F-773-1 (TRANSVERSE)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: TL Capsule: UNIRR Fluence: n/cm^2

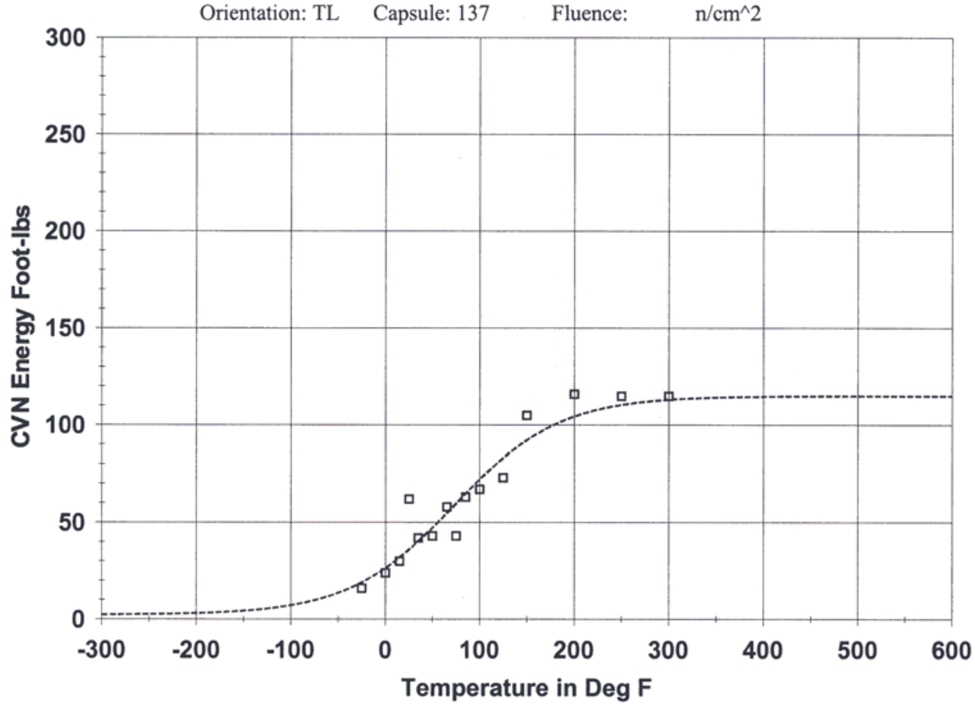
Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
50.00	84.00	64.40	19.60
80.00	69.50	88.26	-18.76
80.00	98.50	88.26	10.24
120.00	104.00	112.94	-8.94
120.00	105.50	112.94	-7.44
160.00	130.50	126.46	4.04
160.00	148.50	126.46	22.04
210.00	124.50	133.34	-8.84
210.00	145.50	133.34	12.16

Correlation Coefficient = .948

CAPSULE 137 LOWER SHELL PLATE F-773-1 (TRANSVERSE)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 12/12/2005 03:32 PM
Page 1
Coefficients of Curve 2
A = 58.6 B = 56.4 C = 112.28 T0 = 72.88 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Upper Shelf Energy=115.0(Fixed) Lower Shelf Energy=2.2(Fixed)
Temp@30 ft-lbs=10.2 Deg F Temp@50 ft-lbs=55.7 Deg F
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: TL Capsule: 137 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
-25.00	16.00	18.99	-2.99
.00	24.00	26.39	-2.39
15.00	30.00	31.86	-1.86
25.00	62.00	35.91	26.09
35.00	42.00	40.26	1.74
50.00	43.00	47.27	-4.27
65.00	58.00	54.65	3.35
75.00	43.00	59.67	-16.67
85.00	63.00	64.67	-1.67

CAPSULE 137 LOWER SHELL PLATE F-773-1 (TRANSVERSE)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: TL Capsule: 137 Fluence: n/cm^2

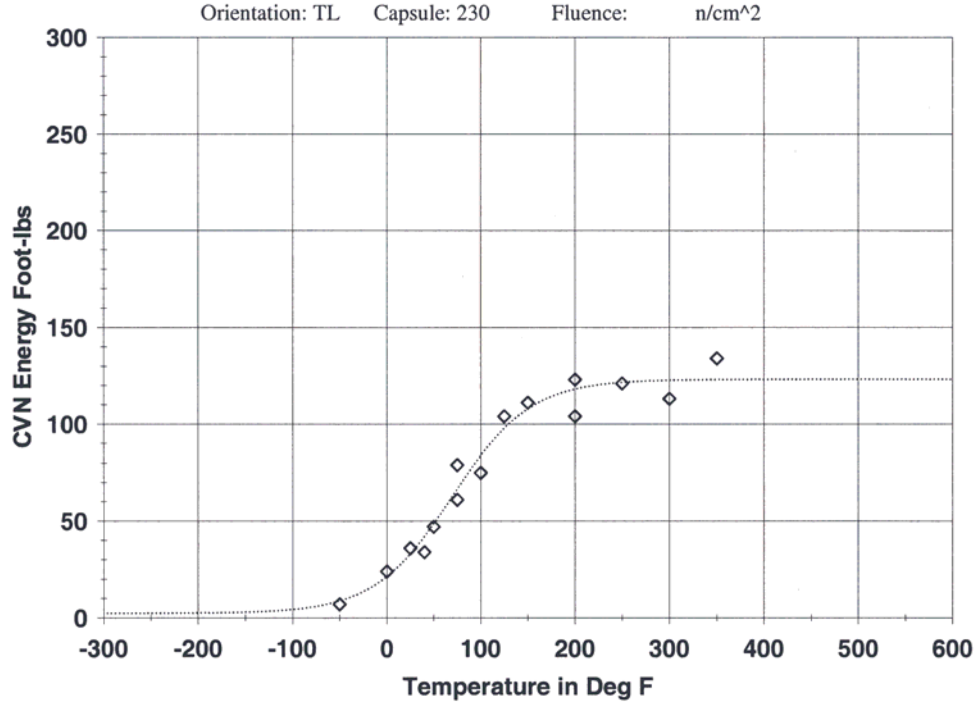
Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
100.00	67.00	71.97	-4.97
125.00	73.00	83.05	-10.05
150.00	105.00	92.21	12.79
200.00	116.00	104.38	11.62
250.00	115.00	110.39	4.61
300.00	115.00	113.06	1.94

Correlation Coefficient = .955

CAPSULE 230 LOWER SHELL PLATE F-773-1 (TRANSVERSE)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/29/2005 04:02 PM
Page 1
Coefficients of Curve 3
A = 62.6 B = 60.4 C = 83.02 T0 = 70.03 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Upper Shelf Energy=123.0(Fixed) Lower Shelf Energy=2.2(Fixed)
Temp@30 ft-lbs=20.0 Deg F Temp@50 ft-lbs=52.5 Deg F
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: TL Capsule: 230 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
-50.00	7.00	8.55	-1.55
.00	24.00	21.06	2.94
25.00	36.00	32.71	3.29
40.00	34.00	41.66	-7.66
50.00	47.00	48.30	-1.30
75.00	79.00	66.21	12.79
75.00	61.00	66.21	-5.21
100.00	75.00	83.50	-8.50
125.00	104.00	97.62	6.38

CAPSULE 230 LOWER SHELL PLATE F-773-1 (TRANSVERSE)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: TL Capsule: 230 Fluence: n/cm^2

Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
150.00	111.00	107.64	3.36
200.00	104.00	117.95	-13.95
200.00	123.00	117.95	5.05
250.00	121.00	121.44	-.44
300.00	113.00	122.53	-9.53
350.00	134.00	122.86	11.14

Correlation Coefficient = .982

UNIRRADIATED LOWER SHELL PLATE F-773-1 (TRANSVERSE)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/29/2005 07:26 PM
Page 1
Coefficients of Curve 1

A = 43.26 B = 42.26 C = 79.9 T0 = 20.5 D = 0.00E+00

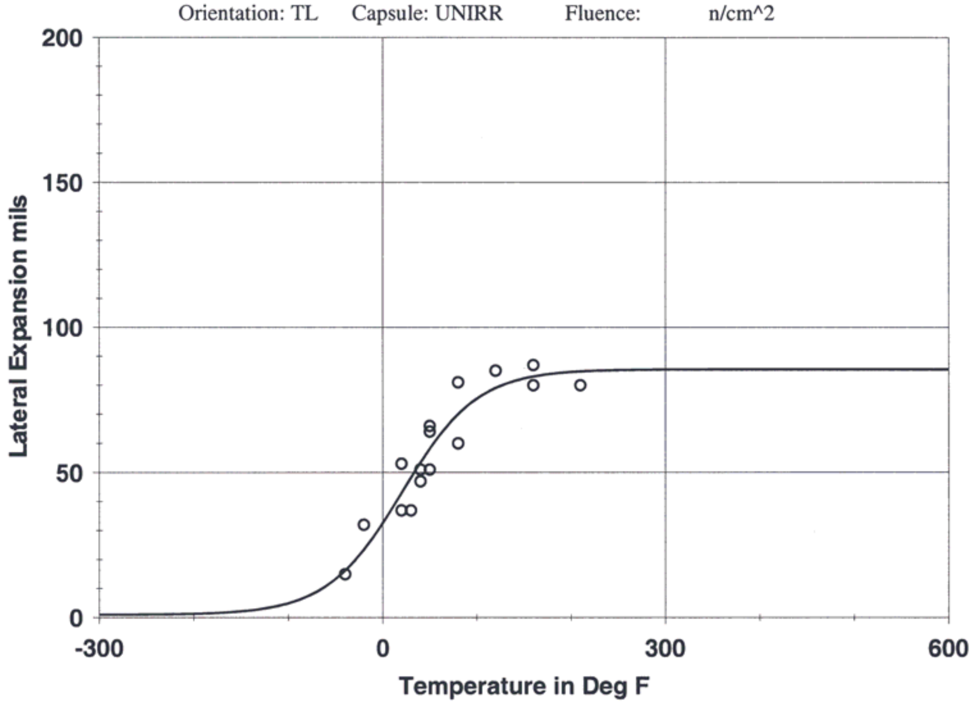
Equation is A + B * [Tanh((T-To)/(C+DT))]

Upper Shelf L.E.=85.5 Lower Shelf L.E.=1.0(Fixed)

Temp.@L.E. 35 mils=4.7 Deg F

Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1

Orientation: TL Capsule: UNIRR Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
-40.00	15.00	16.24	-1.24
-20.00	32.00	23.50	8.50
20.00	37.00	42.99	-5.99
20.00	53.00	42.99	10.01
30.00	37.00	48.26	-11.26
40.00	47.00	53.37	-6.37
40.00	51.00	53.37	-2.37
50.00	51.00	58.19	-7.19
50.00	66.00	58.19	7.81

UNIRRADIATED LOWER SHELL PLATE F-773-1 (TRANSVERSE)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: TL Capsule: UNIRR Fluence: n/cm^2

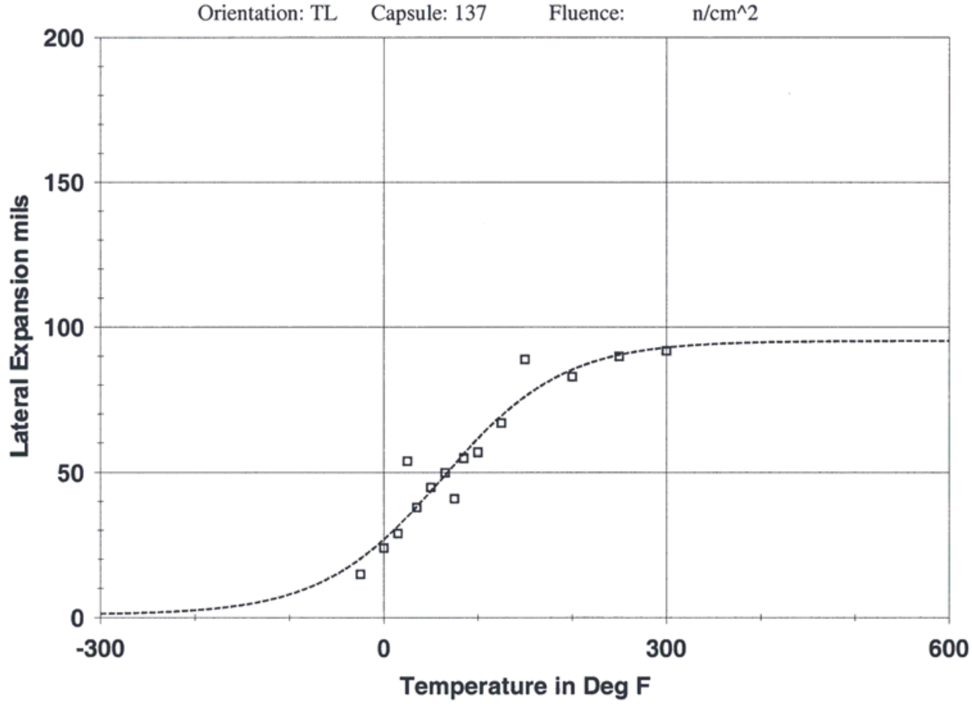
Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
50.00	64.00	58.19	5.81
80.00	60.00	69.96	-9.96
80.00	81.00	69.96	11.04
120.00	85.00	79.05	5.95
120.00	85.00	79.05	5.95
160.00	80.00	83.02	-3.02
160.00	87.00	83.02	3.98
210.00	80.00	84.78	-4.78
210.00	80.00	84.78	-4.78

Correlation Coefficient = .942

CAPSULE 137 LOWER SHELL PLATE F-773-1 (TRANSVERSE)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/29/2005 07:26 PM
Page 1
Coefficients of Curve 2
A = 48.16 B = 47.16 C = 128.67 T0 = 62.44 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Upper Shelf L.E.=95.3 Lower Shelf L.E.=1.0(Fixed)
Temp.@L.E. 35 mils=25.6 Deg F
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: TL Capsule: 137 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
-25.00	15.00	20.28	-5.28
.00	24.00	26.92	-2.92
15.00	29.00	31.52	-2.52
25.00	54.00	34.81	19.19
35.00	38.00	38.25	-.25
50.00	45.00	43.61	1.39
65.00	50.00	49.10	.90
75.00	41.00	52.75	-11.75
85.00	55.00	56.34	-1.34

CAPSULE 137 LOWER SHELL PLATE F-773-1 (TRANSVERSE)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: TL Capsule: 137 Fluence: n/cm^2

Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
100.00	57.00	61.55	-4.55
125.00	67.00	69.43	-2.43
150.00	89.00	76.07	12.93
200.00	83.00	85.37	-2.37
250.00	90.00	90.47	-.47
300.00	92.00	93.02	-1.02

Correlation Coefficient = .955

CAPSULE 230 LOWER SHELL PLATE F-773-1 (TRANSVERSE)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/29/2005 07:26 PM
Page 1
Coefficients of Curve 3

