

BAW-2356

September 1999

**Analysis of Capsule W
Virginia Power
North Anna Unit No. 1 Nuclear Power Plant
Reactor Vessel Material Surveillance Program**

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North Anna Unit No. 1 Nuclear Power Plant
-- Reactor Vessel Material Surveillance Program --**

by

M. J. DeVan
E. Giavedoni

FTI Document No. 77-2356-00
(See Section 9 for document signatures.)

Prepared for
Virginia Power

Prepared by
Framatome Technologies, Inc.
3315 Old Forest Road
P. O. Box 10935
Lynchburg, Virginia 24506-0935



Executive Summary

This report describes the results of the examination of the third capsule (Capsule W) of the Virginia Power North Anna Unit No. 1 as part of their reactor vessel surveillance program (RVSP). The objective of the program is to monitor the effects of neutron irradiation on the mechanical properties of the reactor vessel materials by testing and evaluation of tension test and Charpy V-notch impact specimens. The North Anna unit No. 1 RVSP was designed and furnished by Westinghouse Electric Corporation and was based on ASTM Standard E 185-73.

Capsule W was removed from the North Anna Unit No. 1 reactor vessel at the end-of-cycle 13 (EOC-13) for testing and evaluation. The capsule received an average fast fluence of 2.052×10^{19} n/cm² (E > 1.0 MeV). Based on the calculated cycle 11, 12, and 13 full power flux weighted average, the projected end-of-life (32.2 EFPY) peak fast fluence of the North Anna Unit No. 1 reactor vessel beltline region is 4.108×10^{19} n/cm² (E > 1.0 MeV).

The results of the tension tests indicated that the North Anna Unit No. 1 surveillance materials exhibited normal behavior relative to the neutron fluence exposure. The Charpy impact data results for the North Anna Unit No. 1 surveillance materials exhibited the characteristic behavior of transition temperature shifting to a higher temperature as a result of neutron fluence damage and a decrease in upper-shelf energy.

In accordance with Code of Federal Regulations, Title 10, Part 50.61, (10 CFR 50.61), the North Anna Unit No. 1 reactor vessel beltline materials will not exceed the PTS screening criteria before end-of-life (32.2 EFPY).

Acknowledgement

The author acknowledges the efforts of Kevin Hour of the B&W Services, Inc. Lynchburg Technology Center. His expertise in specimen testing contributed greatly to the success of this project.

List of Tables (cont.)

<u>Table</u>	<u>Page</u>
5-6. Charpy Impact Results for North Anna Unit No. 1 Capsule W Heat-Affected-Zone, Irradiated to 2.052×10^{19} n/cm ² (E > 1.0 MeV).....	5-9
5-7. Instrumented Charpy Impact Properties of North Anna Unit No. 1 Capsule W Base Metal Forging 03, Heat No. 990400/292332, Irradiated to 2.052×10^{19} n/cm ² (E > 1.0 MeV) Tangential Orientation	5-10
5-8. Instrumented Charpy Impact Properties of North Anna Unit No. 1 Capsule W Base Metal Forging 03, Heat No. 990400/292332, Irradiated to 2.052×10^{19} n/cm ² (E > 1.0 MeV) Axial Orientation	5-11
5-9. Instrumented Charpy Impact Properties of North Anna Unit No. 1 Capsule W Weld Metal, Wire Heat 25531 / Flux Lot 1221, Irradiated to 2.052×10^{19} n/cm ² (E > 1.0 MeV).....	5-12
5-10. Instrumented Charpy Impact Properties of North Anna Unit No. 1 Capsule W Heat-Affected-Zone Material, Irradiated to 2.052×10^{19} n/cm ² (E > 1.0 MeV).....	5-13
5-11. Hyperbolic Tangent Curve Fit Coefficients for the North Anna Unit No. 1 Capsule W Surveillance Materials.....	5-14
6-1. Neutron Flux and Fluence Spectrum (E > 1.0 MeV) at the Center of North Anna Unit No. 1 Capsule W.....	6-4
6-2. Neutron Flux and Fluence Spectrum (E > 0.1 MeV) at the Center of North Anna Unit No. 1 Capsule W.....	6-5
6-3. North Anna Unit No. 1 Cycle Lengths	6-6
6-4. E > 1.0 MeV Neutron Fluence at the 15°, 25°, 35°, and 45°F Capsule Locations for North Anna Unit No. 1	6-7
6-5. E > 1.0 MeV Inside Surface Peak Neutron Fluence at the North Anna Unit No. 1 Reactor Vessel 0°, 15°, 30°, and 45°	6-9
6-6. E > 1.0 MeV ¼T Location Peak Neutron Fluence at the North Anna Unit No. 1 Reactor Vessel 0°, 15°, 30°, and 45°	6-11
6-7. E > 1.0 MeV ¾T Location Peak Neutron Fluence at the North Anna Unit No. 1 Reactor Vessel 0°, 15°, 30°, and 45°	6-13
6-8. Extrapolated E > 1.0 MeV Neutron Fluence at the North Anna Unit No. 1 Reactor Vessel 0°, 15°, 30°, and 45°	6-15
6-9. E > 1.0 MeV Peak Neutron Fluence at the North Anna Unit No. 1 Reactor Vessel Nozzle-Belt Forging.....	6-16
6-10. Radial Dependence of the Pressure Vessel Neutron Fluence (Relative to the Mid-Plane Inside Surface).....	6-17
6-11. Axial Dependence of the Pressure Vessel Neutron Fluence (Relative to the Mid-Plane Inside Surface).....	6-18

List of Tables (cont.)

<u>Table</u>	<u>Page</u>
6-12. North Anna Unit No. 1 Capsule W C/M Ratios	6-20
7-1. Copper and Nickel Chemical Composition Data for North Anna Unit No. 1 Reactor Vessel Surveillance Base Metal Forging 03 (Heat No. 990400/292332).....	7-4
7-2. Copper and Nickel Chemical Composition Data for North Anna Unit No. 1 Reactor Vessel Surveillance Weld Metal (Wire Heat 25531 / Flux Lot 1211).....	7-4
7-3. Summary of North Anna Unit No. 1 Reactor Vessel Surveillance Capsules Tensile Test Results	7-5
7-4. Measured vs. Predicted 30 ft-lb Transition Temperature Changes for North Anna Unit No. 1 Capsule W Surveillance Materials - 2.052×10^{19} n/cm ²	7-6
7-5. Measured vs. Predicted Upper-Shelf Energy Decreases for North Anna Unit No. 1 Capsule W Surveillance Materials - 2.052×10^{19} n/cm ²	7-7
7-6. Summary of North Anna Unit No. 1 Reactor Vessel Surveillance Capsules Charpy Impact Test Results.....	7-8
7-7. Evaluation of Adjusted Reference Temperatures for the North Anna Unit No. 1 Reactor Vessel Applicable to 32.2 EFPY	7-9
7-8. Evaluation of Pressurized Thermal Shock Reference Temperatures for the North Anna Unit No. 1 Reactor Vessel Applicable to 32.2 EFPY	7-10
A-1. North Anna Unit No. 1 Surveillance Capsule Identification and Original Location...	A-3
A-2. Description of the North Anna Unit No. 1 Reactor Vessel Beltline Region Materials	A-4
A-3. Heat Treatment of the North Anna Unit No. 1 Reactor Vessel Beltline Region Materials	A-5
C-1. Tensile Properties of Unirradiated Base Metal Forging 03, Heat No. 990400/292332, Axial Orientation	C-2
C-2. Tensile Properties of Unirradiated Weld Metal, Wire Heat 25531 / Flux Lot 1211.....	C-2
D-1. Unirradiated Surveillance Charpy V-Notch Impact Data for North Anna Unit No. 1 Base Metal Forging 03, Heat No. 990400/292332, Tangential Orientation.....	D-2
D-2. North Anna Unit No. 1 Capsule V Surveillance Charpy Impact Data for Base Metal Forging 03, Heat No. 990400/292332, Irradiated to 2.63×10^{18} n/cm ² (E > 1.0 MeV) Tangential Orientation	D-3
D-3. North Anna Unit No. 1 Capsule U Surveillance Charpy Impact Data for Base Metal Forging 03, Heat No. 990400/292332, Irradiated to 8.72×10^{18} n/cm ² (E > 1.0 MeV) Tangential Orientation	D-4
D-4. Hyperbolic Tangent Curve Fit Coefficients for North Anna Unit No. 1 Base Metal Forging, Heat No. 990400/292332, Tangential Orientation.....	D-5

List of Tables (cont.)

<u>Table</u>	<u>Page</u>
D-5. Unirradiated Surveillance Charpy V-Notch Impact Data for North Anna Unit No. 1 Base Metal Forging 03, Heat No. 990400/292332, Axial Orientation.....	D-6
D-6. North Anna Unit No. 1 Capsule V Surveillance Charpy Impact Data for Base Metal Forging 03, Heat No. 990400/292332, Irradiated to 2.63×10^{18} n/cm ² (E > 1.0 MeV) Axial Orientation	D-7
D-7. North Anna Unit No. 1 Capsule U Surveillance Charpy Impact Data for Base Metal Forging 03, Heat No. 990400/292332, Irradiated to 8.72×10^{18} n/cm ² (E > 1.0 MeV) Axial Orientation	D-8
D-8. Hyperbolic Tangent Curve Fit Coefficients for North Anna Unit No. 1 Base Metal Forging, Heat No. 990400/292332, Axial Orientation	D-9
D-9. Unirradiated Surveillance Charpy V-Notch Impact Data for North Anna Unit No. 1 Weld Metal, Wire Heat 25531 / Flux Lot 1211.....	D-10
D-10. North Anna Unit No. 1 Capsule V Surveillance Charpy Impact Data for Weld Metal (Wire Heat 25531 / Flux Lot 1211), Irradiated to 2.63×10^{18} n/cm ² (E > 1.0 MeV).....	D-11
D-11. North Anna Unit No. 1 Capsule U Surveillance Charpy Impact Data for Weld Metal (Wire Heat 25531 / Flux Lot 1211), Irradiated to 8.72×10^{18} n/cm ² (E > 1.0 MeV).....	D-12
D-12. Hyperbolic Tangent Curve Fit Coefficients for North Anna Unit No. 1 Weld Metal (Wire Heat 25531 / Flux Lot 1211).....	D-13
D-13. Unirradiated Surveillance Charpy V-Notch Impact Data for North Anna Unit No. 1 Heat-Affected-Zone Material	D-14
D-14. North Anna Unit No. 1 Capsule V Surveillance Charpy Impact Data for Heat-Affect-Zone Material, Irradiated to 2.63×10^{18} n/cm ² (E > 1.0 MeV).....	D-15
D-15. North Anna Unit No. 1 Capsule V Surveillance Charpy Impact Data for Heat-Affected-Zone Material, Irradiated to 8.72×10^{18} n/cm ² (E > 1.0 MeV)	D-16
D-16. Hyperbolic Tangent Curve Fit Coefficients for North Anna Unit No. 1 Heat-Affect-Zone Material.....	D-17
E-1. Comparison of Curve Fit Transition Temperature Shifts for North Anna Unit No. 1 Surveillance Material, Base Metal Forging 03, Heat No. 990400/292332, Tangential Orientation	E-2
E-2. Comparison of Curve Fit Transition Temperature Shifts for North Anna Unit No. 1 Surveillance Material, Base Metal Forging 03, Heat No. 990400/292332, Axial Orientation	E-3
E-3. Comparison of Curve Fit Transition Temperature Shifts for North Anna Unit No. 1 Surveillance Material, Weld Metal (Wire Heat 25531 / Flux Lot 1211)	E-4
E-4. Comparison of Curve Fit Transition Temperature Shifts for North Anna Unit No. 1 Surveillance Material, Heat-Affected-Zone Material.....	E-5

List of Tables (cont.)

<u>Table</u>	<u>Page</u>
F-1. Bias Correction Factors	F-9
F-2. North Anna Unit No. 1 Monthly Power History.....	F-10

List of Figures

<u>Figure</u>	<u>Page</u>
3-1. Reactor Vessel Cross Section Showing Location of RVSP Capsules in North Anna Unit No. 1 Reactor Vessel	3-6
3-2. Surveillance Capsule Assembly Showing Location of Specimens and Monitors for North Anna Unit No. 1 Capsule W.....	3-7
5-1. Photographs of Thermal Monitors Removed from the North Anna Unit No. 1 RVSP Capsule W	5-15
5-2. Tension Test Stress-Strain Curve for Base Metal Forging 03, Heat No. 990400/292332, Axial Orientation, Specimen No. VT5, Tested at 300°F.....	5-16
5-3. Tension Test Stress-Strain Curve for Base Metal Forging 03, Heat No. 990400/292332, Axial Orientation, Specimen No. VT6, Tested at 550°F.....	5-16
5-4. Tension Test Stress-Strain Curve for Weld Metal, Wire Heat 25531 / Flux Lot 1211, Specimen No. VW6, Tested at 200°F	5-17
5-5. Tension Test Stress-Strain Curve for Weld Metal, Wire Heat 25531 / Flux Lot 1211, Specimen No. XW50, Tested at 550°F.....	5-17
5-6. Photographs of Tested Tension Test Specimens and Corresponding Fracture Surfaces – Base Metal Forging, Heat No. 990400/292332, Axial Orientation.....	5-18
5-7. Photographs of Tested Tension Test Specimens and Corresponding Fracture Surfaces – Weld Metal, Wire Heat 25531 / Flux Lot 1211.....	5-19
5-8. Charpy Impact Data for Irradiated Base Metal Forging 03, Heat No. 990400/292332 Tangential Orientation	5-20
5-9. Charpy Impact Data for Irradiated Base Metal Forging 03, Heat No. 990400/292332 Axial Orientation	5-21
5-10. Charpy Impact Data for Irradiated Weld Metal Wire Heat 25531 / Flux Lot 1211.....	5-22
5-11. Charpy Impact Data for Irradiated Heat-Affected-Zone Material.....	5-23
5-12. Photographs of Charpy Impact Specimen Fracture Surfaces, Base Metal Forging 03, Heat No. 990400/292332, Tangential Orientation.....	5-24
5-13. Photographs of Charpy Impact Specimen Fracture Surfaces, Base Metal Forging 03 Heat No. 990400/292332, Axial Orientation.....	5-25

List of Figures (cont.)

<u>Figure</u>	<u>Page</u>
5-14. Photographs of Charpy Impact Specimen Fracture Surfaces, Weld Heat 25531 / Flux Lot 1211	5-26
5-15. Photographs of Charpy Impact Specimen Fracture Surfaces, Heat-Affect-Zone Material	5-27
6-1. North Anna Unit No. 1 Capsule W Plan View.....	6-21
6-2. Relative $E > 1.0$ MeV Neutron Fluence	6-22
6-3. $E > 1.0$ MeV Neutron Fluence at the 15°, 25°, 35°, and 45° Capsule Locations for North Anna Unit No. 1	6-23
6-4. Extrapolated $E > 1.0$ MeV Inside Surface Neutron Fluence at the North Anna Unit No. 1 Reactor Vessel 0°, 15°, 30°, and 45° Locations.....	6-24
6-5. Extrapolated $E > 1.0$ MeV $\frac{1}{4}$ T Neutron Fluence at the North Anna Unit No. 1 Reactor Vessel 0°, 15°, 30°, and 45° Locations	6-25
6-6. Extrapolated $E > 1.0$ MeV $\frac{3}{4}$ T Neutron Fluence at the North Anna Unit No. 1 Reactor Vessel 0°, 15°, 30°, and 45° Locations	6-26
6-7. Radial Dependence of the Pressure Vessel Neutron Fluence (Relative to the Mid-Plane Inside Surface).....	6-27
6-8. Axial Dependence of the Pressure Vessel Neutron Fluence (Relative to the Mid-Plane Inside Surface).....	6-28
A-1. Location and Identification of Materials Used in the Fabrication of the North Anna Unit No. 1 Reactor Pressure Vessel.....	A-6
A-2. Location of Surveillance Capsule Irradiation Sites in the North Anna Unit No. 1 Reactor Vessel	A-7
B-1. Load-Time Trace for Charpy V-Notch Impact Specimen VL23	B-2
B-2. Load-Time Trace for Charpy V-Notch Impact Specimen VL17	B-2
B-3. Load-Time Trace for Charpy V-Notch Impact Specimen VL22	B-3
B-4. Load-Time Trace for Charpy V-Notch Impact Specimen VL24	B-3
B-5. Load-Time Trace for Charpy V-Notch Impact Specimen VL21	B-4
B-6. Load-Time Trace for Charpy V-Notch Impact Specimen VL18	B-4
B-7. Load-Time Trace for Charpy V-Notch Impact Specimen VL20	B-5
B-8. Load-Time Trace for Charpy V-Notch Impact Specimen VL19	B-5
B-9. Load-Time Trace for Charpy V-Notch Impact Specimen VT30	B-6
B-10. Load-Time Trace for Charpy V-Notch Impact Specimen VT26	B-6
B-11. Load-Time Trace for Charpy V-Notch Impact Specimen VT28	B-7
B-12. Load-Time Trace for Charpy V-Notch Impact Specimen VT35	B-7
B-13. Load-Time Trace for Charpy V-Notch Impact Specimen VT31	B-8

List of Figures (cont.)

<u>Figure</u>	<u>Page</u>
B-14. Load-Time Trace for Charpy V-Notch Impact Specimen VT34	B-8
B-15. Load-Time Trace for Charpy V-Notch Impact Specimen VT32	B-9
B-16. Load-Time Trace for Charpy V-Notch Impact Specimen VT33	B-9
B-17. Load-Time Trace for Charpy V-Notch Impact Specimen VT29	B-10
B-18. Load-Time Trace for Charpy V-Notch Impact Specimen VT27	B-10
B-19. Load-Time Trace for Charpy V-Notch Impact Specimen VT36	B-11
B-20. Load-Time Trace for Charpy V-Notch Impact Specimen VT25	B-11
B-21. Load-Time Trace for Charpy V-Notch Impact Specimen VW36	B-12
B-22. Load-Time Trace for Charpy V-Notch Impact Specimen VW27	B-12
B-23. Load-Time Trace for Charpy V-Notch Impact Specimen VW33	B-13
B-24. Load-Time Trace for Charpy V-Notch Impact Specimen VW30	B-13
B-25. Load-Time Trace for Charpy V-Notch Impact Specimen VW29	B-14
B-26. Load-Time Trace for Charpy V-Notch Impact Specimen VW26	B-14
B-27. Load-Time Trace for Charpy V-Notch Impact Specimen VW34	B-15
B-28. Load-Time Trace for Charpy V-Notch Impact Specimen VW35	B-15
B-29. Load-Time Trace for Charpy V-Notch Impact Specimen VW31	B-16
B-30. Load-Time Trace for Charpy V-Notch Impact Specimen VW32	B-16
B-31. Load-Time Trace for Charpy V-Notch Impact Specimen VW25	B-17
B-32. Load-Time Trace for Charpy V-Notch Impact Specimen VW28	B-17
B-33. Load-Time Trace for Charpy V-Notch Impact Specimen VH28.....	B-18
B-34. Load-Time Trace for Charpy V-Notch Impact Specimen VH34.....	B-18
B-35. Load-Time Trace for Charpy V-Notch Impact Specimen VH29.....	B-19
B-36. Load-Time Trace for Charpy V-Notch Impact Specimen VH27.....	B-19
B-37. Load-Time Trace for Charpy V-Notch Impact Specimen VH25.....	B-20
B-38. Load-Time Trace for Charpy V-Notch Impact Specimen VH31.....	B-20
B-39. Load-Time Trace for Charpy V-Notch Impact Specimen VH26.....	B-21
B-40. Load-Time Trace for Charpy V-Notch Impact Specimen VH36.....	B-21
B-41. Load-Time Trace for Charpy V-Notch Impact Specimen VH30.....	B-22
B-42. Load-Time Trace for Charpy V-Notch Impact Specimen VH33.....	B-22
B-43. Load-Time Trace for Charpy V-Notch Impact Specimen VH32.....	B-23
B-44. Load-Time Trace for Charpy V-Notch Impact Specimen VH35.....	B-23
D-1. Unirradiated Surveillance Charpy V-Notch Impact Data for North Anna Unit No. 1 Base Metal Forging 03, Heat No. 990400/292332, Tangential Orientation - Refitted Using Hyperbolic Tangent Curve-Fitting Method -.....	D-18

List of Figures (cont.)

<u>Figure</u>	<u>Page</u>
D-2. North Anna Unit No. 1 Capsule V Surveillance Charpy Impact Data for Base Metal Forging 03, Heat No. 990400/292332, Tangential Orientation - Refitted Using Hyperbolic Tangent Curve-Fitting Method	D-19
D-3. North Anna Unit No. 1 Capsule U Surveillance Charpy Impact Data for Base Metal Forging 03, Heat No. 990400/292332, Axial Orientation - Refitted Using Hyperbolic Tangent Curve-Fitting Method	D-20
D-4. Unirradiated Surveillance Charpy V-Notch Impact Data for North Anna Unit No. 1 Base Metal Forging 03, Heat No. 990400/292332, Axial Orientation - Refitted Using Hyperbolic Tangent Curve-Fitting Method	D-21
D-5. North Anna Unit No. 1 Capsule V Surveillance Charpy Impact Data for Base Metal Forging 03, Heat No. 990400/292332, Axial Orientation - Refitted Using Hyperbolic Tangent Curve-Fitting Method	D-22
D-6. North Anna Unit No. 1 Capsule U Surveillance Charpy Impact Data for Base Metal Forging 03, Heat No. 990400/292332, Axial Orientation - Refitted Using Hyperbolic Tangent Curve-Fitting Method	D-23
D-7. Unirradiated Surveillance Charpy V-Notch Impact Data for North Anna Unit No. 1 Weld Metal (Wire Heat 25531 / Flux Lot 1211) - Refitted Using Hyperbolic Tangent Curve-Fitting Method	D-24
D-8. North Anna Unit No. 1 Capsule V Surveillance Charpy Impact Data for Weld Metal (Wire Heat 25531 / Flux Lot 1211) - Refitted Using Hyperbolic Tangent Curve-Fitting Method	D-25
D-9. North Anna Unit No. 1 Capsule U Surveillance Charpy Impact Data for Weld Metal (Wire Heat 25531 / Flux Lot 1211) - Refitted Using Hyperbolic Tangent Curve-Fitting Method	D-26
D-10. Unirradiated Surveillance Charpy V-Notch Impact Data for North Anna Unit No. 1 Heat-Affected-Zone Material - Refitted Using Hyperbolic Tangent Curve-Fitting Method	D-27
D-11. North Anna Unit No. 1 Capsule V Surveillance Charpy Impact Data for Heat-Affected-Zone Material - Refitted Using Hyperbolic Tangent Curve-Fitting Method	D-28
D-12. North Anna Unit No. 1 Capsule U Surveillance Charpy Impact Data for Heat-Affected-Zone Material - Refitted Using Hyperbolic Tangent Curve-Fitting Method	D-29
F-1. Fluence Analysis Methodology for North Anna Unit No. 1 Capsule W.....	F-23

1. Introduction

This report presents the examination results of the third reactor vessel surveillance capsule (Capsule W) removed from the Virginia Power's North Anna Unit No. 1 reactor vessel. The capsule was removed and the contents evaluated after being irradiated in the North Anna Unit No. 1 reactor as part of the reactor vessel surveillance program (RVSP) as documented in WCAP-8771.^[1] This report describes the testing and the post-irradiation data obtained from the North Anna Unit No. 1 Capsule W after receiving an average fluence of 2.052×10^{19} n/cm² ($E > 1.0$ MeV). The data are compared to previous North Anna Unit No. 1 RVSP results from Capsule V^[2] and Capsule U.^[3]

The objective of the program is to monitor the effects of neutron irradiation on the mechanical properties of reactor vessel materials under actual plant operating conditions. The program was planned to monitor the effects of neutron irradiation on the reactor vessel materials for the 40-year design life of the reactor pressure vessel. The North Anna Unit No. 1 RVSP was designed and furnished by Westinghouse Electric Corporation and was based on American Society for Testing and Materials (ASTM) Standard E 185-73.^[4]

2. Background

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

Code of Federal Regulation, Title 10, Part 50, (10 CFR 50) Appendix G, "*Fracture Toughness Requirements*,"^[5] specifies minimum fracture toughness requirements for the ferritic materials of the pressure-retaining components of the reactor coolant pressure boundary (RCPB) of light water-cooled power reactors and provides specific guidelines for determining the pressure-temperature limitations for operation of the RCPB. The fracture toughness and operational requirements are specified to provide adequate safety margins during any condition of normal operation, including anticipated operational occurrences and system hydrostatic tests, to which the pressure boundary may be subjected over its service lifetime. Although the requirements of 10 CFR 50, Appendix G, became effective on August 16, 1973, the requirements are applicable to all boiling and pressurized water-cooled nuclear power reactors, including those under construction or in operation on the effective date.

10 CFR 50, Appendix H, "*Reactor Vessel Materials Surveillance Program Requirements*,"^[6] defines the material surveillance program required to monitor changes in the fracture toughness properties of ferritic materials in the reactor vessel beltline region of water-cooled reactors resulting from exposure to neutron irradiation and the thermal environment. Fracture toughness test data are obtained from material specimens contained in capsules that are periodically withdrawn from the reactor vessel. These data permit determination of the conditions under

which the vessel can be operated with adequate safety margins against non-ductile fracture throughout its service life.

A method for guarding against non-ductile fracture in reactor vessels is described in Appendix G to the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (B&PV) Code, Section III, "*Nuclear Power Plant Components*"^[7] and Section XI, "*Rules for Inservice Inspection*."^[8] This method uses fracture mechanics concepts and the reference nil-ductility temperature, RT_{NDT} , which is defined as the greater of the drop weight nil-ductility transition temperature (in accordance with ASTM E 208-81^[9]) or the temperature that is 60°F below that at which the material exhibits 50 ft-lbs and 35 mils lateral expansion. The RT_{NDT} of a given material is used to index that material to a reference stress intensity factor curve (K_{IR} curve), which appears in Appendix G of ASME B&PV Code Section III and Section XI. The K_{IR} curve is a lower bound of dynamic and crack arrest fracture toughness data obtained from several heats of pressure vessel steel. When a given material is indexed to the K_{IR} curve, allowable stress intensity factors can be obtained for the material as a function of temperature. The operating limits can then be determined using these allowable stress intensity factors.

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

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

3. Surveillance Program Description

The reactor vessel surveillance program for North Anna Unit No. 1 includes eight capsules designed to monitor the effects of neutron and thermal environment on the materials of the reactor pressure vessel core region. The capsules, which were inserted into the reactor vessel before initial plant startup, were positioned inside the reactor vessel between the thermal shield and the vessel wall at the locations shown in Figure 3-1. WCAP-8771 includes a full description of the capsule locations and design. Capsule W was irradiated in the 245° position during the time of irradiation in the reactor vessel (cycles 1 through 13).

Capsule W was removed during the thirteenth refueling shutdown of the North Anna Unit No. 1 plant. The capsule contained Charpy V-notch (CVN) impact test specimens fabricated from one base metal forging (SA-508, Class 2), heat-affected-zone (HAZ) material, and a weld metal representative of the North Anna Unit No. 1 reactor vessel beltline region intermediate to lower shell circumferential weld. The tensile test specimens were fabricated from the same base metal forging and weld metal. In addition, wedge opening loading (WOL) specimens, fabricated from the base metal forging, were included in the capsule. The number of specimens of each material contained in Capsule W is described in Table 3-1, and the location of the individual specimens within the capsule is shown in Figure 3-2. The chemical compositions of the surveillance materials in Capsule W, obtained from the original surveillance program report,^[1] are described in Table 3-2. In addition, a chemical analysis was performed on an irradiated Charpy base metal specimen (VT-71) and weld metal specimen (VW-71) from Capsule U.^[3] The heat treatment of the surveillance materials in Capsule W is presented in Table 3-3.

All base metal specimens were machined from the ¼-thickness (¼T) location of the forging material after stress relieving. The base metal, HAZ material, and weld metal specimens were oriented such that the longitudinal axis of the specimen was either parallel or perpendicular to the principal working direction of the forging.

Capsule W contained dosimeter wires of copper, iron, nickel, and aluminum-0.15 weight percent cobalt (cadmium-shielded and unshielded) and cadmium-shielded neptunium-237 (²³⁷Np) and uranium-238 (²³⁸U). The location of these dosimeters within Capsule W is shown in Figure 3-2.

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

2.5% Ag, 97.5% Pb

Melting Point 579°F

1.75% Ag, 0.75% Sn, 97.5% Pb

Melting Point 590°F

Table 3-1. Test Specimens Contained in North Anna Unit No. 1 Capsule W

Material Description	Number of Test Specimens		
	Tension	CVN Impact	WOL
Base Metal Forging 03 (Heat No. 990400/292332)			
Tangential	--	8	--
Axial	2	12	4
HAZ Metal	--	12	--
Weld Metal (Wire Ht. 25531 / Flux Lot 1211)	2	12	--
Total	4	44	4

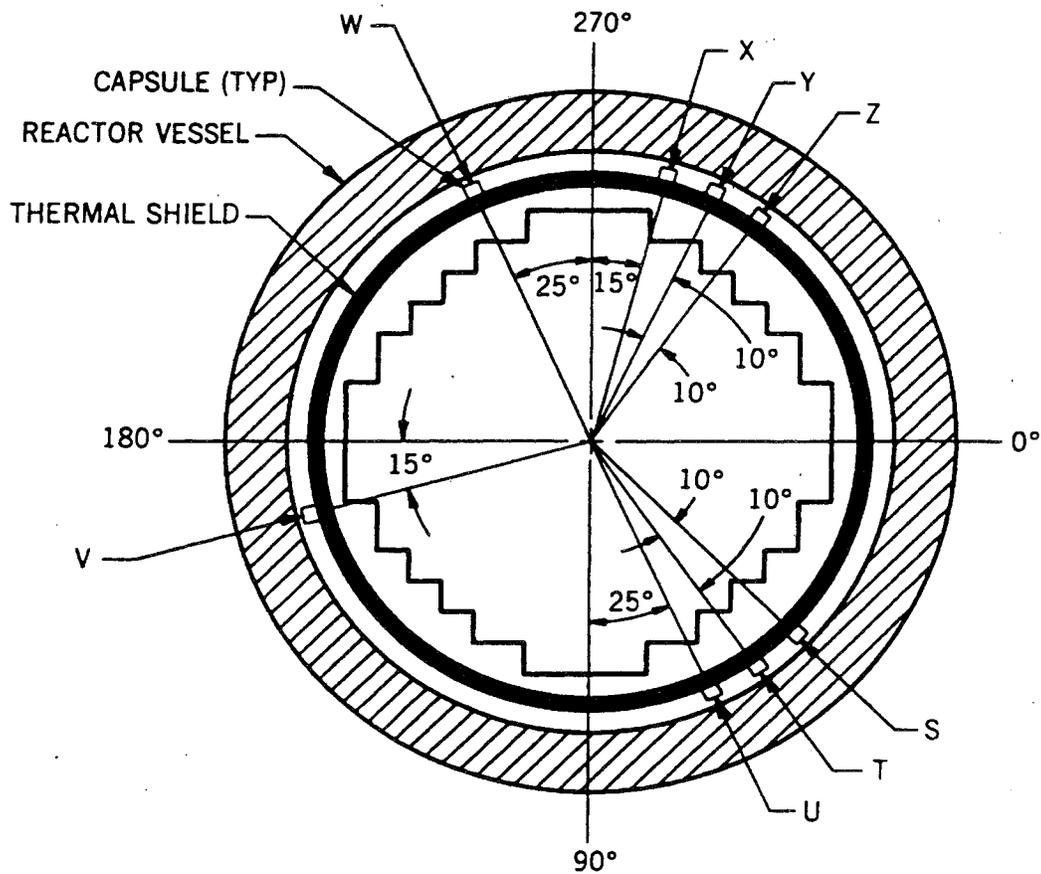
**Table 3-2. Chemical Composition of North Anna Unit No. 1 Capsule W
Surveillance Materials**

Element	Chemical Composition, wt%				
	Base Metal Forging 03 Heat No. 990400/292332			Weld Metal (Wire Ht. 25531 / Flux Lot 1211)	
	Westinghouse Analysis ^[1]	Rotterdam Dockyard Check Analysis ^[1]	Irradiated Charpy Specimen VT-71 ^[3]	Westinghouse Analysis ^[1]	Irradiated Charpy Specimen VW-71 ^[3]
C	0.20	0.19	---	0.06	---
Mn	0.68	0.68	0.749	1.29	1.45
P	0.019	0.010	0.010	0.020	0.022
S	0.011	0.014	---	0.012	---
Si	0.26	0.22	---	0.35	---
Ni	0.79	0.80	0.893	0.11	0.152
Mo	0.61	0.63	0.671	0.49	0.537
Cr	0.30	0.30	0.379	0.025	0.057
Cu	0.16	0.15	0.158	0.086	0.124
Al	0.021	---	---	0.009	---
Co	0.020	---	0.021	0.006	0.02
V	0.037	0.02	0.031	0.001	0.006
Sn	0.017	---	---	0.003	---
N ₂	0.015	---	---	0.015	---

Table 3-3. Heat Treatment of North Anna Unit No. 1 Capsule W Surveillance Materials

Material	Heat Treatment
Base Metal Forging 03 Heat No. 990400/292332	1616-1725°F for 2½ hrs., water quenched 1202-1292°F for 7½ hrs., furnace cooled 1130±25°F for 14¾ hrs., furnace cooled
Weld Metal (Wire Ht. 25531 / Flux Lot 1211)	1130±25°F for 10¾ hrs., furnace cooled

Figure 3-1. Reactor Vessel Cross Section Showing Original Locations of RVSP Capsules in North Anna Unit No. 1 Reactor Vessel.





4. Tests of Unirradiated Material

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

Westinghouse Electric Corporation, as part of the development of the North Anna Unit No. 1 RVSP, performed the testing of the unirradiated surveillance material. The details of the testing procedures are described in Westinghouse Electric Corporation Report WCAP-8771. The unirradiated mechanical properties for the North Anna Unit No. 1 RVSP materials are summarized in Appendices C and D of this report.

The original unirradiated Charpy V-notch impact data were evaluated based on hand-fit Charpy curves generated using engineering judgment. These data were re-evaluated herein using a hyperbolic tangent curve-fitting program, and the results of the re-evaluation are presented in Appendix D. In addition, Appendix E contains a comparison of the Charpy V-notch shift results for each surveillance material, hand-fit versus hyperbolic tangent curve-fit.



5. Post-Irradiation Testing

The post-irradiation testing of the tension test specimens, the Charpy V-notch impact specimens, thermal monitors, and dosimeters for the North Anna Unit No. 1 Capsule W was performed at the BWX Technologies, Lynchburg Technology Center (LTC).^[10]

5.1. Capsule Disassembly and Inventory

After capsule disassembly, the contents of Capsule W were inventoried and found to be consistent with the surveillance program report inventory (WCAP-8771). The capsule contained a total of 44 standard Charpy V-notch specimens, four (4) tensile specimens, four (4) WOL specimens, six (6) dosimetry blocks, and two (2) temperature monitors.

5.2. Thermal Monitors

The low-melting point (579°F and 590°F) eutectic alloys contained in Capsule W were x-rayed to reveal the shape of the monitors and examined for evidence of melting. No indication of melting was observed (see Figure 5-1). Therefore, based on this examination, the maximum temperature that the capsule test specimens were exposed to was less than 579°F.

5.3. Chemical Analysis Check Analysis

One tested irradiated base metal Charpy specimen and one tested irradiated weld metal Charpy specimen were analyzed to determine their chemical compositions. A small sample was removed from Specimen VT-36 (base metal) and from Specimen VW-29 (weld metal). Each sample was analyzed using the inductively coupled plasma (ICP) method to determine the following chemical constituents: manganese (Mn), phosphorous (P), sulfur (S), silicon (Si), nickel, (Ni), chromium (Cr), molybdenum (Mo), copper (Cu), cobalt (Co), vanadium (V). The results of the analyses are presented in Table 5-1.

5.4. Tension Test Results

The results of the post-irradiation tension test are presented in Table 5-2, and the stress-strain curves are presented in Figures 5-2 through 5-5. For the base metal Forging 03 material tests were performed at 300°F and 550°F, and for the weld metal material tests were performed at

200° and 550°F. The tests were performed using a MTS servohydraulic test machine. All tension tests were run using stroke control with an initial actuator travel rate of 0.0075 inch per minute. Following specimen yielding, an actuator speed of 0.03 inch per minute was used. The tension testing was performed in accordance with the applicable requirements of ASTM Standard E 21-92.^[11] Photographs of the tension test specimen fractured surfaces are shown in Figures 5-6 and 5-7.

5.5. Charpy V-Notch Impact Test Results

The Charpy V-notch impact testing was performed in accordance with the applicable requirements of ASTM Standard E 23-91.^[12] Impact energy, lateral expansion, and percent shear fracture were measured at numerous test temperatures and recorded for each specimen. The impact energy was measured using a certified Satec S1-1K Impact tester (traceable to NIST Standard) with a striker velocity of 16.90 ft/sec and 240 ft-lb of available energy. The lateral expansion was measured using a certified dial indicator. The specimen percent shear was estimated by video examination and comparison with the visual standards presented in ASTM Standard E 23-91. In addition, all Charpy V-notch impact testing was performed using instrumentation to record a load-versus-time trace and energy-versus-time trace for each impact event. The load-versus-time traces were analyzed to determine time, load, and impact energy for general yielding, maximum load, fast fracture, and crack arrest properties during the test. The dynamic yield stress is calculated from the three-point bend formula:

$$\sigma_y = 33.33 * (\text{general yielding load})$$

The dynamic flow stress is calculated from the average of the yield and maximum loads, also using the three-point bend formula:

$$\sigma_{flow} = 33.33 * \left(\frac{(\text{general yielding load} + \text{maximum load})}{2} \right)$$

The results of the Charpy V-notch impact testing are shown in Tables 5-3 through 5-10 and Figures 5-8 through 5-11. The curves were generated using a hyperbolic tangent curve-fitting program to produce the best-fit curve through the data. The hyperbolic tangent (TANH) function (test response, i.e., absorbed energy, lateral expansion, and percent shear fracture,

“R,” as a function of test temperature, “T”) used to evaluate the surveillance data is as follows:

$$R = A + B * \tanh \left[\frac{(T - T_0)}{C} \right]$$

The Charpy V-notch data was entered, and the coefficients A , B , T_0 , and C are determined by the program minimizing the sum of the errors squared (least-squares fit) of the data points about the fitted curve. Using these coefficients and the above TANH function, a smooth curve is generated through the data for interpretation of the material transition region behavior. The coefficients determined for irradiated materials in Capsule W are shown in Table 5-11.

Photographs of the Charpy V-notch specimen fracture surfaces are presented in Figures 5-12 through 5-15.

5.6. Wedge Opening Loading Specimens

The wedge opening loading (WOL) specimens were not tested at the request of Virginia Power. The specimens are to be stored at the BWX Technologies LTC facility for possible future testing.

Table 5-1. Chemical Analysis Results of Selected Base Metal and Weld Metal Irradiated Charpy Specimens

Element	Chemical Composition, wt%	
	Irradiated Charpy Specimen VT-36	Irradiated Charpy Specimen VW-29
Mn	0.685	1.39
P	0.0631 ^(a)	0.09
S	<0.0536 ^(b)	0.04 ^(a)
Si	0.248 ^(a)	0.32 ^(a)
Ni	0.785	0.11
Mo	0.701	0.57
Cr	0.323	0.03
Cu	0.155	0.0839
Co	0.0184	0.0188
V	0.0415	< 0.0016 ^(b)

(a) Analyte present. Reported value is estimated; concentration is below the level for accurate qualification.

(b) Below minimum detection limit.

Table 5-2. Tensile Properties of North Anna Unit No. 1 Capsule W Reactor Vessel Surveillance Materials, Irradiated to 2.052×10^{19} n/cm² (E > 1.0 MeV)

Material	Specimen No.	Test Temp. (°F)	Strength		Fracture Properties			Elongation		Reduction in Area (%)
			Yield (ksi)	Ultimate (ksi)	Load (lb)	Stress (ksi)	Strength (ksi)	Uniform (%)	Total (%)	
Base Metal Forging 03 Heat No. 990400/292332 (Axial)	VT5	300	78.5	98.7	3706	142	75.5	7.31	14.4	47.0
	VT6	550	78.1	101.6	3908	114	79.6	8.57	13.1	30.4
Weld Metal (Wire Ht. 25531 / Flux Lot 1211)	VW6	200	73.0	86.8	3124	162	63.6	5.48	16.0	60.8
	VW5	550	72.9	89.2	3639	144	74.1	5.73	14.2	48.6

**Table 5-3. Charpy V-Notch Impact Results for North Anna Unit No. 1 Capsule W
Base Metal Forging 03, Heat No. 990400/292332,
Irradiated to 2.052×10^{19} n/cm² (E > 1.0 MeV)
Tangential Orientation**

Specimen ID	Test Temperature, °F	Impact Energy, ft-lbs	Lateral Expansion, mil	Shear Fracture, %
VL23	74	26.5	15	15
VL17	104	26.5	21	30
VL22	104	38.5	31	40
VL24	129	54.5	43	60
VL21	204	73.0	56	75
VL18	304	93.5*	76	100
VL20	354	93.5*	77	100
VL19	404	97.0*	83	100

* Value used to determine upper-shelf energy (USE) in accordance with ASTM Standard E 185-82.^[13]

**Table 5-4. Charpy V-Notch Impact Results for North Anna Unit No. 2 Capsule W
Base Metal Forging 03, Heat No. 990400/292332,
Irradiated to 2.052×10^{19} n/cm² (E > 1.0 MeV)
Axial Orientation**

Specimen ID	Test Temperature, °F	Impact Energy, ft-lbs	Lateral Expansion, mil	Shear Fracture, %
VT30	74	13.5	6	0
VT26	104	16.0	10	20
VT28	104	23.5	21	30
VT35	129	34.5	31	35
VT31	154	39.0	34	45
VT34	179	39.0	36	50
VT32	204	51.5	46	85
VT33	204	40.0	35	50
VT29	254	67.0	61	95
VT27	304	64.5*	60	100
VT36	354	69.5*	64	100
VT25	404	64.0*	65	100

*Value used to determine upper-shelf energy (USE) in accordance with ASTM Standard E 185-82.^[13]

**Table 5-5. Charpy V-Notch Impact Results for North Anna Unit No. 1 Capsule W
Weld Metal, Wire Heat 25531 / Flux Lot 1211,
Irradiated to 2.052×10^{19} n/cm² (E > 1.0 MeV)**

Specimen ID	Test Temperature, °F	Impact Energy, ft-lbs	Lateral Expansion, mil	Shear Fracture, %
VW36	-76	8.5	7	0
VW27	-36	10.5	6	0
VW33	-36	30.0	26	0
VW30	4	14.0	14	10
VW29	44	31.5	29	45
VW26	74	23.5	22	45
VW34	74	44.5	40	55
VW35	104	42.5	42	55
VW31	129	61.5	55	75
VW32	204	81.5*	70	100
VW25	304	72.5*	71	100
VW28	404	69.0*	70	100

*Value used to determine upper-shelf energy (USE) in accordance with ASTM Standard E 185-82.^[13]

**Table 5-6. Charpy V-Notch Impact Results for North Anna Unit No. 1 Capsule W
Heat-Affected-Zone Material,
Irradiated to 2.052×10^{19} n/cm² (E > 1.0 MeV)**

Specimen ID	Test Temperature, °F	Impact Energy, ft-lbs	Lateral Expansion, mil	Shear Fracture, %
VH28	-76	21.0	19	0
VH34	-36	8.0	5	5
VH29	4	30.5	15	10
VH27	44	56.0	37	60
VH25	74	91.0	55	N/A
VH31	74	10.5	5	10
VH26	104	36.0	30	65
VH36	104	36.5	32	55
VH30	129	82.5	58	65
VH33	204	92.5*	71	100
VH32	304	80.0*	64	100
VH35	404	95.5*	69	100

*Value used to determine upper-shelf energy (USE) in accordance with ASTM Standard E 185-82.^[13]

**Table 5-7. Instrumented Charpy V-Notch Properties of North Anna Unit No. 1 Capsule W, Base Metal Forging 03,
Heat No. 990400/292332, Irradiated to 2.052×10^{19} n/cm² (E > 1.0 MeV)
Tangential Orientation**

Specimen ID	Test Temp. (F)	Charpy Energy (ft-lbf)	Yield Properties			Maximum Load Properties			Fast Fracture Properties			Crack Arrest Properties			Propagation Load Properties		Total Energy Properties		Yield Stress (ksi)	Flow Stress (ksi)
			Time (μsec)	Load (lbf)	Energy (ft-lbf)	Time (μsec)	Load (lbf)	Energy (ft-lbf)	Time (μsec)	Load (lbf)	Energy (ft-lbf)	Time (μsec)	Load (lbf)	Energy (ft-lbf)	Load (lbf)	Energy (ft-lbf)	Time (μsec)	Energy (ft-lbf)		
VL23	74	26.5	151	3793	5.4	395	4499	22.7	395	4499	22.7	453	0	25.2	4517	2.6	453	25.2	126.4	138.2
VL17	104	26.5	169	3606	5.7	387	4345	20.7	387	4345	20.7	452	0	23.2	4359	2.5	452	23.2	120.2	132.5
VL22	104	38.5	163	3646	5.0	539	4632	32.0	569	4575	34.4	640	0	37.3	4598	5.3	640	37.3	121.5	138.0
VL24	129	54.5	164	3531	4.8	622	4566	37.0	752	4340	46.8	872	789	50.4	3551	18.3	2860	55.3	117.7	134.9
VL21	204	73.0	186	3455	4.4	646	4460	35.4	1000	3834	60.4	1104	2001	65.2	1833	42.8	3078	78.2	115.2	131.9
VL18	304	93.5	164	3172	5.0	616	4170	34.5	N/A	N/A	N/A	N/A	N/A	N/A	0	66.8	3444	101.3	105.7	122.4
VL20	354	93.5	160	3112	4.8	612	4138	33.9	N/A	N/A	N/A	N/A	N/A	N/A	0	66.9	3406	100.9	103.7	120.8
VL19	404	97.0	166	2960	4.4	624	4039	32.4	N/A	N/A	N/A	N/A	N/A	N/A	0	70.8	3840	103.2	98.7	116.6

**Table 5-8. Instrumented Charpy V-Notch Properties of North Anna Unit No. 1 Capsule W, Base Metal Forging 03,
Heat No. 990400/292332, Irradiated to 2.052×10^{19} n/cm² (E > 1.0 MeV)
Axial Orientation**

Specimen ID	Test Temp. (F)	Charpy Energy (ft-lbf)	Yield Properties			Maximum Load Properties			Fast Fracture Properties			Crack Arrest Properties			Propagation Load Properties		Total Energy Properties		Yield Stress (ksi)	Flow Stress (ksi)
			Time (μsec)	Load (lbf)	Energy (ft-lbf)	Time (μsec)	Load (lbf)	Energy (ft-lbf)	Time (μsec)	Load (lbf)	Energy (ft-lbf)	Time (μsec)	Load (lbf)	Energy (ft-lbf)	Load (lbf)	Energy (ft-lbf)	Time (μsec)	Energy (ft-lbf)		
VT30	74	13.5	148	3687	5.0	218	3855	9.4	218	3855	9.4	270	0	11.3	3857	1.9	270	11.3	122.9	125.7
VT26	104	16.0	164	3609	4.9	255	3963	10.6	255	3963	10.6	364	637	13.1	3326	4.4	1170	15.0	120.3	126.2
VT28	104	23.5	156	3577	4.9	343	4214	17.1	360	4177	18.3	429	2.3	20.8	4175	3.7	429	20.8	119.2	129.8
VT35	129	34.5	164	3462	5.4	492	4283	27.6	497	4280	28	614	741	31.1	3540	6.0	1729	33.6	115.4	129.1
VT31	154	39.0	168	3411	5.3	533	4347	30.1	533	4347	30.1	661	902	34.5	3445	8.8	1766	38.9	113.7	129.3
VT34	179	39.0	170	3321	5.3	434	4145	22.4	434	4145	22.4	554	2011	27.4	2144	17.3	2814	39.7	110.7	124.4
VT32	204	51.5	168	3266	5.0	532	4039	28.5	536	4039	28.8	702	2742	38.3	1297	24.8	2656	53.4	108.9	121.7
VT33	204	40.0	172	3303	5.2	370	3892	17.5	370	3892	17.5	486	2277	22.8	1615	22.9	3060	40.4	110.1	119.9
VT29	254	67.0	138	3048	3.5	538	4158	28.9	894	3140	52	982	1645	55.3	1495	40.2	3018	69.0	101.6	120.1
VT27	304	64.5	158	3048	4.6	524	3871	27.0	N/A	N/A	N/A	N/A	N/A	N/A	0	39.8	2958	66.8	101.6	115.3
VT36	354	69.5	168	3045	5.0	530	3935	27.2	N/A	N/A	N/A	N/A	N/A	N/A	0	45.5	2920	72.7	101.5	116.3
VT25	404	64.0	164	2972	4.8	534	3864	27.0	N/A	N/A	N/A	N/A	N/A	N/A	0	39.4	3006	66.4	99.1	113.9

**Table 5-9. Instrumented Charpy V-Notch Properties of North Anna Unit No. 1 Capsule W, Weld Metal,
Wire Heat 25531 / Flux Lot 1211, Irradiated to 2.052×10^{19} n/cm² (E > 1.0 MeV)**

Specimen ID	Test Temp. (F)	Charpy Energy (ft-lbf)	Yield Properties			Maximum Load Properties			Fast Fracture Properties			Crack Arrest Properties			Propagation Load Properties		Total Energy Properties		Yield Stress (ksi)	Flow Stress (ksi)
			Time (μsec)	Load (lbf)	Energy (ft-lbf)	Time (μsec)	Load (lbf)	Energy (ft-lbf)	Time (μsec)	Load (lbf)	Energy (ft-lbf)	Time (μsec)	Load (lbf)	Energy (ft-lbf)	Load (lbf)	Energy (ft-lbf)	Time (μsec)	Energy (ft-lbf)		
VW36	-76	8.5	133	3632	3.7	160	3767	5.4	160	3767	5.4	224	0	8.0	3795	2.6	224	8.0	121.1	123.3
VW27	-36	10.5	161	3650	5.2	208	3675	8.2	208	3675	8.2	262	16.1	10.2	3659	2.0	262	10.2	121.7	122.1
VW33	-36	30.0	155	3583	5.1	509	4140	28.7	509	4140	28.7	566	2.3	31.1	4154	2.4	566	31.1	119.4	128.7
VW30	4	14.0	154	3482	4.5	253	3664	10.4	253	3664	10.4	319	0	12.8	3662	2.5	319	12.8	116.1	119.1
VW29	44	31.5	141	3255	4.2	496	3853	25.8	496	3853	25.8	604	828	28.9	3025	5.4	1712	31.2	108.5	118.5
VW26	74	23.5	140	3186	4.1	244	3443	9.9	244	3443	9.9	381	2001	15.6	1442	13.8	1476	23.6	106.2	110.5
VW34	74	44.5	136	3080	4.0	697	3993	38.7	697	3993	38.7	843	885	44.1	3048	7.5	1383	46.2	102.7	117.9
VW35	104	42.5	148	2946	3.6	626	3813	32.0	668	3802	34.7	790	796	38.1	3006	11.1	2488	43.2	98.2	112.6
VW31	129	61.5	142	2834	3.5	708	3685	36.4	908	3494	48.6	1130	1240	55.9	2254	27.6	2760	64.0	94.5	108.6
VW32	204	81.5	142	2677	3.4	710	3632	35.4	N/A	N/A	N/A	N/A	N/A	N/A	0	51.5	3142	86.9	89.2	105.1
VW25	304	72.5	144	2544	3.4	620	3397	28.4	N/A	N/A	N/A	N/A	N/A	N/A	0	47.2	2760	75.5	84.8	99.0
VW28	404	69.0	146	2468	3.5	622	3257	27.6	N/A	N/A	N/A	N/A	N/A	N/A	0	43.4	2868	71.0	82.3	95.4

5-12.

**Table 5-10. Instrumented Charpy V-Notch Properties of North Anna Unit No. 1 Capsule W,
Heat-Affect-Zone Material, Irradiated to 2.052×10^{19} n/cm² (E > 1.0 MeV)**

Specimen ID	Test Temp. (F)	Charpy Energy (ft-lbf)	Yield Properties			Maximum Load Properties			Fast Fracture Properties			Crack Arrest Properties			Propagation Load Properties		Total Energy Properties		Yield Stress (ksi)	Flow Stress (ksi)
			Time (μsec)	Load (lbf)	Energy (ft-lbf)	Time (μsec)	Load (lbf)	Energy (ft-lbf)	Time (μsec)	Load (lbf)	Energy (ft-lbf)	Time (μsec)	Load (lbf)	Energy (ft-lbf)	Load (lbf)	Energy (ft-lbf)	Time (μsec)	Energy (ft-lbf)		
VH28	-76	21.0	153	4267	5.4	326	4717	18.4	326	4717	18.4	381	0	20.9	4745	2.5	381	20.9	142.2	149.7
VH34	-36	8.0	139	4041	4.5	139	4041	4.5	139	4041	4.5	189	0	6.5	4060	1.9	189	6.5	134.7	134.7
VH29	4	30.5	156	3986	5.3	439	4750	26.2	464	4724	28.2	523	0	31.0	4727	4.8	523	31.0	132.9	145.6
VH27	44	56.0	151	3751	5.1	700	4720	45.7	839	4584	56.7	898	0	59.4	4614	13.7	898	59.4	125.0	141.2
VH25	74	91.0	156	3710	5.6	606	4738	38.7	1343	2875	90.4	1443	1573	93.7	1302	60.7	2318	99.5	123.7	140.8
VH31	74	10.5	159	3689	5.5	159	3689	5.5	159	3689	5.5	235	0	8.3	3689	3.1	323	8.6	123.0	123.0
VH26	104	36.0	165	3567	5.6	437	4310	24.1	473	4290	26.7	584	1283	31	3006	12.2	1686	36.3	118.9	131.3
VH36	104	36.5	168	3623	4.9	448	4303	23.8	530	4262	29.7	644	706	33.2	3556	12.9	1754	36.8	120.8	132.1
VH30	129	82.5	166	3425	5.2	706	4497	43.1	1274	3015	80.5	1386	1392	83.9	1624	45.4	2370	88.5	114.2	132.0
VH33	204	92.5	174	3181	5.2	714	4306	41.1	N/A	N/A	N/A	N/A	N/A	N/A	0	58.6	2638	99.7	106.0	124.8
VH32	304	80.0	170	3034	4.9	620	3974	32.6	N/A	N/A	N/A	N/A	N/A	N/A	0	50.4	2908	83.0	101.1	116.8
VH35	404	95.5	160	3018	4.3	716	4073	39.0	N/A	N/A	N/A	N/A	N/A	N/A	0	63.5	2782	102.5	100.6	118.2

5-13

Table 5-11. Hyperbolic Tangent Curve Fit Coefficients for the North Anna Unit No. 1 Capsule W Surveillance Materials

Material Description	Hyperbolic Tangent Curve Fit Coefficients		
	Absorbed Energy	Lateral Expansion	Percent Shear Fracture
Base Metal Forging 03 Ht. No. 990400/292332 (Tangential)	A: 49.3 B: 47.1 C: 108.4 T0: 135.2	A: 41.0 B: 40.0 C: 117.0 T0: 147.3	A: 50.0 B: 50.0 C: 90.6 T0: 130.5
Base Metal Forging 03 Ht. No. 990400/292332 (Axial)	A: 35.5 B: 33.3 C: 110.1 T0: 154.2	A: 33.4 B: 32.4 C: 107.6 T0: 165.6	A: 50.0 B: 50.0 C: 89.4 T0: 165.9
Weld Metal (Wire Ht. 25531 / Flux Lot 1211)	A: 39.7 B: 37.5 C: 121.6 T0: 73.7	A: 37.6 B: 36.6 C: 128.3 T0: 80.6	A: 50.0 B: 50.0 C: 85.4 T0: 77.4
HAZ Metal	A: 48.4 B: 46.2 C: 156.3 T0: 74.3	A: 36.5 B: 35.5 C: 138.0 T0: 85.7	A: 50.0 B: 50.0 C: 98.9 T0: 91.4

Figure 5-1. Photographs of Thermal Monitors Removed from the North Anna Unit No. 1 RVSP Capsule W

NORTH ANNA

**THERMAL
MONITERS**

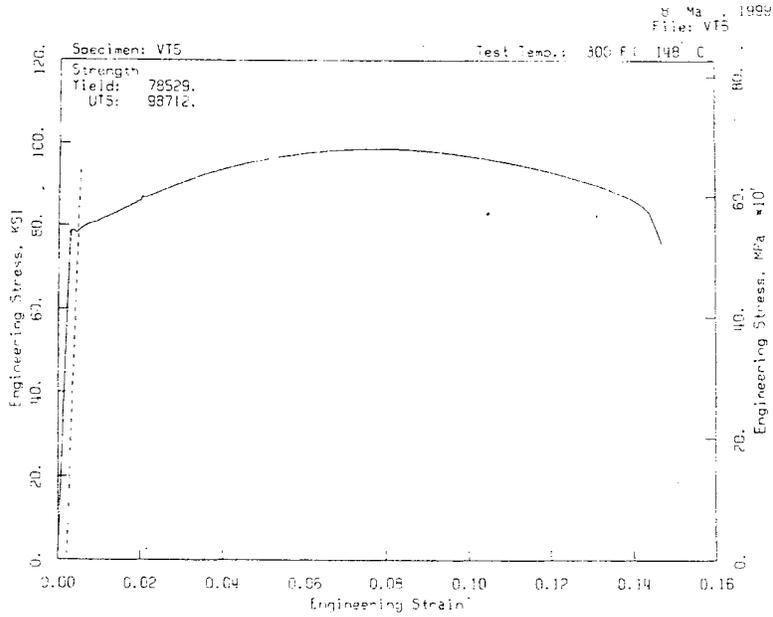
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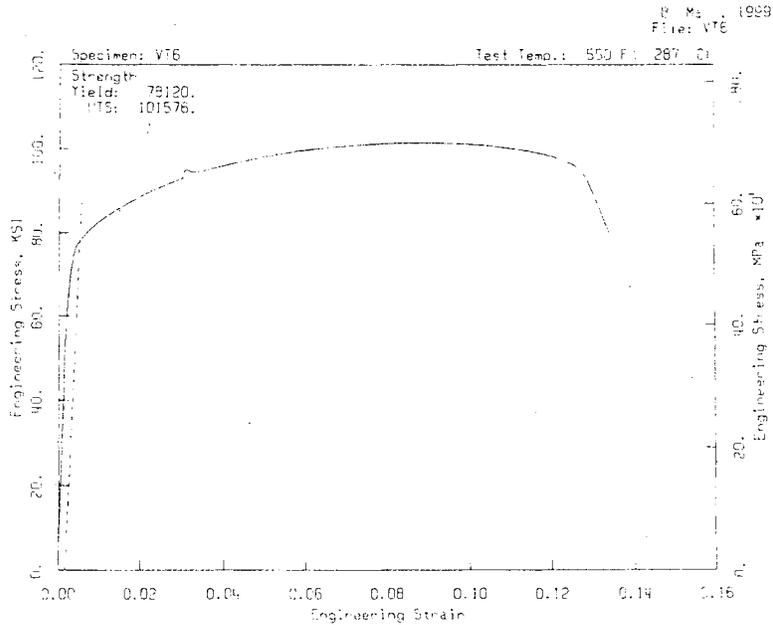
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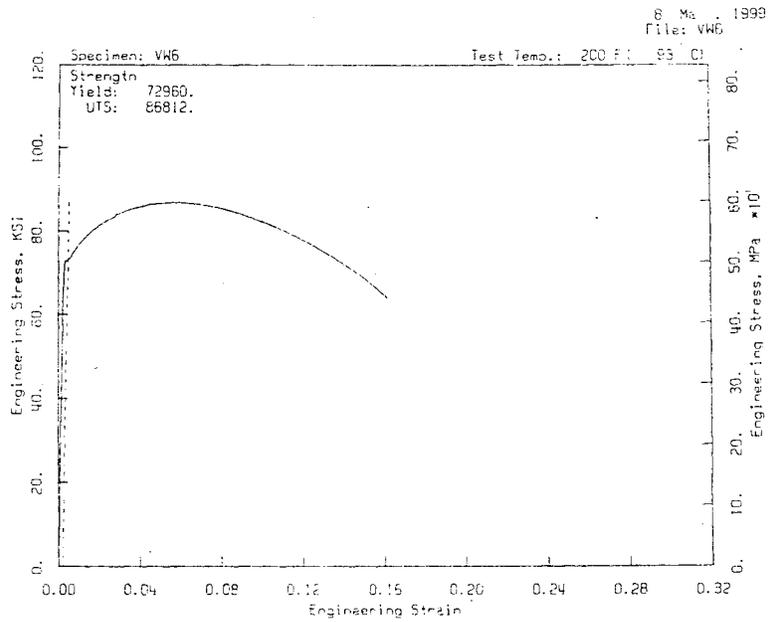
**Figure 5-2. Tension Test Stress-Strain Curve for Base Metal Forging 03,
Heat No. 990400/292332, Axial Orientation,
Specimen No. VT5, Tested at 300°F**



**Figure 5-3. Tension Test Stress-Strain Curve for Base Metal Forging 03,
Heat No. 990400/292332, Axial Orientation,
Specimen No. VT6, Tested at 550°F**



**Figure 5-4. Tension Test Stress-Strain Curve for Weld Metal,
Wire Heat 25531 / Flux Lot 1211,
Specimen No. VW6, Tested at 200°F**



**Figure 5-5. Tension Test Stress-Strain Curve for Weld Metal,
Wire Heat 25531 / Flux Lot 1211,
Specimen No. VW5, Tested at 550°F**

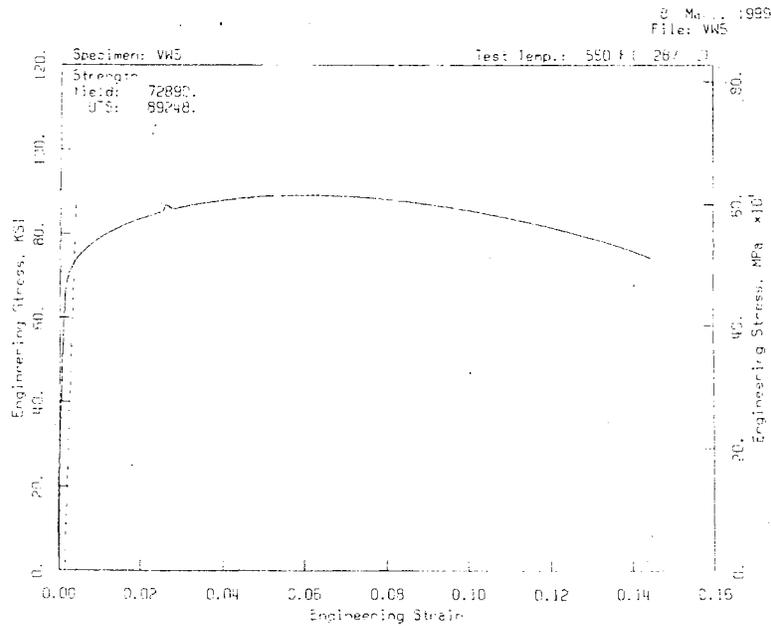
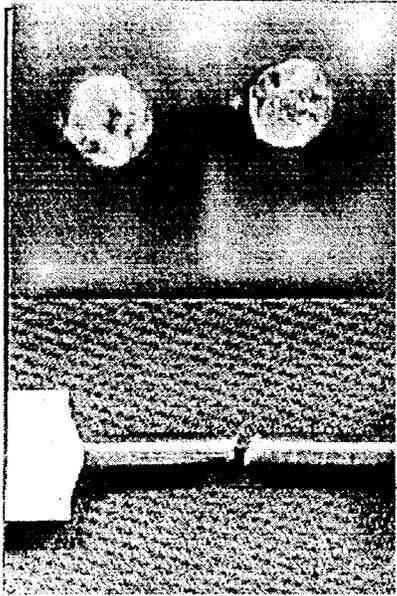
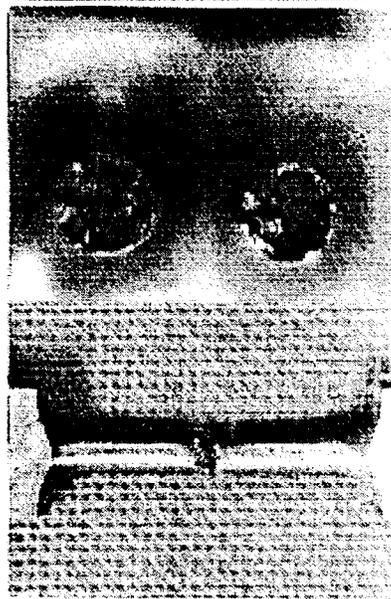


Figure 5-6. Photographs of Tested Tension Test Specimens and Corresponding Fracture Surfaces - Base Metal Forging 03, Heat No. 990400/292332
Axial Orientation

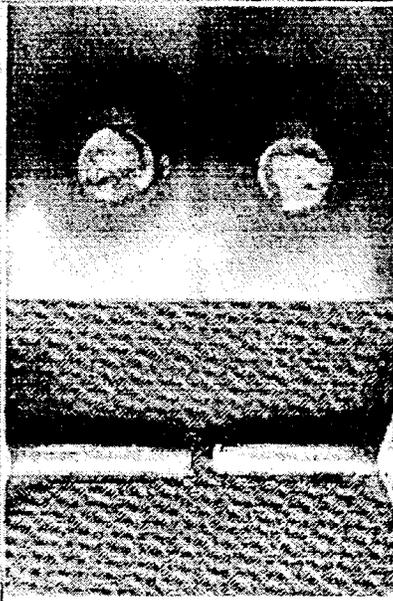


VT5 300°F

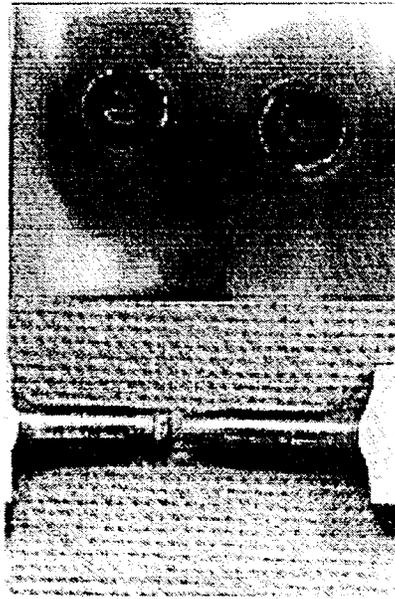


VT6 550°F

Figure 5-7. Photographs of Tested Tension Test Specimens and Corresponding Fracture Surfaces – Weld Metal, Wire Heat 25531 / Flux Lot 1211

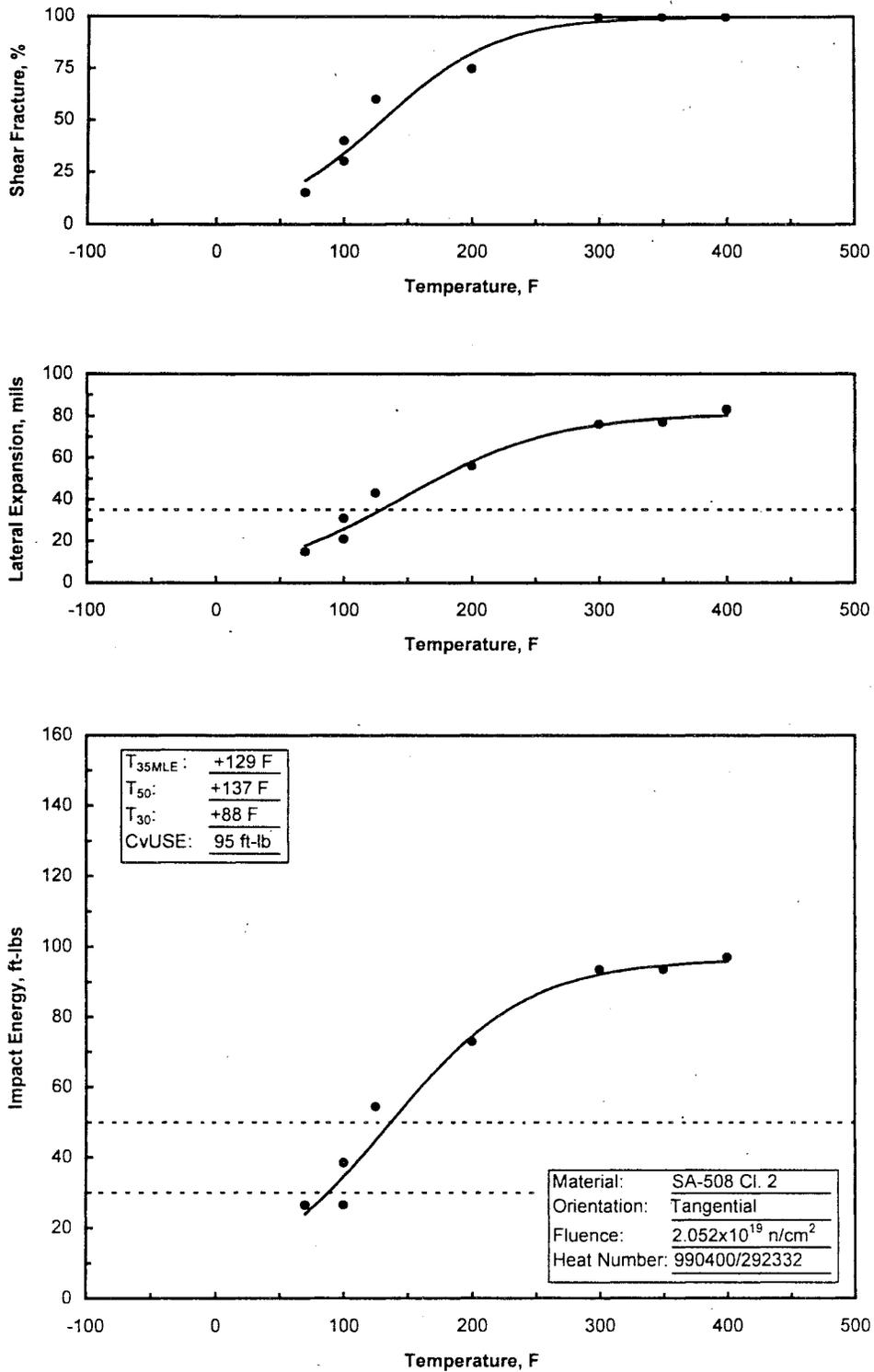


VW6 200°F

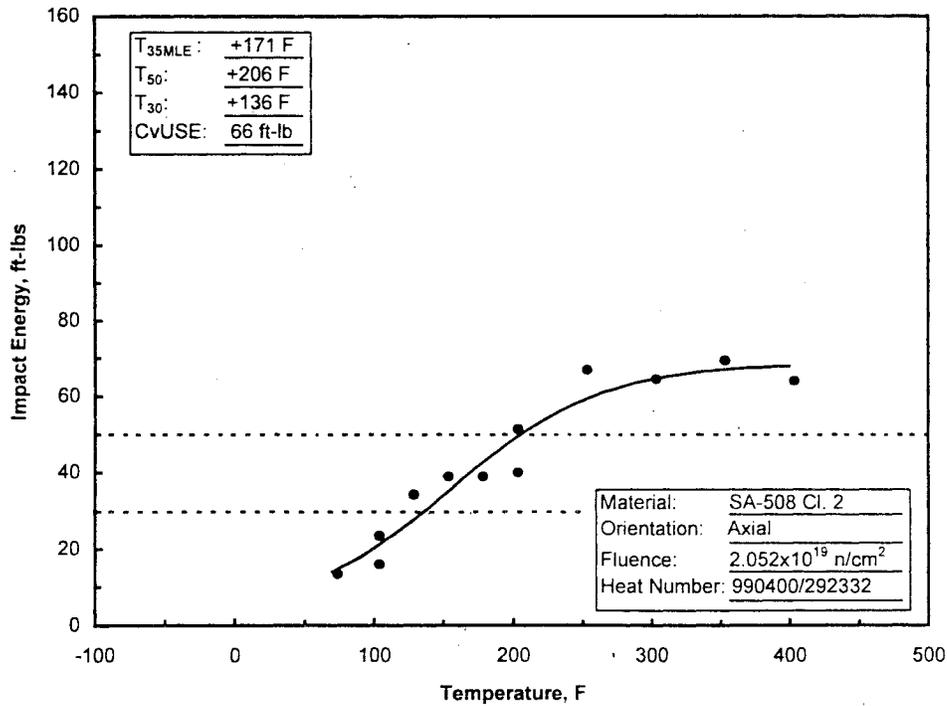
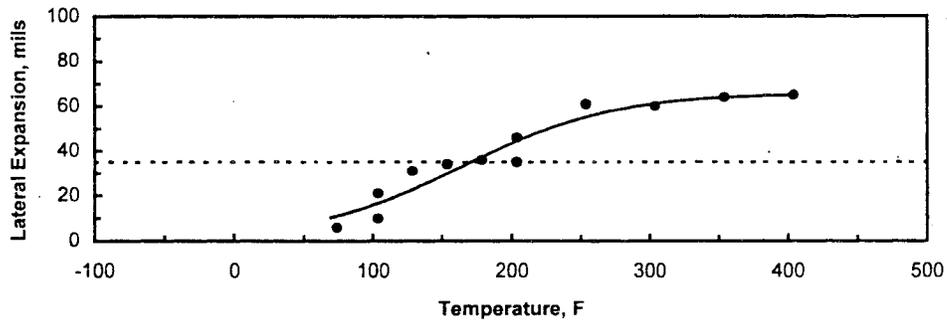
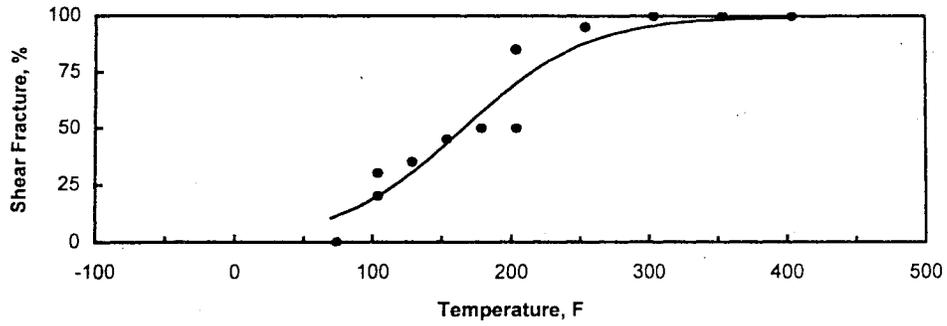


VW5 550°F

Figure 5-8. Charpy Impact Data for Irradiated Base Metal Forging 03, Heat No. 990400/292332, Tangential Orientation