A = 44.65 B = 43.65 C = 97.55 T0 = 55.7 D = 0.00E+00

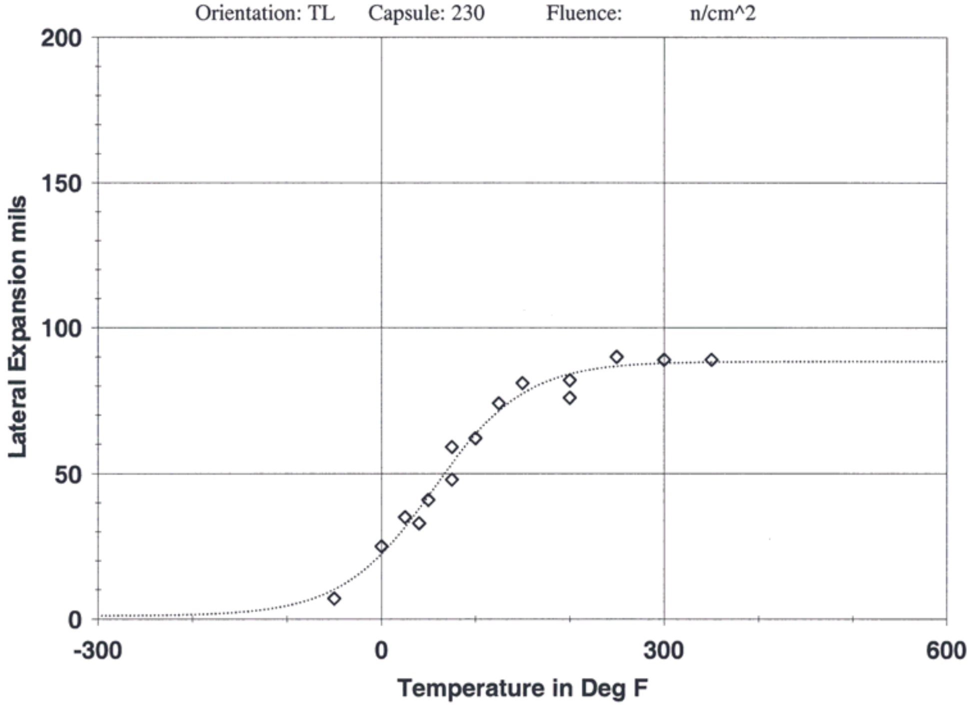
Equation is A + B * [Tanh((T-To)/(C+DT))]

Upper Shelf L.E.=88.3 Lower Shelf L.E.=1.0(Fixed)

Temp.@L.E. 35 mils=33.8 Deg F

Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1

Orientation: TL Capsule: 230 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
-50.00	7.00	9.97	-2.97
.00	25.00	22.13	2.87
25.00	35.00	31.35	3.65
40.00	33.00	37.69	-4.69
50.00	41.00	42.11	-1.11
75.00	59.00	53.18	5.82
75.00	48.00	53.18	-5.18
100.00	62.00	63.22	-1.22
125.00	74.00	71.32	2.68

CAPSULE 230 LOWER SHELL PLATE F-773-1 (TRANSVERSE)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: TL Capsule: 230 Fluence: n/cm^2

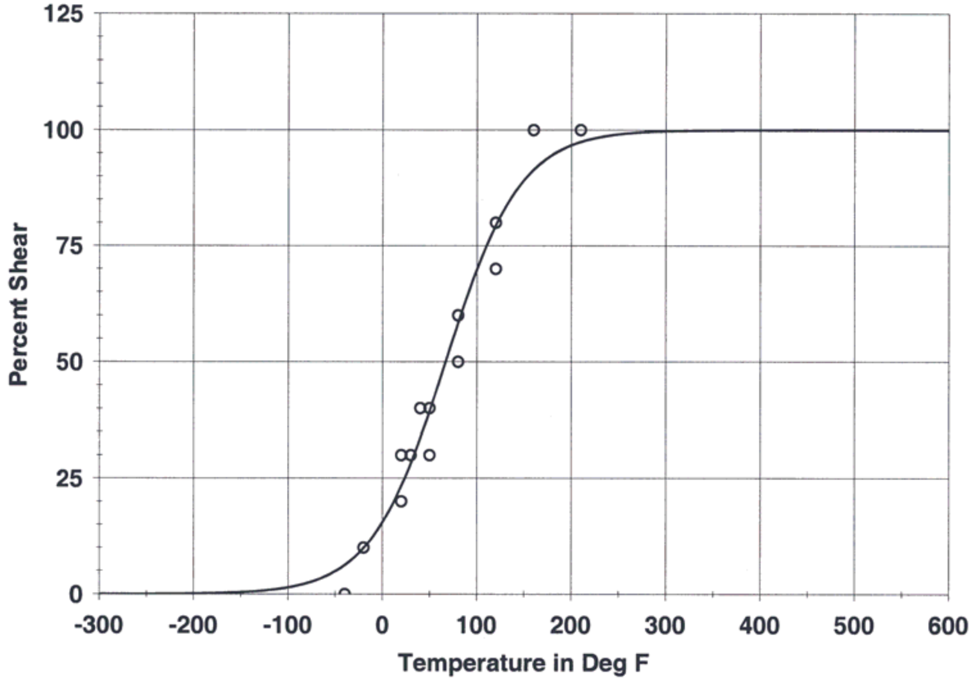
Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
150.00	81.00	77.27	3.73
200.00	76.00	84.00	-8.00
200.00	82.00	84.00	-2.00
250.00	90.00	86.71	3.29
300.00	89.00	87.72	1.28
350.00	89.00	88.09	.91

Correlation Coefficient = .989

UNIRRADIATED LOWER SHELL PLATE F-773-1 (TRANSVERSE)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/29/2005 07:16 PM
Page 1
Coefficients of Curve 1
A = 50. B = 50. C = 78.79 T0 = 66.92 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Temperature at 50% Shear = 67.0
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: TL Capsule: UNIRR Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
-40.00	.00	6.22	-6.22
-20.00	10.00	9.92	.08
20.00	20.00	23.31	-3.31
20.00	30.00	23.31	6.69
30.00	30.00	28.15	1.85
40.00	40.00	33.55	6.45
40.00	40.00	33.55	6.45
50.00	30.00	39.43	-9.43
50.00	40.00	39.43	.57

UNIRRADIATED LOWER SHELL PLATE F-773-1 (TRANSVERSE)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: TL Capsule: UNIRR Fluence: n/cm^2

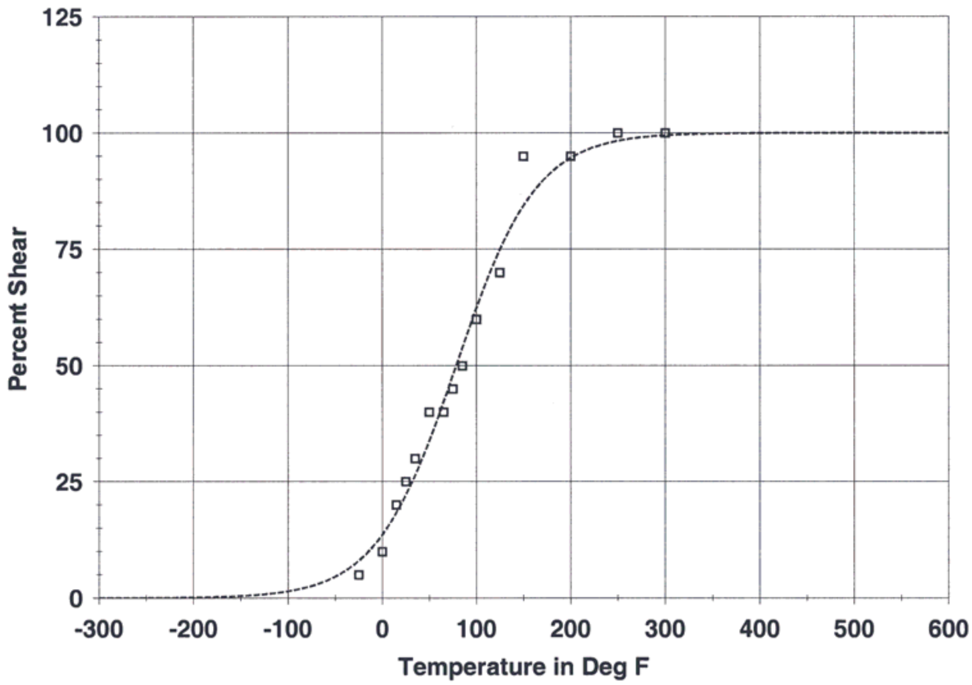
Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
50.00	40.00	39.43	.57
80.00	50.00	58.23	-8.23
80.00	60.00	58.23	1.77
120.00	80.00	79.37	.63
120.00	70.00	79.37	-9.37
160.00	100.00	91.39	8.61
160.00	100.00	91.39	8.61
210.00	100.00	97.42	2.58
210.00	100.00	97.42	2.58

Correlation Coefficient = .984

CAPSULE 137 LOWER SHELL PLATE F-773-1 (TRANSVERSE)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/29/2005 07:16 PM
Page 1
Coefficients of Curve 2
A = 50. B = 50. C = 84.89 T0 = 78.54 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Temperature at 50% Shear = 78.6
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: TL Capsule: 137 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
-25.00	5.00	8.02	-3.02
.00	10.00	13.58	-3.58
15.00	20.00	18.29	1.71
25.00	25.00	22.07	2.93
35.00	30.00	26.39	3.61
50.00	40.00	33.80	6.20
65.00	40.00	42.09	-2.09
75.00	45.00	47.92	-2.92
85.00	50.00	53.80	-3.80

CAPSULE 137 LOWER SHELL PLATE F-773-1 (TRANSVERSE)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: TL Capsule: 137 Fluence: n/cm^2

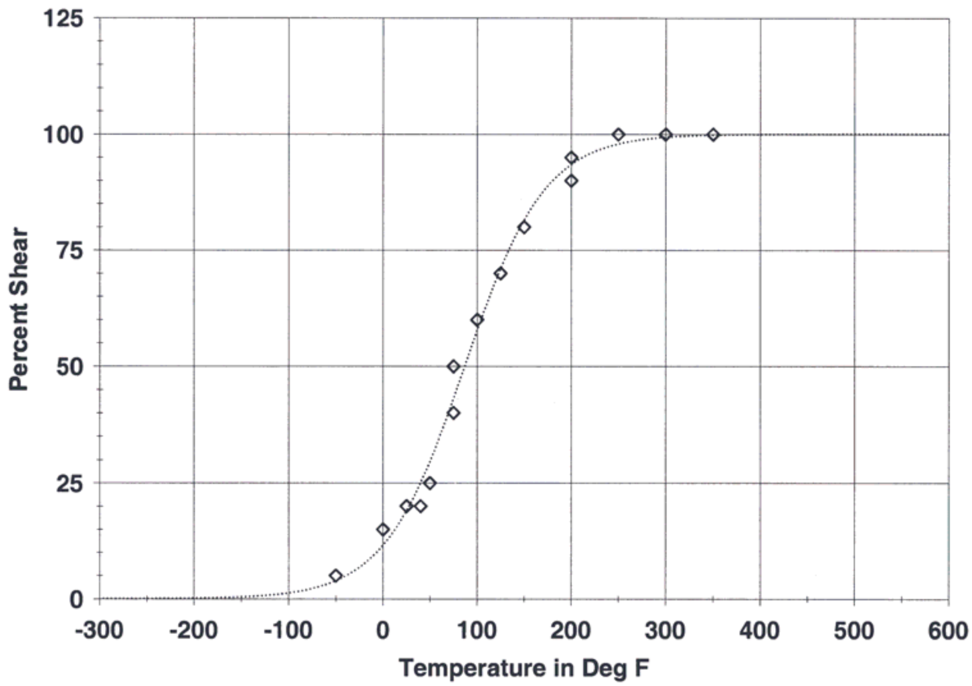
Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
100.00	60.00	62.38	-2.38
125.00	70.00	74.93	-4.93
150.00	95.00	84.34	10.66
200.00	95.00	94.59	.41
250.00	100.00	98.27	1.73
300.00	100.00	99.46	.54

Correlation Coefficient = .992

CAPSULE 230 LOWER SHELL PLATE F-773-1 (TRANSVERSE)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/29/2005 07:16 PM
Page 1
Coefficients of Curve 3
A = 50. B = 50. C = 85.19 T0 = 87.23 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Temperature at 50% Shear = 87.3
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: TL Capsule: 230 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
-50.00	5.00	3.83	1.17
.00	15.00	11.43	3.57
25.00	20.00	18.83	1.17
40.00	20.00	24.81	-4.81
50.00	25.00	29.44	-4.44
75.00	40.00	42.87	-2.87
75.00	50.00	42.87	7.13
100.00	60.00	57.44	2.56
125.00	70.00	70.82	-.82

CAPSULE 230 LOWER SHELL PLATE F-773-1 (TRANSVERSE)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: TL Capsule: 230 Fluence: n/cm^2

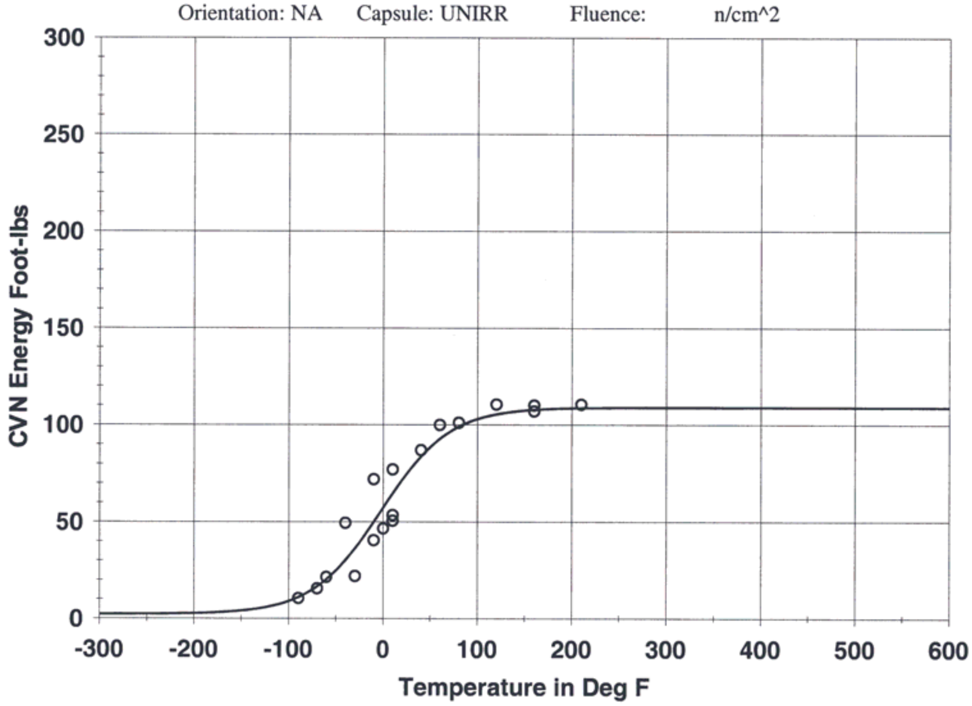
Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
150.00	80.00	81.36	-1.36
200.00	95.00	93.39	1.61
200.00	90.00	93.39	-3.39
250.00	100.00	97.86	2.14
300.00	100.00	99.33	.67
350.00	100.00	99.79	.21

Correlation Coefficient = .996

UNIRRADIATED (WELD)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 03:05 PM
Page 1
Coefficients of Curve 1
A = 55.6 B = 53.4 C = 72.63 T0 = -2.26 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Upper Shelf Energy=109.0(Fixed) Lower Shelf Energy=2.2(Fixed)
Temp@30 ft-lbs=-40.1 Deg F Temp@50 ft-lbs=-9.9 Deg F
Plant: PALO VERDE 2 Material: SAW Heat: 3P7317
Orientation: NA Capsule: UNIRR Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
-90.00	10.50	10.95	-.45
-70.00	15.50	16.52	-1.02
-60.00	21.50	20.29	1.21
-40.00	49.50	30.10	19.40
-30.00	22.00	36.14	-14.14
-10.00	40.50	49.93	-9.43
-10.00	72.00	49.93	22.07
.00	46.50	57.26	-10.76
10.00	50.50	64.53	-14.03

UNIRRADIATED (WELD)

Page 2
Plant: PALO VERDE 2 Material: SAW Heat: 3P7317
Orientation: NA Capsule: UNIRR Fluence: n/cm^2

Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
10.00	53.50	64.53	-11.03
10.00	77.00	64.53	12.47
40.00	87.00	83.58	3.42
60.00	100.00	92.70	7.30
80.00	101.00	98.96	2.04
120.00	110.50	105.44	5.06
160.00	107.00	107.79	-.79
160.00	110.00	107.79	2.21
210.00	110.50	108.69	1.81

Correlation Coefficient = .957

CAPSULE 137 (WELD)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 03:05 PM
Page 1
Coefficients of Curve 2