**Figure 5-9. Charpy Impact Data for Irradiated Base Metal Forging 03,
Heat No. 990400/292332, Axial Orientation**



**Figure 5-10. Charpy Impact Data for Irradiated Weld Metal
Wire Heat 25531 / Flux Lot 1211**

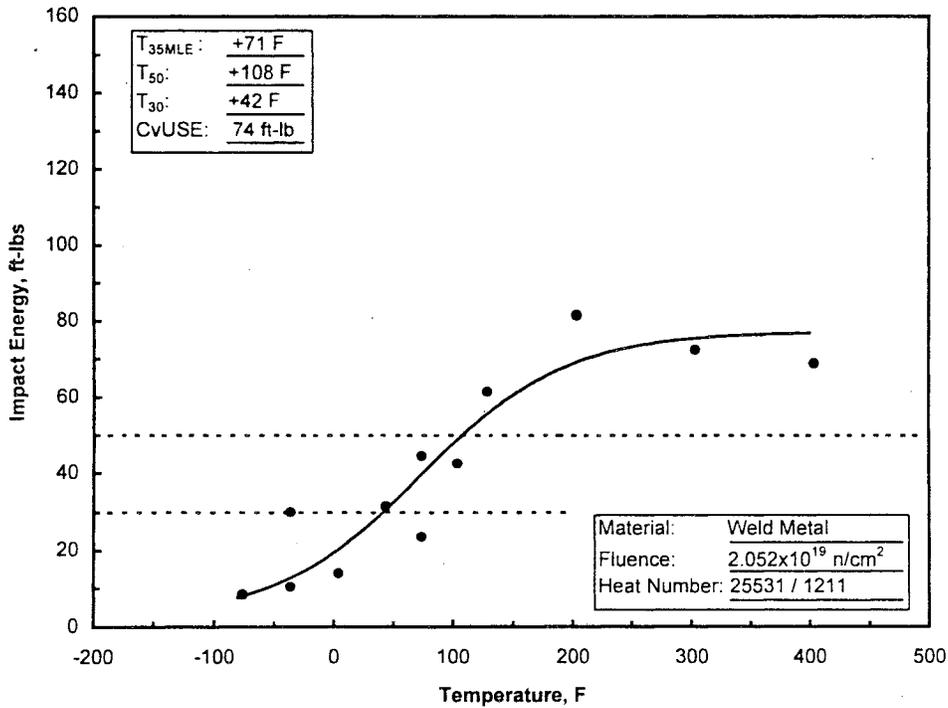
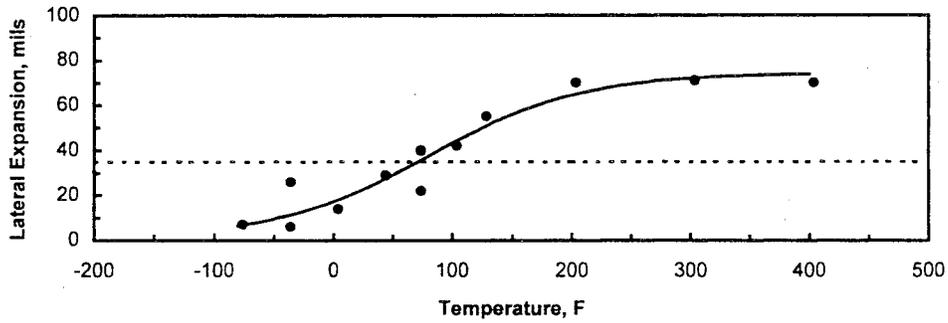
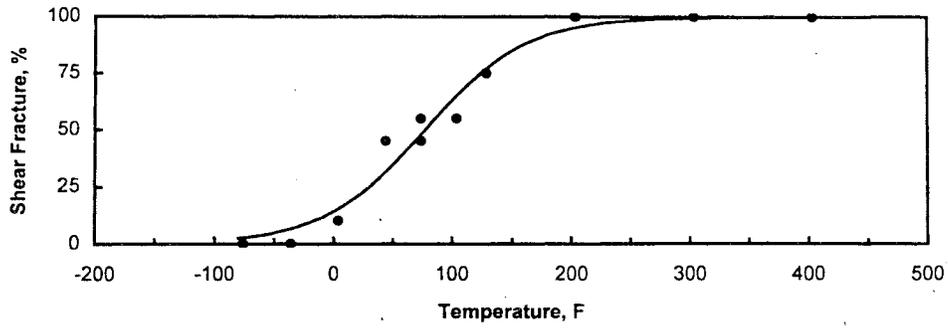
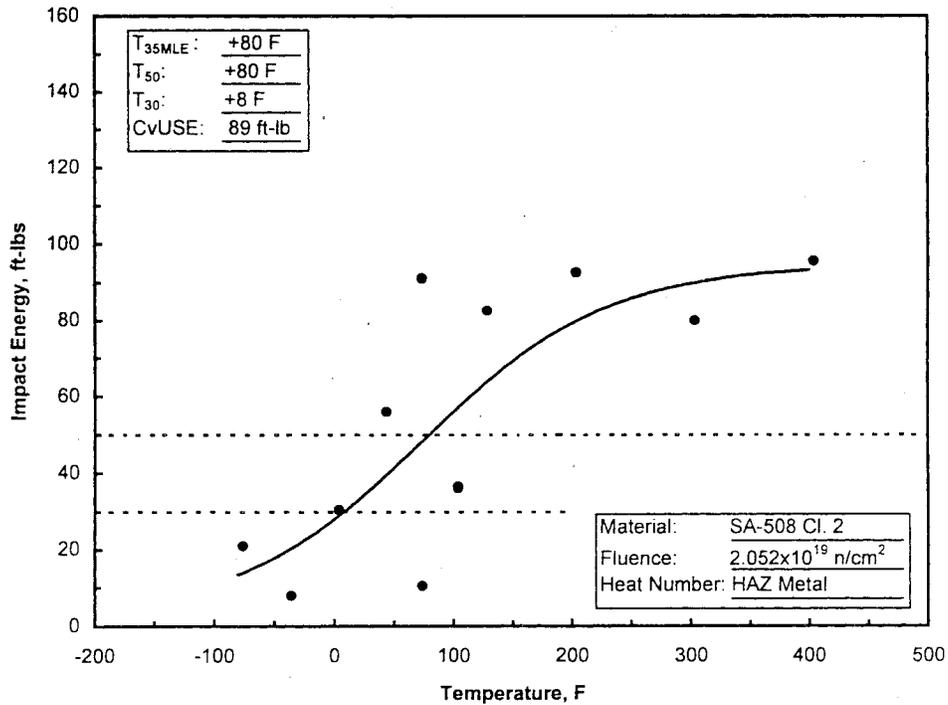
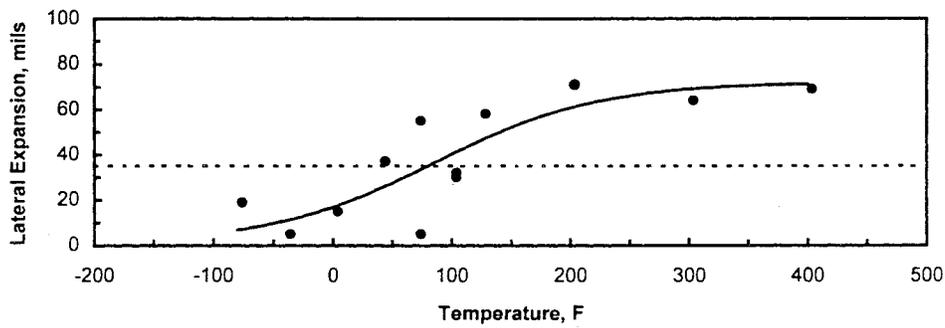
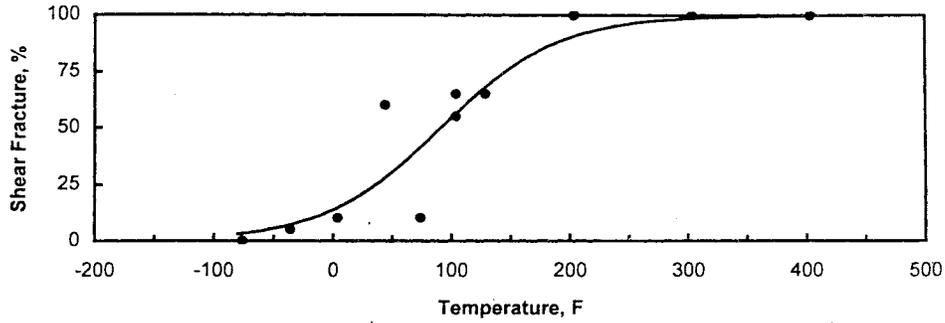


Figure 5-11. Charpy Impact Data Irradiated Heat-Affected-Zone Material



**Figure 5-12. Photographs of Charpy Impact Specimen Fracture Surfaces,
Base Metal Forging 03, Heat No. 990400/292332,
Tangential Orientation**



Specimen No. VL23, Test Temperature 74°F



Specimen No. VL21, Test Temperature 204°F



Specimen No. VL17, Test Temperature 104°F



Specimen No. VL18, Test Temperature 304°F



Specimen No. VL22, Test Temperature 104°F



Specimen No. VL20, Test Temperature 354°F



Specimen No. VL24, Test Temperature 129°F



Specimen No. VL19, Test Temperature 404°F

Figure 5-13. Photographs of Charpy Impact Specimen Fracture Surfaces,
Base Metal Forging 03, Heat No. 990400/292332,
Axial Orientation



Specimen No. VT30, Test Temperature 74°F



Specimen No. VT32, Test Temperature 204°F



Specimen No. VT26, Test Temperature 104°F



Specimen No. VT33, Test Temperature 204°F



Specimen No. VT28, Test Temperature 104°F



Specimen No. VT29, Test Temperature 254°F



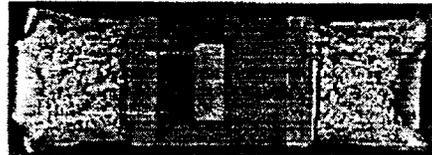
Specimen No. VT35, Test Temperature 129°F



Specimen No. VT27, Test Temperature 304°F



Specimen No. VT31, Test Temperature 154°F



Specimen No. VT36, Test Temperature 354°F



Specimen No. VT34, Test Temperature 179°F



Specimen No. VT25, Test Temperature 404°F

Figure 5-14. Photographs of Charpy Impact Specimen Fracture Surfaces, Weld Metal, Weld Heat 25531 / Flux Lot 1211



Specimen No. VW36, Test Temperature -76°F



Specimen No. VW34, Test Temperature 74°F



Specimen No. VW27, Test Temperature -36°F



Specimen No. VW35, Test Temperature 104°F



Specimen No. VW33, Test Temperature -36°F



Specimen No. VW31, Test Temperature 129°F



Specimen No. VW30, Test Temperature 4°F



Specimen No. VW32, Test Temperature 204°F



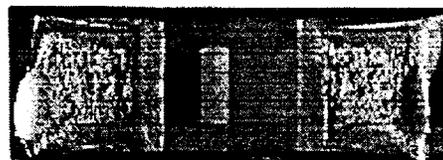
Specimen No. VW29, Test Temperature 44°F



Specimen No. VW25, Test Temperature 304°F



Specimen No. VW26, Test Temperature 74°F



Specimen No. VW28, Test Temperature 404°F

Figure 5-15. Photographs of Charpy Impact Specimen Fracture Surfaces, Heat-Affected-Zone Material



Specimen No. VII28, Test Temperature -76°F



Specimen No. VH26, Test Temperature 104°F



Specimen No. VH34, Test Temperature -36°F



Specimen No. VH36, Test Temperature 104°F



Specimen No. VII29, Test Temperature 4°F



Specimen No. VH30, Test Temperature 129°F



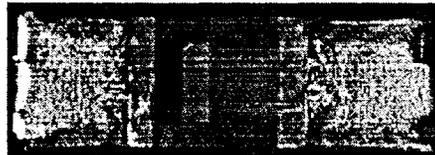
Specimen No. VH27, Test Temperature 44°F



Specimen No. VH33, Test Temperature 204°F



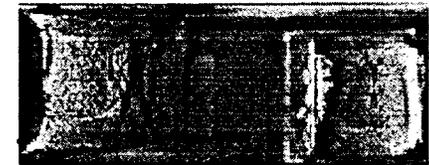
Specimen No. VH25, Test Temperature 74°F



Specimen No. VH32, Test Temperature 304°F



Specimen No. VH31, Test Temperature 74°F



Specimen No. VH35, Test Temperature 404°F



6. Neutron Fluence

6.1. Objectives and Background

Over the last fourteen years, Framatome Technologies, Inc. (FTI) has developed a calculational-based fluence analysis methodology that can be used to accurately predict the fast neutron fluence in the reactor vessel using surveillance capsule dosimetry or cavity dosimetry (or both) to verify the fluence predictions.^[14] The methodology was developed through a full-scale benchmark experiment that was performed at the Davis-Besse Unit 1 reactor.^[14] The results of the benchmark experiment demonstrated that the accuracy of a fluence analysis that employs the FTI methodology would be unbiased and have a precision well within the NRC-suggested limit of 20%.^{[14],[15]}

The FTI methodology was used to calculate the neutron fluence exposure to the pressure vessel, certain vessel welds in the beltline region, and surveillance Capsule X of the HNP reactor vessel. The fast neutron fluences ($E > 1$ MeV) at those points were calculated in accordance with the requirements of the U.S. NRC Draft Regulatory Guide DG-1053,^[15] as described in detail in the FTI fluence topical report, BAW-2241P, Revision 1.^[14]

The energy-dependent flux at the capsule was used to determine the calculated activity of each dosimeter. The calculated activities were adjusted to account for known biases (photofission and U-235 impurity in the U-238), and compared directly to the measured activities. It is noted that the measurements are not used in any way to determine the magnitude of the flux or the fluence. The measurements are used only to show that the calculational results are reasonable and to show that the HNP results are consistent with the FTI benchmark database of uncertainties.

Explicit values of the fast fluence were computed for the following locations:

- Surveillance Capsule
- "Wetted" Surface for the HNP Reactor Vessel Beltline Materials
- Clad-Base Metal Interface for the HNP Reactor Vessel Beltline Materials
- Clad-Base Metal Interface Maximum Peak Location
- $\frac{1}{4}T$, $\frac{1}{2}T$, $\frac{3}{4}T$, and Outside Surface at Maximum Peak Location where T is the reactor vessel thickness.

representative of an average over the cycle 1 through 13 irradiation time period. Geometric detail is selected to explicitly represent the surveillance capsule assembly and reactor vessel. A more detailed discussion of the calculational procedure is given in Appendix F. The calculated activities were adjusted to account for known biases (photo-fission, non-saturation, and power correction), and compared directly to the measured activities. It is noted that the measurements are not used in any way to determine the magnitude of the flux or the fluence. Instead, the measurements are used only to show that the calculational results are reasonable and to show that the North Anna Unit No. 1 Capsule W results are consistent with the FTI benchmark database of uncertainties.

6.2. Capsule Fluence

The North Anna Unit No. 1 Capsule W was positioned in the reactor vessel between the thermal shield and the vessel wall with the vertical center of the capsule opposite the vertical center of the core. The capsule was located in the 25° location (as shown in Figure 6-1) for the equivalent of 5389 effective full power days (EFPDs). The rated thermal full power for cycles 1 through cycle 5 was 2775 MWt while the full power for cycle 6 was an average of 2834 MWt and cycle 7 through cycle 13 was 2893 MWt.

The $E > 1.0$ MeV and $E > 0.1$ MeV neutron fluence spectra incident on the capsule specimens were calculated for Capsule W, as shown in Table 6-1 and Table 6-2.

The $E > 1.0$ MeV neutron fluence spectrum is present graphically in Figure 6-2.

The $E > 1.0$ MeV neutron fluence at each surveillance capsule location (15°, 25°, 35°, and 45°) for each reload cycle is presented in Table 6-4. The cycle lengths for cycle 1 - 13 and the end-of-life (EOL) values are presented in Table 6-3.

The EOL values in Table 6-3 were determined assuming an EOL date of April 1, 2018 and the North Anna Unit No. 1 plant operating at a 90% capacity factor.

The results from Table 6-4 are presented graphically in Figure 6-3.

6.3. Reactor Vessel Fluence

The $E > 1.0$ MeV neutron fluence at the inside surface peak, $\frac{1}{4}$ -thickness ($\frac{1}{4}T$) peak, and $\frac{3}{4}$ -thickness ($\frac{3}{4}T$) peak for the 0°, 15°, 30°, and 45° locations of the North Anna Unit No. 1

reactor vessel as a function of each reload cycle is presented in Table 6-5 (inside surface peak), Table 6-6 ($\frac{1}{4}$ T peak), and Table 6-7 ($\frac{3}{4}$ T peak).

The $E > 1.0$ MeV extrapolated neutron fluence at the inside surface peak, $\frac{1}{4}$ T peak, and $\frac{3}{4}$ T peak for the 0° , 15° , 30° , and 45° locations of the North Anna Unit No. 1 reactor vessel is presented in Table 6-8.

In Table 6-8, the extrapolated fluxes are based on the cycle 11 - 13 irradiation cycles. Also, the $E > 1.0$ MeV fluence functions in Table 6-8 are given in the form:

$$\phi t(T) = (2.06321E+19) + ((1.17020E+18) \times T)$$

where:

$\phi t(T)$...	cumulative neutron fluence (n/cm^2) at time T (where T is in EFPY)
2.06321E+19	...	fluence at EOC 13 (n/cm^2)
1.17020E+18	...	extrapolation flux for EOC 14 - EOL (n/cm^2 -year)

The results from Table 6-8 are presented graphically in Figure 6-4, Figure 6-5, and Figure 6-6.

The $E > 1.0$ MeV neutron fluence at the nozzle-belt forging inner surface is presented in Table 6-9. The nozzle-belt forging inner surface is located 13.6 inches above the active fuel region.

Finally, the axial and radial dependence of the pressure vessel fluence, relative to the mid-plane inside surface, is presented in Table 6-10, Table 6-11, Figure 6-7, and Figure 6-8.

6.4. Dosimetry Activity

The ratio of the calculated specific activities to the measured specific activities^[10] (C/M) is presented in Table 6-12. In Table 6-12, the capsule average C/M is the average C/M for the entire North Anna Unit No. 1 Capsule W.

Table 6-1. Neutron Flux and Fluence Spectrum (E > 1.0 MeV) at the Center of North Anna Unit No. 1 Capsule W

Energy Group	Upper Energy (MeV)	E > 1.0 MeV Neutron Flux (n/cm²-sec)	E > 1.0 MeV Neutron Fluence (n/cm²)
1	1.7332E+01	1.4072E+07	6.5521E+15
2	1.4191E+01	4.0000E+07	1.8624E+16
3	1.2214E+01	1.5784E+08	7.3493E+16
4	1.0000E+01	2.9687E+08	1.3823E+17
5	8.6071E+00	4.9713E+08	2.3147E+17
6	7.4082E+00	1.1729E+09	5.4611E+17
7	6.0653E+00	1.7102E+09	7.9629E+17
8	4.9659E+00	3.1470E+09	1.4653E+18
9	3.6788E+00	2.4286E+09	1.1308E+18
10	3.0119E+00	1.8451E+09	8.5908E+17
11	2.7253E+00	2.1143E+09	9.8443E+17
12	2.4660E+00	1.0350E+09	4.8193E+17
13	2.3653E+00	2.9562E+08	1.3764E+17
14	2.3457E+00	1.4175E+09	6.5998E+17
15	2.2313E+00	3.7533E+09	1.7476E+18
16	1.9205E+00	4.1091E+09	1.9133E+18
17	1.6530E+00	5.9615E+09	2.7757E+18
18	1.3534E+00	1.0330E+10	4.8095E+18
19	1.0026E+00	8.1456E+07	3.7927E+16

Table 6-2. Neutron Flux and Fluence Spectrum (E > 0.1 MeV) at the Center of North Anna Unit No. 1 Capsule W

Energy Group	Upper Energy (MeV)	E > 0.1 MeV Neutron Flux (n/cm²-sec)	E > 0.1 MeV Neutron Fluence (n/cm²)
1	1.7332E+01	1.4072E+07	6.5521E+15
2	1.4191E+01	4.0000E+07	1.8624E+16
3	1.2214E+01	1.5784E+08	7.3493E+16
4	1.0000E+01	2.9687E+08	1.3823E+17
5	8.6071E+00	4.9713E+08	2.3147E+17
6	7.4082E+00	1.1729E+09	5.4611E+17
7	6.0653E+00	1.7102E+09	7.9629E+17
8	4.9659E+00	3.1470E+09	1.4653E+18
9	3.6788E+00	2.4286E+09	1.1308E+18
10	3.0119E+00	1.8451E+09	8.5908E+17
11	2.7253E+00	2.1143E+09	9.8443E+17
12	2.4660E+00	1.0350E+09	4.8193E+17
13	2.3653E+00	2.9562E+08	1.3764E+17
14	2.3457E+00	1.4175E+09	6.5998E+17
15	2.2313E+00	3.7533E+09	1.7476E+18
16	1.9205E+00	4.1091E+09	1.9133E+18
17	1.6530E+00	5.9615E+09	2.7757E+18
18	1.3534E+00	1.0330E+10	4.8095E+18
19	1.0026E+00	6.3022E+09	2.9344E+18
20	8.2085E-01	3.5746E+09	1.6644E+18
21	7.4274E-01	8.6852E+09	4.0439E+18
22	6.0810E-01	7.3186E+09	3.4076E+18
23	4.9787E-01	8.3630E+09	3.8939E+18
24	3.6883E-01	6.9421E+09	3.2323E+18
25	2.9721E-01	1.0884E+10	5.0677E+18
26	1.8316E-01	9.9358E+09	4.6262E+18
27	1.1109E-01	1.6697E+09	7.7742E+17

Table 6-3. North Anna Unit No. 1 Cycle Lengths

Cycle	EFPD	EFPY	EFPS	Cumulative EFPY
1	413	1.1307	3.5683E+07	1.1307
2	279	0.7639	2.4106E+07	1.8946
3	347	0.9500	2.9981E+07	2.8446
4	350	0.9582	3.0240E+07	3.8029
5	349	0.9555	3.0154E+07	4.7584
6	401	1.0979	3.4646E+07	5.8563
7	423	1.1581	3.6547E+07	7.0144
8	485	1.3279	4.1904E+07	8.3422
9	503	1.3771	4.3459E+07	9.7194
10	494	1.3525	4.2682E+07	11.0719
11	474	1.2977	4.0954E+07	12.3696
12	419	1.1472	3.6202E+07	13.5168
13	452	1.2375	3.9053E+07	14.7543
Cycles 14 through EOL	6383	17.4750	5.5147E+08	32.2293
			TOTAL: 4.6561E+08	

Table 6-4. E > 1.0 MeV Neutron Fluence at the 15°, 25°, 35°, and 45° Capsule Locations for North Anna Unit No. 1

Cycle	15° Capsule Location		
	Neutron Flux (n/cm ² -sec)	Neutron Fluence (n/cm ²)	Cumulative Fluence (n/cm ²)
1	7.03258E+10	2.50945E+18	2.50945E+18
2	8.22936E+10	1.98374E+18	4.49319E+18
3	5.37861E+10	1.61255E+18	6.10574E+18
4	5.99914E+10	1.81414E+18	7.91988E+18
5	4.47085E+10	1.34812E+18	9.26800E+18
6	5.05221E+10	1.75041E+18	1.10184E+19
7	5.16233E+10	1.88669E+18	1.29051E+19
8	4.66531E+10	1.95495E+18	1.48600E+19
9	4.79910E+10	2.08565E+18	1.69457E+19
10	4.44792E+10	1.89844E+18	1.88441E+19
11	4.34429E+10	1.77914E+18	2.06233E+19
12	4.48328E+10	1.62302E+18	2.22463E+19
13	4.87556E+10	1.90404E+18	2.41503E+19

Cycle	25° Capsule Location		
	Neutron Flux (n/cm ² -sec)	Neutron Fluence (n/cm ²)	Cumulative Fluence (n/cm ²)
1	5.82714E+10	2.07931E+18	2.07931E+18
2	6.61649E+10	1.59495E+18	3.67425E+18
3	4.52053E+10	1.35529E+18	5.02955E+18
4	4.32535E+10	1.30799E+18	6.33753E+18
5	3.72312E+10	1.12265E+18	7.46019E+18
6	4.42370E+10	1.53265E+18	8.99284E+18
7	4.37186E+10	1.59779E+18	1.05906E+19
8	4.13484E+10	1.73267E+18	1.23233E+19
9	4.05032E+10	1.76024E+18	1.40835E+19
10	3.94823E+10	1.68517E+18	1.57687E+19
11	4.01221E+10	1.64314E+18	1.74118E+19
12	3.95285E+10	1.43099E+18	1.88428E+19
13	4.28174E+10	1.67214E+18	2.05150E+19

Table 6-4. (cont'd.) E > 1.0 MeV Neutron Fluence at the 15°, 25°, 35°, and 45° Capsule Locations for North Anna Unit No. 1

Cycle	35° Capsule Location		
	Neutron Flux (n/cm ² -sec)	Neutron Fluence (n/cm ²)	Cumulative Fluence (n/cm ²)
1	3.38377E+10	1.20744E+18	1.20744E+18
2	3.75175E+10	9.04382E+17	2.11182E+18
3	2.47176E+10	7.41055E+17	2.85287E+18
4	2.26192E+10	6.84003E+17	3.53688E+18
5	2.19300E+10	6.61269E+17	4.19815E+18
6	2.46444E+10	8.53840E+17	5.05199E+18
7	2.58351E+10	9.44200E+17	5.99619E+18
8	2.42727E+10	1.01712E+18	7.01331E+18
9	2.38618E+10	1.03702E+18	8.05032E+18
10	2.34470E+10	1.00076E+18	9.05108E+18
11	2.46378E+10	1.00901E+18	1.00601E+19
12	2.31746E+10	8.38957E+17	1.08990E+19
13	2.48430E+10	9.70187E+17	1.18692E+19

Cycle	45° Capsule Location		
	Neutron Flux (n/cm ² -sec)	Neutron Fluence (n/cm ²)	Cumulative Fluence (n/cm ²)
1	2.65869E+10	9.48707E+17	9.48707E+17
2	2.84206E+10	6.85095E+17	1.63380E+18
3	1.91302E+10	5.73539E+17	2.20734E+18
4	1.75113E+10	5.29543E+17	2.73688E+18
5	1.76770E+10	5.33026E+17	3.26991E+18
6	1.89478E+10	6.56471E+17	3.92638E+18
7	2.06157E+10	7.53446E+17	4.67983E+18
8	1.90746E+10	7.99304E+17	5.47913E+18
9	1.88250E+10	8.18119E+17	6.29725E+18
10	1.87143E+10	7.98757E+17	7.09601E+18
11	1.90318E+10	7.79422E+17	7.87543E+18
12	1.80373E+10	6.52977E+17	8.52841E+18
13	1.92789E+10	7.52895E+17	9.28130E+18

Table 6-5. E > 1.0 MeV Inside Surface Peak Neutron Fluence at the North Anna Unit No. 1 Reactor Vessel 0°, 15°, 30°, and 45° Locations

Cycle	Inside Surface Peak at 0°		
	Neutron Flux (n/cm ² -sec)	Neutron Fluence (n/cm ²)	Cumulative Fluence (n/cm ²)
1	6.43993E+10	2.29797E+18	2.29797E+18
2	7.64406E+10	1.84265E+18	4.14062E+18
3	5.01348E+10	1.50308E+18	5.64370E+18
4	5.69905E+10	1.72339E+18	7.36709E+18
5	4.02111E+10	1.21251E+18	8.57960E+18
6	4.33875E+10	1.50322E+18	1.00828E+19
7	4.09471E+10	1.49650E+18	1.15793E+19
8	3.59571E+10	1.50674E+18	1.30861E+19
9	4.05685E+10	1.76308E+18	1.48491E+19
10	3.45300E+10	1.47380E+18	1.63229E+19
11	3.75037E+10	1.53591E+18	1.78588E+19
12	3.49990E+10	1.26702E+18	1.91259E+19
13	3.85688E+10	1.50622E+18	2.06321E+19

Cycle	Inside Surface Peak at 15°		
	Neutron Flux (n/cm ² -sec)	Neutron Fluence (n/cm ²)	Cumulative Fluence (n/cm ²)
1	3.23987E+10	1.15609E+18	1.15609E+18
2	3.78998E+10	9.13597E+17	2.06969E+18
3	2.48153E+10	7.43982E+17	2.81367E+18
4	2.75080E+10	8.31840E+17	3.64551E+18
5	2.05586E+10	6.19915E+17	4.26542E+18
6	2.32186E+10	8.04439E+17	5.06986E+18
7	2.35926E+10	8.62244E+17	5.93211E+18
8	2.13211E+10	8.93439E+17	6.82555E+18
9	2.20270E+10	9.57275E+17	7.78282E+18
10	2.03589E+10	8.68949E+17	8.65177E+18
11	2.00113E+10	8.19535E+17	9.47130E+18
12	2.05192E+10	7.42827E+17	1.02141E+19
13	2.23094E+10	8.71245E+17	1.10854E+19

Table 6-5. (cont'd.) E > 1.0 MeV Inside Surface Peak Neutron Fluence at the North Anna Unit No. 1 Reactor Vessel 0°, 15°, 30°, and 45° Locations

Cycle	Inside Surface Peak at 30°		
	Neutron Flux (n/cm ² -sec)	Neutron Fluence (n/cm ²)	Cumulative Fluence (n/cm ²)
1	1.87158E+10	6.67839E+17	6.67839E+17
2	2.09816E+10	5.05773E+17	1.17361E+18
3	1.41552E+10	4.24383E+17	1.59800E+18
4	1.31507E+10	3.97679E+17	1.99567E+18
5	1.20502E+10	3.63356E+17	2.35903E+18
6	1.40766E+10	4.87704E+17	2.84673E+18
7	1.42023E+10	5.19053E+17	3.36579E+18
8	1.34233E+10	5.62490E+17	3.92828E+18
9	1.31385E+10	5.70991E+17	4.49927E+18
10	1.28647E+10	5.49084E+17	5.04835E+18
11	1.34050E+10	5.48983E+17	5.59733E+18
12	1.27735E+10	4.62422E+17	6.05976E+18
13	1.38124E+10	5.39411E+17	6.59917E+18

Cycle	Inside Surface Peak at 45°		
	Neutron Flux (n/cm ² -sec)	Neutron Fluence (n/cm ²)	Cumulative Fluence (n/cm ²)
1	1.25287E+10	4.47063E+17	4.47063E+17
2	1.34089E+10	3.23230E+17	7.70292E+17
3	9.10381E+09	2.72940E+17	1.04323E+18
4	8.31075E+09	2.51317E+17	1.29455E+18
5	8.38202E+09	2.52748E+17	1.54730E+18
6	9.01818E+09	3.12447E+17	1.85974E+18
7	1.42023E+10	5.19053E+17	2.37880E+18
8	9.05762E+09	3.79551E+17	2.75835E+18
9	8.94114E+09	3.88575E+17	3.14692E+18
10	8.88589E+09	3.79264E+17	3.52619E+18
11	9.05525E+09	3.70845E+17	3.89703E+18
12	8.58663E+09	3.10850E+17	4.20788E+18
13	9.16730E+09	3.58009E+17	4.56589E+18

Table 6-6. E > 1.0 MeV ¼T Location Peak Neutron Fluence at the North Anna Unit No. 1 Reactor Vessel 0°, 15°, 30°, and 45° Locations

Cycle	¼T Peak at 0°		
	Neutron Flux (n/cm ² -sec)	Neutron Fluence (n/cm ²)	Cumulative Fluence (n/cm ²)
1	4.03526E+10	1.43991E+18	1.43991E+18
2	4.79029E+10	1.15473E+18	2.59464E+18
3	3.13314E+10	9.39341E+17	3.53398E+18
4	3.56512E+10	1.07809E+18	4.61207E+18
5	2.51610E+10	7.58696E+17	5.37077E+18
6	2.71986E+10	9.42332E+17	6.31310E+18
7	2.57405E+10	9.40745E+17	7.25385E+18
8	2.25928E+10	9.46729E+17	8.20057E+18
9	2.54299E+10	1.10516E+18	9.30574E+18
10	2.16853E+10	9.25561E+17	1.02313E+19
11	2.35003E+10	9.62420E+17	1.11937E+19
12	2.19654E+10	7.95181E+17	1.19889E+19
13	2.42127E+10	9.45575E+17	1.29345E+19

Cycle	¼T Peak at 15°		
	Neutron Flux (n/cm ² -sec)	Neutron Fluence (n/cm ²)	Cumulative Fluence (n/cm ²)
1	2.06484E+10	7.36800E+17	7.36800E+17
2	2.41394E+10	5.81895E+17	1.31870E+18
3	1.57997E+10	4.73689E+17	1.79238E+18
4	1.75213E+10	5.29843E+17	2.32223E+18
5	1.30976E+10	3.94938E+17	2.71717E+18
6	1.47768E+10	5.11962E+17	3.22913E+18
7	1.50038E+10	5.48347E+17	3.77747E+18
8	1.35566E+10	5.68077E+17	4.34555E+18
9	1.40137E+10	6.09022E+17	4.95457E+18
10	1.29457E+10	5.52542E+17	5.50712E+18
11	1.27510E+10	5.22197E+17	6.02931E+18
12	1.30381E+10	4.72002E+17	6.50131E+18
13	1.41837E+10	5.53914E+17	7.05523E+18

Table 6-6. (cont'd). E > 1.0 MeV ¼T Location Peak Neutron Fluence at the North Anna Unit No. 1 Reactor Vessel 0°, 15°, 30°, and 45° Locations

Cycle	¼T Peak at 30°		
	Neutron Flux (n/cm ² -sec)	Neutron Fluence (n/cm ²)	Cumulative Fluence (n/cm ²)
1	1.17711E+10	4.20030E+17	4.20030E+17
2	1.31795E+10	3.17701E+17	7.37731E+17
3	8.90804E+09	2.67070E+17	1.00480E+18
4	8.28823E+09	2.50636E+17	1.25544E+18
5	7.59227E+09	2.28934E+17	1.48437E+18
6	8.85064E+09	3.06643E+17	1.79101E+18
7	8.93840E+09	3.26674E+17	2.11769E+18
8	8.44700E+09	3.53963E+17	2.47165E+18
9	8.27731E+09	3.59725E+17	2.83138E+18
10	8.10322E+09	3.45858E+17	3.17723E+18
11	8.42483E+09	3.45027E+17	3.52226E+18
12	8.04311E+09	2.91173E+17	3.81343E+18
13	8.69764E+09	3.39667E+17	4.15310E+18

Cycle	¼T Peak at 45°		
	Neutron Flux (n/cm ² -sec)	Neutron Fluence (n/cm ²)	Cumulative Fluence (n/cm ²)
1	7.95678E+09	2.83923E+17	2.83923E+17
2	8.52105E+09	2.05405E+17	4.89328E+17
3	5.78857E+09	1.73546E+17	6.62874E+17
4	5.28548E+09	1.59833E+17	8.22707E+17
5	5.32630E+09	1.60607E+17	9.83314E+17
6	5.73527E+09	1.98706E+17	1.18202E+18
7	8.93840E+09	3.26674E+17	1.50869E+18
8	5.76433E+09	2.41548E+17	1.75024E+18
9	5.69021E+09	2.47292E+17	1.99754E+18
10	5.65164E+09	2.41221E+17	2.23876E+18
11	5.76461E+09	2.36082E+17	2.47484E+18
12	5.46532E+09	1.97853E+17	2.67269E+18
13	5.83350E+09	2.27815E+17	2.90051E+18

Table 6-7. E > 1.0 MeV $\frac{3}{4}$ T Location Peak Neutron Fluence at the North Anna Unit No. 1 Reactor Vessel 0°, 15°, 30°, and 45° Locations

Cycle	$\frac{3}{4}$ T Peak at 0°		
	Neutron Flux (n/cm ² -sec)	Neutron Fluence (n/cm ²)	Cumulative Fluence (n/cm ²)
1	8.57639E+09	3.06033E+17	3.06033E+17
2	1.01793E+10	2.45378E+17	5.51411E+17
3	6.62565E+09	1.98642E+17	7.50054E+17
4	7.55290E+09	2.28400E+17	9.78453E+17
5	5.33796E+09	1.60959E+17	1.13941E+18
6	5.78618E+09	2.00470E+17	1.33988E+18
7	5.50875E+09	2.01330E+17	1.54121E+18
8	4.83438E+09	2.02580E+17	1.74379E+18
9	5.41617E+09	2.35382E+17	1.97917E+18
10	4.63850E+09	1.97979E+17	2.17715E+18
11	4.99996E+09	2.04766E+17	2.38192E+18
12	4.69274E+09	1.69885E+17	2.55180E+18
13	5.17206E+09	2.01984E+17	2.75379E+18

Cycle	$\frac{3}{4}$ T Peak at 15°		
	Neutron Flux (n/cm ² -sec)	Neutron Fluence (n/cm ²)	Cumulative Fluence (n/cm ²)
1	4.61386E+09	1.64637E+17	1.64637E+17
2	5.39070E+09	1.29946E+17	2.94583E+17
3	3.53341E+09	1.05934E+17	4.00518E+17
4	3.91308E+09	1.18332E+17	5.18849E+17
5	2.92600E+09	8.82295E+16	6.07079E+17
6	3.29781E+09	1.14257E+17	7.21336E+17
7	3.33692E+09	1.21955E+17	8.43291E+17
8	3.01480E+09	1.26332E+17	9.69624E+17
9	3.12270E+09	1.35710E+17	1.10533E+18
10	2.87867E+09	1.22866E+17	1.22820E+18
11	2.85033E+09	1.16731E+17	1.34493E+18
12	2.89813E+09	1.04917E+17	1.44985E+18
13	3.15435E+09	1.23186E+17	1.57303E+18

Table 6-7. (cont'd). E > 1.0 MeV $\frac{3}{4}$ T Location Peak Neutron Fluence at the North Anna Unit No. 1 Reactor Vessel 0°, 15°, 30°, and 45° Locations

Cycle	$\frac{3}{4}$ T Peak at 30°		
	Neutron Flux (n/cm ² -sec)	Neutron Fluence (n/cm ²)	Cumulative Fluence (n/cm ²)
1	2.58109E+09	9.21015E+16	9.21015E+16
2	2.88710E+09	6.95953E+16	1.61697E+17
3	1.95594E+09	5.86407E+16	2.20338E+17
4	1.83235E+09	5.54101E+16	2.75748E+17
5	1.66919E+09	5.03320E+16	3.26080E+17
6	1.93733E+09	6.71217E+16	3.93201E+17
7	1.95868E+09	7.15843E+16	4.64786E+17
8	1.84989E+09	7.75178E+16	5.42303E+17
9	1.81320E+09	7.88002E+16	6.21104E+17
10	1.77358E+09	7.56991E+16	6.96803E+17
11	1.83762E+09	7.52573E+16	7.72060E+17
12	1.76457E+09	6.38803E+16	8.35940E+17
13	1.90723E+09	7.44827E+16	9.10423E+17

Cycle	$\frac{3}{4}$ T Peak at 45°		
	Neutron Flux (n/cm ² -sec)	Neutron Fluence (n/cm ²)	Cumulative Fluence (n/cm ²)
1	1.78061E+09	6.35380E+16	6.35380E+16
2	1.91229E+09	4.60969E+16	1.09635E+17
3	1.30305E+09	3.90665E+16	1.48701E+17
4	1.19175E+09	3.60385E+16	1.84740E+17
5	1.19488E+09	3.60298E+16	2.20770E+17
6	1.29094E+09	4.47265E+16	2.65496E+17
7	1.95868E+09	7.15843E+16	3.37080E+17
8	1.29536E+09	5.42810E+16	3.91361E+17
9	1.27875E+09	5.55734E+16	4.46935E+17
10	1.26861E+09	5.41462E+16	5.01081E+17
11	1.29595E+09	5.30739E+16	5.54155E+17
12	1.22982E+09	4.45213E+16	5.98676E+17
13	1.31292E+09	5.12733E+16	6.49949E+17

Table 6-8. Extrapolated E > 1.0 MeV Neutron Fluence at the North Anna Unit No. 1 Reactor Vessel 0°, 15°, 30°, and 45° Locations

Inside Surface Peak				
Location	Extrapolated Flux (n/cm ² -year)	Fluence at EOC 13 (n/cm ²)	Cycle 14 through EOL Fluence Function	EOL Fluence (n/cm ²)
0°	1.17020E+18	2.06321E+19	$\phi t(T) = 2.06321E19 + (1.17020E18 \times T)$	4.10813E+19
15°	6.60873E+17	1.10854E+19	$\phi t(T) = 1.10854E19 + (6.60873E17 \times T)$	2.26342E+19
30°	4.21142E+17	6.59917E+18	$\phi t(T) = 6.59917E18 + (4.21142E17 \times T)$	1.39586E+19
45°	2.82343E+17	4.56589E+18	$\phi t(T) = 4.56589E18 + (2.82343E17 \times T)$	9.49985E+18