A = 55.1 B = 52.9 C = 101.78 T0 = 12.23 D = 0.00E+00

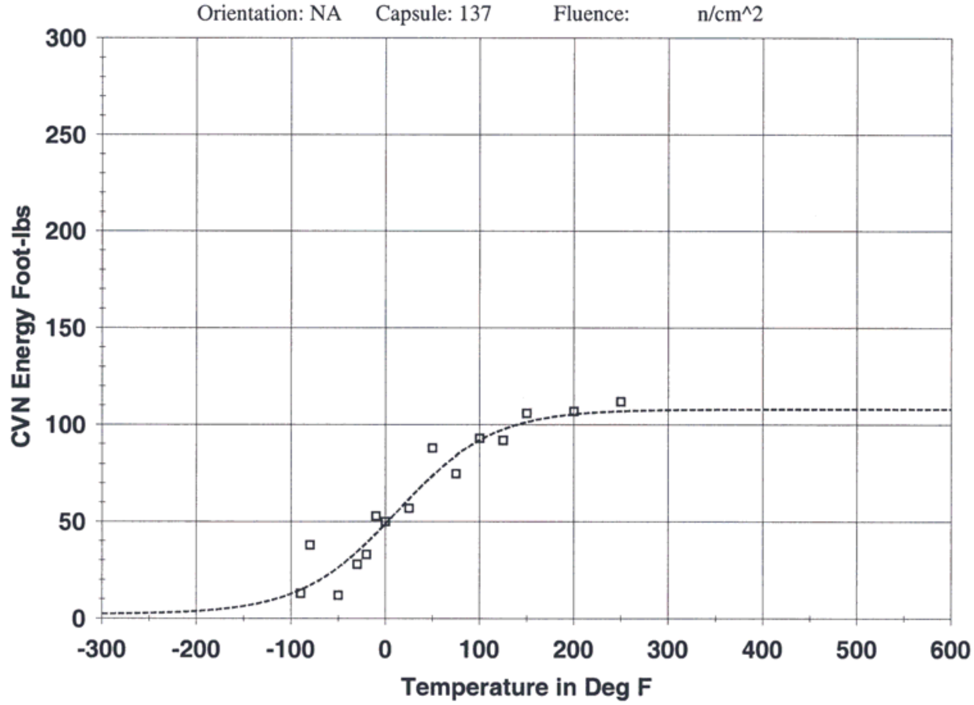
Equation is A + B * [Tanh((T-To)/(C+DT))]

Upper Shelf Energy=108.0(Fixed) Lower Shelf Energy=2.2(Fixed)

Temp@30 ft-lbs=-40.2 Deg F Temp@50 ft-lbs=2.4 Deg F

Plant: PALO VERDE 2 Material: SAW Heat: 3P7317

Orientation: NA Capsule: 137 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
-90.00	13.00	14.72	-1.72
-80.00	38.00	17.05	20.95
-50.00	12.00	26.27	-14.27
-30.00	28.00	34.33	-6.33
-20.00	33.00	38.89	-5.89
-10.00	53.00	43.73	9.27
.00	50.00	48.78	1.22
25.00	57.00	61.70	-4.70
50.00	88.00	73.88	14.12

CAPSULE 137 (WELD)

Page 2
Plant: PALO VERDE 2 Material: SAW Heat: 3P7317
Orientation: NA Capsule: 137 Fluence: n/cm^2

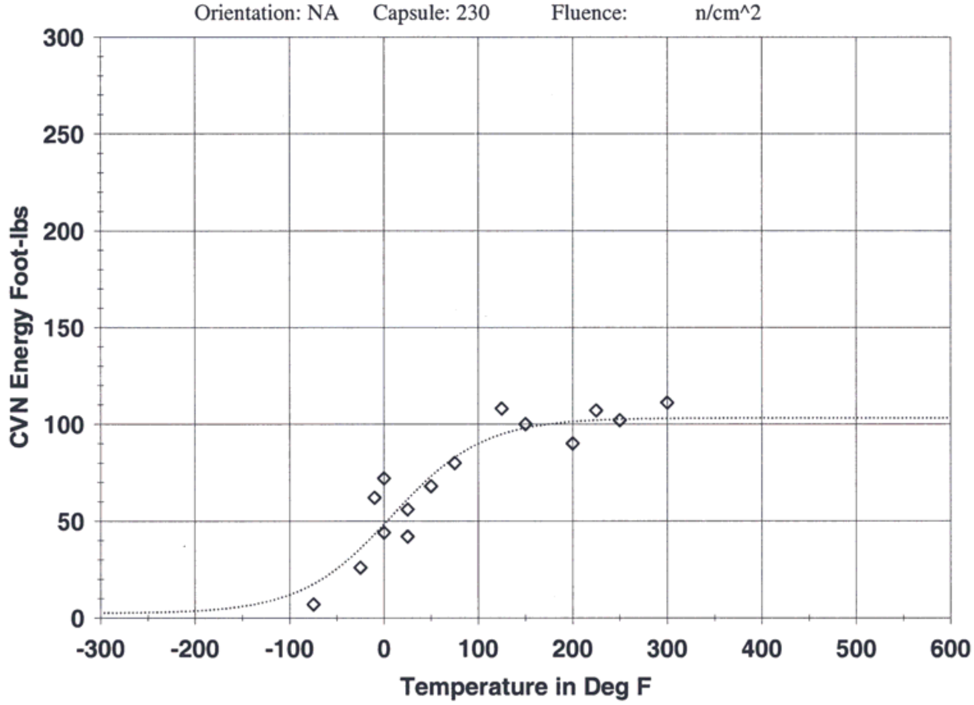
Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
75.00	75.00	84.13	-9.13
100.00	93.00	92.00	1.00
125.00	92.00	97.60	-5.60
150.00	106.00	101.38	4.62
200.00	107.00	105.42	1.58
250.00	112.00	107.02	4.98

Correlation Coefficient = .964

CAPSULE 230 (WELD)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 03:05 PM
Page 1
Coefficients of Curve 3
A = 52.6 B = 50.4 C = 96.62 T0 = 9. D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Upper Shelf Energy=103.0(Fixed) Lower Shelf Energy=2.2(Fixed)
Temp@30 ft-lbs=-37.6 Deg F Temp@50 ft-lbs=4.1 Deg F
Plant: PALO VERDE 2 Material: SAW Heat: 3P7317
Orientation: NA Capsule: 230 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
-75.00	7.00	17.27	-10.27
-25.00	26.00	35.56	-9.56
-10.00	62.00	42.81	19.19
.00	72.00	47.92	24.08
.00	44.00	47.92	-3.92
25.00	42.00	60.87	-18.87
25.00	56.00	60.87	-4.87
50.00	68.00	72.79	-4.79
75.00	80.00	82.51	-2.51

CAPSULE 230 (WELD)

Page 2
Plant: PALO VERDE 2 Material: SAW Heat: 3P7317
Orientation: NA Capsule: 230 Fluence: n/cm^2

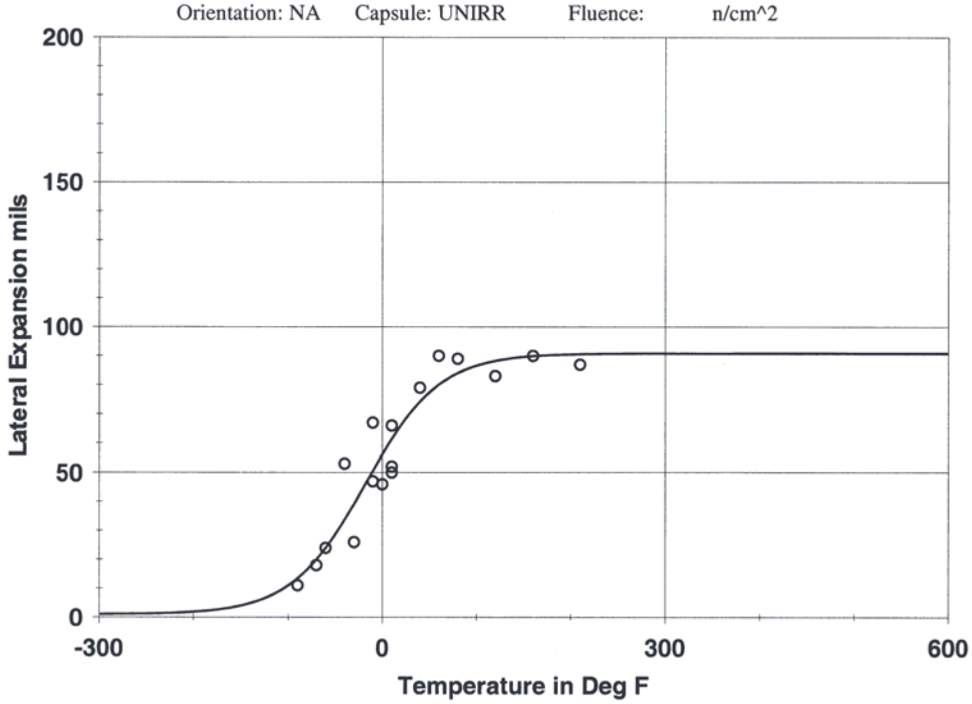
Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
125.00	108.00	94.62	13.38
150.00	100.00	97.83	2.17
200.00	90.00	101.10	-11.10
225.00	107.00	101.86	5.14
250.00	102.00	102.32	-.32
300.00	111.00	102.76	8.24

Correlation Coefficient = .931

UNIRRADIATED (WELD)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 03:17 PM
Page 1
Coefficients of Curve 1
A = 45.93 B = 44.93 C = 78.66 T0 = -18. D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Upper Shelf L.E.=90.9 Lower Shelf L.E.=1.0(Fixed)
Temp.@L.E. 35 mils=-37.5 Deg F
Plant: PALO VERDE 2 Material: SAW Heat: 3P7317
Orientation: NA Capsule: UNIRR Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
-90.00	11.00	13.42	-2.42
-70.00	18.00	19.91	-1.91
-60.00	24.00	23.99	.01
-40.00	53.00	33.68	19.32
-30.00	26.00	39.13	-13.13
-10.00	47.00	50.49	-3.49
-10.00	67.00	50.49	16.51
.00	46.00	56.04	-10.04
10.00	50.00	61.28	-11.28

UNIRRADIATED (WELD)

Page 2
Plant: PALO VERDE 2 Material: SAW Heat: 3P7317
Orientation: NA Capsule: UNIRR Fluence: n/cm^2

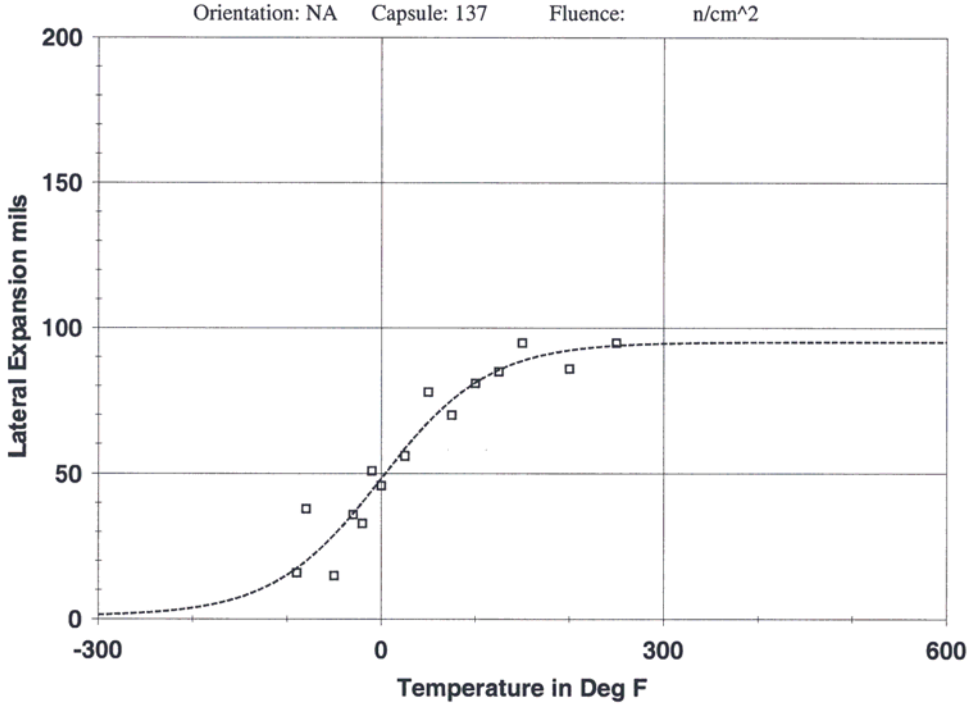
Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
10.00	52.00	61.28	-9.28
10.00	66.00	61.28	4.72
40.00	79.00	74.13	4.87
60.00	90.00	79.99	10.01
80.00	89.00	84.00	5.00
120.00	83.00	88.25	-5.25
160.00	90.00	89.90	.10
160.00	90.00	89.90	.10
210.00	87.00	90.59	-3.59

Correlation Coefficient = .943

CAPSULE 137 (WELD)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 03:17 PM
Page 1
Coefficients of Curve 2
A = 48.1 B = 47.1 C = 115.27 T0 = -.42 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Upper Shelf L.E.=95.2 Lower Shelf L.E.=1.0(Fixed)
Temp.@L.E. 35 mils=-33.3 Deg F
Plant: PALO VERDE 2 Material: SAW Heat: 3P7317
Orientation: NA Capsule: 137 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
-90.00	16.00	17.43	-1.43
-80.00	38.00	19.92	18.08
-50.00	15.00	29.00	-14.00
-30.00	36.00	36.27	-.27
-20.00	33.00	40.18	-7.18
-10.00	51.00	44.20	6.80
.00	46.00	48.27	-2.27
25.00	56.00	58.32	-2.32
50.00	78.00	67.48	10.52

CAPSULE 137 (WELD)

Page 2
Plant: PALO VERDE 2 Material: SAW Heat: 3P7317
Orientation: NA Capsule: 137 Fluence: n/cm^2

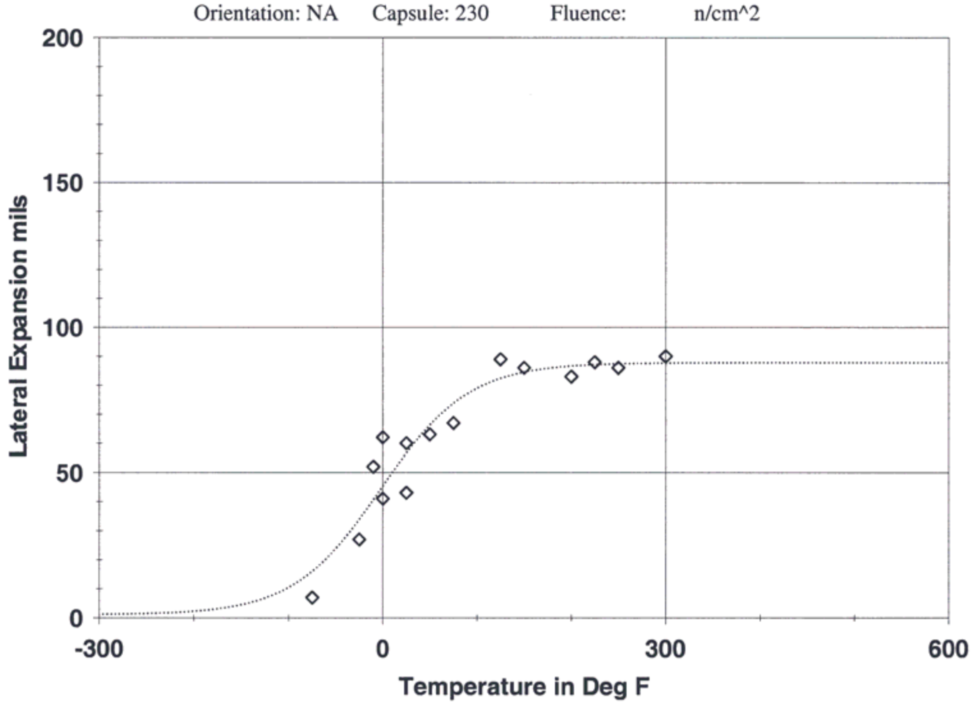
Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
75.00	70.00	75.16	-5.16
100.00	81.00	81.16	-.16
125.00	85.00	85.60	-.60
150.00	95.00	88.75	6.25
200.00	86.00	92.38	-6.38
250.00	95.00	94.00	1.00

Correlation Coefficient = .959

CAPSULE 230 (WELD)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 03:17 PM
Page 1
Coefficients of Curve 3
A = 44.36 B = 43.36 C = 93.2 T0 = -1.42 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Upper Shelf L.E.=87.7 Lower Shelf L.E.=1.0(Fixed)
Temp.@L.E. 35 mils=-21.8 Deg F
Plant: PALO VERDE 2 Material: SAW Heat: 3P7317
Orientation: NA Capsule: 230 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
-75.00	7.00	15.82	-8.82
-25.00	27.00	33.62	-6.62
-10.00	52.00	40.38	11.62
.00	62.00	45.02	16.98
.00	41.00	45.02	-4.02
25.00	43.00	56.33	-13.33
25.00	60.00	56.33	3.67
50.00	63.00	66.12	-3.12
75.00	67.00	73.63	-6.63

CAPSULE 230 (WELD)

Page 2
Plant: PALO VERDE 2 Material: SAW Heat: 3P7317
Orientation: NA Capsule: 230 Fluence: n/cm^2

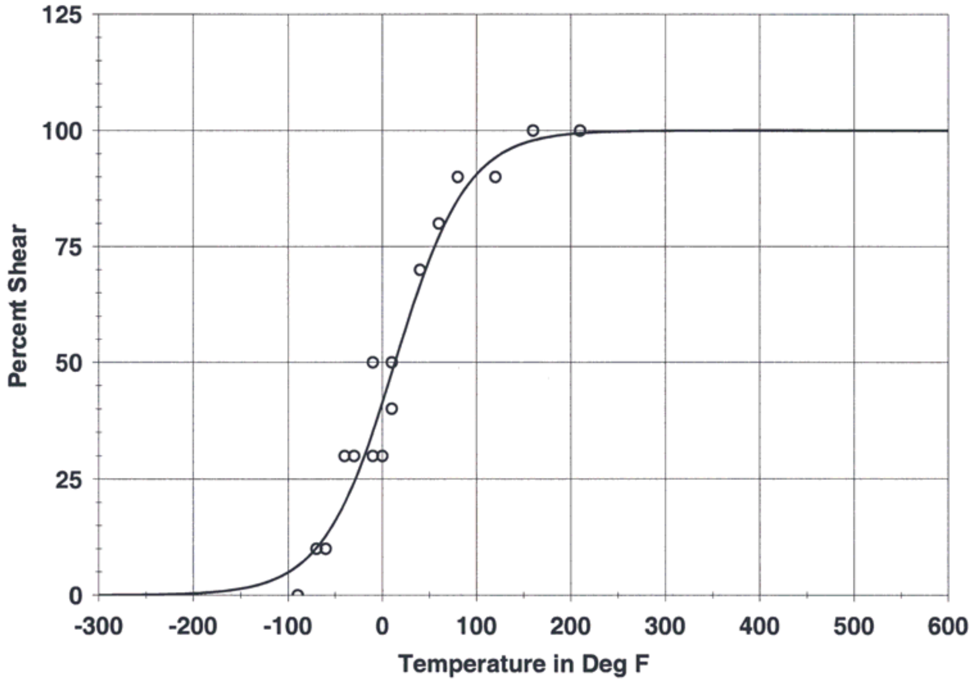
Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
125.00	89.00	82.33	6.67
150.00	86.00	84.48	1.52
200.00	83.00	86.59	-3.59
225.00	88.00	87.05	.95
250.00	86.00	87.33	-1.33
300.00	90.00	87.59	2.41

Correlation Coefficient = .950

UNIRRADIATED (WELD)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 03:13 PM
Page 1
Coefficients of Curve 1
A = 50. B = 50. C = 76.54 T0 = 13.54 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Temperature at 50% Shear = 13.6
Plant: PALO VERDE 2 Material: SAW Heat: 3P7317
Orientation: NA Capsule: UNIRR Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
-90.00	.00	6.26	-6.26
-70.00	10.00	10.13	-.13
-60.00	10.00	12.77	-2.77
-40.00	30.00	19.80	10.20
-30.00	30.00	24.27	5.73
-10.00	30.00	35.09	-5.09
-10.00	50.00	35.09	14.91
.00	30.00	41.24	-11.24
10.00	40.00	47.69	-7.69

UNIRRADIATED (WELD)

Page 2
Plant: PALO VERDE 2 Material: SAW Heat: 3P7317
Orientation: NA Capsule: UNIRR Fluence: n/cm^2

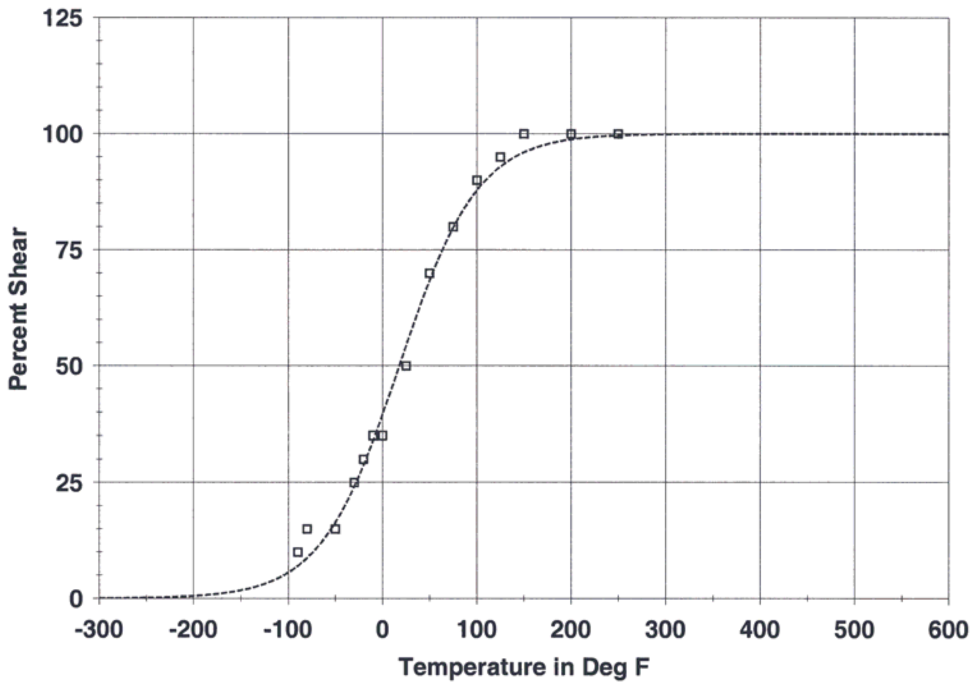
Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
10.00	50.00	47.69	2.31
10.00	40.00	47.69	-7.69
40.00	70.00	66.63	3.37
60.00	80.00	77.10	2.90
80.00	90.00	85.02	4.98
120.00	90.00	94.17	-4.17
160.00	100.00	97.87	2.13
160.00	100.00	97.87	2.13
210.00	100.00	99.41	.59

Correlation Coefficient = .980

CAPSULE 137 (WELD)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 03:13 PM
Page 1
Coefficients of Curve 2
A = 50. B = 50. C = 83.28 T0 = 17.86 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Temperature at 50% Shear = 17.9
Plant: PALO VERDE 2 Material: SAW Heat: 3P7317
Orientation: NA Capsule: 137 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
-90.00	10.00	6.98	3.02
-80.00	15.00	8.71	6.29
-50.00	15.00	16.39	-1.39
-30.00	25.00	24.06	.94
-20.00	30.00	28.72	1.28
-10.00	35.00	33.87	1.13
.00	35.00	39.44	-4.44
25.00	50.00	54.28	-4.28
50.00	70.00	68.39	1.61

CAPSULE 137 (WELD)

Page 2
Plant: PALO VERDE 2 Material: SAW Heat: 3P7317
Orientation: NA Capsule: 137 Fluence: n/cm^2

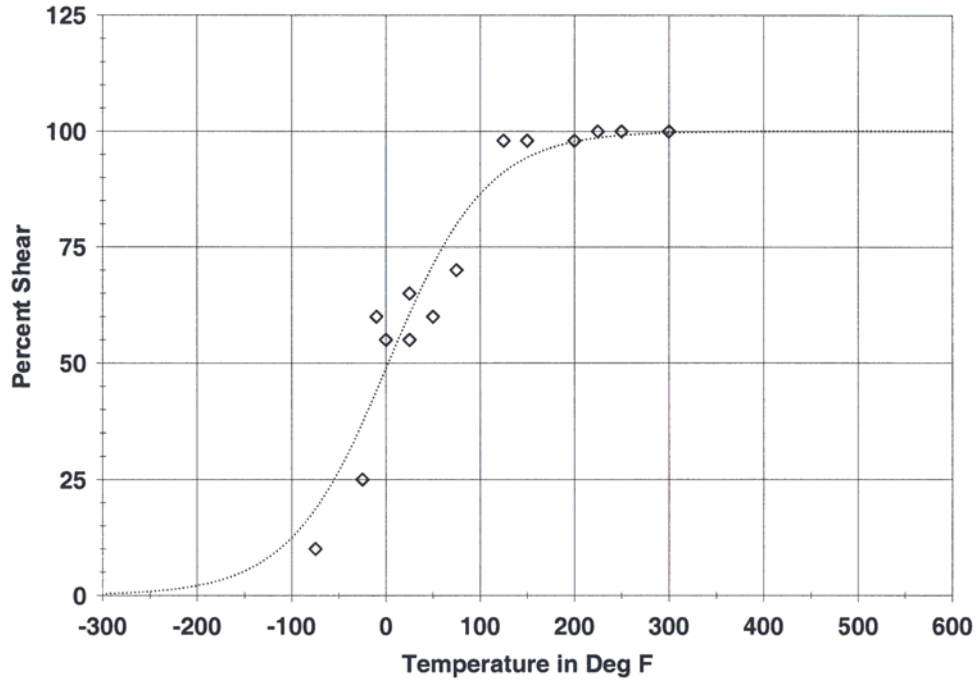
Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
75.00	80.00	79.78	.22
100.00	90.00	87.79	2.21
125.00	95.00	92.91	2.09
150.00	100.00	95.98	4.02
200.00	100.00	98.76	1.24
250.00	100.00	99.62	.38

Correlation Coefficient = .997

CAPSULE 230 (WELD)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 03:13 PM
Page 1
Coefficients of Curve 3
A = 50. B = 50. C = 105.05 T0 = 3.08 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Temperature at 50% Shear = 3.1
Plant: PALO VERDE 2 Material: SAW Heat: 3P7317
Orientation: NA Capsule: 230 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
-75.00	10.00	18.44	-8.44
-25.00	25.00	36.94	-11.94
-10.00	60.00	43.81	16.19
.00	55.00	48.54	6.46
.00	55.00	48.54	6.46
25.00	55.00	60.29	-5.29
25.00	65.00	60.29	4.71
50.00	60.00	70.96	-10.96
75.00	70.00	79.73	-9.73

CAPSULE 230 (WELD)

Page 2
Plant: PALO VERDE 2 Material: SAW Heat: 3P7317
Orientation: NA Capsule: 230 Fluence: n/cm^2

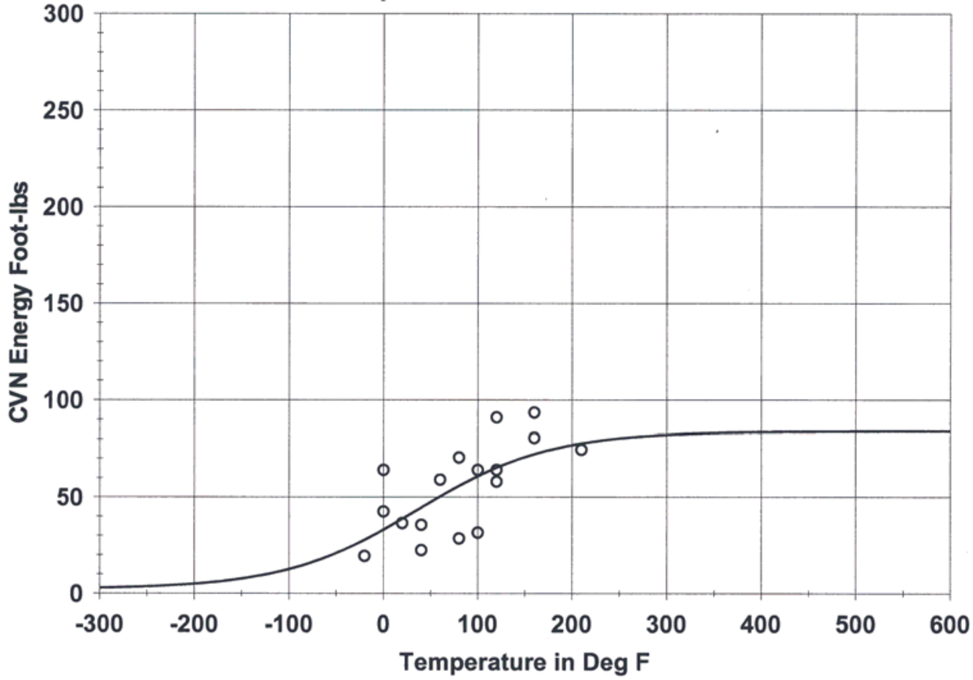
Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
125.00	98.00	91.06	6.94
150.00	98.00	94.25	3.75
200.00	98.00	97.70	.30
225.00	100.00	98.56	1.44
250.00	100.00	99.10	.90
300.00	100.00	99.65	.35

Correlation Coefficient = .961

UNIRRADIATED (HEAT AFFECTED ZONE)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 12/12/2005 03:36 PM
Page 1
Coefficients of Curve 1
A = 43.1 B = 40.9 C = 140.39 T0 = 35.24 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Upper Shelf Energy=84.0(Fixed) Lower Shelf Energy=2.2(Fixed)
Temp@30 ft-lbs=-11.3 Deg F Temp@50 ft-lbs=59.2 Deg F
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: NA Capsule: UNIRR Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
-20.00	19.50	27.79	-8.29
.00	42.50	33.05	9.45
.00	64.00	33.05	30.95
20.00	36.50	38.68	-2.18
40.00	22.50	44.49	-21.99
40.00	35.50	44.49	-8.99
60.00	59.00	50.24	8.76
80.00	28.50	55.72	-27.22
80.00	70.50	55.72	14.78

UNIRRADIATED (HEAT AFFECTED ZONE)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: NA Capsule: UNIRR Fluence: n/cm^2

Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
100.00	31.50	60.73	-29.23
100.00	64.00	60.73	3.27
120.00	58.00	65.17	-7.17
120.00	64.00	65.17	-1.17
120.00	91.00	65.17	25.83
160.00	80.50	72.17	8.33
160.00	93.50	72.17	21.33
210.00	74.50	77.74	-3.24