1/4T Peak				
Location	Extrapolated Flux (n/cm ² -year)	Fluence at EOC 13 (n/cm ²)	Cycle 14 through EOL Fluence Function	EOL Fluence (n/cm ²)
0°	7.34078E+17	1.29345E+19	$\phi t(T) = 1.29345E19 + (7.34078E17 \times T)$	2.57625E+19
15°	4.20408E+17	7.05523E+18	$\phi t(T) = 7.05523E18 + (4.20408E17 \times T)$	1.44019E+19
30°	2.65008E+17	4.15310E+18	$\phi t(T) = 4.15310E18 + (2.65008E17 \times T)$	8.78412E+18
45°	1.79706E+17	2.90051E+18	$\phi t(T) = 2.90051E18 + (1.79706E17 \times T)$	6.04086E+18

3/4T Peak				
Location	Extrapolated Flux (n/cm ² -year)	Fluence at EOC 13 (n/cm ²)	Cycle 14 through EOL Fluence Function	EOL Fluence (n/cm ²)
0°	1.56361E+17	2.75379E+18	$\phi t(T) = 2.75379E18 + (1.56361E17 \times T)$	5.48620E+18
15°	9.35057E+16	1.57303E+18	$\phi t(T) = 1.57303E18 + (9.35057E16 \times T)$	3.20705E+18
30°	5.79256E+16	9.10423E+17	$\phi t(T) = 9.10423E17 + (5.79256E16 \times T)$	1.92267E+18
45°	4.03673E+16	6.49949E+17	$\phi t(T) = 6.49949E17 + (4.03673E16 \times T)$	1.35537E+18

**Table 6-9. E > 1.0 MeV Peak Neutron Fluence at the North Anna Unit No. 1
Reactor Vessel Nozzle-Belt Forging**

Cycle	Peak Fluence on Nozzle-Belt Inner Surface		
	Neutron Flux (n/cm ² -sec)	Neutron Fluence (n/cm ²)	Cumulative Fluence (n/cm ²)
1	6.08943E+09	2.17290E+17	2.17290E+17
2	7.22802E+09	1.74236E+17	3.91526E+17
3	4.74062E+09	1.42127E+17	5.33653E+17
4	5.38887E+09	1.62959E+17	6.96613E+17
5	3.80225E+09	1.14652E+17	8.11265E+17
6	4.10261E+09	1.42141E+17	9.53405E+17
7	3.87185E+09	1.41505E+17	1.09491E+18
8	3.40001E+09	1.42474E+17	1.23738E+18
9	3.83605E+09	1.66712E+17	1.40410E+18
10	3.26507E+09	1.39358E+17	1.54345E+18
11	3.54625E+09	1.45232E+17	1.68869E+18
12	3.30941E+09	1.19806E+17	1.80849E+18
13	3.64697E+09	1.42424E+17	1.95092E+18

Nozzle-Belt Inner Surface Peak				
Location	Extrapolated Flux (n/cm ² -year)	Fluence at EOC 13 (n/cm ²)	Cycle 14 through EOL Fluence Function	EOL Fluence (n/cm ²)
0°	1.10651E+17	1.95092E+18	$\phi t(T) = 1.95092E18 + (1.10651E17 \times T)$	3.88454E+18

**Table 6-10. Radial Dependence of the Pressure Vessel Neutron Fluence
(Relative to the Mid-Plane Inside Surface)**

Distance from Core Centerline (cm)	Pressure Vessel Radial Fluence Relative to Mid-Plane IS
200.090	1.00000
200.890	0.93860
202.390	0.80627
204.390	0.63465
206.390	0.48865
208.390	0.37227
209.890	0.30029
211.340	0.24597
213.290	0.18603
215.290	0.13859
217.340	0.10166
219.315	0.07366

**Table 6-11. Axial Dependence of the Pressure Vessel Neutron Fluence
(Relative to the Mid-Plane Inside Surface)**

Distance from Bottom of Active Fuel (cm)	Pressure Vessel Axial Fluence Relative to Mid-Plane IS	Distance from Bottom of Active Fuel (cm)	Pressure Vessel Axial Fluence Relative to Mid-Plane IS
0.000	0.33180	57.299	1.03239
1.152	0.34830	62.069	1.03424
2.303	0.36805	66.839	1.03275
3.455	0.38927	71.609	1.03194
4.607	0.41235	76.379	1.01396
5.758	0.43545	81.149	0.98073
6.905	0.45653	85.919	0.96275
8.048	0.47636	89.815	0.95937
9.190	0.50109	92.718	0.95844
10.333	0.51475	95.502	0.95748
11.809	0.53879	99.475	0.95516
13.970	0.58098	104.636	0.96214
16.483	0.62477	109.797	0.98514
18.995	0.66866	114.958	1.01649
21.326	0.71263	120.119	1.01962
23.838	0.75929	125.279	1.01717
26.532	0.80487	130.440	1.02095
29.044	0.83837	135.601	1.01314
31.556	0.86877	140.762	0.98453
34.069	0.89587	145.923	0.96909
36.581	0.92359	151.084	0.96091
39.093	0.94434	155.579	0.95899
41.606	0.96267	158.873	0.96328
44.118	0.98162	162.018	0.95745
47.759	0.99957	165.550	0.96165
52.529	1.01759	169.772	0.97869

**Table 6-11. (cont'd.) Axial Dependence of the Pressure Vessel Neutron Fluence
(Relative to the Mid-Plane Inside Surface)**

Distance from Bottom of Active Fuel (cm)	Pressure Vessel Axial Fluence Relative to Mid-Plane IS	Distance from Bottom of Active Fuel (cm)	Pressure Vessel Axial Fluence Relative to Mid-Plane IS
174.683	0.99715	306.863	0.94470
179.594	1.00000	310.940	0.93057
184.505	1.00130	315.018	0.92011
189.416	0.99759	319.096	0.91710
194.327	0.97585	322.319	0.90955
199.238	0.96295	324.688	0.90026
204.149	0.96111	327.057	0.88026
208.514	0.96206	329.426	0.84951
212.905	0.96202	331.794	0.82591
217.866	0.96814	334.163	0.79541
222.827	0.97983	336.532	0.76657
227.788	0.99955	338.901	0.74242
232.749	1.01260	341.270	0.71567
237.711	1.00367	344.364	0.67472
242.672	0.98624	347.441	0.63196
247.633	0.97895	349.773	0.59576
252.594	0.97679	352.105	0.56102
256.984	0.97645	354.438	0.52627
261.525	0.98170	356.242	0.50359
266.788	0.98263	357.518	0.49660
272.050	0.99519	358.793	0.48574
277.313	1.01895	360.069	0.47475
282.575	1.01719	361.344	0.46010
287.838	0.99083	362.620	0.43863
293.100	0.97463	363.895	0.42092
298.363	0.96564	364.696	0.41056
302.909	0.95473	365.021	0.40686

Table 6-12. North Anna Unit No. 1 Capsule W C/M Ratios

Dosimeter Identification	Measured Activity (μCi/g)	Calculated Activity (μCi/g)	C/M	Capsule Average C/M
Top Mid Cu	6.675E+00	6.740E+00	1.010	1.03
Middle Cu	7.177E+00	7.294E+00	1.016	
Bottom Mid Cu	6.908E+00	6.683E+00	0.967	
Top Mid Ni	9.231E+02	1.015E+03	1.099	
Middle Ni	1.000E+03	1.091E+03	1.091	
Bottom Mid Ni	9.426E+02	9.939E+02	1.054	
Top Fe	8.114E+02	8.761E+02	1.080	
Top Mid Fe	7.501E+02	8.129E+02	1.084	
Middle Fe	8.001E+02	8.759E+02	1.095	
Bottom Mid Fe	7.748E+02	7.984E+02	1.030	
Bottom Fe	7.720E+02	8.249E+02	1.069	
Sh U-238	2.014E+01	1.929E+01	0.958	

**Figure 6-1. North Anna Unit No. 1 Capsule W Location
Plan View**

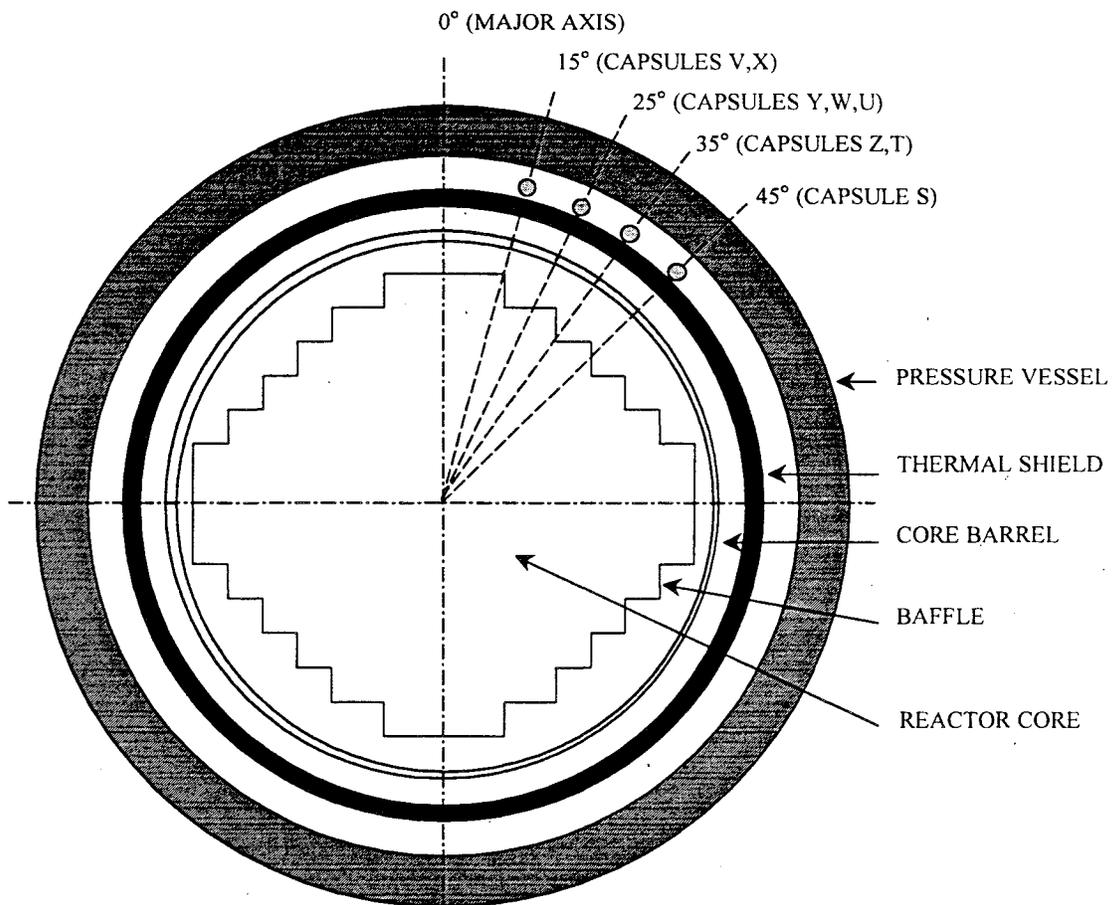


Figure 6-2. Relative E > 1.0 MeV Neutron Fluence

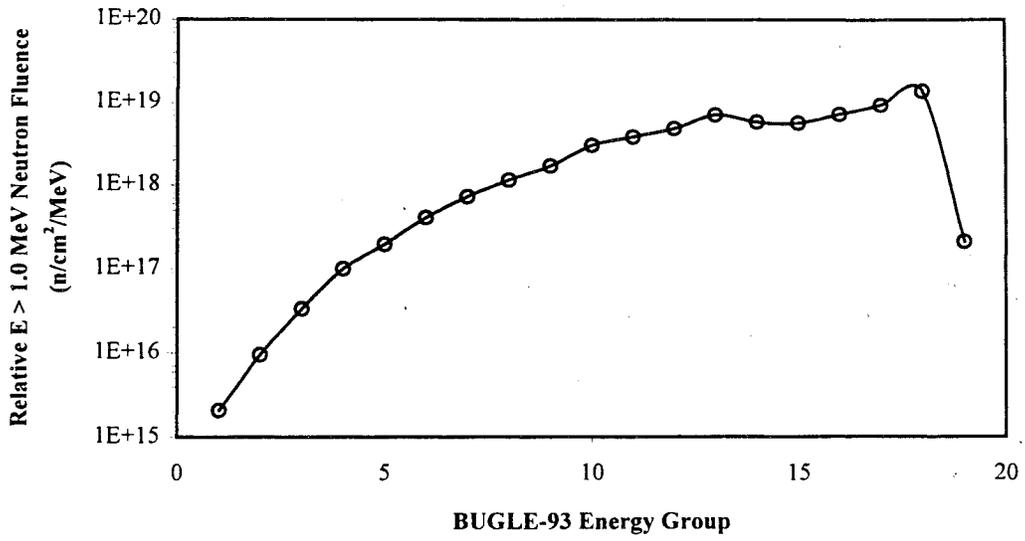


Figure 6-3. E > 1.0 MeV Neutron Fluence at the 15°, 25°, 35°, and 45° Capsule Locations for North Anna Unit No. 1

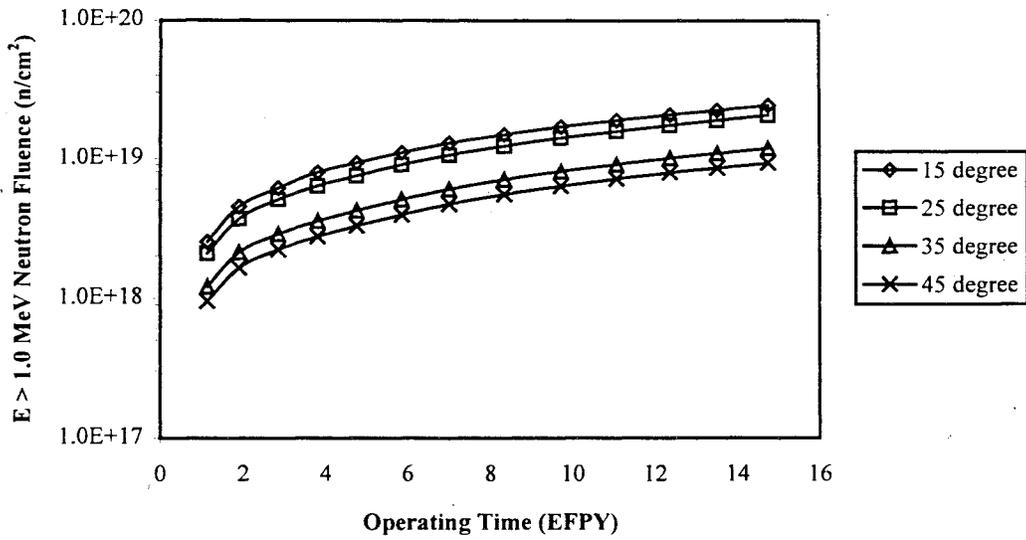


Figure 6-4. Extrapolated $E > 1.0$ MeV Inside Surface Neutron Fluence at the North Anna Unit No. 1 Reactor Vessel 0° , 15° , 30° , and 45° Locations

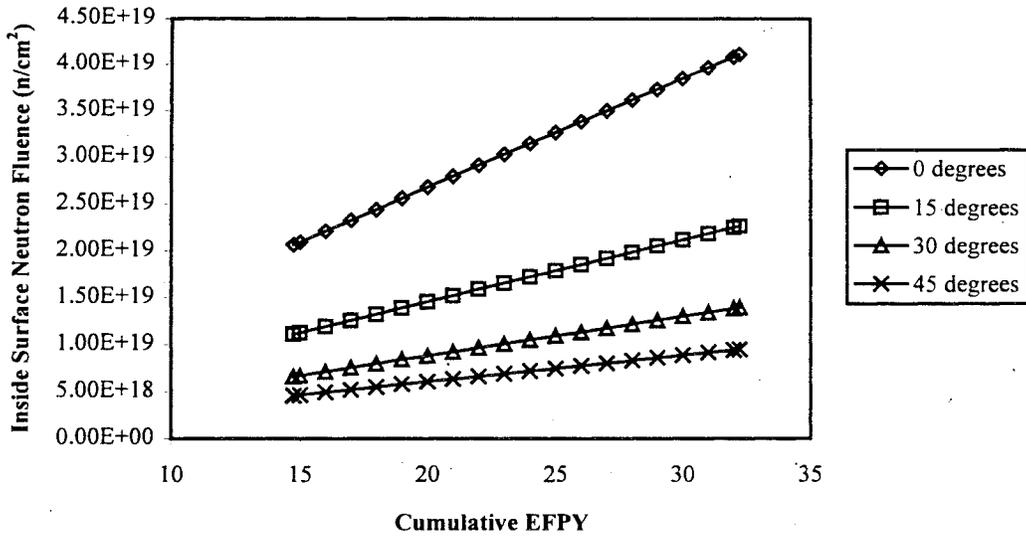


Figure 6-5. Extrapolated $E > 1.0$ MeV $\frac{1}{4}T$ Neutron Fluence at the North Anna Unit No. 1 Reactor Vessel 0° , 15° , 30° , and 45° Locations

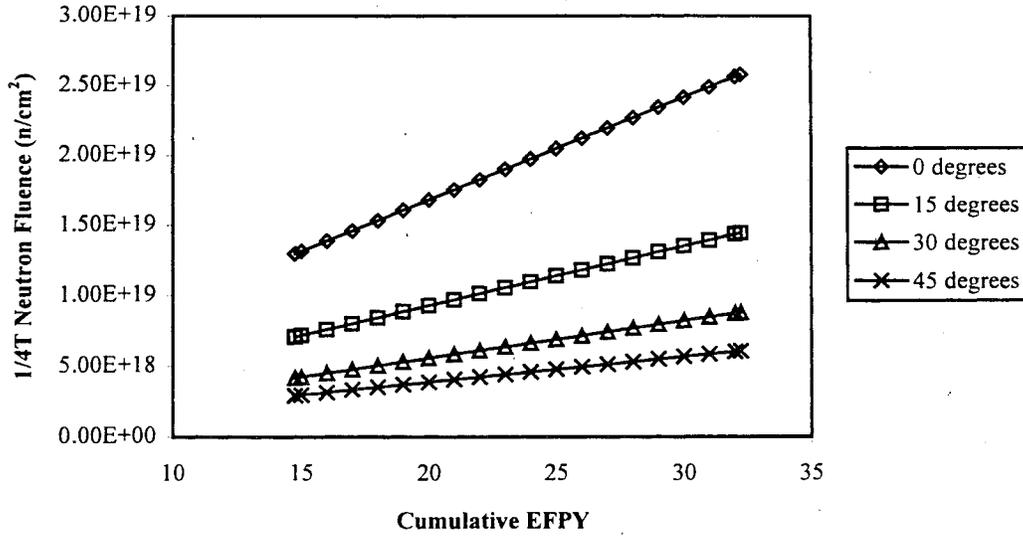
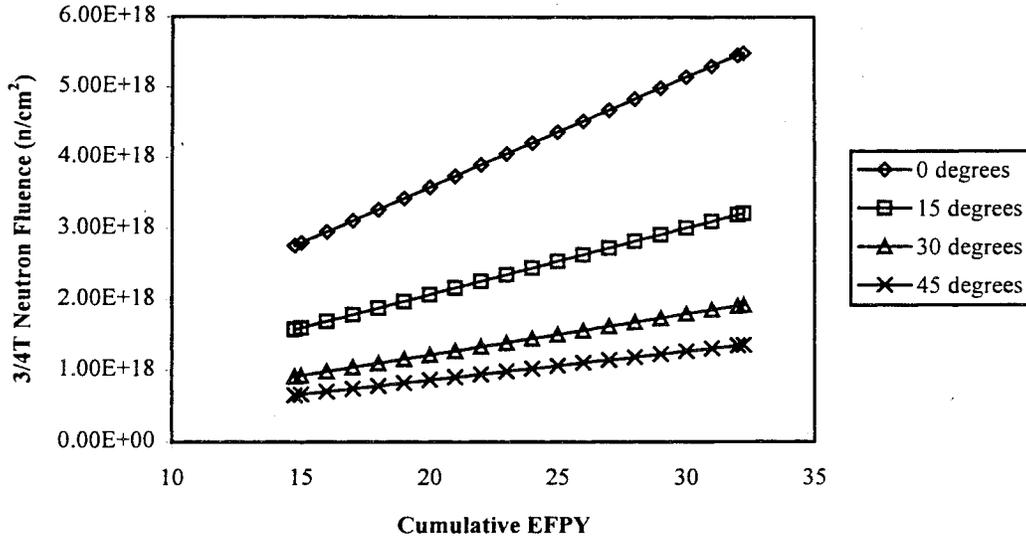
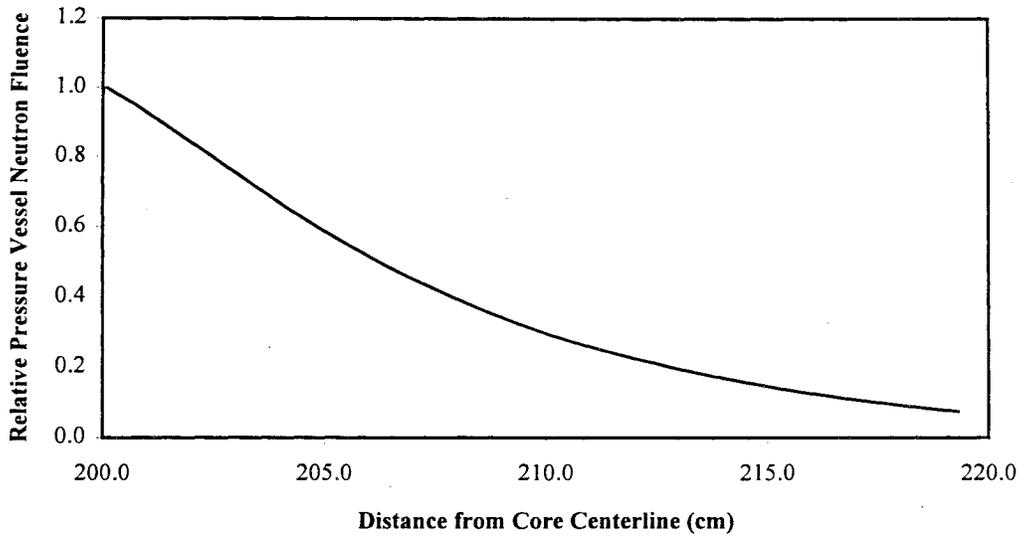


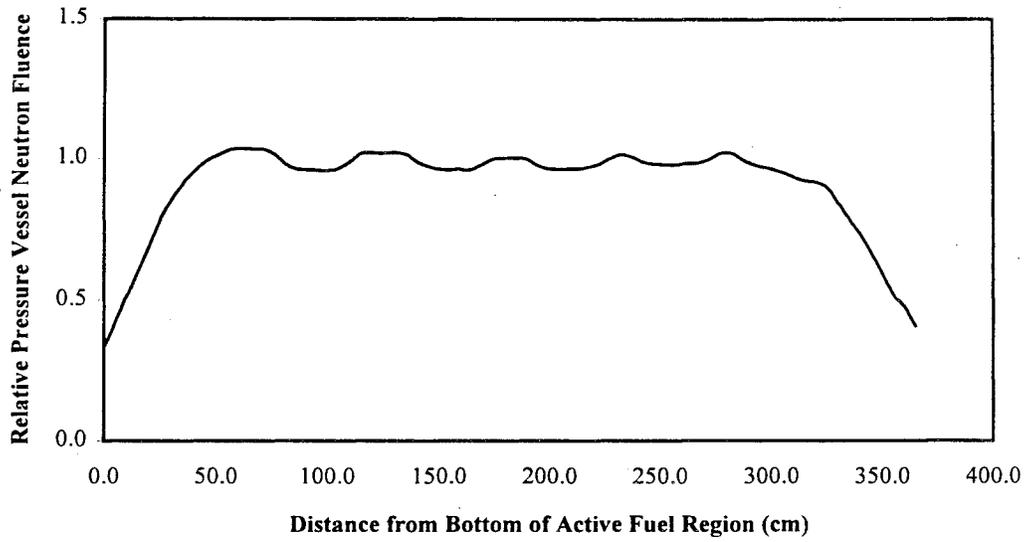
Figure 6-6. Extrapolated $E > 1.0$ MeV $3/4T$ Neutron Fluence at the North Anna Unit No. 1 Reactor Vessel 0° , 15° , 30° , and 45° Locations



**Figure 6-7. Radial Dependence of the Pressure Vessel Neutron Fluence
(Relative to the Mid-Plane Inside Surface)**



**Figure 6-8. Axial Dependence of the Pressure Vessel Neutron Fluence
(Relative to the Mid-Plane Inside Surface)**



7. Discussion of Capsule Results

7.1. Copper and Nickel Chemical Composition Data

To date, several chemical analyses have been performed on the North Anna Unit No. 1 RVSP base metal forging and weld metal. These analyses have been performed on the unirradiated surveillance materials, broken Charpy specimens tested as part of the North Anna Unit No. 1, Capsule U analysis, and broken Charpy specimens tested as part of the North Anna Unit No. 1, Capsule W analysis. The mean copper and nickel contents for the North Anna No. 1 RVSP base metal forging and weld metal represent the best-estimate chemical contents for these materials. The copper and nickel chemical content data and their calculated means are presented in Tables 7-1 and 7-2.

7.2. Unirradiated Material Property Data

The base metal and weld metal were selected for inclusion in the North Anna Unit No. 1 surveillance program in accordance with the criteria in effect at the time the program was designed. The applicable selection criterion was based on the unirradiated properties of the North Anna Unit No. 1 reactor vessel beltline region materials only.

The unirradiated mechanical properties for the North Anna Unit No. 1 RVSP materials are summarized in Appendices C and D of this report.

7.3. Irradiated Property Data

In addition to the Capsule W mechanical test data, surveillance data is available from the North Anna Unit No. 1 RVSP Capsules V and U. Framatome Technologies, Inc. (formally Babcock & Wilcox Nuclear Power Generation Division) performed the testing and evaluation for Capsule V,^[2] while the testing and evaluation for Capsule U was performed by Westinghouse Electric Corporation.^[3]

The capsule fluences for the North Anna Unit No. 1 Capsule V and Capsule U have been reanalyzed, and the results have been documented in WCAP-14044.^[16] Based on this re-evaluation, the capsule fluences ($E > 1.0$ MeV) for Capsule V and Capsule U are 2.63×10^{18} n/cm² and 8.72×10^{18} n/cm² respectively.

7.3.1. Tensile Properties

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

7.3.2. Impact Properties

Tables 7-4 and 7-5 compare the measured changes in irradiated Charpy V-notch impact properties from Capsule W with the predicted changes in accordance with Regulatory Guide 1.99, Revision 2.^[17]

The measured 30 ft-lb transition temperature shifts for the surveillance base metal forging are less than the shifts predicted using Regulatory Guide 1.99, Revision 2, Position 1.1, and with the addition of the margin (σ) the predicted shifts for these materials have a large amount of conservatism. The measured 30 ft-lb transition temperature shift for the surveillance weld metal is greater than the shift predicted using Regulatory Guide 1.99, Revision 2, Position 1.1. However, this measured 30 ft-lb transition temperature shift falls within one standard deviation (σ) of the predicted shift (see Table 7-4).

The measured upper-shelf energies for the North Anna Unit No. 1 Capsule W surveillance materials do not fall below the required 50 ft-lb limit. The measured percent decrease in C_v USE for the measured surveillance base metal forging and the surveillance weld metal are in agreement with the values predicted using Regulatory Guide 1.99, Revision 2. The base metal forging in the axial orientation and the weld metal have a predicted percent decrease in C_v USE slightly greater than the measured values. The percent reduction in C_v USE for the base metal forging in the tangential orientation showed the best comparison between its measured data and the value predicted using Regulatory Guide 1.99, Revision 2.

The original unirradiated Charpy impact data and irradiated Charpy impact data for Capsules V and U were evaluated based on hand-fit Charpy curves generated using engineering judgement. These data were re-plotted and re-evaluated herein using a hyperbolic tangent curve-fitting

program to be consistent with the Capsule W Charpy curves and evaluation. The results of the re-evaluation are presented in Appendix D. In addition, Appendix E contains a comparison of the Charpy V-notch shift results for each surveillance material, hand-fit versus hyperbolic tangent curve-fit.

The radiation-induced changes in toughness of the North Anna Unit No. 1 surveillance materials are summarized in Table 7-6.

In addition, the Sequoyah Unit No. 1 plant specific RVSP and the Sequoyah Unit No. 2 plant specific RVSP provide data for the weld metal W05A (wire heat 25295 / flux lot 1170) and weld metal W05B (wire heat 4278 / flux lot 1211) respectively. The original unirradiated Charpy impact data and irradiated Charpy impact data for both RVSPs were evaluated based on hand-fit Charpy curves generated using engineering judgement. These data were re-plotted and re-evaluated using a hyperbolic tangent curve-fitting program to be consistent with the evaluation of the NA1 plant specific RVSP data.^[18] The radiation-induced changes in toughness of the Sequoyah Unit No. 1 and Sequoyah Unit No. 2 surveillance materials are summarized in Table 7-7.

7.4. Reactor Vessel Fracture Toughness

7.4.1. Adjusted Reference Temperature Evaluation

The adjusted reference temperatures for the North Anna Unit No. 1 reactor vessel beltline region materials were calculated in accordance with Regulatory Guide 1.99, Revision 2 applicable to 32.2 effective full power years (EFPY), and the results are presented in Table 7-8. The evaluations were performed at the $\frac{1}{4}$ -thickness ($\frac{1}{4}T$) and $\frac{3}{4}$ -thickness ($\frac{3}{4}T$) wall location of each beltline material. Based on these results, the controlling beltline material for the North Anna Unit No. 1 reactor vessel is the lower shell forging (Forging 03), heat no. 990400/292332.

7.4.2. Pressurized Thermal Shock Evaluation

A pressurized thermal shock (PTS) evaluation for the North Anna Unit No. 1 reactor vessel beltline materials was performed in accordance with 10 CFR 50.61,^[19] and the results are shown in Table 7-9. The results of the PTS evaluation demonstrate that the North Anna Unit No. 1 reactor vessel beltline materials will not exceed the PTS screening criteria before end-of-life (32.2 EFPY). The controlling beltline material for the North Anna Unit No. 1 reactor vessel with respect to PTS is the lower shell forging (Forging 03), heat no. 990400/292332 with a RT_{PTS} value of 184.9°F which is well below the PTS screening criterion of 270°F.

**Table 7-1. Copper and Nickel Chemical Composition Data for North Anna Unit No. 1
Reactor Vessel Surveillance Base Metal Forging 03
(Heat No. 990400/292332)**

Analysis Source	Cu Wt%	Ni Wt%	Reference
RVSP Baseline Chemistry (Westinghouse Analysis)	0.16	0.79	WCAP-8771 (RVSP Description)
RVSP Baseline Chemistry (Rotterdam Dockyard Analysis)	0.15	0.80	WCAP-8771 (RVSP Description)
CVN Specimen: VT-71	0.158	0.893	WCAP-11777 (Capsule U)
CVN Specimen: VT-36	0.155	0.785	Capsule W
Mean	0.156	0.817	

**Table 7-2. Copper and Nickel Chemical Composition Data for North Anna Unit No. 1
Reactor Vessel Surveillance Weld Metal
(Wire Heat 25531 / Flux Lot 1211)**

Analysis Source	Cu Wt%	Ni Wt%	Reference
RVSP Baseline Chemistry (Westinghouse Analysis)	0.086	0.11	WCAP-8771 (RVSP Description)
CVN Specimen: VW-71	0.124	0.152	WCAP-11777 (Capsule U)
CVN Specimen: VW-29	0.084	0.11	Capsule W
Mean	0.098	0.124	

Table 7-3. Summary of North Anna Unit No. 1 Reactor Vessel Surveillance Capsules Tensile Test Results

Material	Fluence, 10 ¹⁹ n/cm ²	Test Temp., F	Strength, ksi				Ductility, %				
			Ultimate	% ^(a)	Yield	% ^(a)	Total Elong.	% ^(a)	Reduction of Area	% ^(a)	
Base Metal Forging 03, Ht. No. 990400/292332 (Axial)	0.00	Room	92.6 ^(b)	---	70.7 ^(b)	---	18.8 ^(b)	---	58.8 ^(b)	---	
		300	84.9 ^(b)	---	64.4 ^(b)	---	22.6 ^(b)	---	62.5 ^(b)	---	
		550	86.2 ^(b)	---	55.6 ^(b)	---	23.3 ^(b)	---	54.5 ^(b)	---	
	0.263	76	99.3	+7.2	80.4	+13.7	20.9	+11.2	54.9	-6.6	
		548	95.7	+11.0	64.7	+16.4	18.4	-21.0	47.0	-13.8	
	0.872	275	96.8	+14.0	75.9	+17.9	16.4	-27.4	46	-26.4	
		550	95.7	+11.0	69.4	+24.8	13.5	-42.1	41	-24.8	
	2.052	300	98.7	+16.3	78.5	+21.9	14.4	-36.3	47.0	-24.8	
		550	101.6	+17.9	78.1	+40.5	13.1	-43.8	30.4	-44.2	
	Weld Metal, (Wire Heat 25541 / Flux Lot 1211)	0.00	Room	79.4 ^(b)	---	64.2 ^(b)	---	19.2 ^(b)	---	71.0 ^(b)	---
			300	75.8 ^(b)	---	62.0 ^(b)	---	21.0 ^(b)	---	68.0 ^(b)	---
			550	78.7 ^(b)	---	60.9 ^(b)	---	19.0 ^(b)	---	60.0 ^(b)	---
0.263		78	84.5	+6.4	70.8	+10.3	19.3	+0.5	65.0	-8.5	
		548	84.5	+7.4	63.6	+4.4	19.0	0.0	56.5	-5.8	
0.872		275	86.6	+14.2	72.3	+16.6	16.5	-21.4	72	+5.9	
		550	89.2	+13.3	71.8	+17.9	14.4	-24.2	66	+10.0	
2.052		200	86.8	+14.5 ^(c)	73.0	+17.7 ^(c)	16.0	-23.8 ^(c)	60.8	-10.6 ^(c)	
		550	89.2	+13.3	72.9	+19.7	14.2	-25.3	48.6	-19.0	

- (a) Change relative to unirradiated material property.
- (b) Mean value of available test data.
- (c) Calculated relative to 300°F unirradiated tests.

Table 7-4. Measured vs. Predicted 30 ft-lb Transition Temperature Changes for North Anna Unit No. 1 Capsule W Surveillance Materials – 2.052×10^{19} n/cm²

Material	Measured 30 ft-lb Transition Temperature, F			30 ft-lb Transition Temperature Shift Predicted in Accordance With Regulatory Guide 1.99, Revision 2				
	Unirradiated	Irradiated	Difference	Chemistry Factor ^(a)	$\Delta RT_{NDT}^{(b)}$	Margin (σ)	$\Delta RT_{NDT} - \sigma$	$\Delta RT_{NDT} + \sigma$
Base Metal Forging 03, Heat No. 990400/292332 (Tangential Orientation)	-5	88	93	120.0	143.5	17	126.5	160.5
Base Metal Forging 03, Heat No. 990400/292332 (Axial Orientation)	40	136	96	120.0	143.5	17	126.5	160.5
Weld Metal (Wire Heat 25531 / Flux Lot 1211)	-44	42	86	56.2	67.2	28	39.2	95.2
Heat-Affect-Zone Material	-76	8	84	120.0	143.5	17	126.5	160.5

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

(b) $\Delta RT_{NDT} = \text{Chemistry Factor} * \text{fluence factor (using the Capsule W fluence)}$.

**Table 7-5. Measured vs. Predicted Upper-Shelf Energy Decreases for North Anna Unit No. 1 Capsule W
Surveillance Materials – 2.052×10^{19} n/cm²**

Material	Measured Upper-Shelf Energy, ft-lb			% Decrease Predicted In Accordance With Regulatory Guide 1.99, Rev. 2 Figure 2
	Unirradiated	Irradiated	% Decrease	
Base Metal Forging 03, Heat No. 990400/292332 (Tangential Orientation)	135	95	29.6	29.2 ^(a)
Base Metal Forging 03, Heat No. 990400/292332 (Axial Orientation)	85	66	22.4	29.2 ^(a)
Weld Metal (Wire Heat 25531 / Flux Lot 1211)	95	74	22.1	28.2 ^(a)
Heat-Affect-Zone Material	146	89	39.0	29.2 ^(a)

(a) Based on mean copper content as shown in Tables 7-1 and 7-2.

**Table 7-6. Summary of North Anna Unit No. 1 Reactor Vessel Surveillance Capsules
Charpy Impact Test Results**

Material	Capsule	Fluence, 10 ¹⁹ n/cm ²	Measured Transition Temperature		Measured Upper-Shelf	
			ΔCv30, F	ΔCv50, F	Energy, ft-lb	% Decrease
Base Metal Forging 03, Heat No. 990400/292332 (Tangential Orientation)	Baseline	---	---	---	135	---
	V	0.263	51	61	122	9.6
	U	0.872	116	122	110	18.5
	W	2.052	93	114	95	29.6
Base Metal Forging 03, Heat No. 990400/292332 (Axial Orientation)	Baseline	---	---	---	85	---
	V	0.263	29	39	69	18.8
	U	0.872	72	81	93	-9.4
	W	2.052	96	122	66	22.4
Weld Metal (Wire Heat 25541 / Flux Lot 1211)	Baseline	---	---	---	95	---
	V	0.263	88	73	86	9.5
	U	0.872	30	78	92	3.2
	W	2.052	86	91	74	22.1
Heat-Affected Zone Material	Baseline	---	---	---	146	---
	V	0.263	57	74	103	29.5
	U	0.872	3	91	123	15.8
	W	2.052	84	107	89	39.0

Table 7-7. Summary of Sequoyah Unit No. 1 and Sequoyah Unit No. 2 Reactor Vessel Surveillance Capsules Charpy Impact Test Results^[18]

Material	Capsule	Fluence, 10 ¹⁹ n/cm ²	Capsule Irradiation Temp., °F	Chemical Composition ^[20]		Measured ΔCv30, °F
				Cu wt%	Ni, wt%	
Sequoyah Unit No. 1 Surveillance Weld Metal (Wire Heat 25295)	T	0.288	545	0.375	0.125	128
	U	0.955	545	0.375	0.125	145
	X	1.39	545	0.375	0.125	157
Sequoyah Unit No. 2 Surveillance Weld Metal (Wire Heat 4278)	T	0.242	545	0.13	0.11	81
	U	0.608	545	0.13	0.11	154
	X	1.03	545	0.13	0.11	30

**Table 7-8. Evaluation of Adjusted Reference Temperatures for the North Anna Unit No. 1
Reactor Vessel Applicable to 32.2 EFPY**

Material Description ^(a)				Chemical Composition ^(a)		Initial RT _{SR} ^(a)	Chemistry Factor	32.2 EFPY Fluence, n/cm ²			ΔRT _{SR} , F at 32.2 EFPY		Margin		ART, F at 32.2 EFPY	
Reactor Vessel Beltline Region Location	Matl. Ident.	Heat Number	Type	Cu wt%	Ni wt%			Inside Surface	T/4 Location ^(b)	3/4T Location ^(b)	T/4 Location	3/4T Location	T/4 Location	3/4T Location	T/4 Location	3/4T Location
Regulatory Guide 1.99, Revision 2, Position 1.1																
Nozzle Belt Shell Forging	Forging 05	990286/295213	SA-508 Cl. 2	0.16	0.74	+6	121.5	3.885E+18	2.424E+18	9.436E+17	74.8	49.2	69.0	69.0	149.8	124.2
Intermediate Shell Forging	Forging 04	990311/298244	SA-508 Cl. 2	0.12	0.82	+17	86.0	4.108E+19	2.563E+19	9.978E+18	107.7	85.9	34.0	34.0	158.7	136.9
Lower Shell Forging	Forging 03	990400/292332	SA-508 Cl. 2	0.156	0.817	+38	120.0	4.108E+19	2.563E+19	9.978E+18	150.2	119.9	34.0	34.0	222.2	191.9
NS to IS Circ. Weld (OD 94%)	W05A	25295	ASA/SMIT 89	0.352	0.125	0	163.3	N/A	2.424E+18	9.436E+17	100.3	65.9	68.8	68.8	169.1	134.7
NS to IS Circ. Weld (ID 6%)	W05B	4278	ASA/SMIT 89	0.12	0.11	0	63.0	3.885E+18	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
IS to LS Circ. Weld (100%)	W04	25531	ASA/SMIT 89	0.098	0.124	+19	56.2	4.108E+19	2.563E+19	9.978E+18	70.4	56.1	56.0	56.0	145.4	131.1
Regulatory Guide 1.99, Revision 2, Position 2.1																
Lower Shell Forging	Forging 03	990400/292332	SA-508 Cl. 2	0.156	0.817	+38	82.9	4.108E+19	2.563E+19	9.978E+18	103.8	82.8	34.0 ^(c)	34.0 ^(c)	[175.8]	[154.8]
NS to IS Circ. Weld (OD 94%)	W05A	25295	ASA/SMIT 89	0.352	0.125	0	137.7	N/A	2.424E+18	9.436E+17	84.8	55.8	48.8	48.8	133.6	104.6
NS to IS Circ. Weld (ID 6%)	W05B	4278	ASA/SMIT 89	0.12	0.11	0	85.2	3.885E+18	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
IS to LS Circ. Weld (100%)	W04	25531	ASA/SMIT 89	0.098	0.124	+19	68.0	4.108E+19	2.563E+19	9.978E+18	85.1	67.9	56.0 ^(c)	56.0 ^(c)	160.1	142.9

(a) See Appendix A.

(b) Calculated based on the guidelines in Regulatory Guide 1.99, Revision 2 ("x" for ¼T = 1.9655 in. and "x" for ¾T = 5.8965 in.).

(c) Two of the surveillance data points are not credible, however, all surveillance data points are conservatively bounded by the +2σ curve based on Regulatory Guide 1.99, Revision 2, Position 1.1 chemistry factor. Therefore, a full margin value and the Regulatory Guide 1.99, Revision 2, Position 2.1 chemistry factor are used to calculate the adjusted reference temperature value.

[] Controlling values of the adjusted reference temperatures.

7-10

Table 7-9. Evaluation of Pressurized Thermal Shock Reference Temperatures for the North Anna Unit No. 1 Reactor Vessel Applicable to 32.2 EFPY

Material Description ^(a)				Chemical Composition ^(a)		Chem. Factor	Initial RT _{NDT} , F ^(a)	32.2 EFPY Fluence, n/cm ²	Fluence Factor	ΔRT _{PTS} , F	Margin, F	RT _{PTS} , F	Screening Criteria
Reactor Vessel Beltline Region Matl.	Matl. Ident.	Heat Number	Type	Cu wt%	Ni wt%								
RT _{PTS} Calculation Per 10 CFR 50.61 Using Tables													
Nozzle Belt Shell Forging (NS)	Forging 05	990286/295213	SA-508 Cl. 2	0.16	0.74	121.5	6	3.885E+18	0.738	89.7	69.0	164.7	270
Intermediate Shell Forging (IS)	Forging 04	990311/298244	SA-508 Cl. 2	0.12	0.82	86.0	17	4.108E+19	1.362	117.1	34.0	168.1	270
Lower Shell Forging (LS)	Forging 03	990400/292332	SA-508 Cl. 2	0.156	0.817	120.0	38	4.108E+19	1.362	163.4	34.0	235.4	270
NS to IS Circ. Weld (OD 94%)	W05A	25295	ASA/SMIT 89	0.352	0.125	163.3	0	N/A	N/A	N/A	N/A	N/A	300
NS to IS Circ. Weld (ID 6%)	W05B	4278	ASA/SMIT 89	0.12	0.11	63.0	0	3.885E+18	0.738	46.5	61.3	107.8	300
IS to LS Circ. Weld (100%)	W04	25531	ASA/SMIT 89	0.098	0.124	56.2	19	4.108E+19	1.362	76.5	56.0	151.5	300
RT _{PTS} Calculation Per 10 CFR 50.61 Using Surveillance Data													
Lower Shell Forging (LS)	Forging 03	990400/292332	SA-508 Cl. 2	0.156	0.817	82.9	38	4.108E+19	1.362	112.9	34.0 ^(b)	[184.9]	270
NS to IS Circ. Weld (OD 94%)	W05A	25295	ASA/SMIT 89	0.352	0.125	137.7	0	N/A	N/A	N/A	N/A	N/A	300
NS to IS Circ. Weld (ID 6%)	W05B	4278	ASA/SMIT 89	0.12	0.11	85.2	0	3.885E+18	0.738	62.9	68.8 ^(b)	131.7	300
IS to LS Circ. Weld (100%)	W04	25531	ASA/SMIT 89	0.098	0.124	68.0	19	4.108E+19	1.362	92.6	56.0 ^(b)	167.6	300

^(a) See Appendix A.

^(b) Two of the surveillance data points are not credible, however, all surveillance data points are conservatively bounded by the +2σ curve based on generic chemistry factor Tables in 10 CFR 50.61. Therefore, a full margin value and the chemistry factor determined using surveillance data are used to calculate the adjusted reference temperature value.

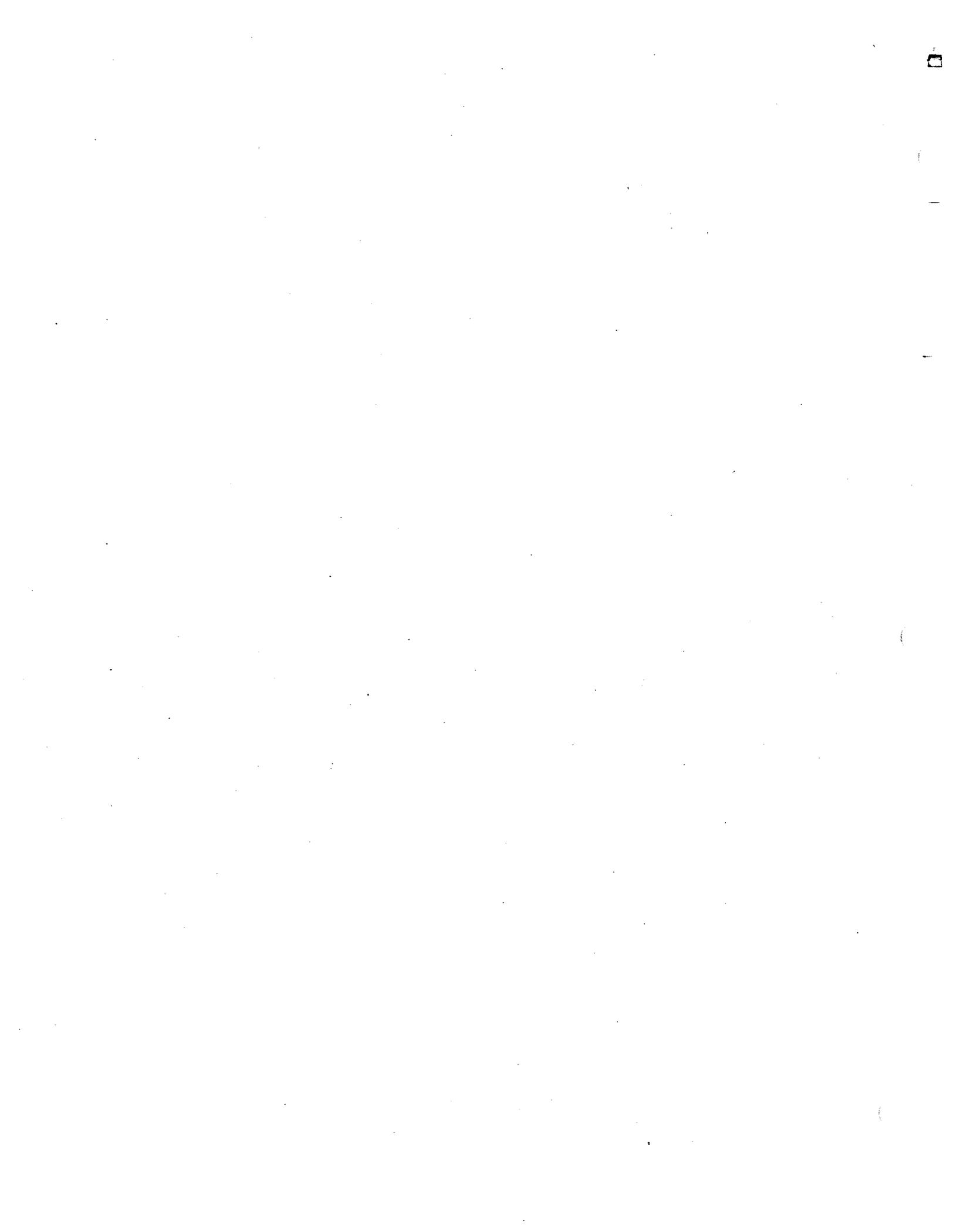
[] Limiting reactor vessel beltline region material in accordance with 10 CFR 50.61.



8. Summary of Results

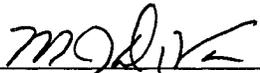
The analysis of the reactor vessel material contained in the third surveillance capsule, Capsule W, removed for evaluation as part of the North Anna Unit No. 1 Reactor Vessel Surveillance Program, led to the following conclusions:

1. The capsule received an average fast neutron fluence of 2.052×10^{19} n/cm² (E > 1.0 MeV).
2. Based on the calculated cycle 11, 12, and 13 full power flux weighted average, the projected end-of-life (32.2 EFPY) peak fast fluence of the North Anna Unit No. 1 reactor vessel beltline region is 4.108×10^{19} n/cm² (E > 1.0 MeV). The corresponding fluences based on the FTI fluence methodology at the ¼-thickness and ¾-thickness vessel wall locations in this peak location are 2.576×10^{19} and 5.486×10^{18} n/cm² (E > 1.0 MeV) respectively.
3. The 30 ft-lb transition temperature for the surveillance base metal forging (Forging 03), heat no. 990400/292332, in the tangential orientation, increased 93°F after the irradiation to 2.052×10^{19} n/cm² (E > 1.0 MeV). In addition, the C_vUSE for this material decreased 29.6%.
4. The 30 ft-lb transition temperature for the surveillance base metal forging (Forging 03), heat no. 990400/292332, in the axial orientation, increased 96°F after the irradiation to 2.052×10^{19} n/cm² (E > 1.0 MeV). In addition, the C_vUSE for this material decreased 22.4%.
5. The 30 ft-lb transition temperature for the surveillance weld metal, weld wire heat 25531 / flux lot 1211, increased 86°F after the irradiation to 2.052×10^{19} n/cm² (E > 1.0 MeV). In addition, the C_vUSE for this material decreased 22.1%.
6. The measured upper-shelf energies for the North Anna Unit No. 1 Capsule W surveillance materials do not fall below the required 50 ft-lbs limit after the irradiation to 2.052×10^{19} n/cm² (E > 1.0 MeV).
7. In accordance with 10 CFR 50.61, the North Anna Unit No. 1 reactor vessel beltline materials will not exceed the PTS screening criteria before end-of-life (32.2 EFPY).



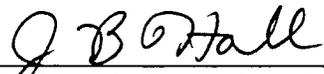
9. Certification

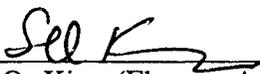
The specimens obtained from the Virginia Power North Anna Unit No. 1 reactor vessel surveillance capsule (Capsule W) were tested and evaluated using accepted techniques and established standard methods and procedures in accordance with the requirements of 10 CFR 50, Appendices G and H.


M. J. DeVan (Material Analysis) 9/1/99
Date
Materials & Structural Analysis Unit


E. Giavedoni (Fluence Analysis) 9/1/99
Date
Performance Analysis Unit

This report has been reviewed for technical content and accuracy.

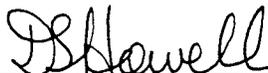

J. B. Hall (Material Analysis) 9-2-99
Date
Materials & Structural Analysis Unit


S. Q. King (Fluence Analysis) 9-2-99
Date
Performance Analysis Unit

Verification of independent review.


K. E. Moore, Manager 9-2-99
Date
Materials & Structural Analysis Unit

This report is approved for release.


D. L. Howell 9/2/99
Date
Program Manager



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2. A. L. Lowe, Jr., et al., "Analysis of Capsule V Virginia Electric & Power Company North Anna Unit No. 1 - Reactor Vessel Material Surveillance Program --," BAW-1638, Babcock & Wilcox, Lynchburg, Virginia, May 1981.*
3. S. E. Yanichko, L. Albertin, and E. P. Lippincott, "Analysis of Capsule U from the Virginia Electric & Power Company North Anna Unit 1 Reactor Vessel Radiation Surveillance Program," WCAP-11777, Westinghouse Electric Corporation, Pittsburgh, Pennsylvania, February 1988.
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5. Code of Federal Regulation, Title 10, Part 50, "Domestic Licensing of Production and Utilization Facilities," Appendix G, Fracture Toughness Requirements.
6. Code of Federal Regulation, Title 10, Part 50, "Domestic Licensing of Production and Utilization Facilities," Appendix H, Reactor Vessel Material Surveillance Program Requirements.
7. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, "Nuclear Power Plant Components," Appendix G, Protection Against Nonductile Failure, 1989 Edition.
8. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section XI, "Rules for Inservice Inspection of Nuclear Power Plant Components," Appendix G, Fracture Toughness Criteria for Protection Against Failure, 1989 Edition.
9. ASTM Standard E 208-81, "Method for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels," American Society for Testing and Materials, Philadelphia, Pennsylvania.

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10. K. Y. Hour, "Evaluation of Virginia Power Company North Anna Unit 1 Capsule W," 00:475-0189-01:02 (FTG Document No. 31-1023292-01), B&W Services, Inc., Lynchburg, Virginia, August 1999.
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18. E. D. Eason, J. E. Wright, and G. R. Odette, "Improved Embrittlement Correlations for Reactor Pressure Vessel Steels," NUREG/CR-6551, Modeling and Computing Services, Boulder, Colorado, August 1998.
19. Code of Federal Regulations, Title 10, "Domestic Licensing of Production and Utilization Facilities," Part 50.61, "Fracture Toughness Requirements for Protection Against Pressurized Thermal Shock," Federal Register, dated December 19, 1995 as amended by Federal Register, dated July 29, 1996.
20. M. J. DeVan, "Response to Generic Letter 92-01, Revision 1, Supplement 1 for Virginia Power' North Anna Units 1 and 2 Beltline Materials and Surry Units 1 and 2 Rotterdam Beltline Weld Metals," BAW-2260, B&W Nuclear Technologies, Inc., Lynchburg, Virginia, October 1995.*

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

APPENDIX A

**Reactor Vessel Surveillance Program
Background Data and Information**

A.1. Capsule Identification

The capsules, used in the North Anna Unit No. 1 reactor vessel surveillance program, are identified in Table A-1 by identification and location. The capsule locations within the North Anna Unit No. 1 reactor vessel are shown in Figure A-2.

A.2. North Anna Unit No. 1 Reactor Pressure Vessel

The North Anna Unit No. 1 reactor pressure vessel was fabricated by the Rotterdam Dockyard Company. The North Anna Unit No. 1 reactor vessel beltline region consists of two shells, containing two heats of base metal forging and one circumferential weld seam. Table A-2 presents a description of the North Anna Unit No. 1 reactor vessel beltline materials including their copper and nickel chemical contents and their unirradiated mechanical properties. The heat treatments of the beltline materials are presented in Table A-3. The locations of the materials within the reactor vessel beltline region are shown in Figure A-1.

A.3. Surveillance Material Selection Data

The data used to select the materials for the specimens in the surveillance program, in accordance with ASTM Standard E 185-73, are shown in Table A-2. The North Anna Unit No. 1 RVSP capsules include the limiting reactor vessel beltline material, Forging 03, heat no. 990400/292332. The surveillance weld used in the North Anna Unit No. 1 RVSP was fabricated using the wire heat 25531 and SMIT 89 flux lot 1211 which is identical to the intermediate to lower shell circumferential weld in the North Anna Unit No. 1 reactor vessel.

Table A-1. North Anna Unit No. 1 Surveillance Capsule Identifications and Original Locations

Capsule Identification	Capsule Location ^(a)
S	45°
T	55°
U	65°
V	165°
W	245°
X	285°
Y	295°
Z	305°

(a) Reference irradiation capsule locations as shown in Figure A-2.

Table A-2. Description of the North Anna Unit No. 1 Reactor Vessel Beltline Region Materials^{[A-1],[A-2],[A-3],[A-4]}

Material Heat No.	Material Type	Beltline Region Location	Chemical Composition		Unirradiated Toughness Properties					
			Cu, wt%	Ni, wt%	30 ft-lb, F	50 ft-lb, F	35 MLE, F	C _v USE, ft-lbs	T _{NDT} , F	RT _{NDT} , F
990286/295213	SA-508 Cl. 2	Nozzle Belt Shell	0.16	0.74	---	---	---	74	2	6
990311/298244	SA-508 Cl. 2	Intermediate Shell	0.12	0.82	---	---	---	92	-31	17
990400/292332	SA-508 Cl. 2	Lower Shell	0.156 ^(b)	0.817 ^(b)	---	---	---	85	-13	38
25295 / 1170 ^(a)	ASA Weld/ SMIT 89 Flux	Nozzle Belt to Interm. Shell Circ. Weld (OD 94%)	0.352	0.125	---	---	---	111	0	0
4278 / 1211 ^(a)	ASA Weld/ SMIT 89 Flux	Nozzle Belt to Interm. Shell Circ. Weld (ID 6%)	0.12	0.11	---	---	---	105	0	0
25531 / 1211 ^(a)	ASA Weld/ SMIT 89 Flux	Intermediate to Lower Shell Circ. Weld	0.098 ^(b)	0.124 ^(b)	---	---	---	102	-13	19

(a) Weld wire heat number and flux lot identifiers.

(b) New best estimate values (see Section 7).

A-4

**Table A-3. Heat Treatment of the North Anna Unit No. 1 Reactor Vessel
Beltline Region Materials**

Material	Heat Treatment
Nozzle Belt Forging 05 (Ht. No. 990286/295213)	Austenitizing: 1616-1697°F for 3 hrs., water quenched Tempering: 1202-1238°F for 6 hrs., furnace cooled to 761°F Post Weld: 1130±25°F for 14¾ hrs. (min.), furnace cooled ^{(a),(b)}
Intermediate Shell Forging 04 (Ht. No. 990311/29824)	Austenitizing: 1616-1697°F for 6 hrs., water quenched Tempering: 1202-1238°F for 6 hrs., furnace cooled to 824°F Post Weld: 1130±25°F for 14¾ hrs. (min.), furnace cooled ^{(a),(b)}
Lower Shell Forging 03 (Ht. No. 990400/292332)	Austenitizing: 1616-1706°F for 5 hrs., water quenched Tempering: 1202-1247°F for 7½ hrs., furnace cooled to 851°F Post Weld: 1130±25°F for 14¾ hrs. (min.), furnace cooled ^{(a),(b)}
Nozzle Belt to Intermediate Shell Girth Seam Weld (OD 94%) (Wire Heat 25295/Flux Lot 1170)	Post Weld: 1130±25°F for 10¾ hrs. (min.), furnace cooled ^(c)
Nozzle Belt to Intermediate Shell Girth Seam Weld (ID 6%) (Wire Heat 4278/Flux Lot 1211)	Post Weld: 1130±25°F for 10¾ hrs. (min.), furnace cooled ^(c)
Intermediate to Lower Shell Girth Seam Weld (Wire Heat 25531/Flux Lot 1211)	Post Weld: 1130±25°F for 10¾ hrs. (min.), furnace cooled ^(c)

^(a) Austenitizing and tempering times are from Rotterdam Dockyard Company Test Certificates. ^[A-5]

^(b) Post weld heat treatments based on heat treatment of North Anna Unit No. 1 surveillance base metal.

^(c) Post weld heat treatments based on heat treatment of North Anna Unit No. 1 surveillance weld metal.

Figure A-1. Location and Identification of Materials Used in the Fabrication of the North Anna Unit No. 1 Reactor Pressure Vessel

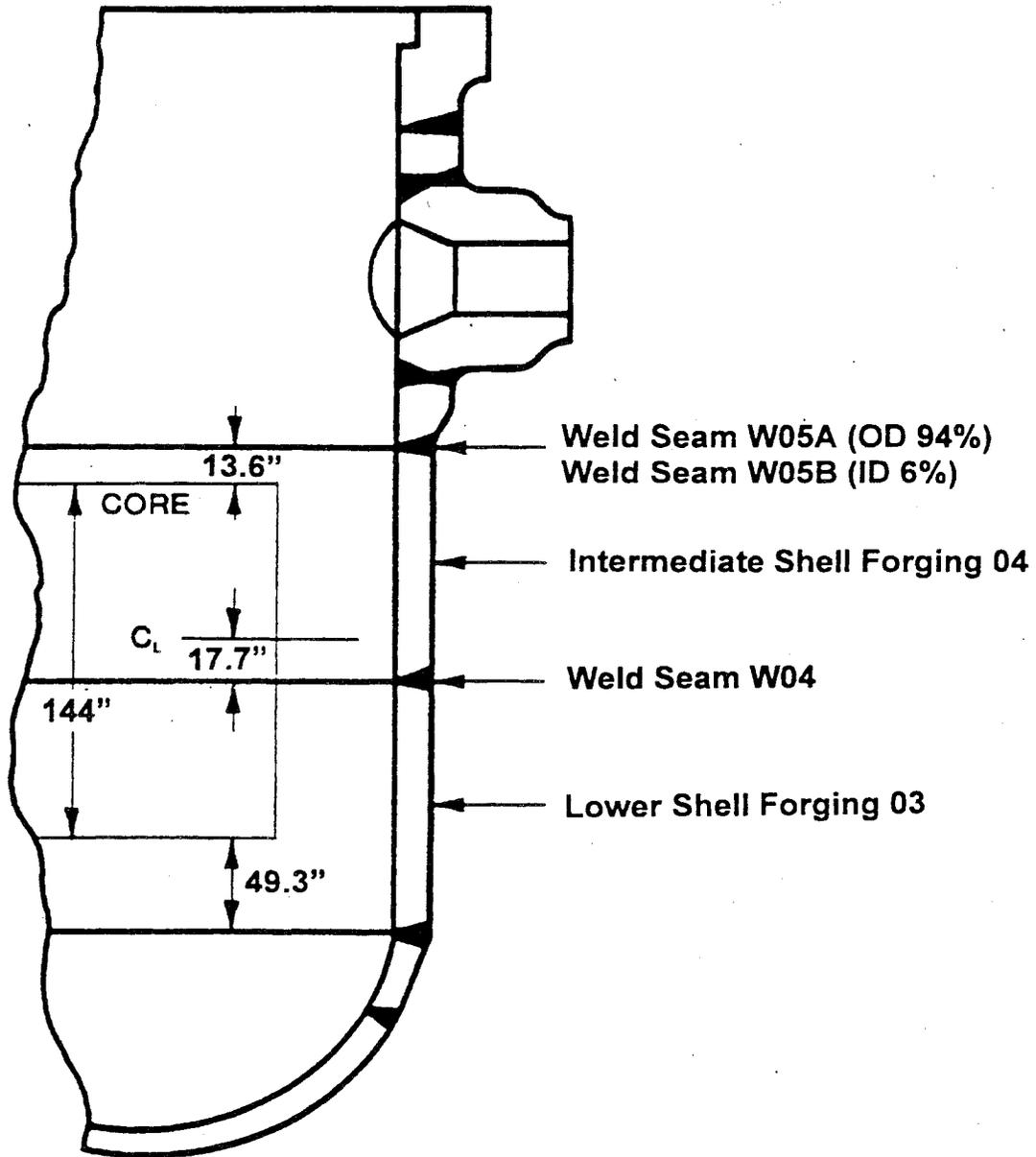
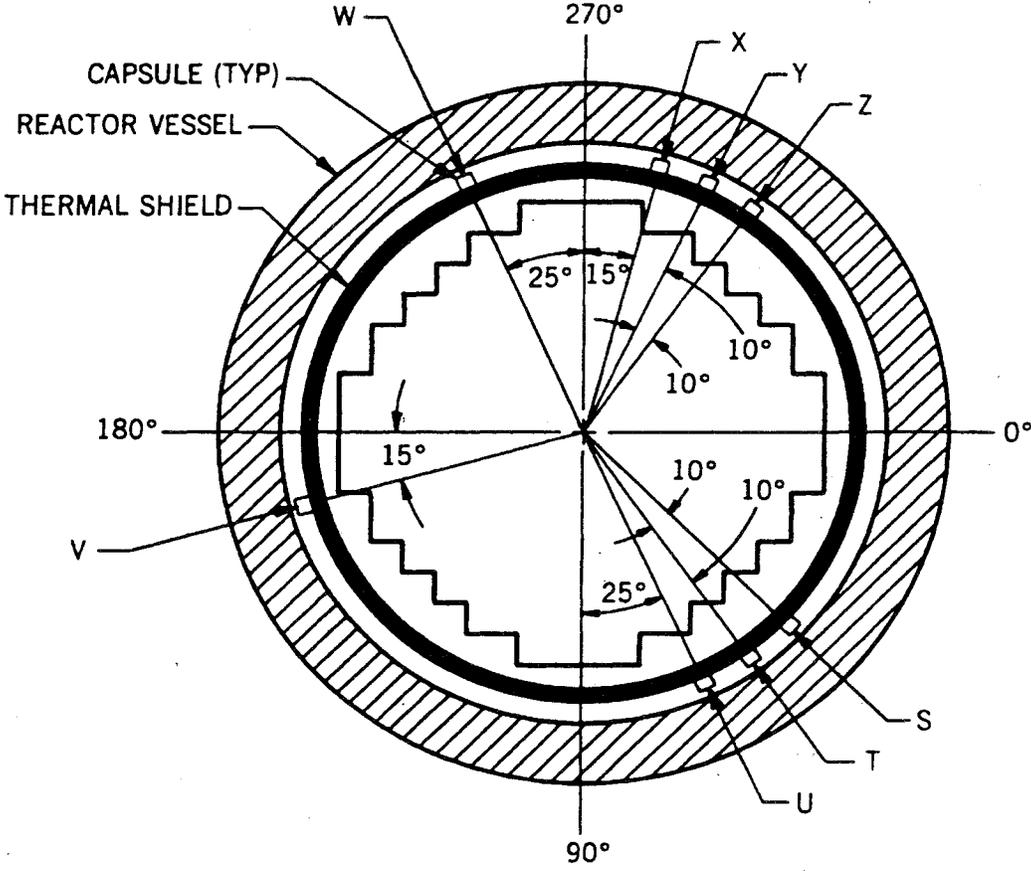


Figure A-2. Original Locations of Surveillance Capsule Irradiation Sites in the North Anna Unit No. 1 Reactor Vessel



A.4. References

- A-1. A. L. Lowe, Jr., "*Reactor Pressure Vessel and Surveillance Program Materials Licensing Information for North Anna Units 1 and 2,*" BAW-1911, Revision 1, Babcock & Wilcox, Lynchburg, Virginia, August 1986.*
- A-2. M. J. DeVan and A. L. Lowe, Jr., "*Response to Generic Letter 92-01 for Virginia Electric & Power Company North Anna Unit 1 and North Anna Unit 2,*" BAW-2168, Revision 1, B&W Nuclear Technologies, Inc., Lynchburg, Virginia, September 1992.*
- A-3. M. J. DeVan, "*North Anna Units 1 and 2 Response to Closure Letter for NRC Generic Letter 92-01, Revision 1,*" BAW-2224, B&W Nuclear Technologies, Inc., Lynchburg, Virginia, July 1994.*
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- A-5. Framatome Technologies Inc. Document 38-1247870-00, "*North Anna Units 1 & 2 and Surry Units 1 & 2 Reactor Vessel Beltline Materials Data,*" release September 1999.