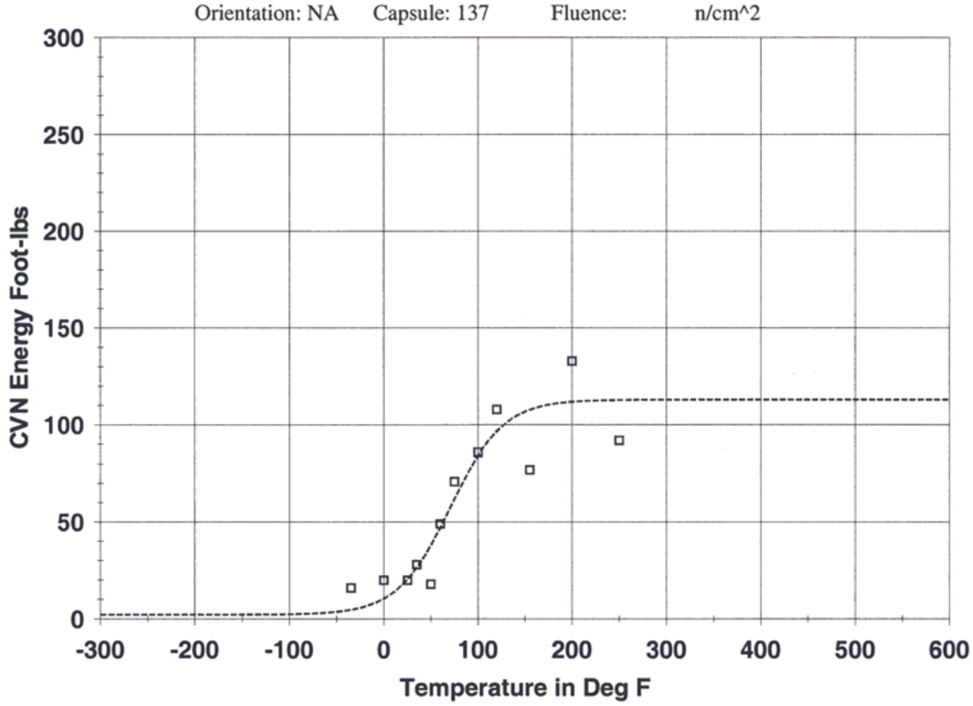
Correlation Coefficient = .670

CAPSULE 137 (HEAT AFFECTED ZONE)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 03:28 PM
Page 1
Coefficients of Curve 2

A = 57.6 B = 55.4 C = 56.12 T0 = 70.69 D = 0.00E+00

Equation is A + B * [Tanh((T-To)/(C+DT))]
Upper Shelf Energy=113.0(Fixed) Lower Shelf Energy=2.2(Fixed)
Temp@30 ft-lbs=40.0 Deg F Temp@50 ft-lbs=63.0 Deg F
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: NA Capsule: 137 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
-35.00	16.00	4.71	11.29
.00	20.00	10.46	9.54
25.00	20.00	20.38	-.38
35.00	28.00	26.46	1.54
50.00	18.00	38.06	-20.06
60.00	49.00	47.18	1.82
75.00	71.00	61.85	9.15
100.00	86.00	84.17	1.83
120.00	108.00	96.70	11.30

CAPSULE 137 (HEAT AFFECTED ZONE)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: NA Capsule: 137 Fluence: n/cm^2

Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
155.00	77.00	107.77	-30.77
200.00	133.00	111.91	21.09
250.00	92.00	112.81	-20.81

Correlation Coefficient = .927

CAPSULE 230 (HEAT AFFECTED ZONE)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 03:28 PM
Page 1
Coefficients of Curve 3

A = 46.1 B = 43.9 C = 93.02 T0 = 70.7 D = 0.00E+00

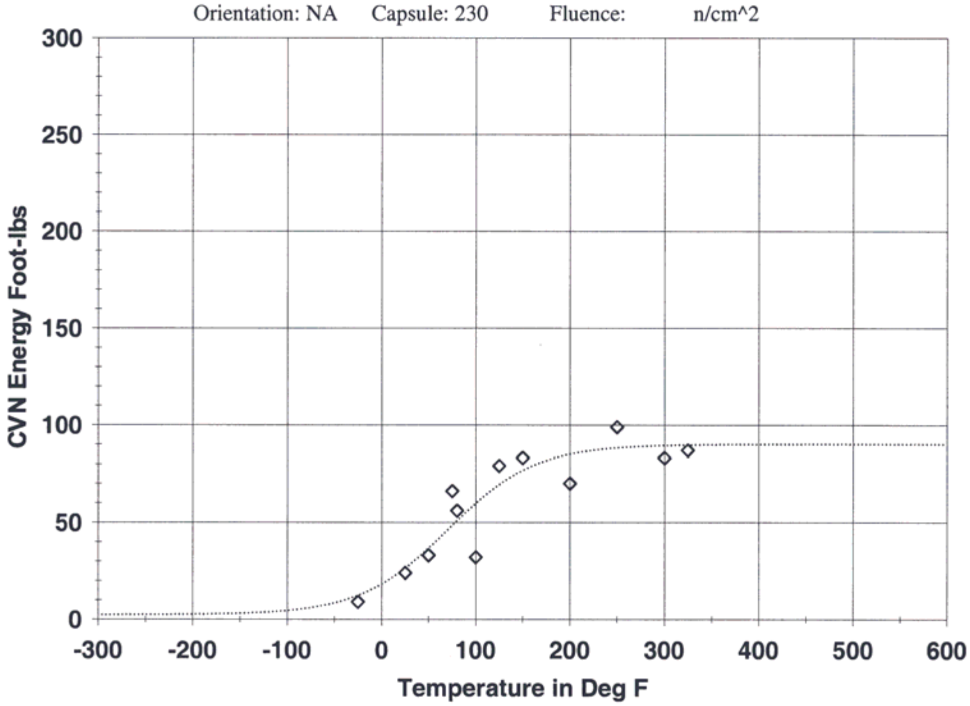
Equation is A + B * [Tanh((T-To)/(C+DT))]

Upper Shelf Energy=90.0(Fixed) Lower Shelf Energy=2.2(Fixed)

Temp@30 ft-lbs=35.0 Deg F Temp@50 ft-lbs=79.0 Deg F

Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1

Orientation: NA Capsule: 230 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
-25.00	9.00	12.15	-3.15
25.00	24.00	26.11	-2.11
50.00	33.00	36.49	-3.49
75.00	66.00	48.13	17.87
80.00	56.00	50.47	5.53
100.00	32.00	59.49	-27.49
125.00	79.00	69.17	9.83
150.00	83.00	76.50	6.50
200.00	70.00	84.87	-14.87

CAPSULE 230 (HEAT AFFECTED ZONE)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: NA Capsule: 230 Fluence: n/cm^2

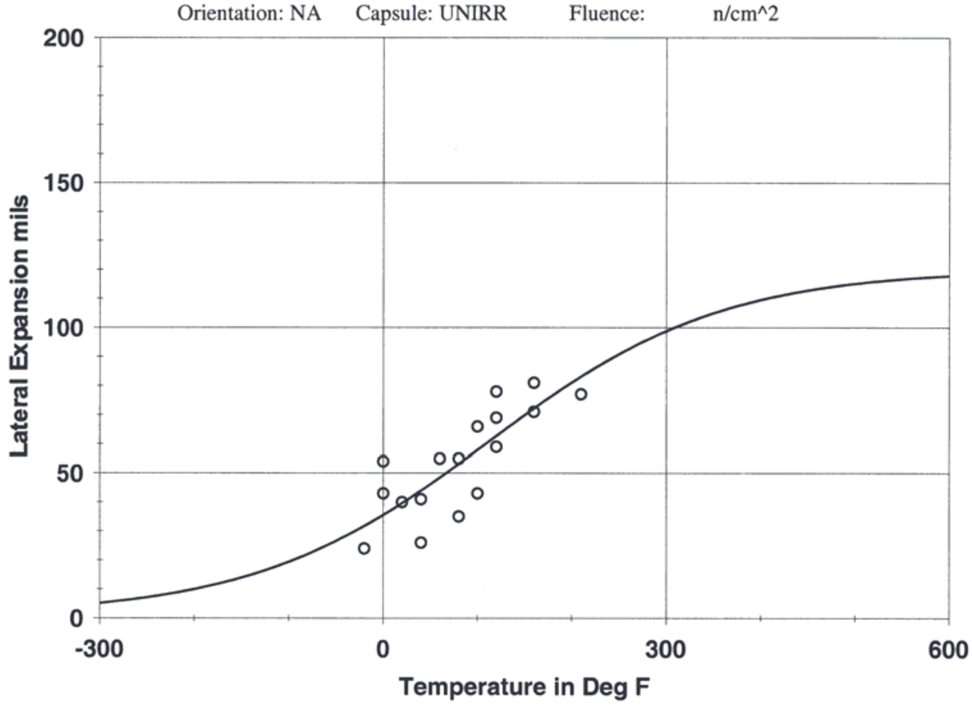
Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
250.00	99.00	88.18	10.82
300.00	83.00	89.37	-6.37
325.00	87.00	89.63	-2.63

Correlation Coefficient = .906

UNIRRADIATED (HEAT AFFECTED ZONE)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 03:47 PM
Page 1
Coefficients of Curve 1
A = 60.57 B = 59.57 C = 248.15 T0 = 111.13 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Upper Shelf L.E.=120.1 Lower Shelf L.E.=1.0(Fixed)
Temp.@L.E. 35 mils=-2.7 Deg F
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: NA Capsule: UNIRR Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
-20.00	24.00	31.73	-7.73
.00	43.00	35.54	7.46
.00	54.00	35.54	18.46
20.00	40.00	39.63	.37
40.00	26.00	43.95	-17.95
40.00	41.00	43.95	-2.95
60.00	55.00	48.47	6.53
80.00	35.00	53.13	-18.13
80.00	55.00	53.13	1.87

UNIRRADIATED (HEAT AFFECTED ZONE)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: NA Capsule: UNIRR Fluence: n/cm^2

Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
100.00	43.00	57.90	-14.90
100.00	66.00	57.90	8.10
120.00	59.00	62.70	-3.70
120.00	69.00	62.70	6.30
120.00	78.00	62.70	15.30
160.00	71.00	72.15	-1.15
160.00	81.00	72.15	8.85
210.00	77.00	83.12	-6.12

Correlation Coefficient = .801

CAPSULE 137 (HEAT AFFECTED ZONE)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 03:48 PM
Page 1
Coefficients of Curve 2

A = 41.94 B = 40.94 C = 59.73 T0 = 56.31 D = 0.00E+00

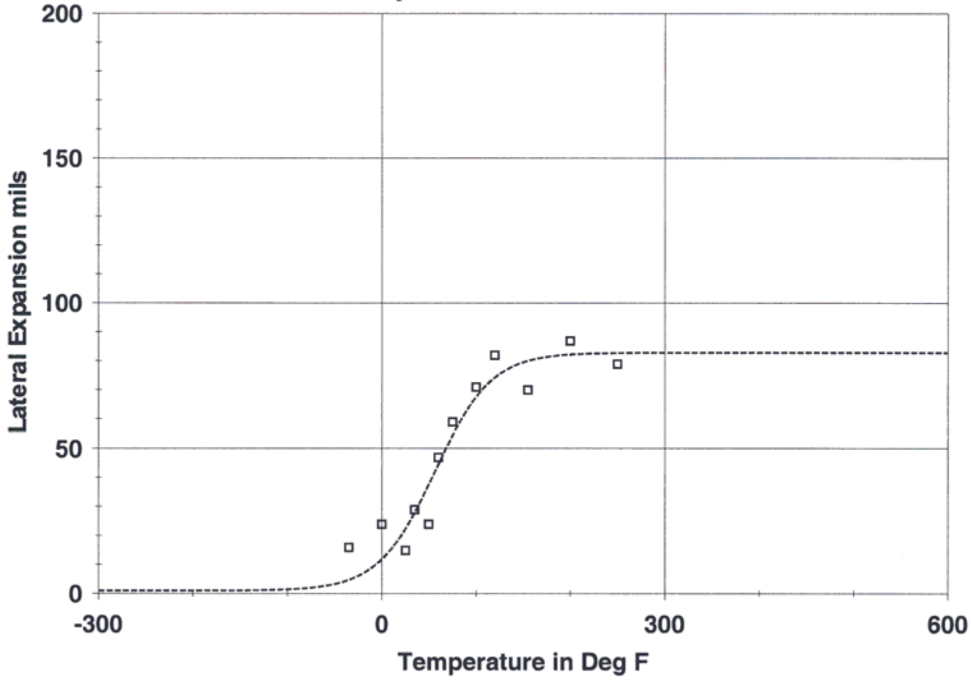
Equation is A + B * [Tanh((T-To)/(C+DT))]

Upper Shelf L.E.=82.9 Lower Shelf L.E.=1.0(Fixed)

Temp.@L.E. 35 mils=46.1 Deg F

Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1

Orientation: NA Capsule: 137 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
-35.00	16.00	4.68	11.32
.00	24.00	11.79	12.21
25.00	15.00	22.26	-7.26
35.00	29.00	27.93	1.07
50.00	24.00	37.64	-13.64
60.00	47.00	44.47	2.53
75.00	59.00	54.36	4.64
100.00	71.00	67.49	3.51
120.00	82.00	74.21	7.79

CAPSULE 137 (HEAT AFFECTED ZONE)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: NA Capsule: 137 Fluence: n/cm^2

Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
155.00	70.00	79.99	-9.99
200.00	87.00	82.23	4.77
250.00	79.00	82.76	-3.76

Correlation Coefficient = .957

CAPSULE 230 (HEAT AFFECTED ZONE)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 03:48 PM
Page 1
Coefficients of Curve 3

A = 39.31 B = 38.31 C = 111.71 T0 = 72.11 D = 0.00E+00

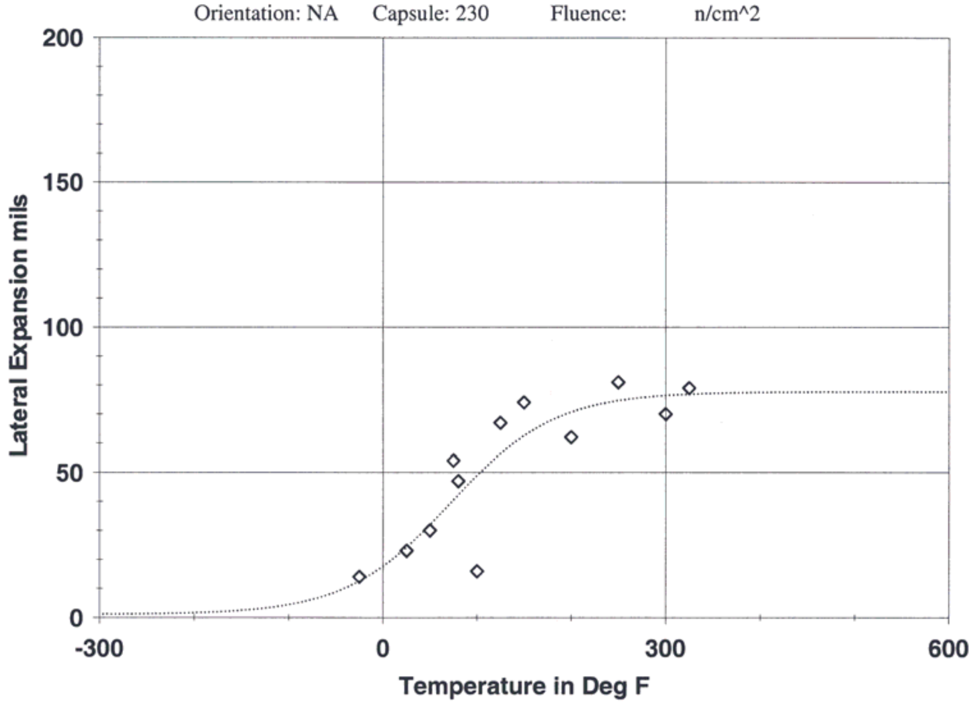
Equation is A + B * [Tanh((T-To)/(C+DT))]

Upper Shelf L.E.=77.6 Lower Shelf L.E.=1.0(Fixed)

Temp.@L.E. 35 mils=59.6 Deg F

Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1

Orientation: NA Capsule: 230 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
-25.00	14.00	12.45	1.55
25.00	23.00	24.04	-1.04
50.00	30.00	31.82	-1.82
75.00	54.00	40.30	13.70
80.00	47.00	42.01	4.99
100.00	16.00	48.67	-32.67
125.00	67.00	56.20	10.80
150.00	74.00	62.39	11.61
200.00	62.00	70.56	-8.56

CAPSULE 230 (HEAT AFFECTED ZONE)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: NA Capsule: 230 Fluence: n/cm^2

Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
250.00	81.00	74.57	6.43
300.00	70.00	76.34	-6.34
325.00	79.00	76.79	2.21