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

APPENDIX B

**Instrumented Charpy V-Notch Specimen Test Results
Load-Time Traces**

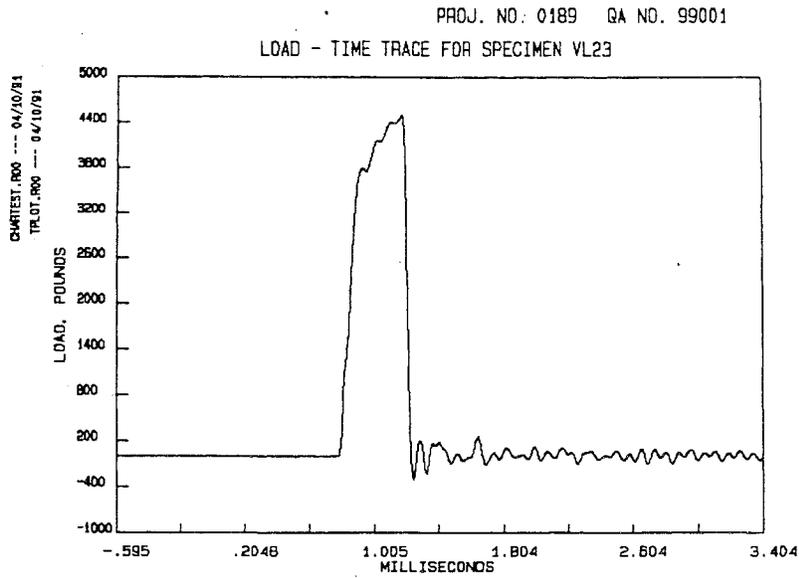


Figure B-1. Load-Time Trace for Charpy V-Notch Impact Specimen VL23

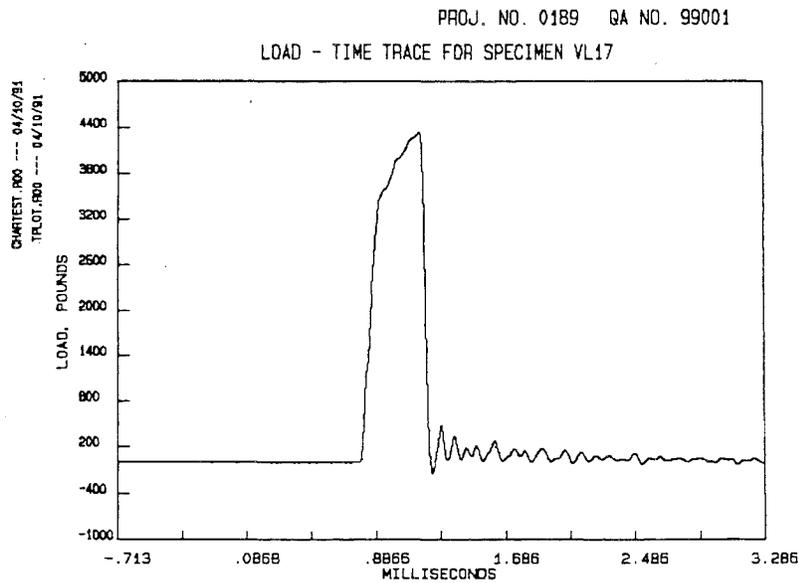


Figure B-2. Load-Time Trace for Charpy V-Notch Impact Specimen VL17

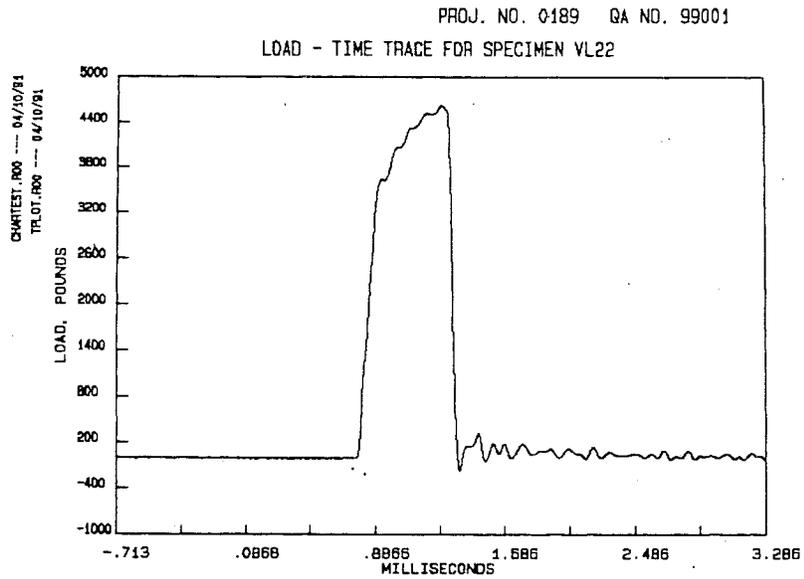


Figure B-3. Load-Time Trace for Charpy V-Notch Impact Specimen VL22

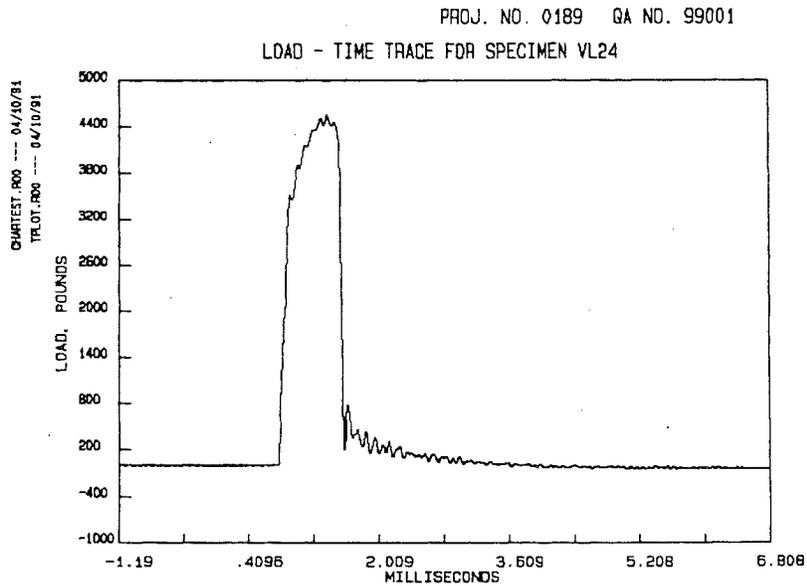


Figure B-4. Load-Time Trace for Charpy V-Notch Impact Specimen VL24

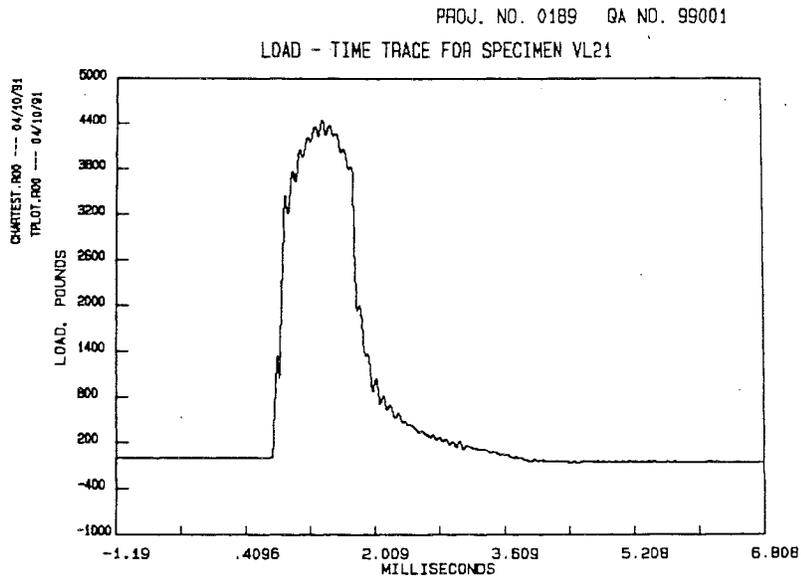


Figure B-5. Load-Time Trace for Charpy V-Notch Impact Specimen VL21

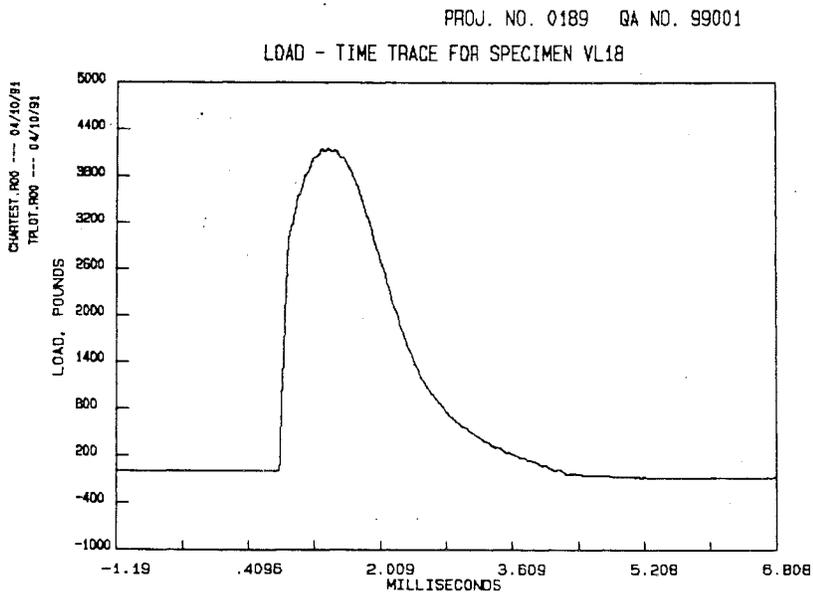


Figure B-6. Load-Time Trace for Charpy V-Notch Impact Specimen VL18

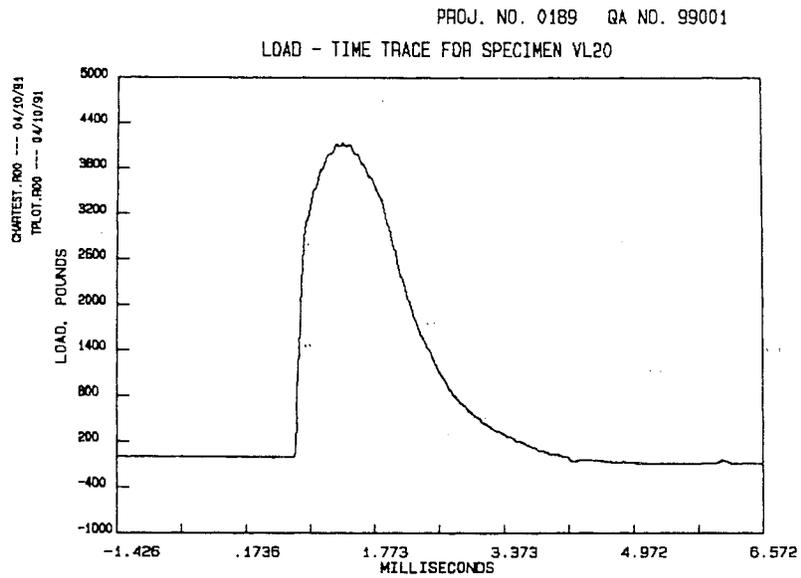


Figure B-7. Load-Time Trace for Charpy V-Notch Impact Specimen VL20

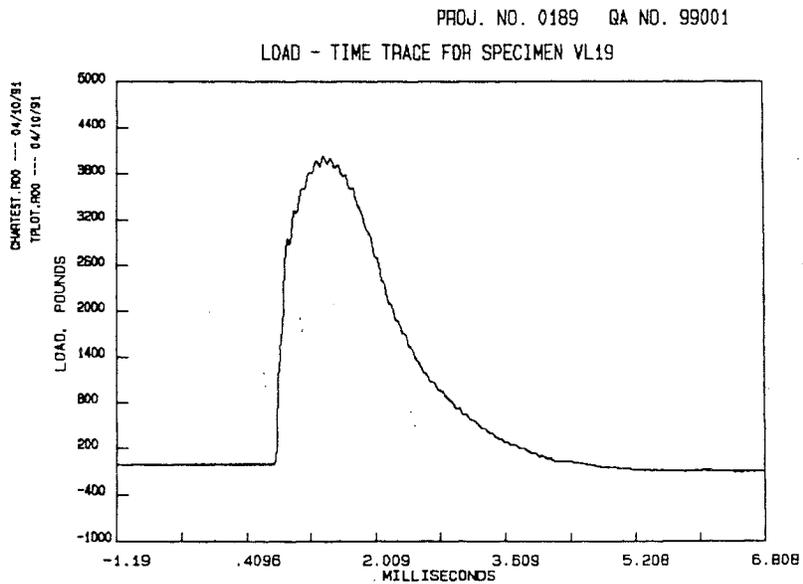


Figure B-8. Load-Time Trace for Charpy V-Notch Impact Specimen VL19

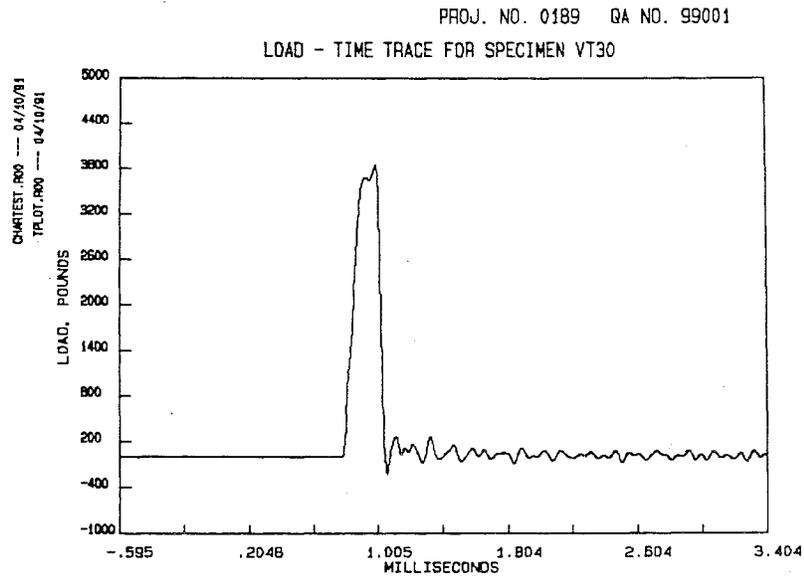


Figure B-9. Load-Time Trace for Charpy V-Notch Impact Specimen VT30

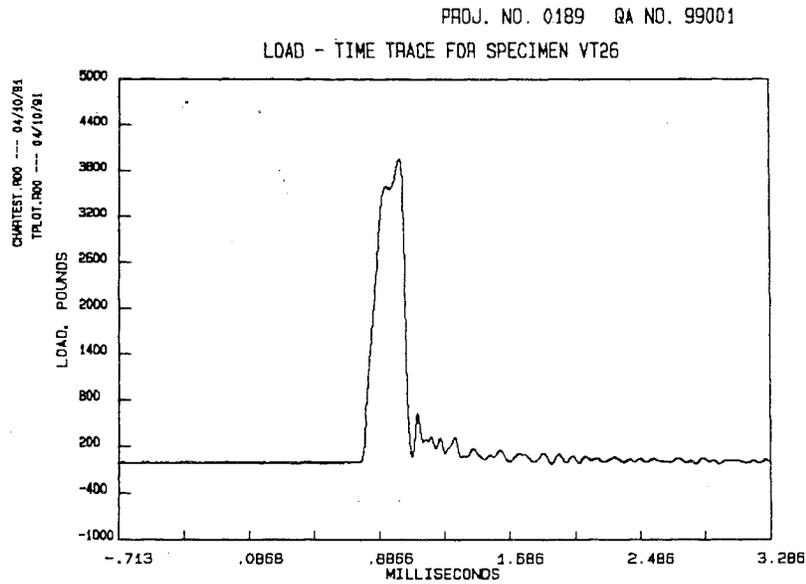


Figure B-10. Load-Time Trace for Charpy V-Notch Impact Specimen VT26

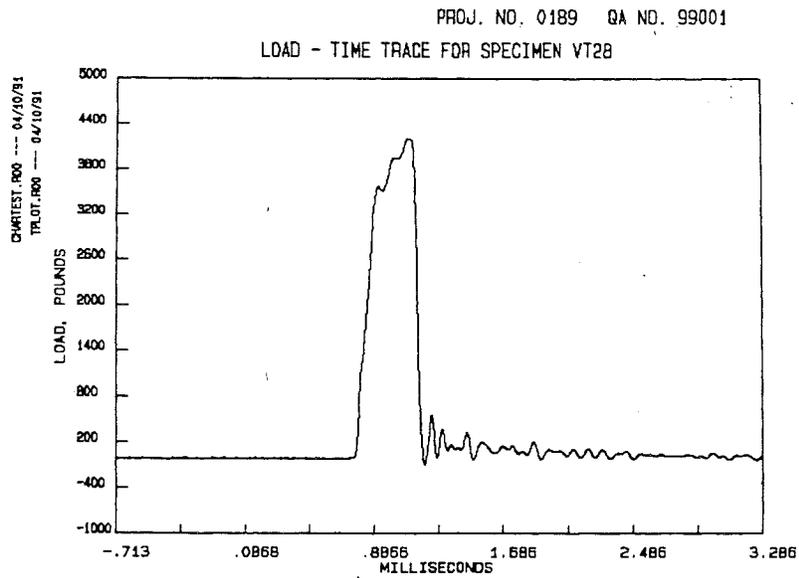


Figure B-11. Load-Time Trace for Charpy V-Notch Impact Specimen VT28

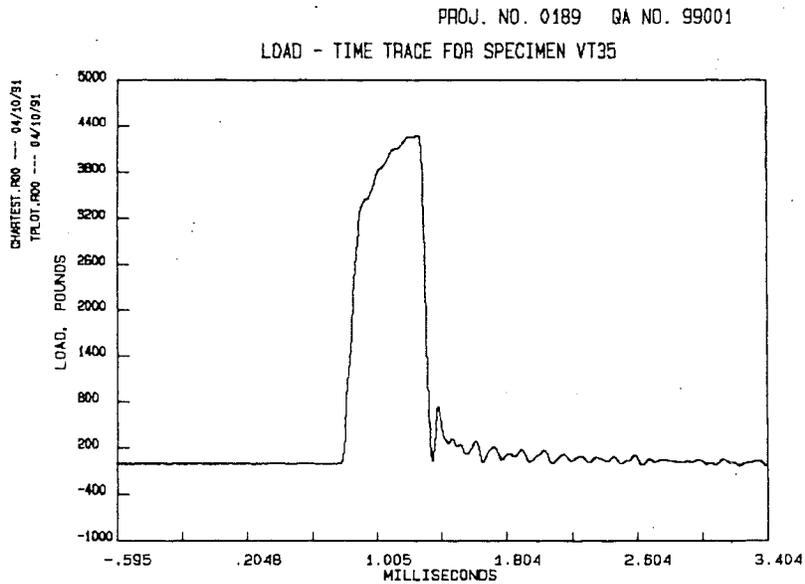


Figure B-12. Load-Time Trace for Charpy V-Notch Impact Specimen VT35

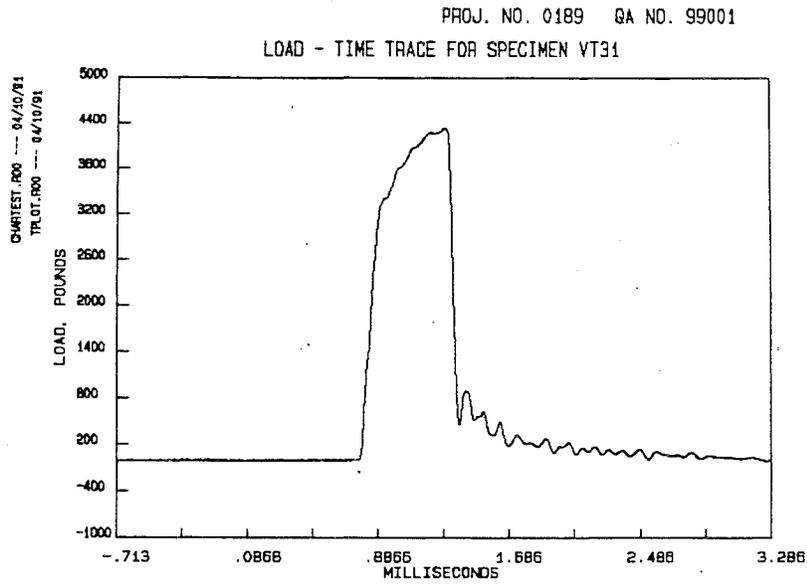


Figure B-13. Load-Time Trace for Charpy V-Notch Impact Specimen VT31

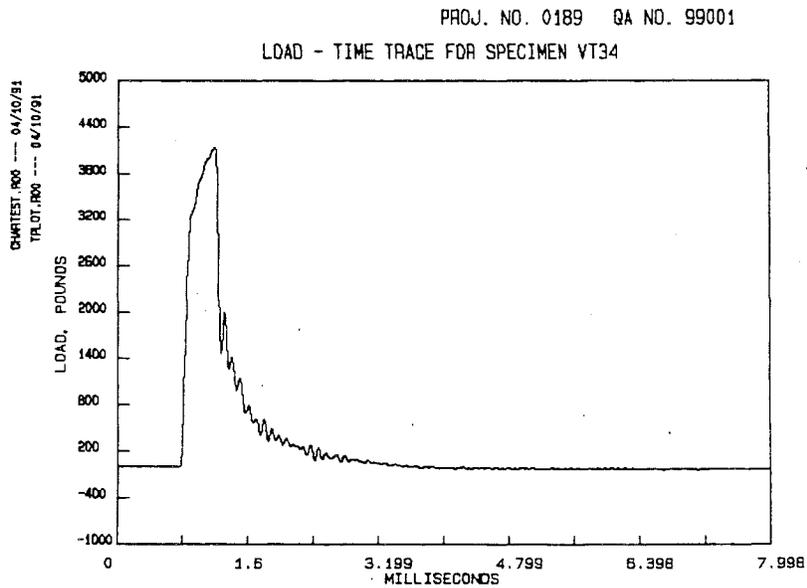


Figure B-14. Load-Time Trace for Charpy V-Notch Impact Specimen VT34

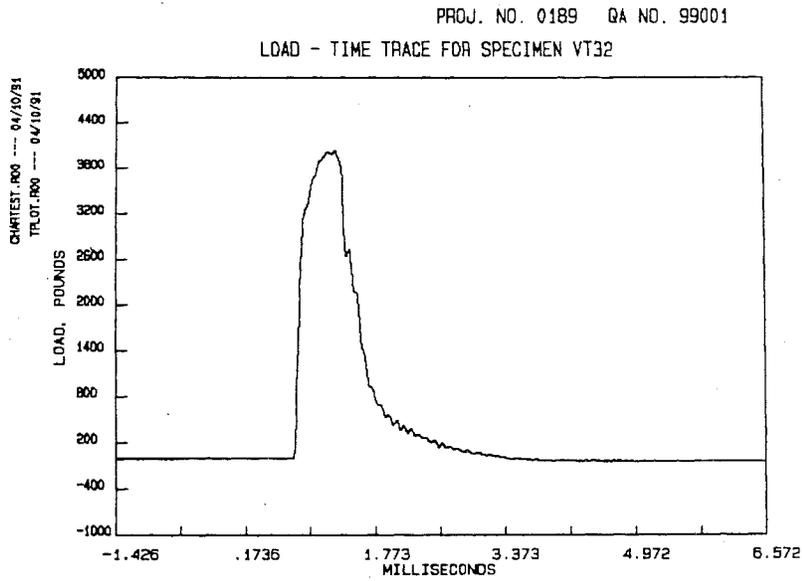


Figure B-15. Load-Time Trace for Charpy V-Notch Impact Specimen VT32

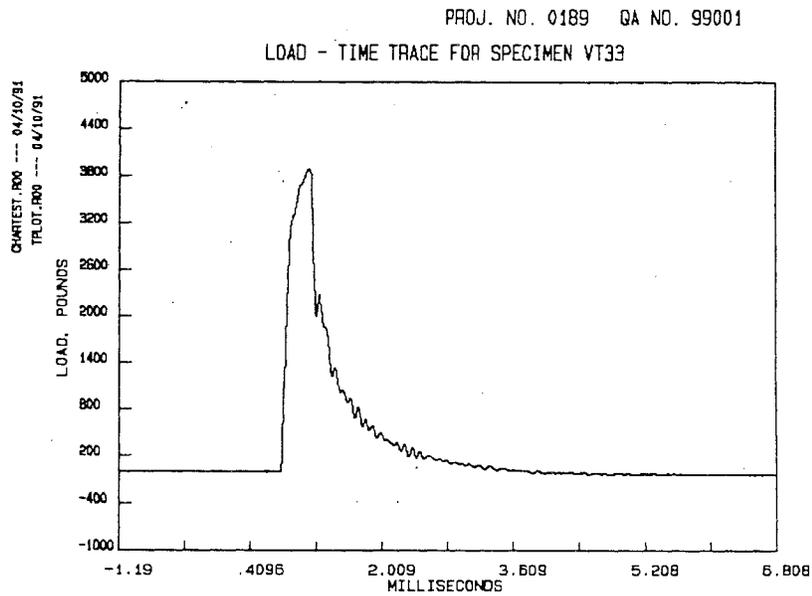


Figure B-16. Load-Time Trace for Charpy V-Notch Impact Specimen VT33

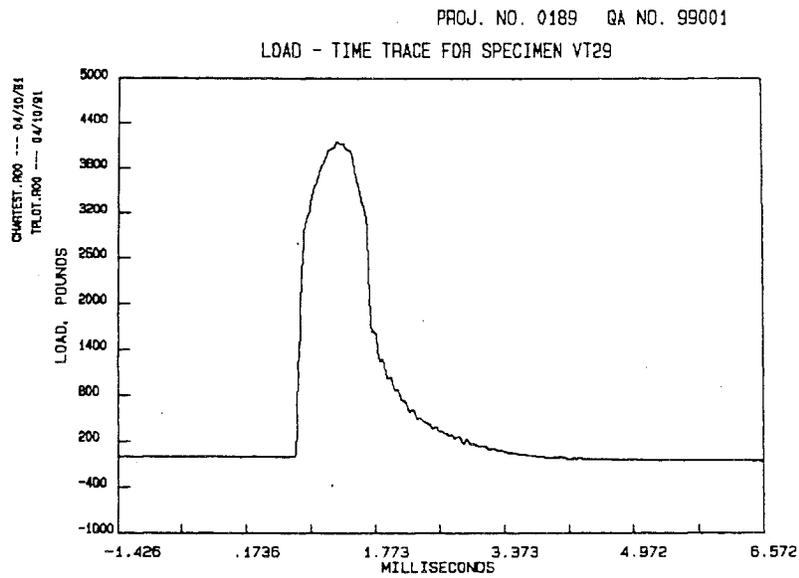


Figure B-17. Load-Time Trace for Charpy V-Notch Impact Specimen VT29

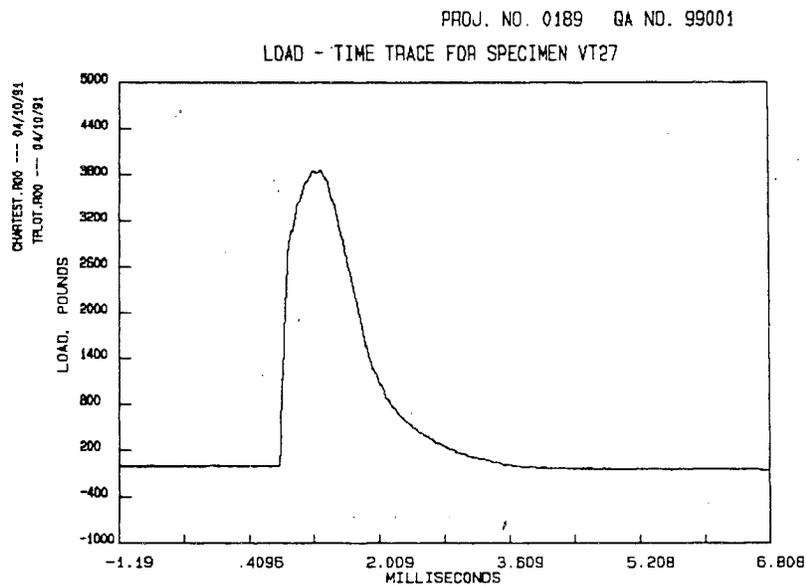


Figure B-18. Load-Time Trace for Charpy V-Notch Impact Specimen VT27

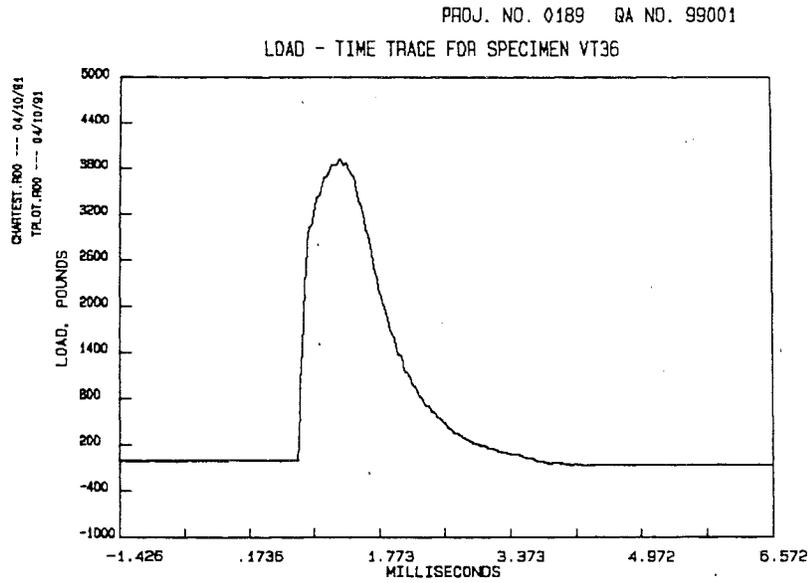


Figure B-19. Load-Time Trace for Charpy V-Notch Impact Specimen VT36

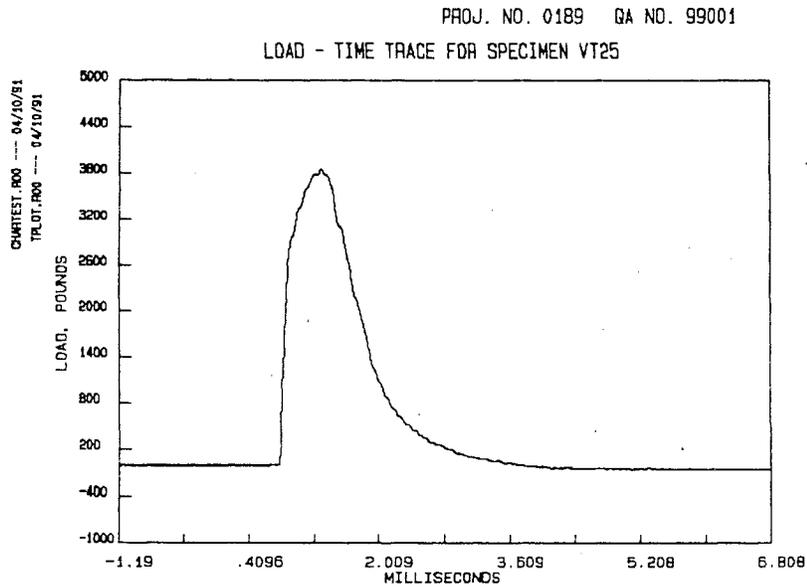


Figure B-20. Load-Time Trace for Charpy V-Notch Impact Specimen VT25

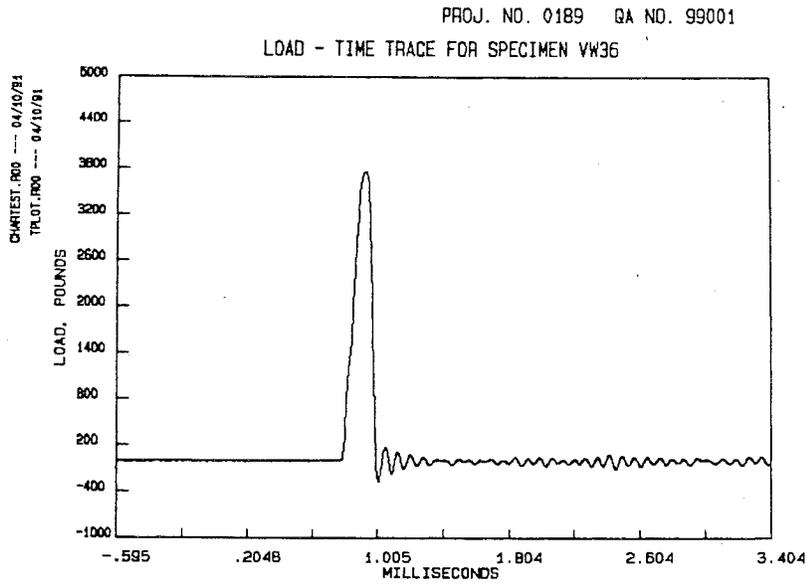


Figure B-21. Load-Time Trace for Charpy V-Notch Impact Specimen VW36

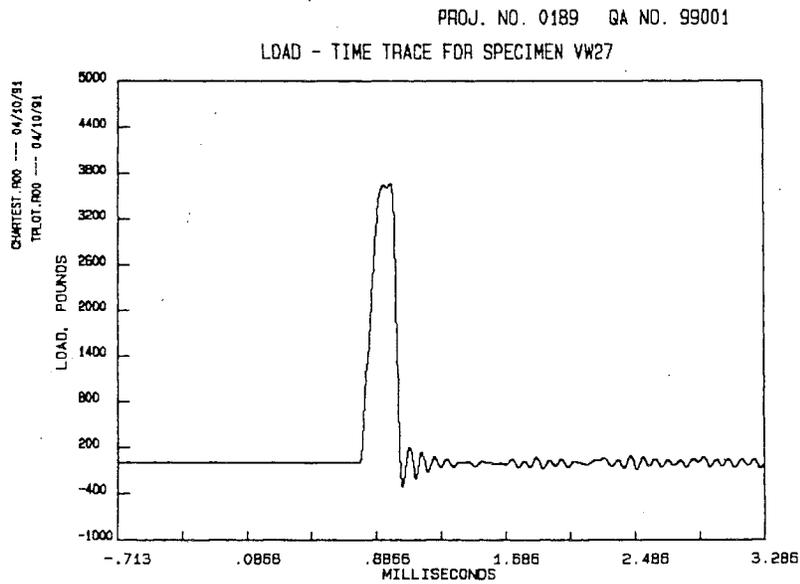


Figure B-22. Load-Time Trace for Charpy V-Notch Impact Specimen VW27

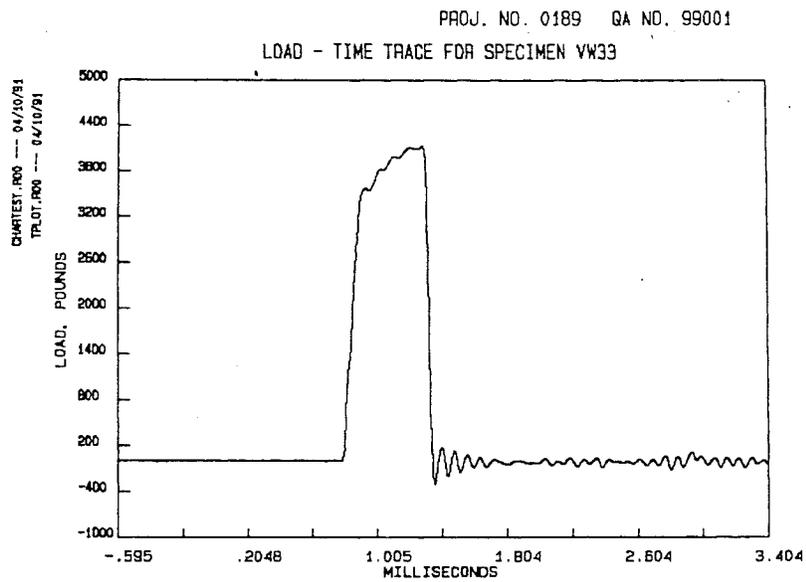


Figure B-23. Load-Time Trace for Charpy V-Notch Impact Specimen VW33

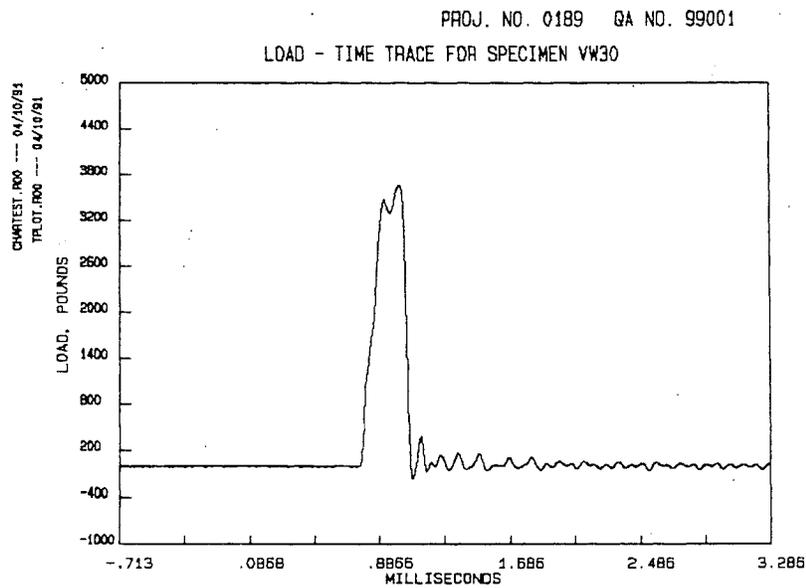


Figure B-24. Load-Time Trace for Charpy V-Notch Impact Specimen VW30

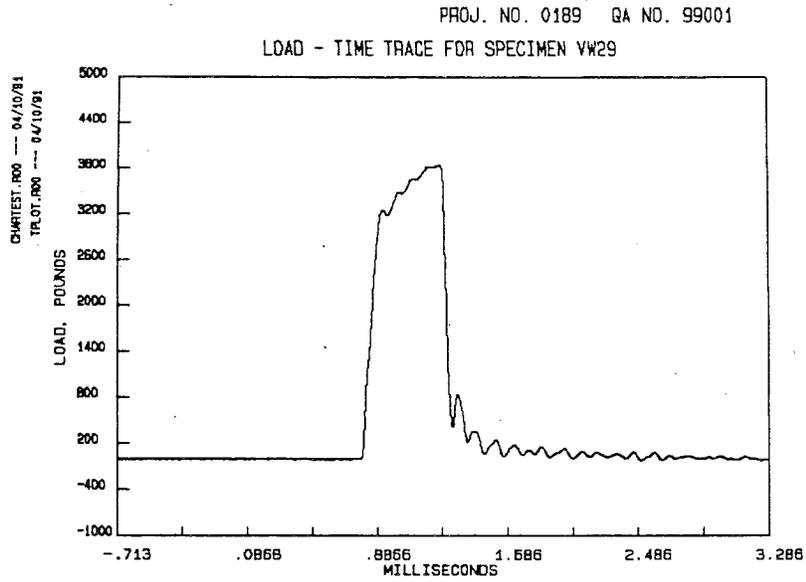


Figure B-25. Load-Time Trace for Charpy V-Notch Impact Specimen VW29

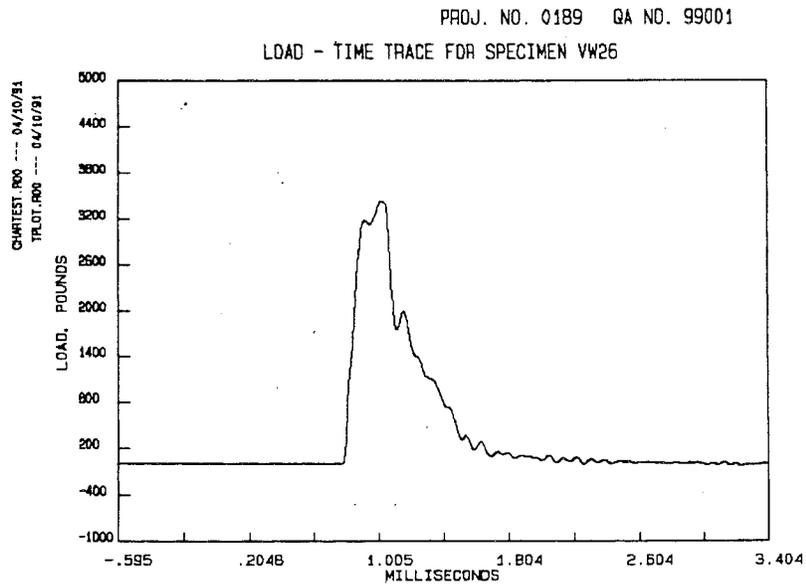


Figure B-26. Load-Time Trace for Charpy V-Notch Impact Specimen VW26

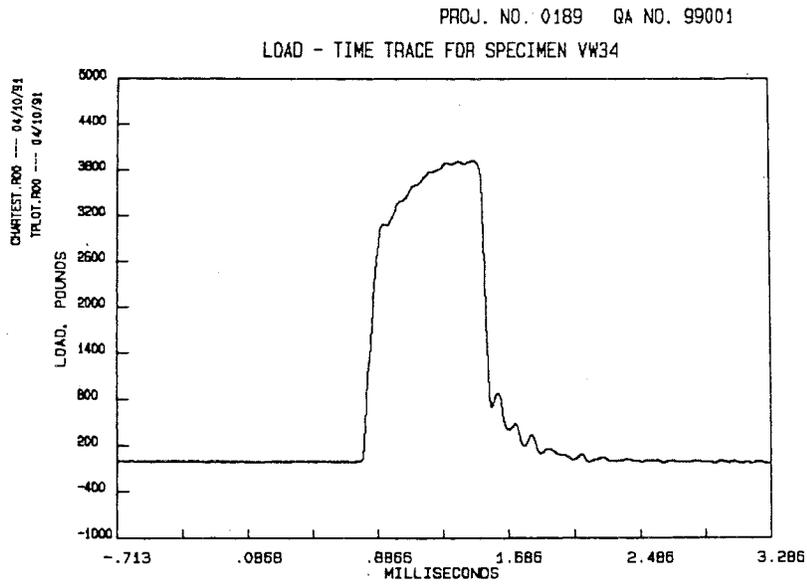


Figure B-27. Load-Time Trace for Charpy V-Notch Impact Specimen VW34

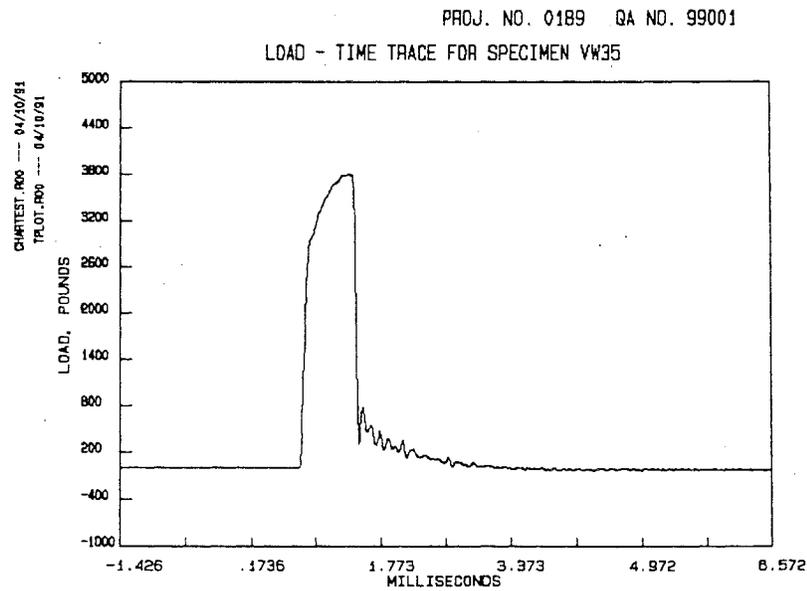


Figure B-28. Load-Time Trace for Charpy V-Notch Impact Specimen VW35

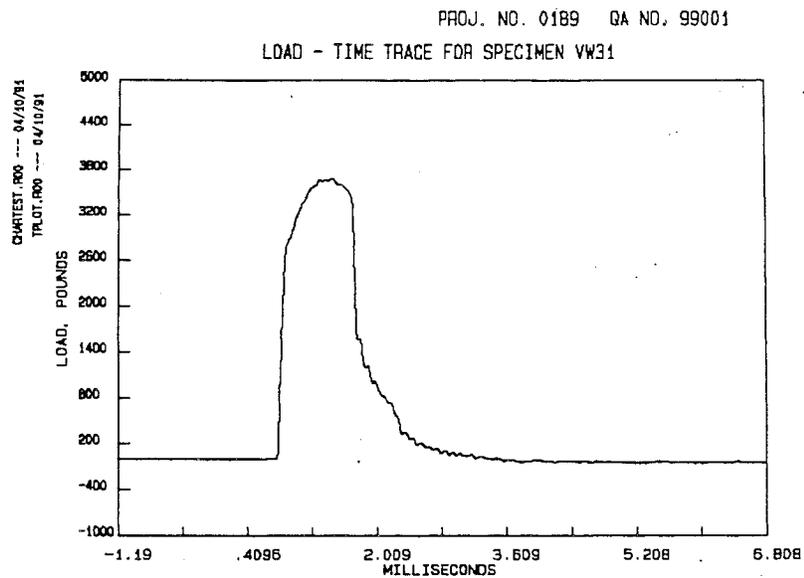


Figure B-29. Load-Time Trace for Charpy V-Notch Impact Specimen VW31

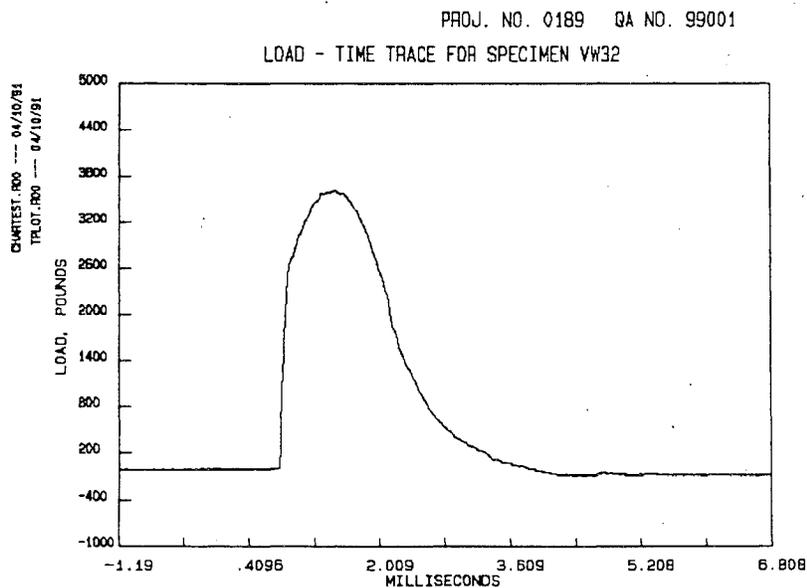


Figure B-30. Load-Time Trace for Charpy V-Notch Impact Specimen VW32

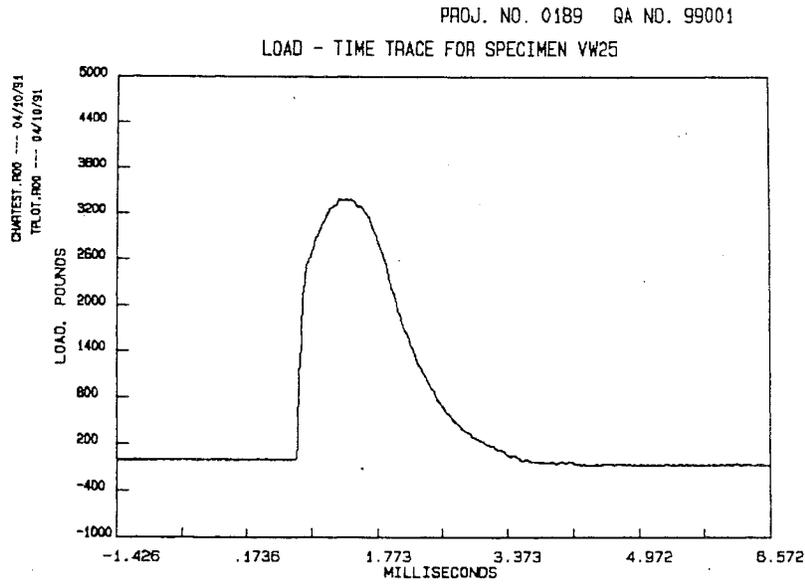


Figure B-31. Load-Time Trace for Charpy V-Notch Impact Specimen VW25

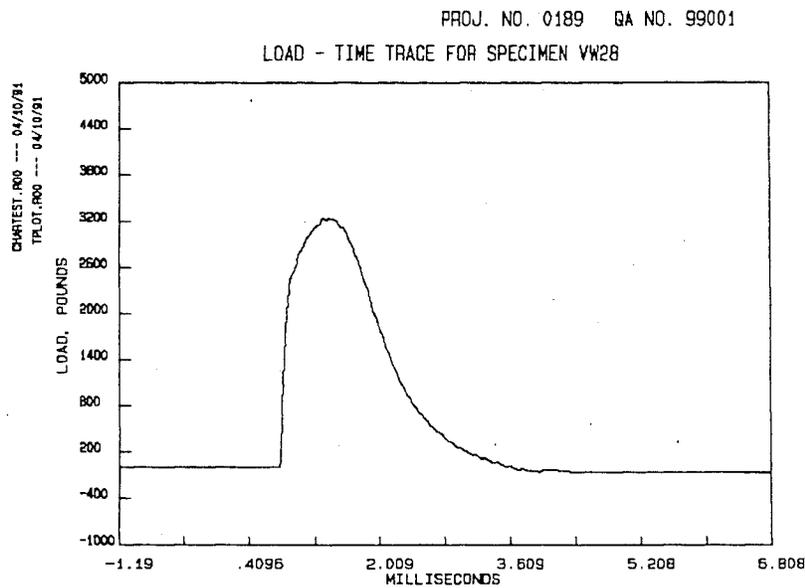


Figure B-32. Load-Time Trace for Charpy V-Notch Impact Specimen VW28

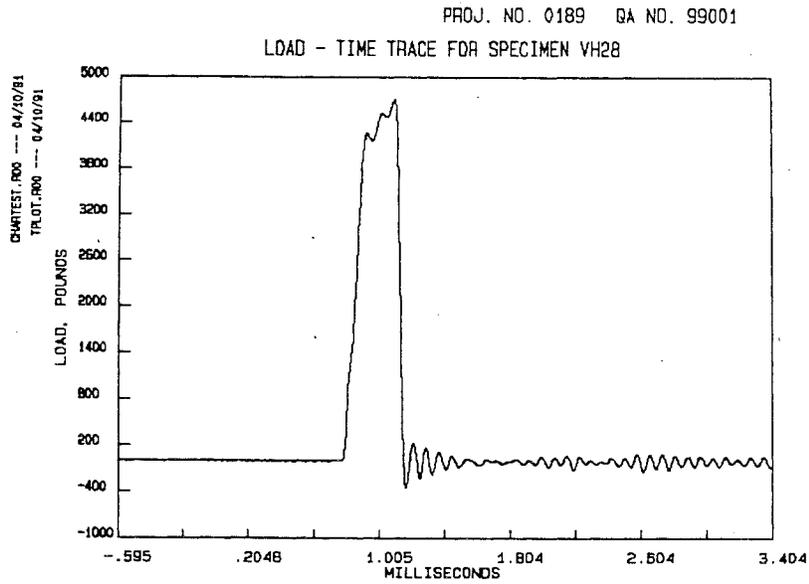


Figure B-33. Load-Time Trace for Charpy V-Notch Impact Specimen VH28

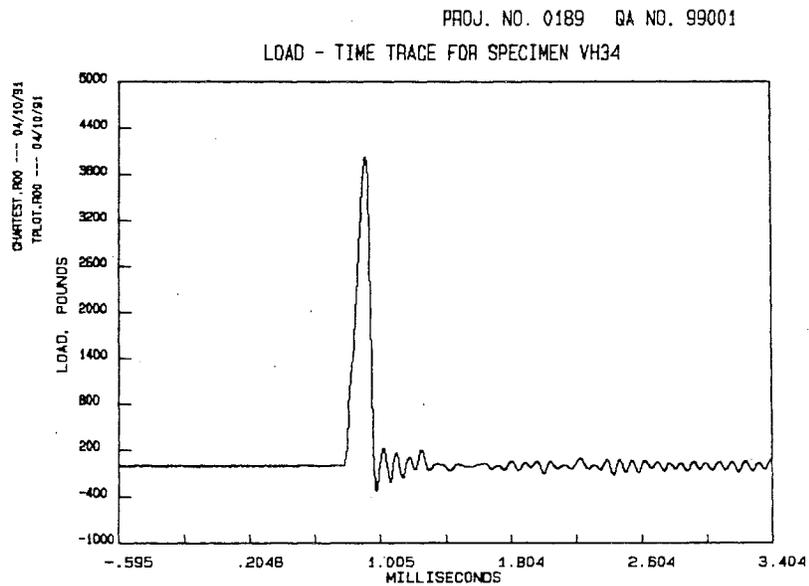


Figure B-34. Load-Time Trace for Charpy V-Notch Impact Specimen VH34

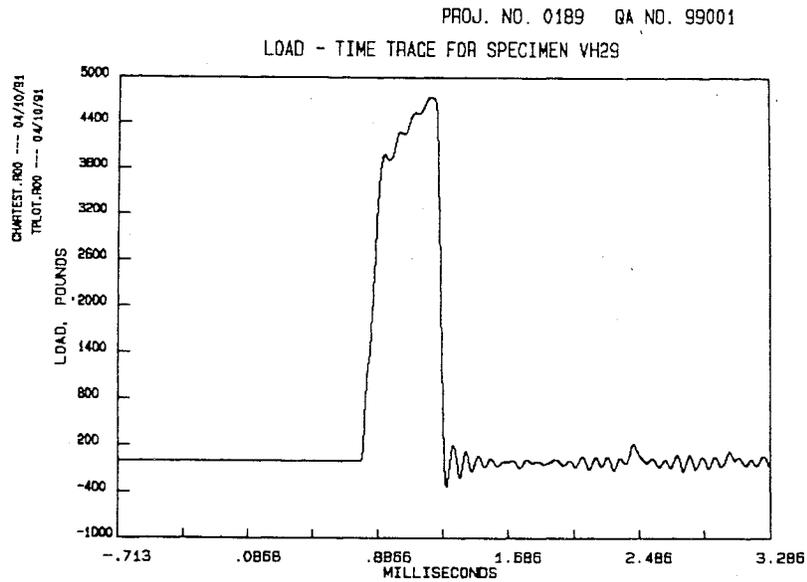


Figure B-35. Load-Time Trace for Charpy V-Notch Impact Specimen VH29

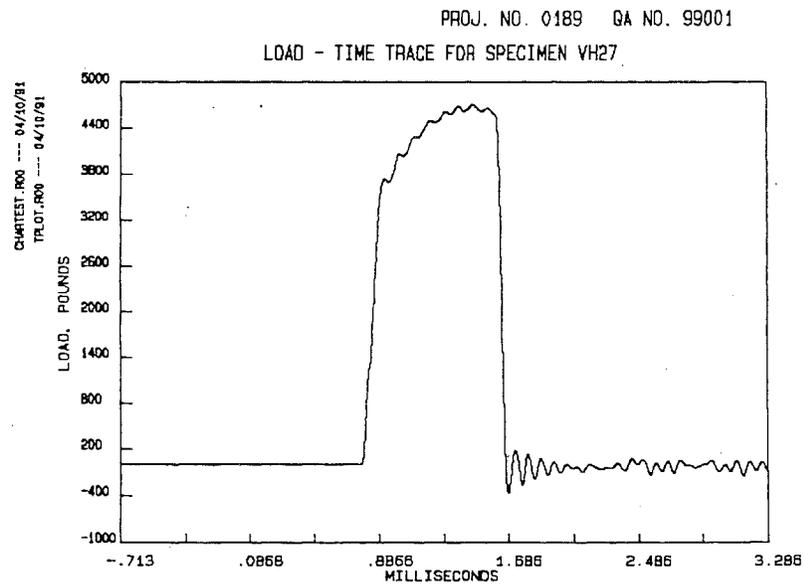


Figure B-36. Load-Time Trace for Charpy V-Notch Impact Specimen VH27

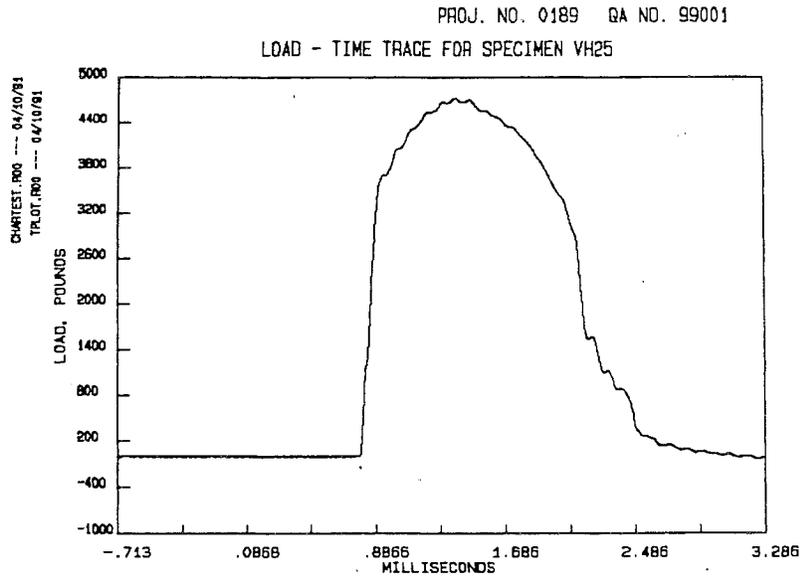


Figure B-37. Load-Time Trace for Charpy V-Notch Impact Specimen VH25

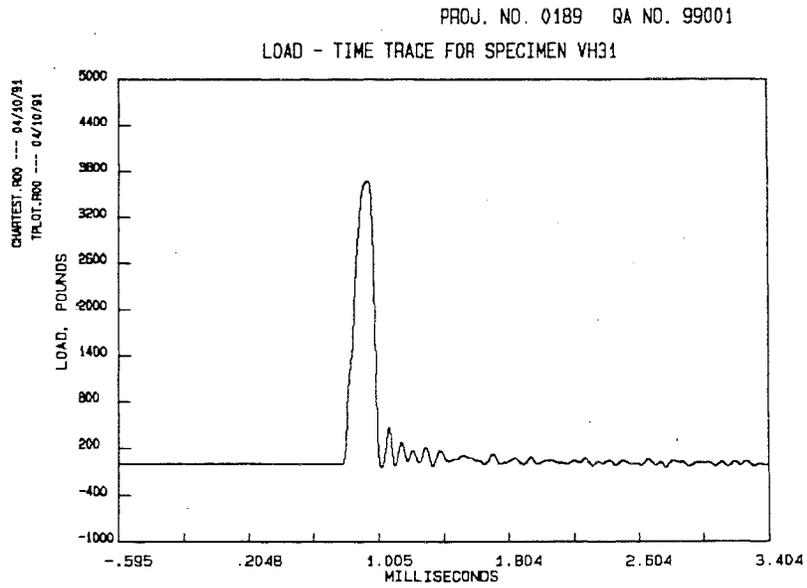


Figure B-38. Load-Time Trace for Charpy V-Notch Impact Specimen VH31

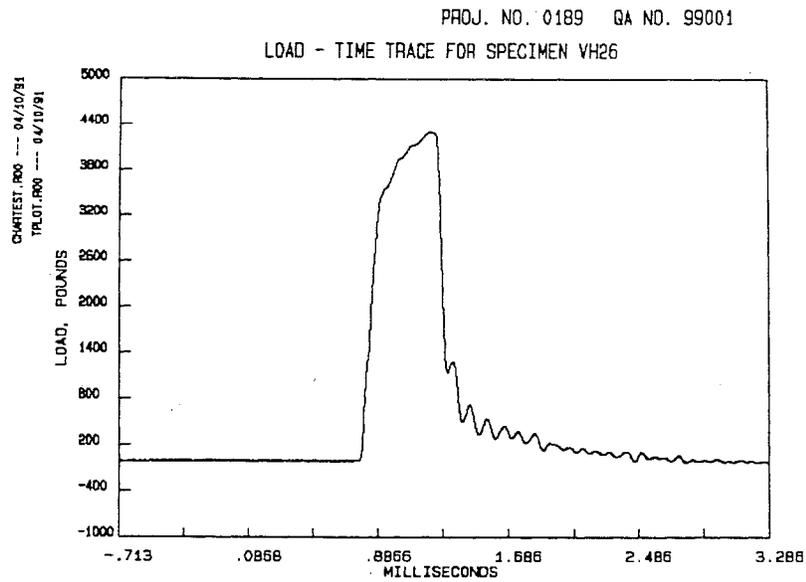


Figure B-39. Load-Time Trace for Charpy V-Notch Impact Specimen VH26

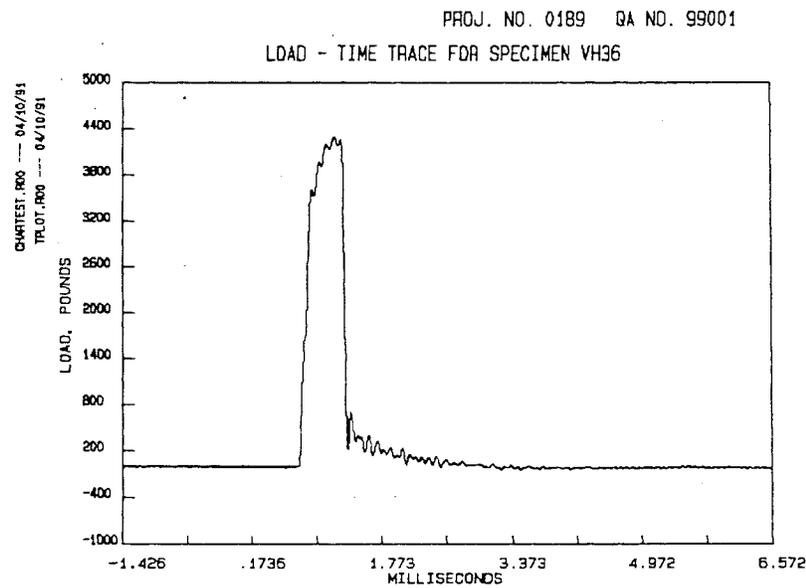


Figure B-40. Load-Time Trace for Charpy V-Notch Impact Specimen VH36

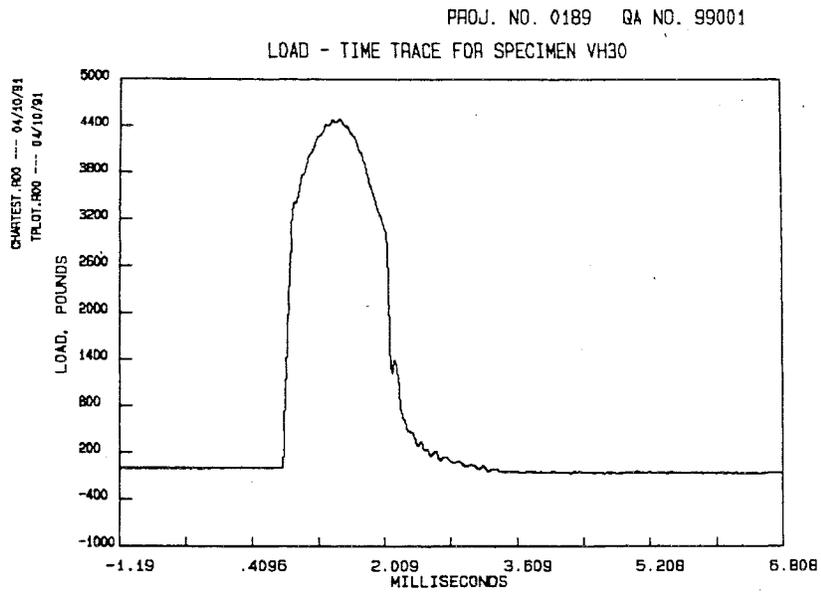


Figure B-41. Load-Time Trace for Charpy V-Notch Impact Specimen VH30

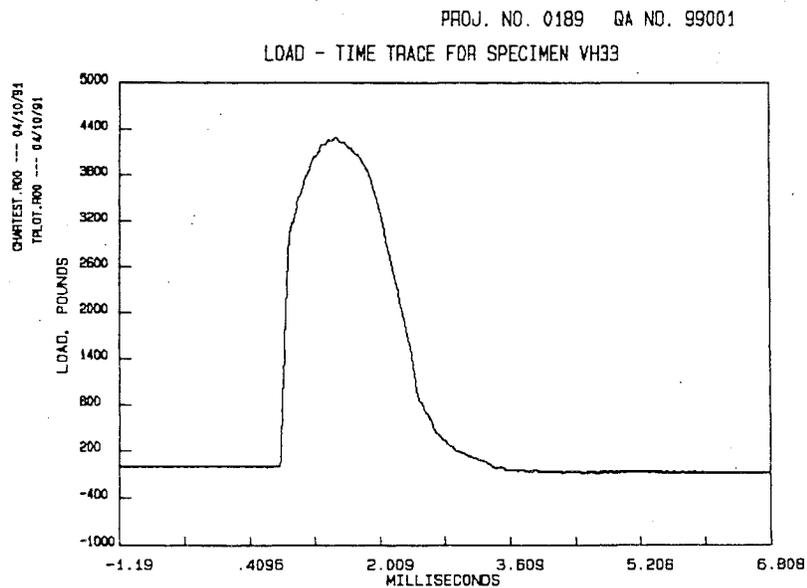


Figure B-42. Load-Time Trace for Charpy V-Notch Impact Specimen VH33

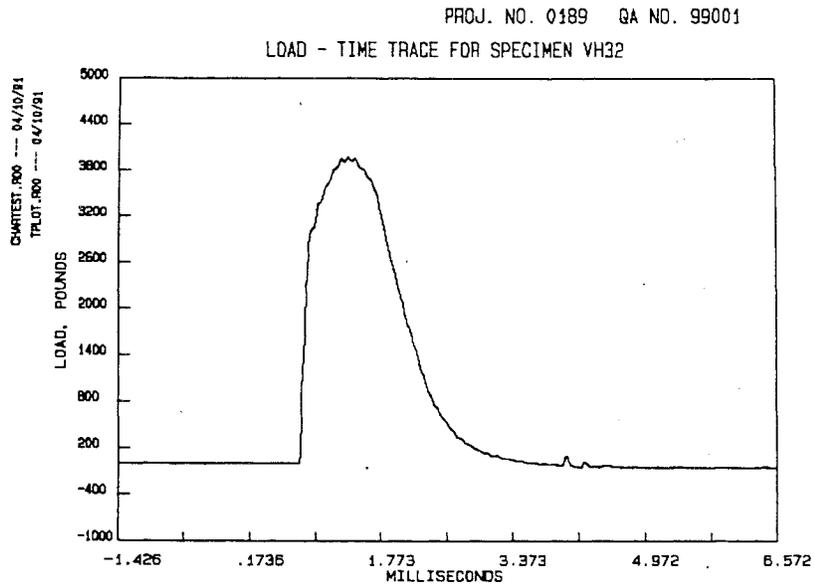


Figure B-43. Load-Time Trace for Charpy V-Notch Impact Specimen VH32

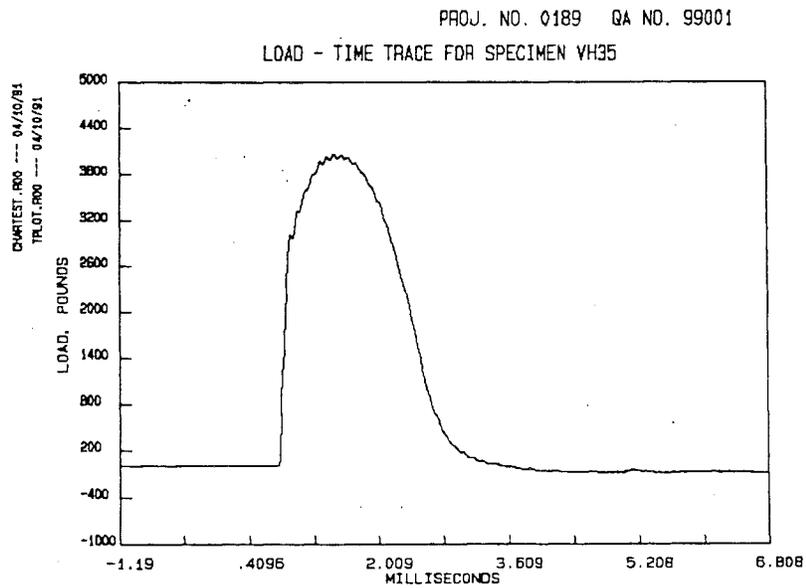


Figure B-44. Load-Time Trace for Charpy V-Notch Impact Specimen VH35



APPENDIX C

**Unirradiated Tensile Data for the
North Anna Unit No. 1 RVSP Materials**

**Table C-1. Tensile Properties of Unirradiated Base Metal Forging 03,
Heat No. 990400/292332, Axial Orientation**

Specimen No.	Test Temp. (F)	Strength, psi		Elongation, %		Reduction of Area, %
		Yield	Ultimate	Uniform	Total	
---	Room	70,050	92,404	11.4	18.8	60.7
---	Room	71,300	92,700	12.3	18.8	57.0
---	300	64,075	84,600	13.0	21.5	61.0
---	300	64,750	85,200	13.7	23.7	64.0
---	550	58,027	87,150	13.7	20.6	52.0
---	550	53,137	85,325	17.2	26.0	57.0

**Table C-2. Tensile Properties of Unirradiated Weld Metal,
Wire Heat 25531 / Flux Lot 1211**

Specimen No.	Test Temp. (F)	Strength, psi		Elongation, %		Reduction of Area, %
		Yield	Ultimate	Uniform	Total	
---	Room	63,150	78,300	9.6	18.9	71.0
---	Room	65,200	80,400	9.8	19.5	71.0
---	300	64,300	77,875	8.6	19.5	67.0
---	300	59,675	73,625	10.8	22.5	68.9
---	550	60,175	76,850	9.8	20.0	63.0
---	550	61,650	80,500	8.9	18.0	57.0

APPENDIX D

**Unirradiated and Irradiated
Charpy V-Notch Impact Surveillance Data for the
North Anna Unit No. 1 RVSP Materials
Using Hyperbolic Tangent Curve-Fitting Method**

**Table D-1. Unirradiated Surveillance Charpy V-Notch Impact Data for
North Anna Unit No. 1, Base Metal Forging 03,
Heat No. 990400/292332, Tangential Orientation**

Specimen No.	Test Temp. (F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
---	-15	30	21	9
---	-15	9	5	0
---	-15	19	16	3
---	40	66	48	40
---	40	84	60	45
---	40	78	59	56
---	74	96.5	67	38
---	74	101	74	64
---	74	73.5	59	38
---	125	116	74	77
---	125	115	78	92
---	125	99	67.5	79
---	170	143	80	100
---	170	147	83	100
---	170	144	81	100
---	210	126.5	88	100
---	210	123	84.5	100
---	210	127	80	100

**Table D-2. North Anna Unit No. 1 Capsule V Surveillance Charpy Impact Data for
Base Metal Forging 03, Heat No. 990400/29232,
Irradiated to 2.63×10^{18} n/cm² (E > 1.0 MeV)
Tangential Orientation**

Specimen No.	Test Temp. (F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
VL15	0	7.0	4.0	0
VL13	40	36.0	26.5	0
VL9	60	51.0	40.0	5
VL16	73	32.0	23.0	25
VL12	100	50.0	39.0	43
VL10	120	76.5	57.5	56
VL11	196	113.0	78.0	89
VL14	280	122.0	86.0	100

**Table D-3. North Anna Unit No. 1 Capsule U Surveillance Charpy Impact Data for
Base Metal Forging 03, Heat No. 990400/292332,
Irradiated to 8.72×10^{18} n/cm² (E > 1.0 MeV)
Tangential Orientation**

Specimen No.	Test Temp. (F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
VL46	10	10.0	10.0	5
VL41	74	38.0	28.5	20
VL44	77	12.0	15.5	15
VL48	125	---(a)	---(a)	---(a)
VL45	125	17.0	23.0	20
VL43	175	75.0	62.0	70
VL42	250	110.0	82.0	100
VL47	350	109.0	81.0	100

(a) Machine malfunction.

**Table D-4. Hyperbolic Tangent Curve Fit Coefficients for North Anna Unit No. 1,
Base Metal Forging 03 Heat No. 990400/292332,
Tangential Orientation**

	Hyperbolic Tangent Curve Fit Coefficients		
	Absorbed Energy	Lateral Expansion	Percent Shear Fracture
Unirradiated	A: 67.5	A: 40.4	A: 50.0
	B: 65.3	B: 39.4	B: 50.0
	C: 73.9	C: 52.5	C: 76.0
	T0: 42.9	T0: 24.6	T0: 64.2
Capsule V	A: 65.1	A: 44.7	A: 50.0
	B: 62.9	B: 43.7	B: 50.0
	C: 99.8	C: 98.5	C: 53.4
	T0: 108.8	T0: 100.2	T0: 111.8
Capsule U	A: 59.9	A: 44.1	A: 50.0
	B: 57.7	B: 43.1	B: 50.0
	C: 83.7	C: 99.1	C: 68.3
	T0: 159.1	T0: 143.1	T0: 151.6

Table D-5. Unirradiated Surveillance Charpy V-Notch Impact Data for North Anna Unit No. 1, Base Metal Forging 03, Heat No. 990400/292332, Axial Orientation

Specimen No.	Test Temp. (F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
---	-15	16	7	10
---	-15	17	10	10
---	-15	15	10	10
---	45	31.5	21	35
---	45	30	20	35
---	45	25	21	30
---	75	47.5	37	30
---	75	43.5	37	23
---	75	47.5	33	27
---	105	62.5	50	55
---	105	56.5	50	55
---	105	59	50	55
---	150	80.5	66	90
---	150	84.5	72	100
---	150	67.5	62	78
---	210	85	69	100
---	210	82.5	68	100
---	210	86.5	73	100

**Table D-6. North Anna Unit No. 1 Capsule V Surveillance Charpy Impact Data for
Base Metal Forging 03, Heat No. 990400/292332,
Irradiated to 2.63×10^{18} n/cm² (E > 1.0 MeV)
Axial Orientation**

Specimen No.	Test Temp. (F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
VT19	0	12.5	7.0	0
VT14	40	15.5	11.5	0
VT16	60	29.0	23.5	14
VT13	73	39.0	29.0	0
VT22	100	40.0	32.0	34
VT15	120	41.0	35.0	42
VT24	130	51.0	42.0	38
VT18	140	59.0	48.0	98
VT23	160	60.0	50.0	98
VT21	195	79.0	66.0	100
VT20	240	68.5	60.0	100
VT17	280	77.0	68.0	100

**Table D-7. North Anna Unit No. 1 Capsule U Surveillance Charpy Impact Data for
Base Metal Forging 03, Heat No. 990400/292332,
Irradiated to 8.72×10^{18} n/cm² (E > 1.0 MeV)
Axial Orientation**

Specimen No.	Test Temp. (F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
VT70	0	2.0	2.5	2
VT67	74	20.0	20.0	10
VT63	100	28.0	29.0	15
VT69	100	26.0	30.0	15
VT64	125	42.0	39.0	25
VT68	125	33.0	35.0	20
VT71	150	47.0	44.0	35
VT66	200	45.0	42.0	45
VT62	225	76.0	56.5	80
VT61	275	98.0	70.0	100
VT65	350	90.0	75.0	100
VT72	400	90.0	66.0	100

**Table D-8. Hyperbolic Tangent Curve Fit Coefficients for North Anna Unit No. 1
Base Metal Forging 03, Heat No. 990400/292332,
Axial Orientation**

	Hyperbolic Tangent Curve Fit Coefficients		
	Absorbed Energy	Lateral Expansion	Percent Shear Fracture
Unirradiated	A: 46.6	A: 37.3	A: 50.0
	B: 44.4	B: 36.3	B: 50.0
	C: 93.4	C: 73.6	C: 74.8
	T0: 76.4	T0: 76.9	T0: 93.0
Capsule V	A: 40.4	A: 34.9	A: 50.0
	B: 38.2	B: 33.9	B: 50.0
	C: 100.0	C: 98.8	C: 32.4
	T0: 97.3	T0: 106.0	T0: 121.8
Capsule U	A: 48.9	A: 36.3	A: 50.0
	B: 46.7	B: 35.3	B: 50.0
	C: 116.8	C: 128.8	C: 86.7
	T0: 162.5	T0: 134.2	T0: 181.2

**Table D-9. Unirradiated Surveillance Charpy V-Notch Impact Data for
North Anna Unit No. 1, Weld Metal,
Wire Heat 25531 / Flux Lot 1211**

Specimen No.	Test Temp. (F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
---	-110	9	9	0
---	-110	5	9	0
---	-110	13	7	0
---	0	74.5	61	48
---	0	58	52	54
---	0	60	70	43
---	48	37.5	39.5	31
---	48	40	45	51
---	48	42	49.5	40
---	75	83	68	79
---	75	81	71.5	81
---	75	49.5	50	65
---	175	106	89	100
---	175	106	88	100
---	175	94	76	96
---	250	87	79	100
---	250	90.5	81	100
---	250	84.5	77	100

**Table D-10. North Anna Unit No. 1 Capsule V Surveillance Charpy Impact Data for
Weld Metal (Wire Heat 25531 / Flux Lot 1211),
Irradiated to 2.63×10^{18} n/cm² (E > 1.0 MeV)**

Specimen No.	Test Temp. (F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
VW20	-40	4.5	4.5	0
VW22	0	25.0	25.5	50
VW24	40	26.0	29.0	46
VW17	60	33.0	31.5	28
VW16	73	39.0	31.0	34
VW23	90	47.0	49.0	89
VW21	100	60.0	56.0	25
VW14	120	73.0	62.0	72
VW15	160	62.5	52.5	96
VW18	198	92.5	73.0	100
VW13	240	100.0	80.0	100
VW19	280	87.0	77.0	100

Table D-11. North Anna Unit No. 1 Capsule U Surveillance Charpy Impact Data for Weld Metal (Wire Heat 25531 / Flux Lot 1211), Irradiated to 8.72×10^{18} n/cm² (E > 1.0 MeV)

Specimen No.	Test Temp. (F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
VW71	-60	---(a)	---(a)	---(a)
VW63	-25	38.0	33.5	30
VW61	25	25.0	28.0	20
VW71	25	34.0	40.5	25
VW64	40	50.0	45.5	45
VW68	60	53.0	48.0	45
VW69	74	30.0	30.0	45
VW65	125	51.0	52.5	50
VW70	200	71.0	70.0	85
VW66	275	95.0	85.0	100
VW62	350	87.0	77.0	100
VW67	400	94.0	84.5	100

(a) Machine malfunction.

**Table D-12. Hyperbolic Tangent Curve Fit Coefficients for North Anna Unit No. 1
Weld Metal (Wire Heat 25531 / Flux Lot 1211)**

	Hyperbolic Tangent Curve Fit Coefficients		
	Absorbed Energy	Lateral Expansion	Percent Shear Fracture
Unirradiated	A: 49.9	A: 41.5	A: 50.0
	B: 47.7	B: 40.5	B: 50.0
	C: 136.7	C: 126.4	C: 106.7
	T0: 16.9	T0: -5.8	T0: 31.9
Capsule V	A: 49.1	A: 40.5	A: 50.0
	B: 46.9	B: 39.5	B: 50.0
	C: 101.2	C: 115.2	C: 112.3
	T0: 88.2	T0: 75.9	T0: 72.3
Capsule U	A: 54.6	A: 46.3	A: 50.0
	B: 52.4	B: 45.3	B: 50.0
	C: 258.9	C: 245.7	C: 153.9
	T0: 117.2	T0: 78.8	T0: 88.0

Table D-13. Unirradiated Surveillance Charpy V-Notch Impact Data for North Anna Unit No. 1, Heat-Affected-Zone Material

Specimen No.	Test Temp. (°F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
---	-125	21	13	9
---	-125	4.5	2.5	5
---	-125	13	6	5
---	-80	25.5	13	3
---	-80	76.5	47	29
---	-80	53	21	18
---	-25	22.5	13	18
---	-25	47	25	23
---	-25	31.5	15	13
---	40	104	65	81
---	40	62	43.5	45
---	40	78.5	46	42
---	100	156.5	78	100
---	100	127.5	81	79
---	100	125.5	73	90
---	170	152.5	72	100
---	170	166	82	100
---	170	109	74	100

**Table D-14. North Anna Unit No. 1 Capsule V Surveillance Charpy Impact Data for
Heat-Affected-Zone Material,
Irradiated to 2.63×10^{18} n/cm² (E > 1.0 MeV)**

Specimen No.	Test Temp. (°F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
VH18	-40	66.0	48.0	3
VH13	0	19.5	8.0	10
VH16	40	22.5	15.0	60
VH19	50	16.5	15.0	40
VH20	60	49.5	30.5	89
VH23	73	89.0	66.0	62
VH21	100	81.0	55.0	71
VH15	120	67.5	42.0	55
VH24	160	93.0	67.0	99
VH22	198	105.0	71.0	100
VH14	240	113.0	70.0	100
VH17	280	102.0	74.0	100

**Table D-15. North Anna Unit No. 1 Capsule U Surveillance Charpy Impact Data for
Heat-Affected-Zone Material,
Irradiated to 8.72×10^{18} n/cm² (E > 1.0 MeV)**

Specimen No.	Test Temp. (°F)	Impact Energy (ft-lb)	Lateral Expansion (mils)	Shear Fracture (%)
VH68	-100	25.0	21.5	10
VH67	-60	55.0	44.5	45
VH65	0	14.0	12.5	20
VH62	0	42.0	35.0	35
VH63	40	70.0	52.0	65
VH70	40	57.0	46.0	55
VH69	74	55.0	35.0	50
VH71	74	18.0	16.0	15
VH61	125	54.0	46.0	65
VH66	200	71.0	66.0	95
VH64	275	120.0	83.0	100
VH72	400	125.0	71.0	100

Table D-16. Hyperbolic Tangent Curve Fit Coefficients for North Anna Unit No. 1 Heat-Affected-Zone Material

Weld Metal	Hyperbolic Tangent Curve Fit Coefficients		
	Absorbed Energy	Lateral Expansion	Percent Shear Fracture
Unirradiated	A: 87.2	A: 44.1	A: 50.0
	B: 85.0	B: 43.1	B: 50.0
	C: 140.3	C: 119.1	C: 82.6
	T0: 38.6	T0: 16.8	T0: 26.3
Capsule V	A: 64.4	A: 44.4	A: 50.0
	B: 62.2	B: 43.4	B: 50.0
	C: 172.7	C: 183.5	C: 87.8
	T0: 88.2	T0: 90.9	T0: 47.8
Capsule U	A: 113.6	A: 47.8	A: 50.0
	B: 111.4	B: 46.8	B: 50.0
	C: 419.6	C: 340.1	C: 189.3
	T0: 336.1	T0: 116.2	T0: 60.9

Figure D-1. Unirradiated Surveillance Charpy V-Notch Impact Data for North Anna Unit No. 1, Base Metal Forging 03, Heat No. 990400/292332, Tangential Orientation - Refitted Using Hyperbolic Tangent Curve-Fitting Method -