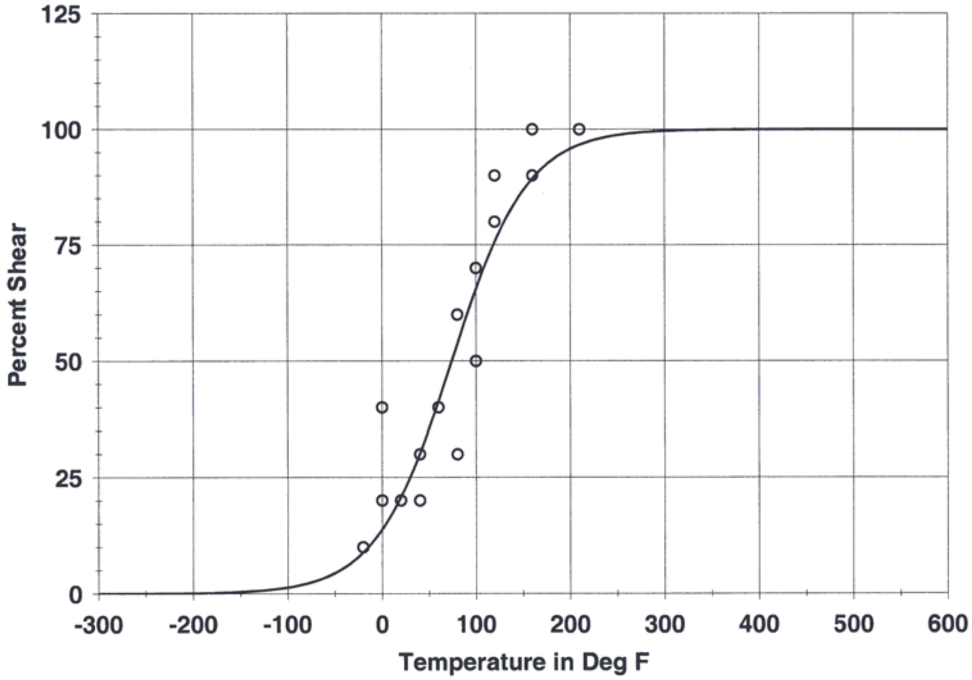
Correlation Coefficient = .866

UNIRRADIATED (HEAT AFFECTED ZONE)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 03:38 PM
Page 1
Coefficients of Curve 1

A = 50. B = 50. C = 80.75 T0 = 74.13 D = 0.00E+00

Equation is A + B * [Tanh((T-To)/(C+DT))]
Temperature at 50% Shear = 74.2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: NA Capsule: UNIRR Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
-20.00	10.00	8.86	1.14
.00	20.00	13.75	6.25
.00	40.00	13.75	26.25
20.00	20.00	20.74	-.74
40.00	20.00	30.04	-10.04
40.00	30.00	30.04	-.04
60.00	40.00	41.34	-1.34
80.00	30.00	53.63	-23.63
80.00	60.00	53.63	6.37

UNIRRADIATED (HEAT AFFECTED ZONE)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: NA Capsule: UNIRR Fluence: n/cm^2

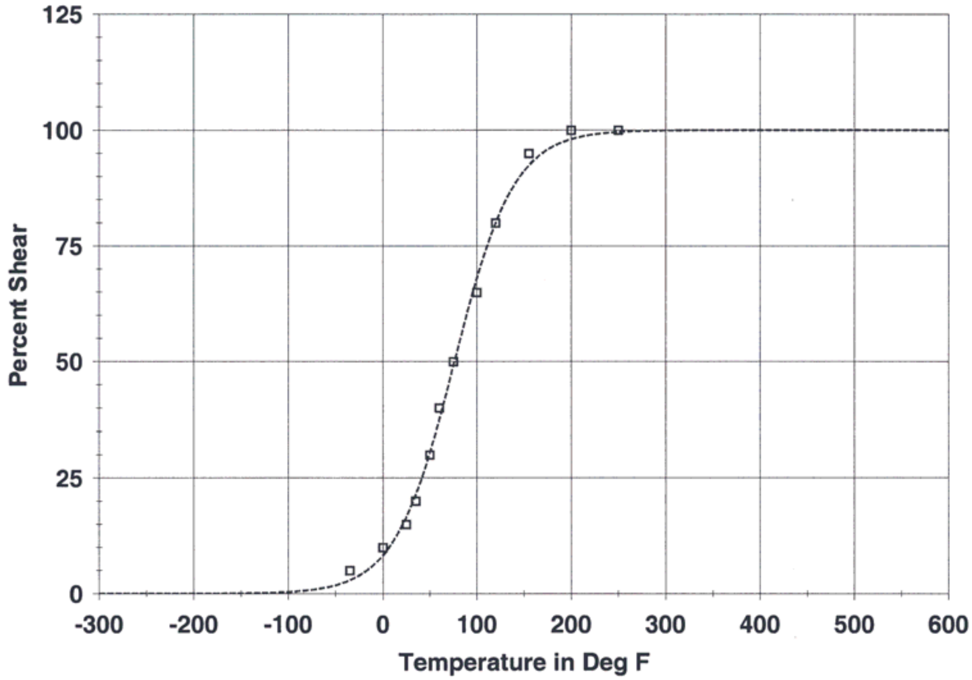
Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
100.00	50.00	65.49	-15.49
100.00	70.00	65.49	4.51
120.00	80.00	75.70	4.30
120.00	80.00	75.70	4.30
120.00	90.00	75.70	14.30
160.00	90.00	89.35	.65
160.00	100.00	89.35	10.65
210.00	100.00	96.66	3.34

Correlation Coefficient = .933

CAPSULE 137 (HEAT AFFECTED ZONE)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 03:38 PM
Page 1
Coefficients of Curve 2
A = 50. B = 50. C = 63.19 T0 = 76.11 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Temperature at 50% Shear = 76.2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: NA Capsule: 137 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
-35.00	5.00	2.88	2.12
.00	10.00	8.25	1.75
25.00	15.00	16.55	-1.55
35.00	20.00	21.40	-1.40
50.00	30.00	30.44	-.44
60.00	40.00	37.52	2.48
75.00	50.00	49.12	.88
100.00	65.00	68.05	-3.05
120.00	80.00	80.04	-.04

CAPSULE 137 (HEAT AFFECTED ZONE)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: NA Capsule: 137 Fluence: n/cm^2

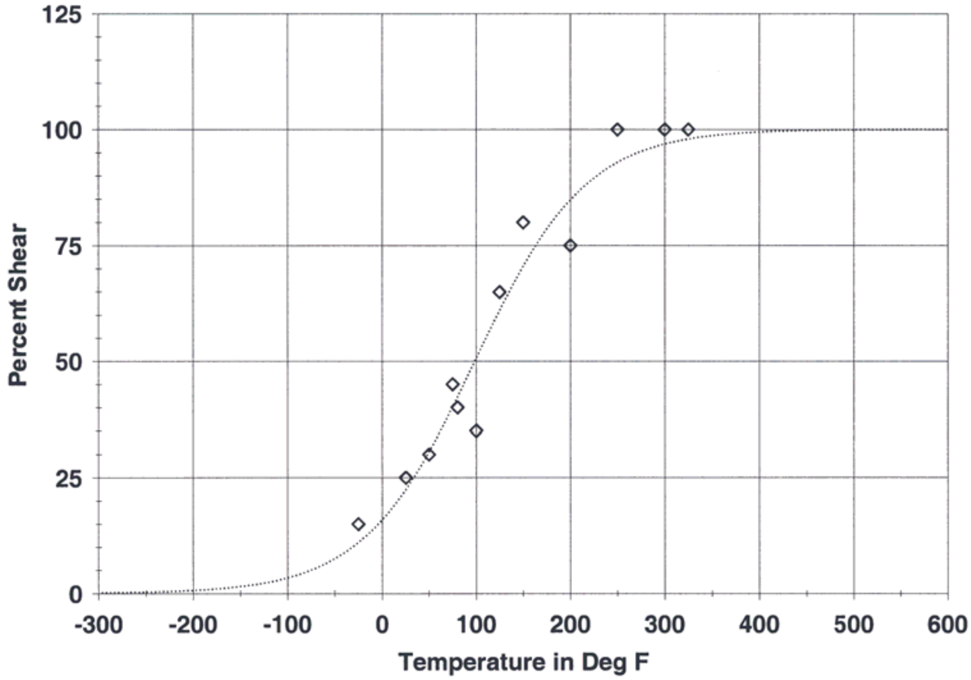
Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
155.00	95.00	92.39	2.61
200.00	100.00	98.06	1.94
250.00	100.00	99.59	.41

Correlation Coefficient = .999

CAPSULE 230 (HEAT AFFECTED ZONE)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 03:38 PM
Page 1
Coefficients of Curve 3
A = 50. B = 50. C = 118.1 T0 = 98.95 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Temperature at 50% Shear = 99.0
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: NA Capsule: 230 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
-25.00	15.00	10.92	4.08
25.00	25.00	22.23	2.77
50.00	30.00	30.39	-.39
75.00	45.00	40.00	5.00
80.00	40.00	42.05	-2.05
100.00	35.00	50.44	-15.44
125.00	65.00	60.85	4.15
150.00	80.00	70.36	9.64
200.00	75.00	84.70	-9.70

CAPSULE 230 (HEAT AFFECTED ZONE)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: F-773-1
Orientation: NA Capsule: 230 Fluence: n/cm^2

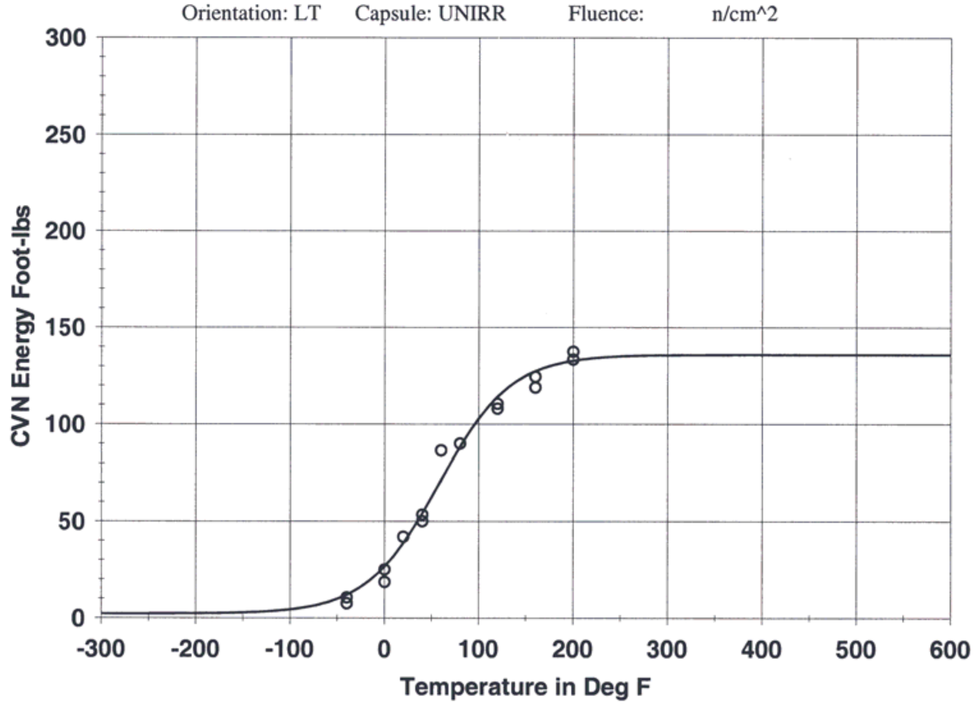
Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
250.00	100.00	92.81	7.19
300.00	100.00	96.78	3.22
325.00	100.00	97.87	2.13

Correlation Coefficient = .974

UNIRRADIATED (STANDARD REFERENCE MATERIAL)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 04:39 PM
Page 1
Coefficients of Curve 1
A = 69.1 B = 66.9 C = 76.59 T0 = 57.47 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Upper Shelf Energy=136.0(Fixed) Lower Shelf Energy=2.2(Fixed)
Temp@30 ft-lbs=6.3 Deg F Temp@50 ft-lbs=35.0 Deg F
Plant: PALO VERDE 2 Material: SA533B1 Heat: A-1008
Orientation: LT Capsule: UNIRR Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
-40.00	7.50	11.93	-4.43
-40.00	10.50	11.93	-1.43
.00	18.50	26.59	-8.09
.00	25.00	26.59	-1.59
20.00	42.00	38.75	3.25
40.00	50.00	54.10	-4.10
40.00	53.50	54.10	-.60
60.00	86.50	71.31	15.19
80.00	90.00	88.23	1.77

UNIRRADIATED (STANDARD REFERENCE MATERIAL)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: A-1008
Orientation: LT Capsule: UNIRR Fluence: n/cm^2

Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
120.00	108.00	114.13	-6.13
120.00	110.50	114.13	-3.63
160.00	119.00	127.39	-8.39
160.00	124.50	127.39	-2.89
200.00	133.50	132.84	.66
200.00	137.50	132.84	4.66

Correlation Coefficient = .992

CAPSULE 137 (STANDARD REFERENCE MATERIAL)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 04:39 PM

Page 1

Coefficients of Curve 2

A = 53.6 B = 51.4 C = 113.89 T0 = 178.77 D = 0.00E+00

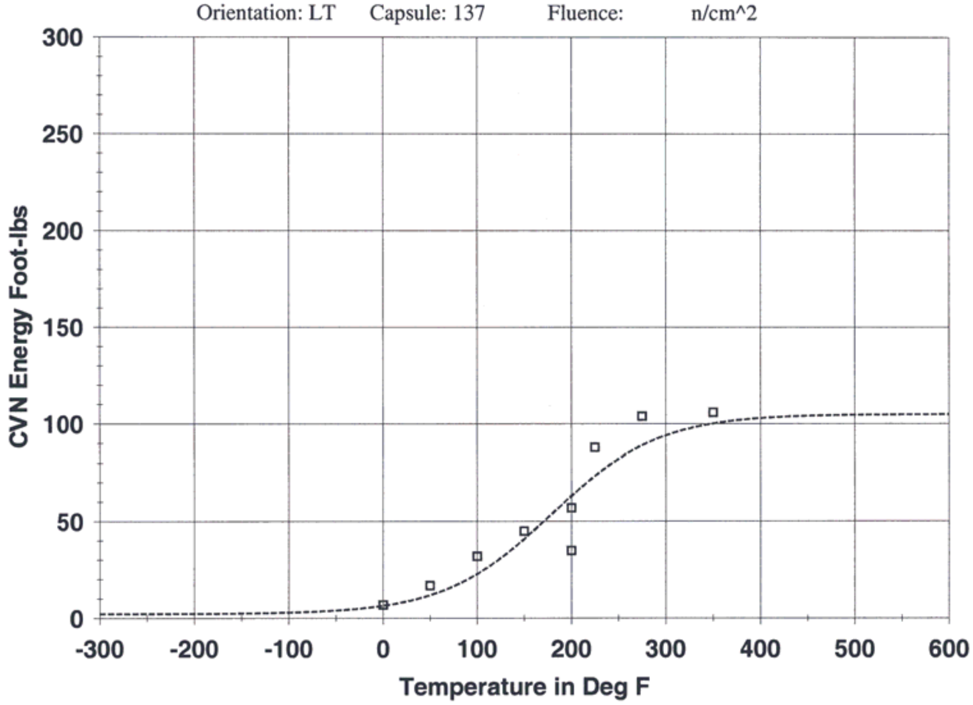
Equation is A + B * [Tanh((T-To)/(C+DT))]

Upper Shelf Energy=105.0(Fixed) Lower Shelf Energy=2.2(Fixed)

Temp@30 ft-lbs=122.3 Deg F Temp@50 ft-lbs=170.8 Deg F

Plant: PALO VERDE 2 Material: SA533B1 Heat: A-1008

Orientation: LT Capsule: 137 Fluence: n/cm^2



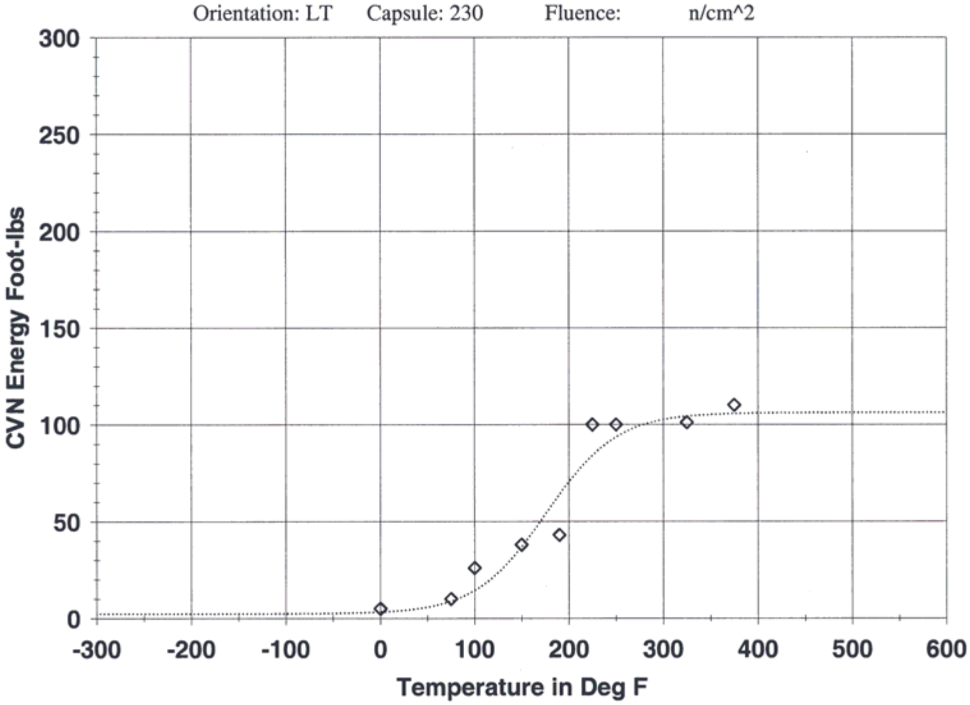
Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
.00	7.00	6.47	.53
50.00	17.00	11.90	5.10
100.00	32.00	22.81	9.19
150.00	45.00	40.88	4.12
200.00	35.00	63.07	-28.07
200.00	57.00	63.07	-6.07
225.00	88.00	73.39	14.61
275.00	104.00	88.98	15.02
350.00	106.00	100.16	5.84

Correlation Coefficient = .935

CAPSULE 230 (STANDARD REFERENCE MATERIAL)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 04:39 PM
Page 1
Coefficients of Curve 3
A = 54.1 B = 51.9 C = 74.63 T0 = 176.18 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Upper Shelf Energy=106.0(Fixed) Lower Shelf Energy=2.2(Fixed)
Temp@30 ft-lbs=138.7 Deg F Temp@50 ft-lbs=170.3 Deg F
Plant: PALO VERDE 2 Material: SA533B1 Heat: A-1008
Orientation: LT Capsule: 230 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input CVN	Computed CVN	Differential
.00	5.00	3.12	1.88
75.00	10.00	8.67	1.33
100.00	26.00	14.13	11.87
150.00	38.00	36.61	1.39
190.00	43.00	63.60	-20.60
225.00	100.00	83.91	16.09
250.00	100.00	93.39	6.61
325.00	101.00	104.11	-3.11
375.00	110.00	105.50	4.50

Correlation Coefficient = .971

UNIRRADIATED (STANDARD REFERENCE MATERIAL)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 12/12/2005 03:44 PM
Page 1
Coefficients of Curve 1

A = 42.3 B = 41.3 C = 52.17 T0 = 23.42 D = 0.00E+00

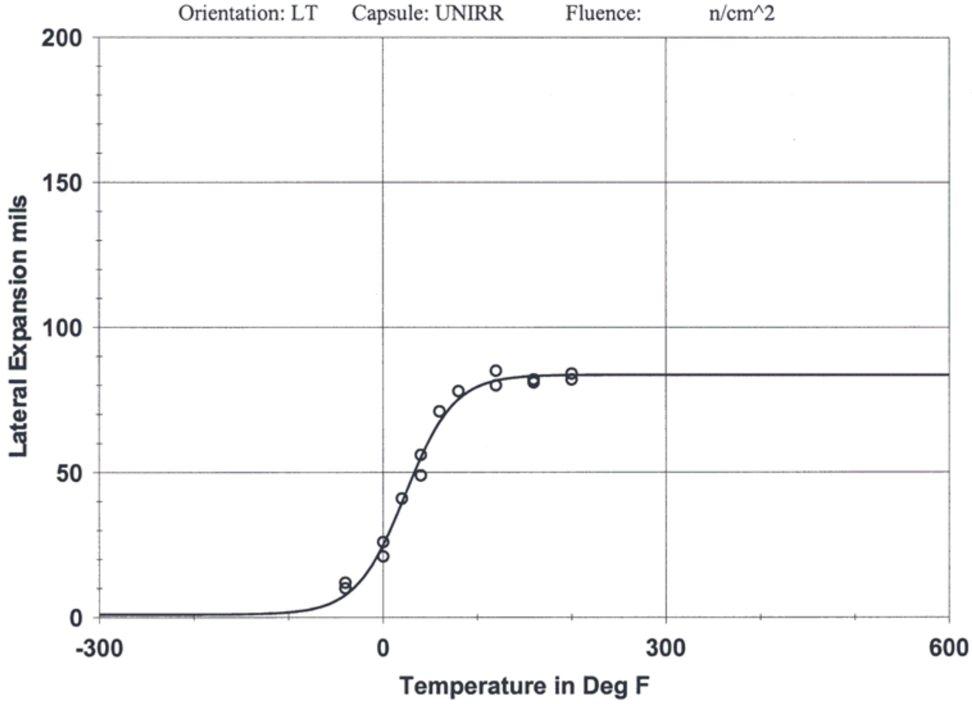
Equation is A + B * [Tanh((T-To)/(C+DT))]

Upper Shelf L.E.=83.6 Lower Shelf L.E.=1.0(Fixed)

Temp.@L.E. 35 mils=14.1 Deg F

Plant: PALO VERDE 2 Material: SA533B1 Heat: A-1008

Orientation: LT Capsule: UNIRR Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
-40.00	10.00	7.67	2.33
-40.00	12.00	7.67	4.33
.00	21.00	24.91	-3.91
.00	26.00	24.91	1.09
20.00	41.00	39.60	1.40
40.00	49.00	55.01	-6.01
40.00	56.00	55.01	.99
60.00	71.00	67.30	3.70
80.00	78.00	75.14	2.86

UNIRRADIATED (STANDARD REFERENCE MATERIAL)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: A-1008
Orientation: LT Capsule: UNIRR Fluence: n/cm^2

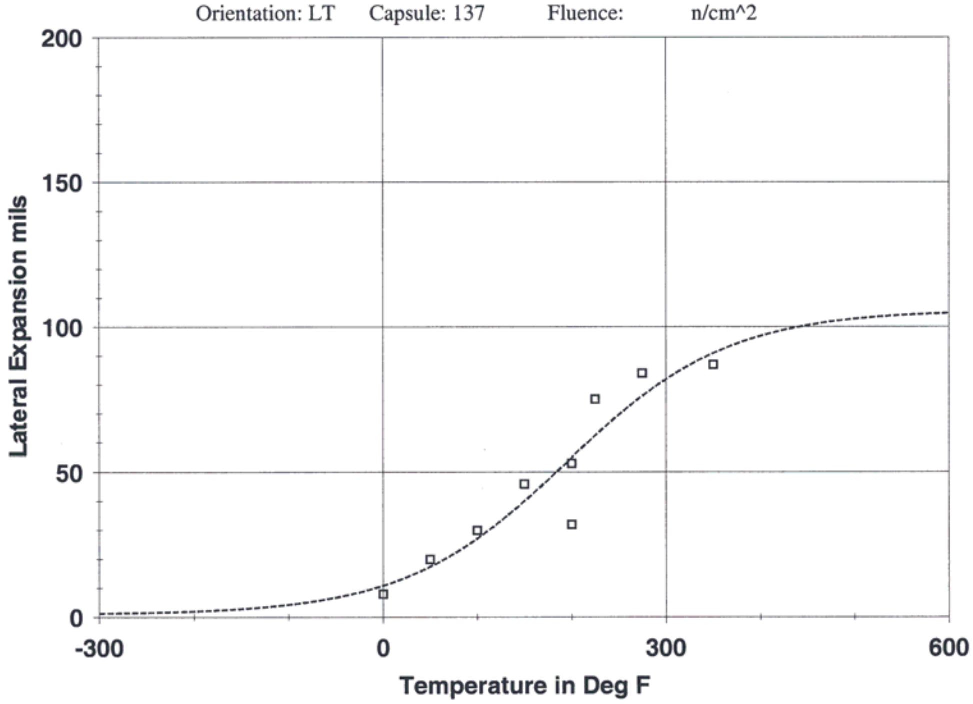
Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
120.00	85.00	81.62	3.38
120.00	80.00	81.62	-1.62
160.00	81.00	83.17	-2.17
160.00	82.00	83.17	-1.17
200.00	82.00	83.51	-1.51
200.00	84.00	83.51	.49

Correlation Coefficient = .995

CAPSULE 137 (STANDARD REFERENCE MATERIAL)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 05:02 PM
Page 1
Coefficients of Curve 2
A = 53.32 B = 52.32 C = 172.14 T0 = 194.72 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Upper Shelf L.E.=105.6 Lower Shelf L.E.=1.0(Fixed)
Temp.@L.E. 35 mils=131.8 Deg F
Plant: PALO VERDE 2 Material: SA533B1 Heat: A-1008
Orientation: LT Capsule: 137 Fluence: n/cm^2



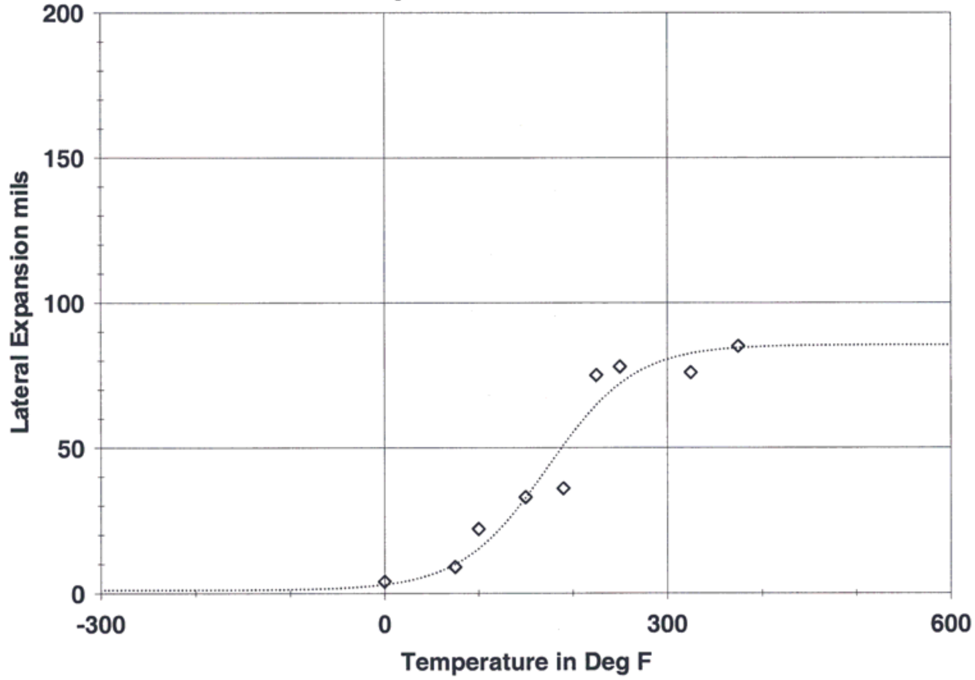
Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
.00	8.00	10.87	-2.87
50.00	20.00	17.42	2.58
100.00	30.00	27.13	2.87
150.00	46.00	40.03	5.97
200.00	32.00	54.93	-22.93
200.00	53.00	54.93	-1.93
225.00	75.00	62.44	12.56
275.00	84.00	76.10	7.90
350.00	87.00	90.86	-3.86

Correlation Coefficient = .935

CAPSULE 230 (STANDARD REFERENCE MATERIAL)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 04:58 PM
Page 1
Coefficients of Curve 3
A = 43.2 B = 42.2 C = 91.63 T0 = 173.7 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Upper Shelf L.E.=85.4 Lower Shelf L.E.=1.0(Fixed)
Temp.@L.E. 35 mils=155.7 Deg F
Plant: PALO VERDE 2 Material: SA533B1 Heat: A-1008
Orientation: LT Capsule: 230 Fluence: n/cm^2



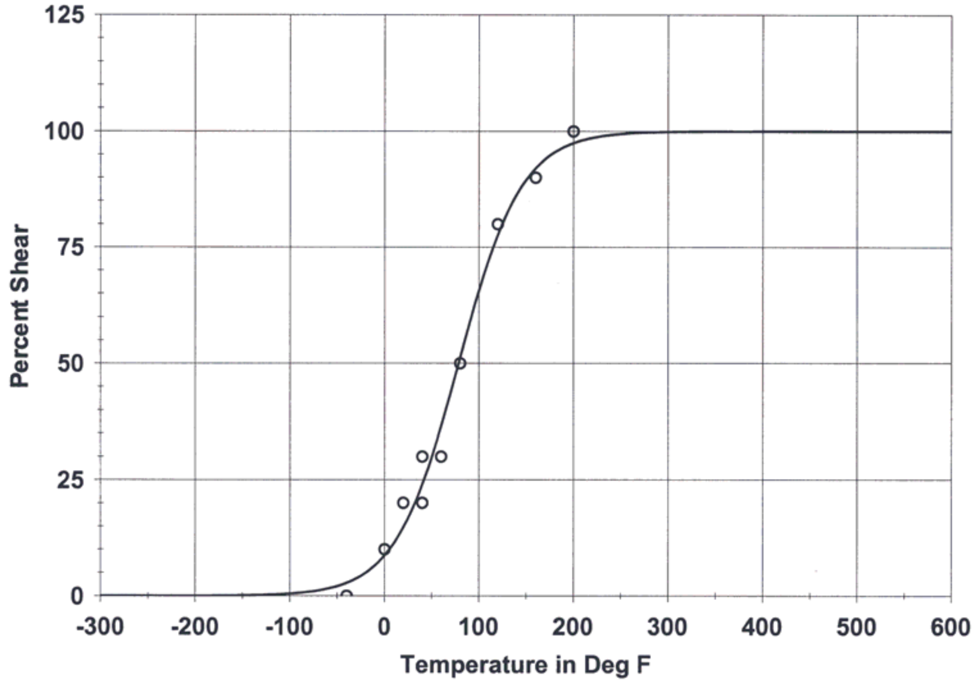
Charpy V-Notch Data

Temperature	Input L.E.	Computed L.E.	Differential
.00	4.00	2.86	1.14
75.00	9.00	9.77	-.77
100.00	22.00	15.08	6.92
150.00	33.00	32.52	.48
190.00	36.00	50.63	-14.63
225.00	75.00	64.63	10.37
250.00	78.00	71.98	6.02
325.00	76.00	82.41	-6.41
375.00	85.00	84.37	.63

Correlation Coefficient = .973

UNIRRADIATED (STANDARD REFERENCE MATERIAL)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 12/12/2005 03:45 PM
Page 1
Coefficients of Curve 1
A = 50. B = 50. C = 66.66 T0 = 78.54 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Temperature at 50% Shear = 78.6
Plant: PALO VERDE 2 Material: SA533B1 Heat: A-1008
Orientation: LT Capsule: UNIRR Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
-40.00	.00	2.77	-2.77
-40.00	.00	2.77	-2.77
.00	10.00	8.66	1.34
.00	10.00	8.66	1.34
20.00	20.00	14.73	5.27
40.00	20.00	23.94	-3.94
40.00	30.00	23.94	6.06
60.00	30.00	36.44	-6.44
80.00	50.00	51.10	-1.10

UNIRRADIATED (STANDARD REFERENCE MATERIAL)

Page 2
Plant: PALO VERDE 2 Material: SA533B1 Heat: A-1008
Orientation: LT Capsule: UNIRR Fluence: n/cm^2

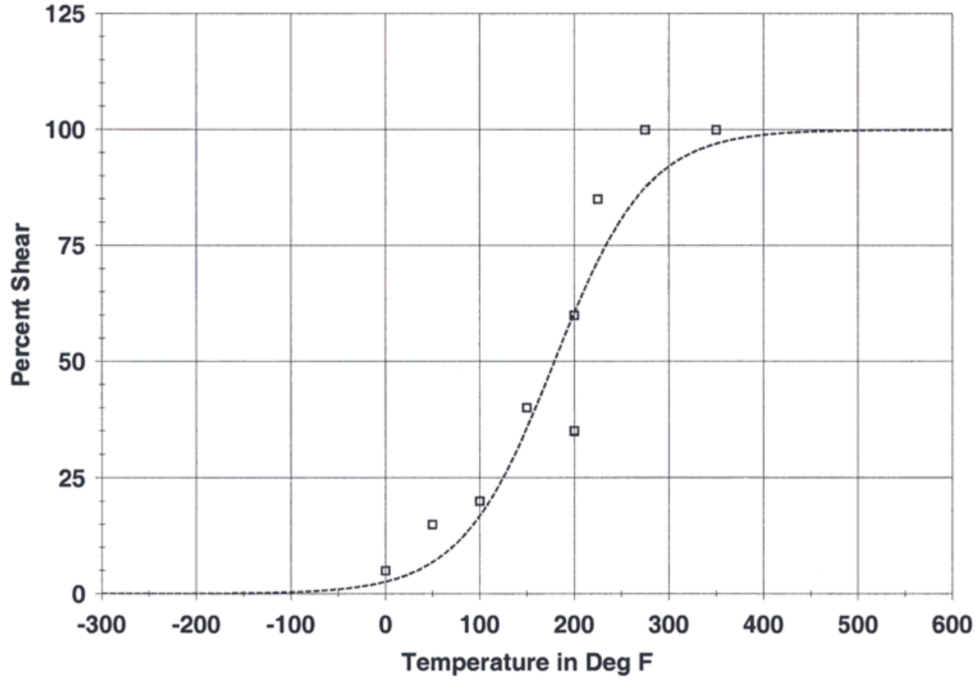
Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
120.00	80.00	77.63	2.37
120.00	80.00	77.63	2.37
160.00	90.00	92.01	-2.01
160.00	90.00	92.01	-2.01
200.00	100.00	97.45	2.55
200.00	100.00	97.45	2.55

Correlation Coefficient = .996

CAPSULE 137 (STANDARD REFERENCE MATERIAL)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 04:44 PM
Page 1
Coefficients of Curve 2
A = 50. B = 50. C = 98.82 T0 = 179.08 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Temperature at 50% Shear = 179.1
Plant: PALO VERDE 2 Material: SA533B1 Heat: A-1008
Orientation: LT Capsule: 137 Fluence: n/cm^2



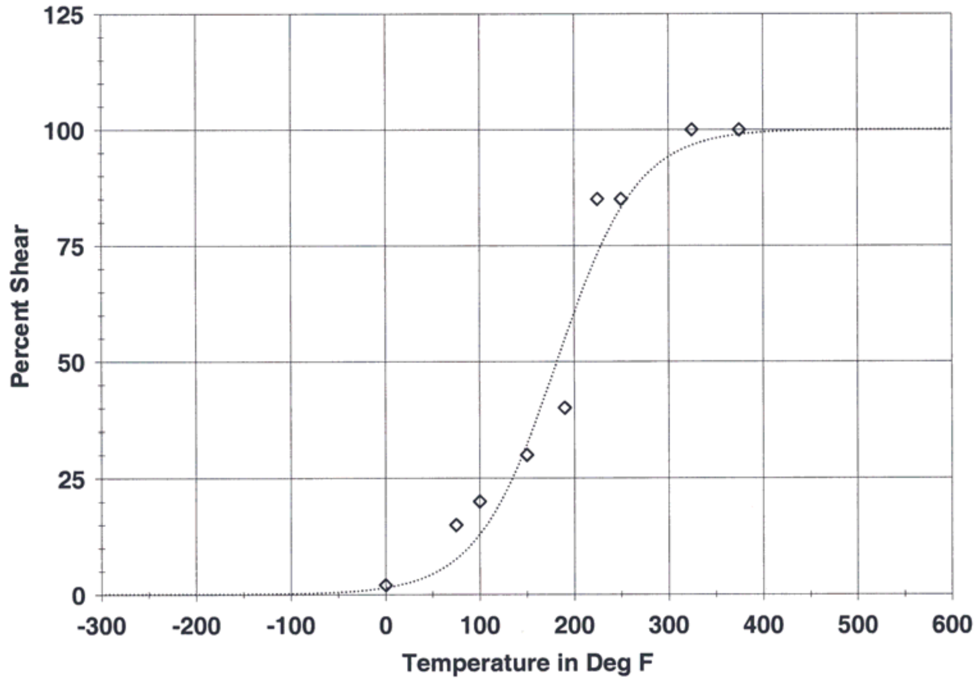
Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
.00	5.00	2.60	2.40
50.00	15.00	6.83	8.17
100.00	20.00	16.79	3.21
150.00	40.00	35.70	4.30
200.00	35.00	60.43	-25.43
200.00	60.00	60.43	-.43
225.00	85.00	71.70	13.30
275.00	100.00	87.45	12.55
350.00	100.00	96.95	3.05

Correlation Coefficient = .950

CAPSULE 230 (STANDARD REFERENCE MATERIAL)

CVGRAPH 5.0.2 Hyperbolic Tangent Curve Printed on 11/30/2005 04:44 PM
Page 1
Coefficients of Curve 3
A = 50. B = 50. C = 85.57 T0 = 182.12 D = 0.00E+00
Equation is A + B * [Tanh((T-To)/(C+DT))]
Temperature at 50% Shear = 182.2
Plant: PALO VERDE 2 Material: SA533B1 Heat: A-1008
Orientation: LT Capsule: 230 Fluence: n/cm^2



Charpy V-Notch Data

Temperature	Input Percent Shear	Computed Percent Shear	Differential
.00	2.00	1.40	.60
75.00	15.00	7.56	7.44
100.00	20.00	12.79	7.21
150.00	30.00	32.06	-2.06
190.00	40.00	54.59	-14.59
225.00	85.00	73.15	11.85
250.00	85.00	83.01	1.99
325.00	100.00	96.58	3.42
375.00	100.00	98.91	1.09

Correlation Coefficient = .982

Appendix C References

C-1 WCAP-14370, *Use of the Hyperbolic Tangent Function for Fitting Transition Temperature Toughness Data*, T. R. Mager, et al., May 1995.

APPENDIX D
PALO VERDE UNIT 2 SURVEILLANCE PROGRAM CREDIBILITY EVALUATION

Introduction

Regulatory Guide 1.99, Revision 2 (Reference 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 two surveillance capsules removed from the Palo Verde Unit 2 reactor vessel. To use these surveillance data sets, they must be shown to be credible. In accordance with the discussion of Regulatory Guide 1.99, Revision 2, there are five requirements that must be met for the surveillance data to be judged credible.

The purpose of this evaluation is to apply the credibility requirements of Regulatory Guide 1.99, Revision 2, to the Palo Verde Unit 2 reactor vessel surveillance data and determine if the Palo Verde Unit 2 surveillance data is credible.

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" (Reference D-2), as follows:

> "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 Palo Verde Unit 2 reactor vessel consists of the following beltline region materials:

- Intermediate shell plates F-765-4, 5, 6
- Lower shell plates F-773-1, 2, 3
- Intermediate shell longitudinal (axial) weld seams 101-124 A,B,C
- Lower shell longitudinal (axial) weld seams 101-142 A,B,C
- Intermediate to lower shell circumferential (girth) weld seam 101-171

From TR-V-MCM-004 (Reference D-3), selection of the surveillance material was based on an evaluation of initial toughness (characterized by the reference temperature, RT_{NDT}), and the predicted effect of chemical composition (residual copper and phosphorus) and neutron fluence on the toughness (RT_{NDT} shift) during reactor operation. Lower shell plate numbered F-773-1 (Heat 64071-1) was selected as the surveillance base metal since it had the highest adjusted EOL RT_{NDT} of the six beltline region plates. Weld Heat 3P7317 was selected because it is the same heat used in fabrication of the axial welds joining the lower shell plates (101-142 A,B,C).

Based on this discussion, Criterion 1 is met for the Palo Verde Unit 2 reactor vessel.

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 is small enough to permit the determination of the 30 ft-lb temperature and the upper shelf energy of the Palo Verde Unit 2 surveillance materials unambiguously. Hence, the Palo Verde Unit 2 surveillance program meets this criterion.

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.

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.

The Palo Verde Unit 2 lower shell plate F-773-1 and surveillance weld will be evaluated for credibility. The surveillance weld is made from weld wire Heat 3P7317 and is not in any other plant surveillance program.

The NRC methods for credibility determination were presented to industry at a meeting held by the NRC on February 12 and 13, 1998. At these meetings, the NRC presented five cases. Of the five cases, Case 1 (the "straightforward RG. Method") most closely represents the situation described above for Palo Verde Unit 2 surveillance weld metal. Note that the straightforward method of Regulatory Guide 1.99, Revision 2 will also be followed for the plate material.

Table D-1 contains the calculation of chemistry factors for the Palo Verde Unit 2 reactor vessel beltline materials contained in the surveillance program. These chemistry factors are calculated per Regulatory Guide 1.99, Revision 2, Position 2.1. [*Note that when evaluating surveillance weld data, an adjustment called the "Ratio Procedure" is applied. This "Ratio" is not required when evaluating the credibility of the surveillance weld data.*]

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 indicates that no data points fall outside the $\pm 1\sigma$ of 17°F scatter band for the lower shell plate F-773-1 surveillance data. Therefore, the plate surveillance data are deemed credible. No weld data points fall outside the $\pm 1\sigma$ of 28°F scatter band for the surveillance weld data; therefore, the weld data are also 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 capsule specimens are located in the reactor between the fuel and the vessel wall opposite the center of the core. The test capsules are in baskets attached to the vessel wall. 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, this criterion is met.

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 Palo Verde Unit 2 surveillance program does contain correlation monitor material. NUREG/CR-6413, ORNL/TM-13133 (Reference D-4) contains a plot of residual vs. Fast fluence for the correlation monitor material (Figure 11 in that report). The data used for this plot is contained in Table 14. However, the data within this report does not contain the two capsules from Palo Verde Unit 2. Thus, Table D-3 contains an updated calculation of Residual vs. Fast fluence.

Table D-3 shows a 2σ uncertainty of less than 50°F, which is the allowable scatter in NUREG/CR-6413, ORNL/TM-13133. Hence, this criterion is met.

Conclusion

Based on the preceding responses to all five criteria of Regulatory Guide 1.99, Revision 2, Section B and 10 CFR 50.61, the Palo Verde Unit 2 surveillance plate and weld data are “Credible.”

Table D-1 Calculation of Chemistry Factors using Palo Verde Unit 2 Surveillance Capsule Data						
Material	**Capsule**	**Capsule f[a]**	**FF[b]**	**ΔRT_{NDT}[c]**	**FF*ΔRT_{NDT}**	**FF^2**
Lower Shell Plate F-773-1 (Longitudinal)	137°	0.387	0.7372	13.3°F	9.804	0.5434
	230°	0.992	0.9978	17.7°F	17.660	0.9955
Lower Shell Plate F-773-1 (Transverse)	137°	0.387	0.7372	9.5°F	7.003	0.5434
	230°	0.992	0.9978	19.3°F	19.257	0.9955
				SUM:	53.724	3.0778
	$CF_{F\text{-}773\text{-}1} = \Sigma(FF * RT_{NDT}) \div \Sigma(FF^2) = (53.724) \div (3.0778) = 17.5°F$					
Surveillance Weld Material (Heat # 3P7317)	137°	0.387	0.7372	0.0 °F[d]	0.0	0.5434
	230°	0.992	0.9978	2.5°F	2.494	0.9955
				SUM:	2.494	1.5389
	$CF_{Surv.\ Weld} = \Sigma(FF * RT_{NDT}) \div \Sigma(FF^2) = (2.494) \div (1.5389) = 1.6°F$					

Notes:

a. f = fluence. Units are x 10^{19} n/cm^2 (E > 1.0 MeV). See Section 6.

b. FF = fluence factor = $f^{(0.28 - 0.1*\log f)}$.

c. ΔRT_{NDT} values are the measured 30 ft-lb shift values. See Appendix C herein, Units are [°F].

d. A decrease in RT_{NDT} is not technically valid for irradiated material. As such, the measured shift in RT_{NDT} (-0.1°F) is conservatively assumed to be zero.

Table D-2 Palo Verde Unit 2 Surveillance Capsule Data Scatter about the Best-Fit Line for Surveillance Forging Materials							
Material	**Capsule**	**CF ($Slope_{best fit}$)**	**FF**	**Measured ΔRT_{NDT}**	**Predicted ΔRT_{NDT}**	**Scatter ΔRT_{NDT} (°F)**	**<17°F (Base Metals) <28°F (Weld)**
Lower Shell Plate F-773-1 (Longitudinal)	137°	17.5°F	0.7372	13.3°F	12.9°F	-0.4°F	Yes
	230°	17.5°F	0.9978	17.7°F	17.5°F	-0.2°F	Yes
Lower Shell Plate F-773-1 (Transverse)	137°	17.5°F	0.7372	9.5°F	12.9°F	3.4°F	Yes
	230°	17.5°F	0.9978	19.3°F	17.5°F	-1.8°F	Yes
Surveillance Weld Material (Heat # 3P7317)	137°	1.6°F	0.7372	-0.1°F	1.2°F	1.3°F	Yes
	230°	1.6°F	0.9978	2.5°F	1.6°F	-0.9°F	Yes

Table D-3 Calculation of Residual vs. Fast Fluence					
Capsule	**Fluence (x 10^{19} n/cm^2)**	**Fluence Factor (FF)**	**Measured Shift**	**RG 1.99 Shift (CF*FF)[(a)]**	**Residual (Meas.- RG Shift)**
137°	0.387	0.7372	116.0°F	97.1°F	-18.9°F
230°	0.992	0.9978	132.4°F	131.4°F	-1.0°F

Note:

a. Per NUREG/CR-6551 (Reference D-5), the Cu and Ni values for the Correlation Monitor Material (HSST 01MY, Heat # A-1008) is 0.174 Cu and 0.665 Ni. Using Cu/Ni Tables in Reg. Guide 1.99 Rev. 2, this equates to a Chemistry Factor of 131.7°F.

Appendix D References

D-1 Regulatory Guide 1.99, Revision 2, *Radiation Embrittlement of Reactor Vessel Materials,* U.S. Nuclear Regulatory Commission, May 1998.

D-2 Code of Federal Regulations, 10 CFR 50, Appendix G, *Fracture Toughness Requirements*, and Appendix H, *Reactor Vessel Material Surveillance Program Requirements*, U.S. Nuclear Regulatory Commission, Washington, D.C.

D-3 TR-V-MCM-004, "Summary Report on Manufacture of Test Specimens and Assembly of Capsules for Irradiation Surveillance of Palo Verde Unit 2 Reactor Vessel Materials," A. D. Emery, May 26, 1983.

D-4 NUREG/CR-6413, ORNL/TM-13133, *Analysis of the Irradiation Data for A302B and A533B Correlation Monitor Materials*, April 1996.

D-5 NUREG/CR-6551, *Improved Embrittlement Correlations for Reactor Pressure Vessel Steels*, E. D. Eason, et al., November 1998.