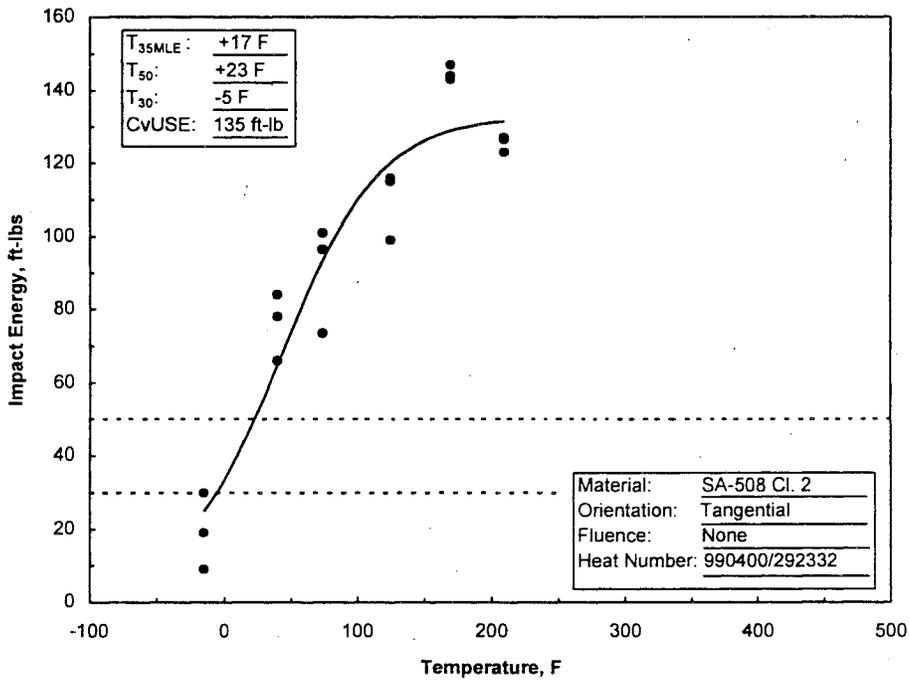
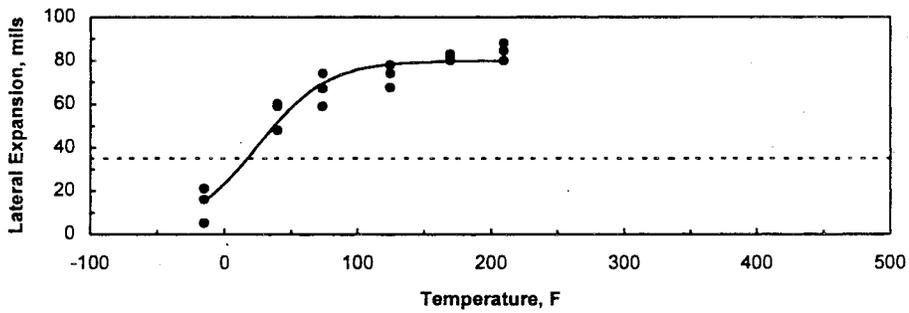
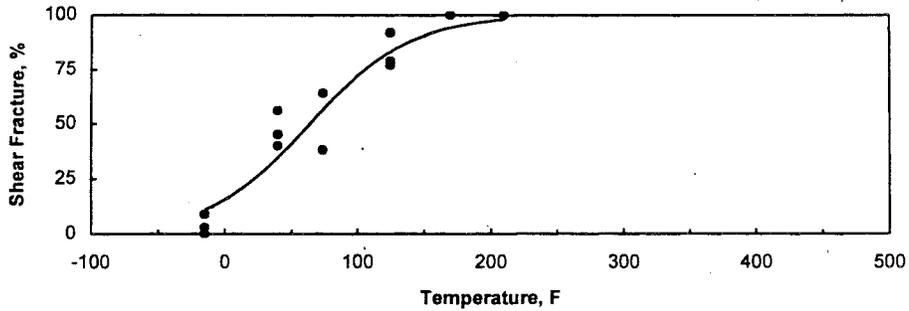
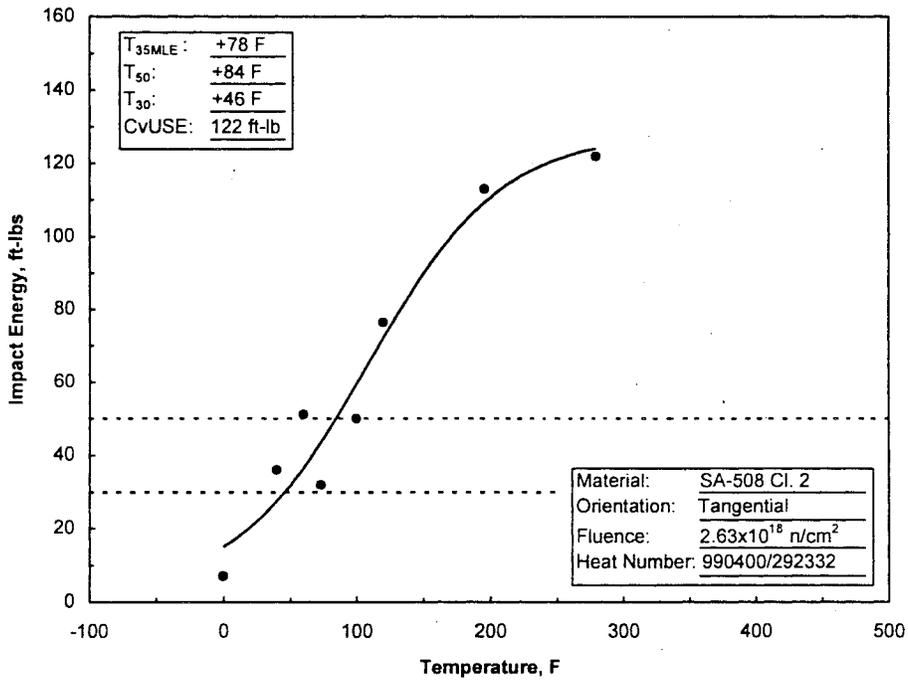
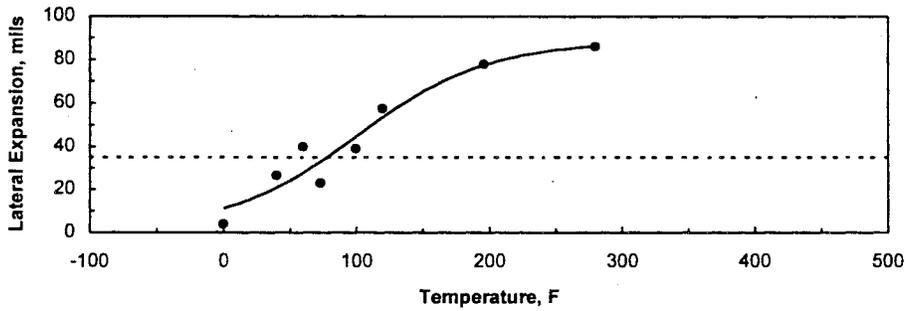
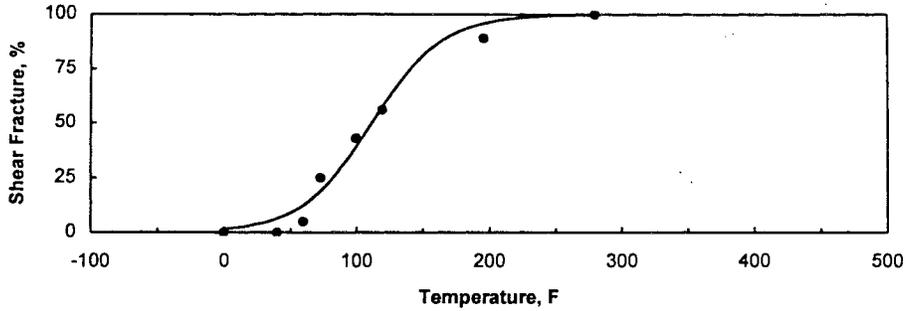
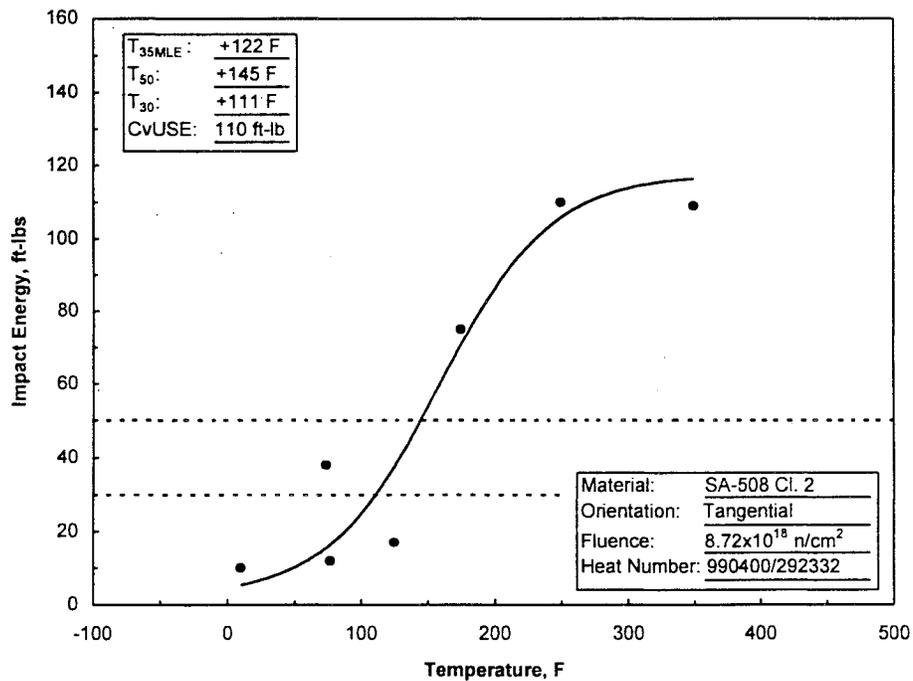
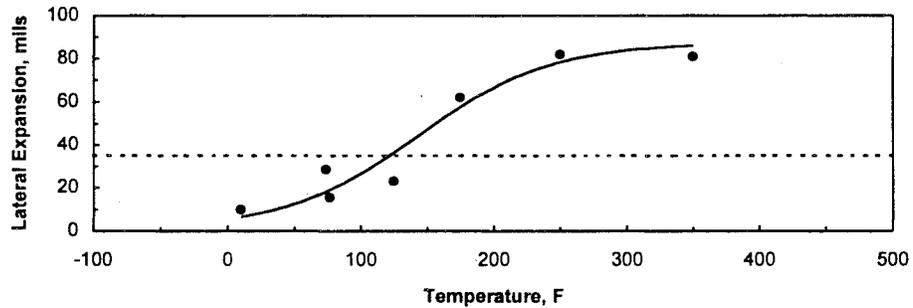
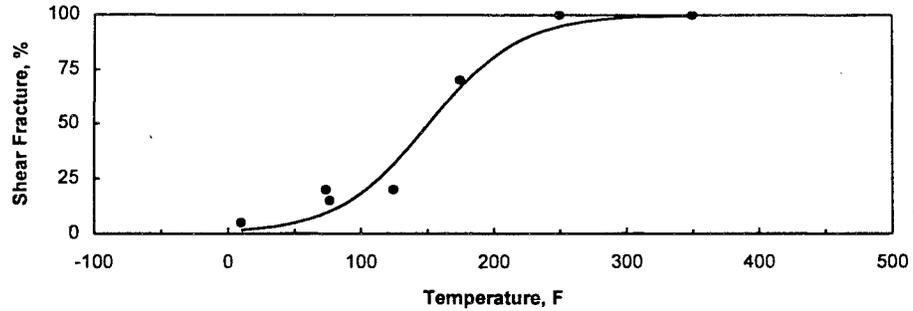


Figure D-2. North Anna Unit No. 1 Capsule V Surveillance Charpy Impact Data for
 Base Metal Forging 03, Heat No. 990400/292332,
 Tangential Orientation
 - Refitted Using Hyperbolic Tangent Curve-Fitting Method -



**Figure D-3. North Anna Unit No. 1 Capsule U Surveillance Charpy Impact Data for
Base Metal Forging 03, Heat No. 990400/292332,
Tangential Orientation
- Refitted Using Hyperbolic Tangent Curve-Fitting Method -**



**Figure D-4. Unirradiated Surveillance Charpy V-Notch Impact Data for
 North Anna Unit No. 1, Base Metal Forging 03,
 Heat No. 990400/292332, Axial Orientation
 - Refitted Using Hyperbolic Tangent Curve-Fitting Method -**

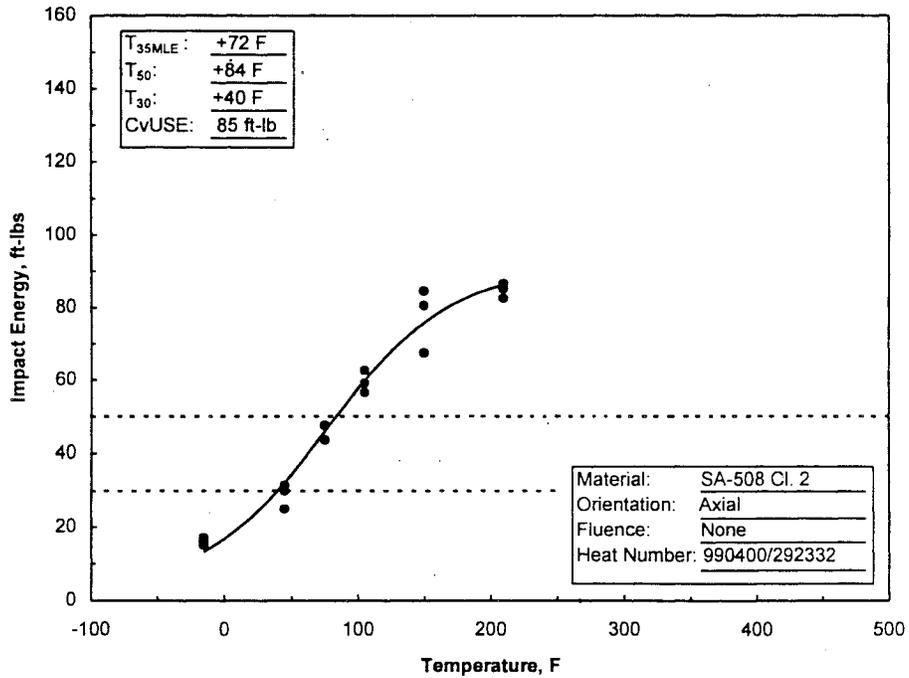
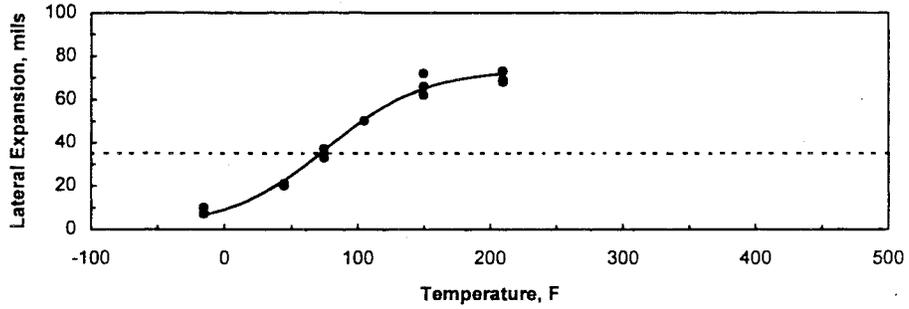
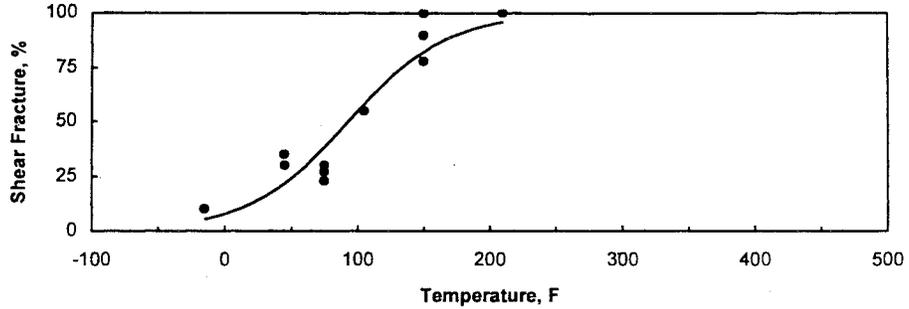


Figure D-5. North Anna Unit No. 1 Capsule V Surveillance Charpy Impact Data for
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 Axial Orientation
 - Refitted Using Hyperbolic Tangent Curve-Fitting Method -

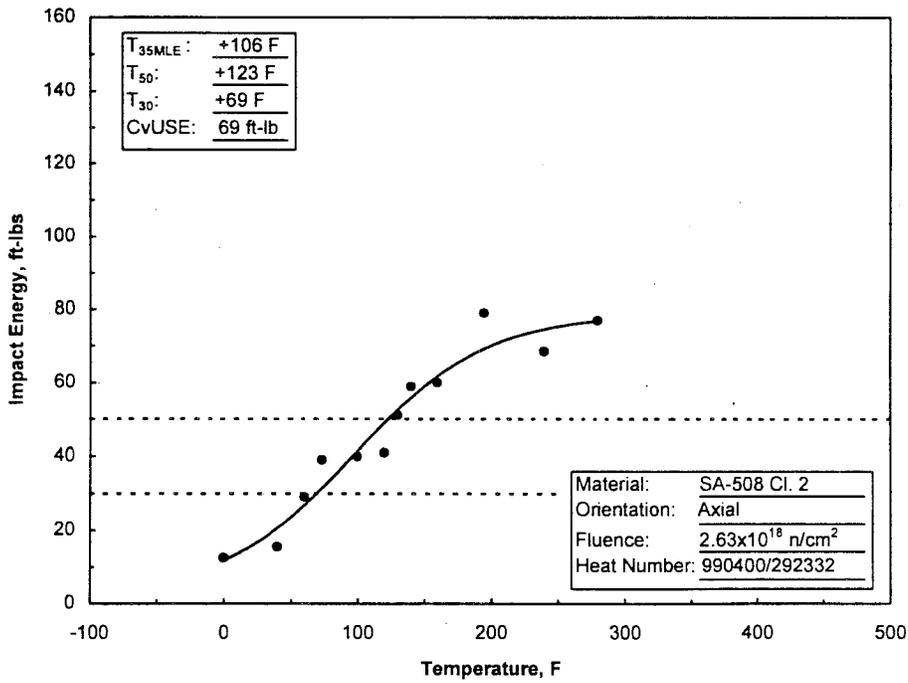
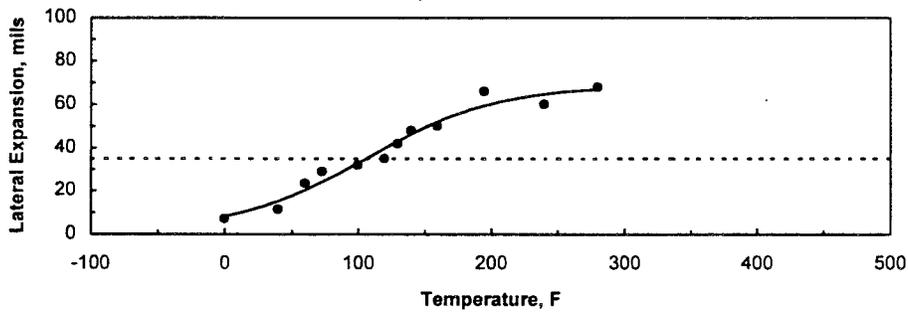
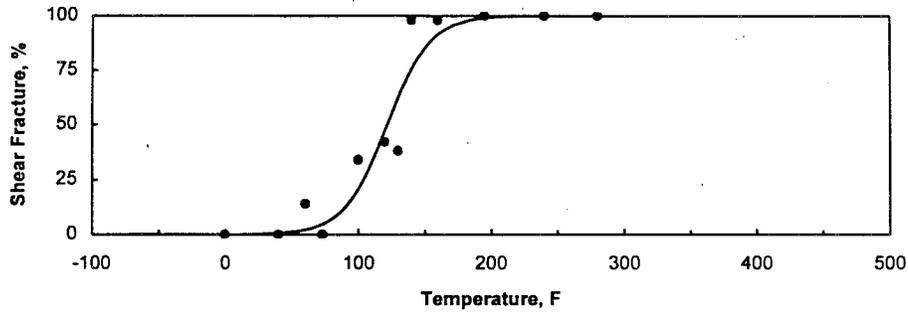
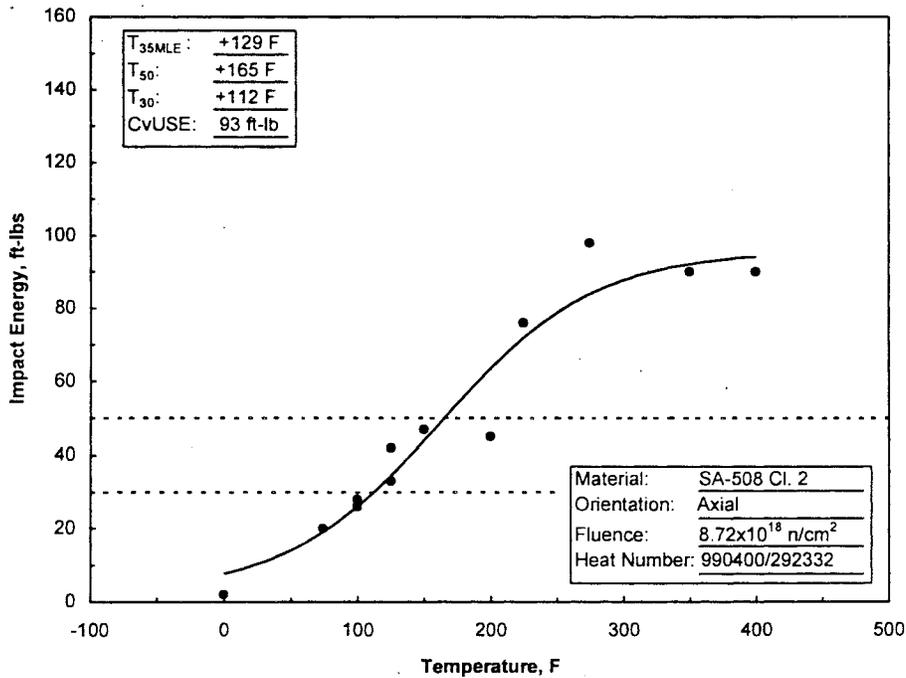
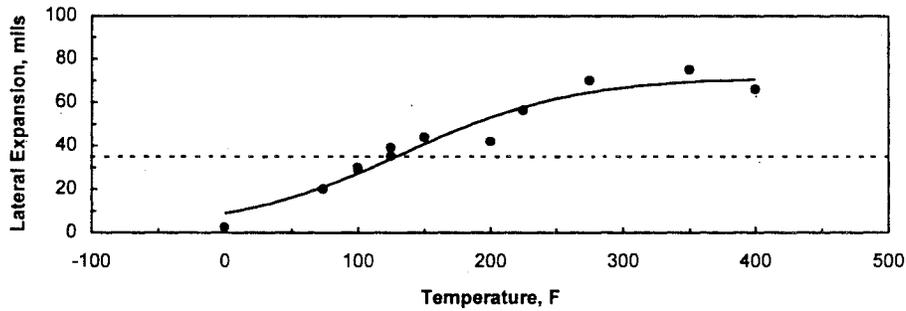
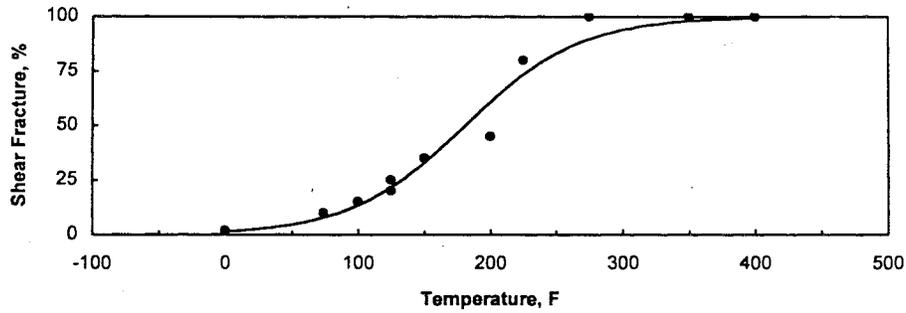


Figure D-6. North Anna Unit No. 1 Capsule U Surveillance Charpy Impact Data for
 Base Metal Forging 03, Heat No. 990400/292332,
 Axial Orientation
 - Refitted Using Hyperbolic Tangent Curve-Fitting Method -



**Figure D-7. Unirradiated Surveillance Charpy V-Notch Impact Data for
North Anna Unit No. 1, Weld Metal
(Wire Heat 25531 / Flux Lot 1211)
- Refitted Using Hyperbolic Tangent Curve-Fitting Method -**

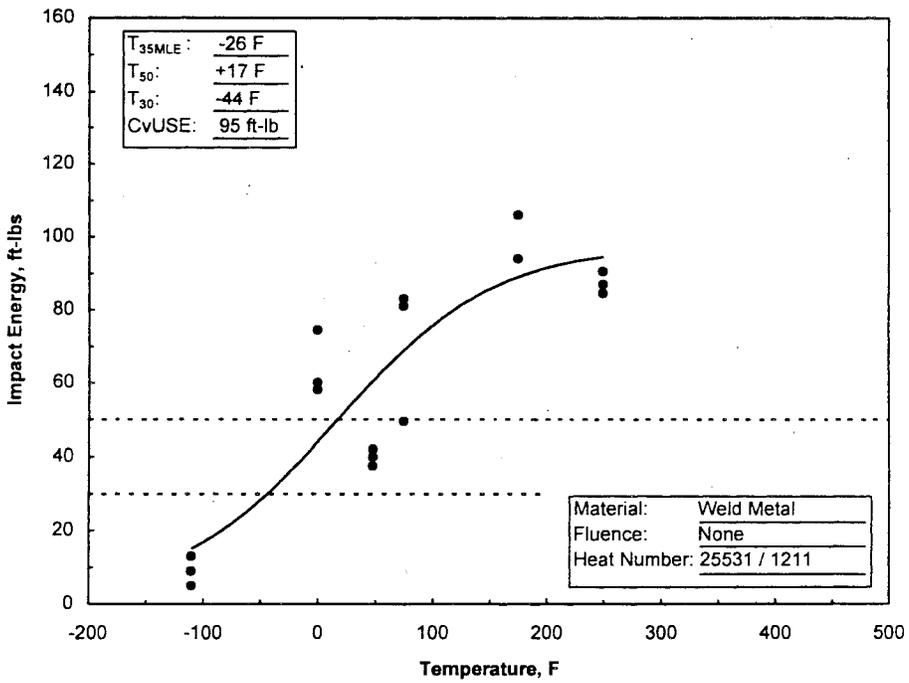
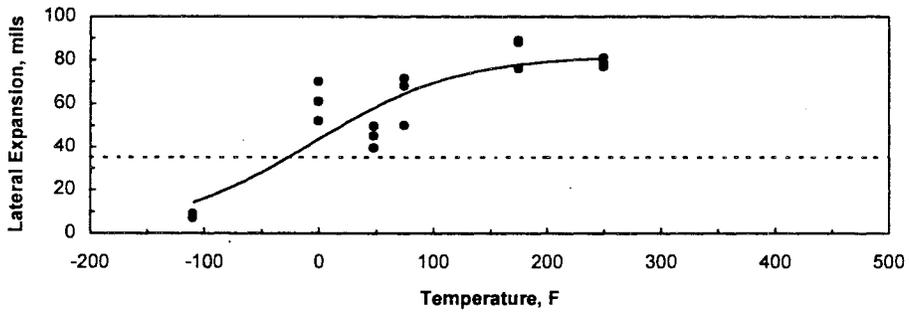
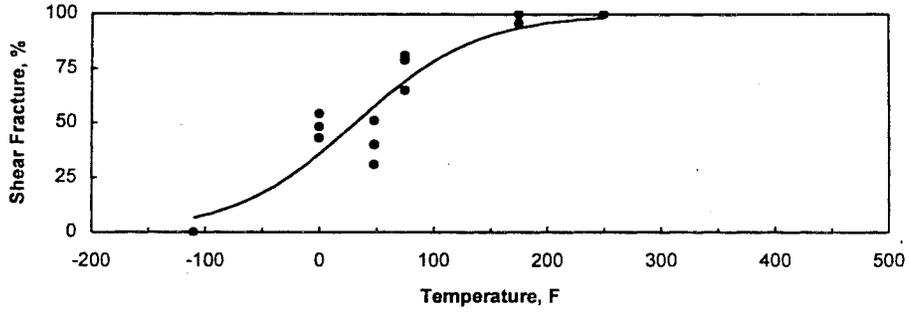


Figure D-8. North Anna Unit No. 1 Capsule V Surveillance Charpy Impact Data for Weld Metal (Wire Heat 25531 / Flux Lot 1211) - Refitted Using Hyperbolic Tangent Curve-Fitting Method -

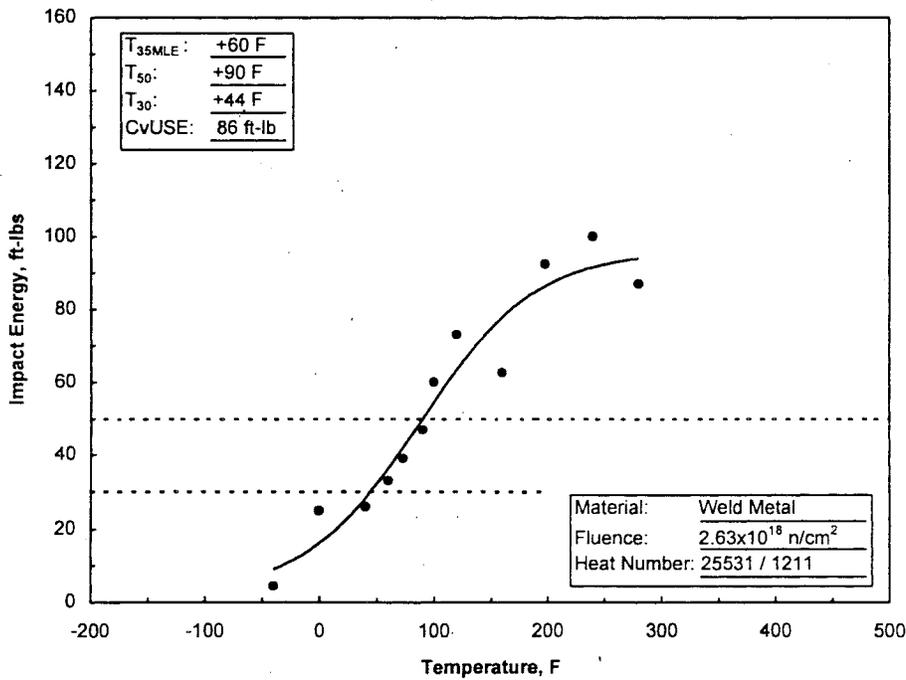
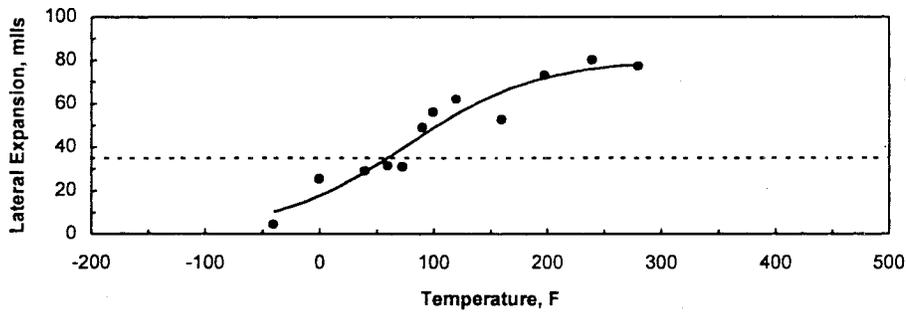
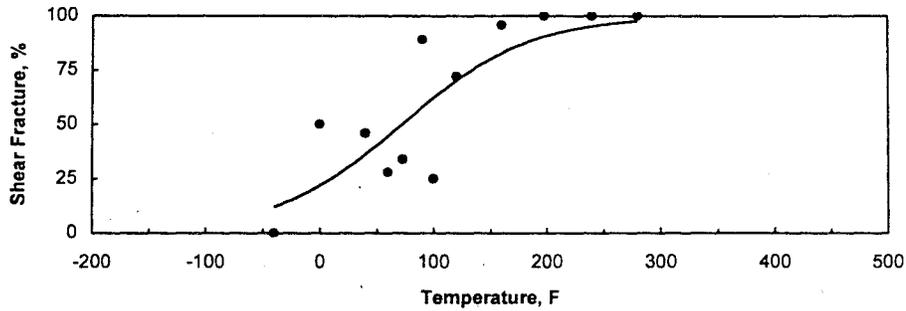


Figure D-9. North Anna Unit No. 1 Capsule U Surveillance Charpy Impact Data for Weld Metal (Wire Heat 25531 / Flux Lot 1211) - Refitted Using Hyperbolic Tangent Curve-Fitting Method -

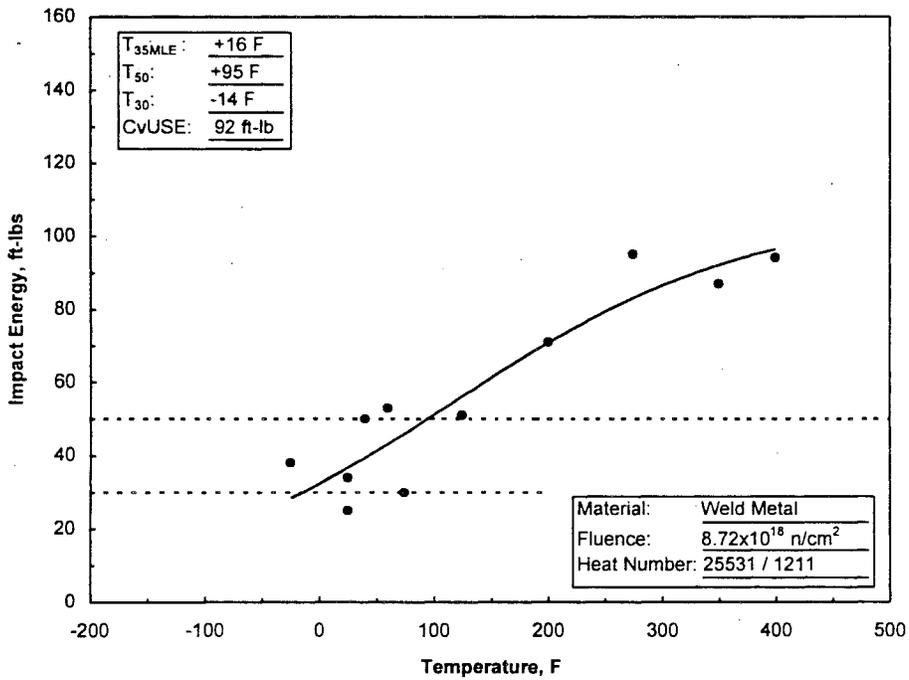
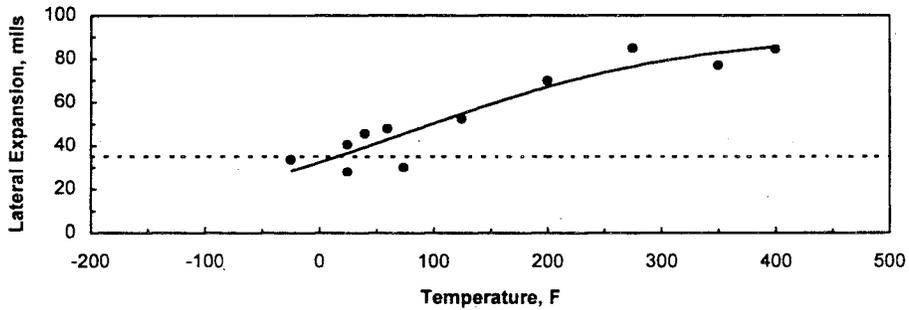
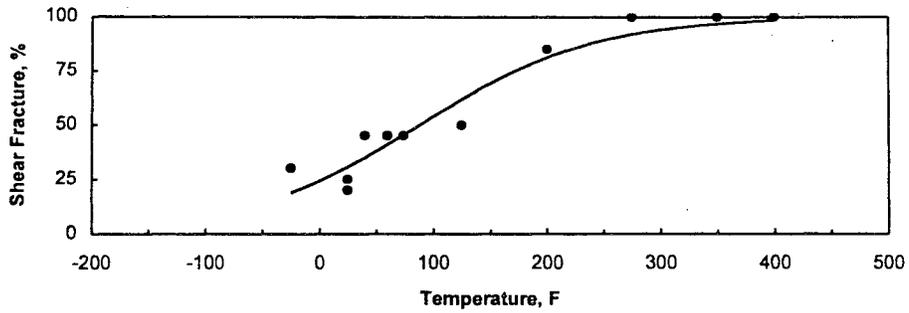


Figure D-10. Unirradiated Surveillance Charpy V-Notch Impact Data for North Anna Unit No. 1, Heat-Affected-Zone Material - Refitted Using Hyperbolic Tangent Curve-Fitting Method -

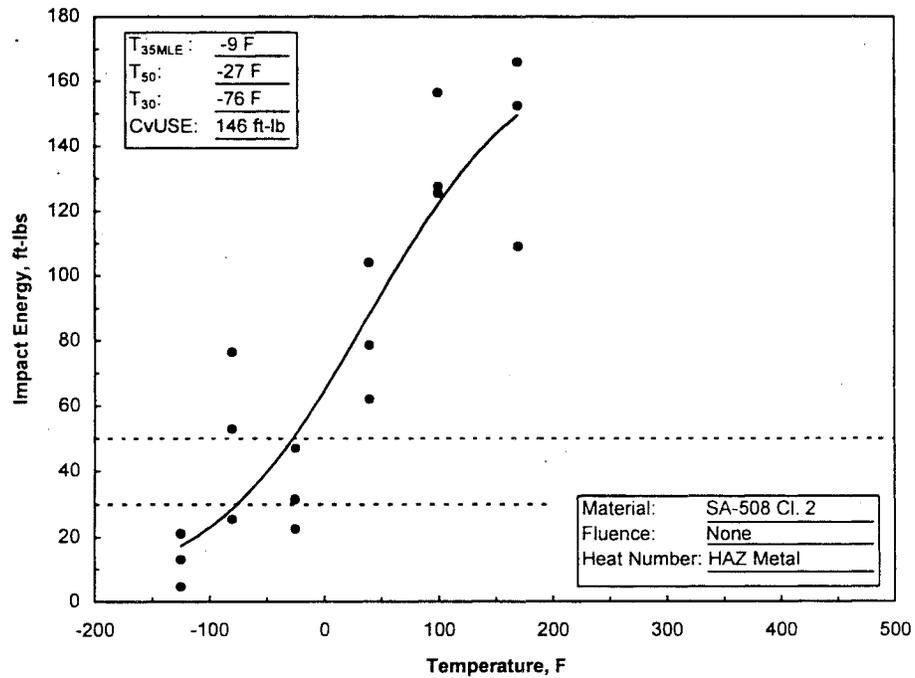
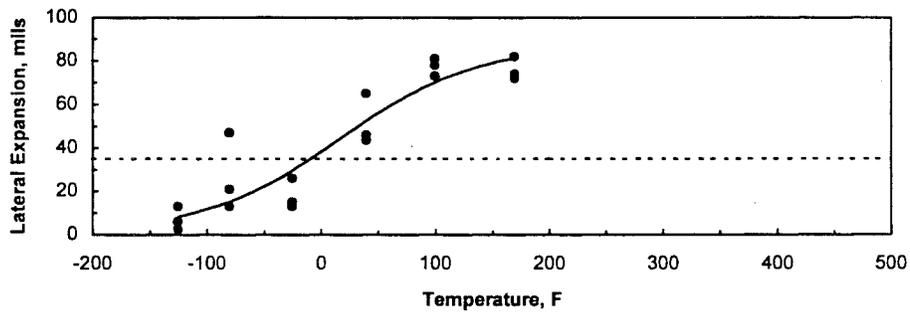
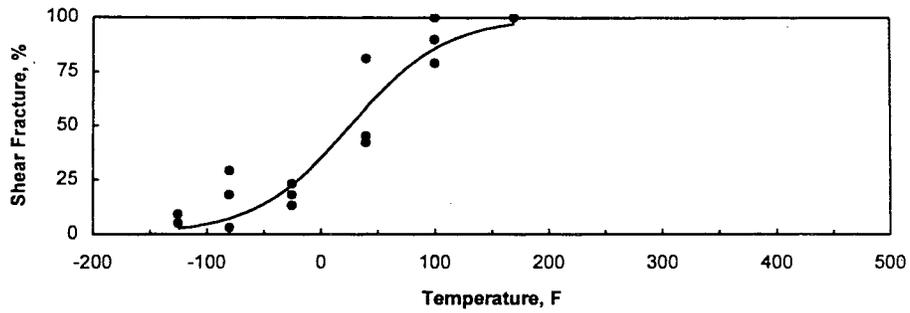


Figure D-11. North Anna Unit No. 1 Capsule V Surveillance Charpy Impact Data for Heat-Affected-Zone Material - Refitted Using Hyperbolic Tangent Curve-Fitting Method -

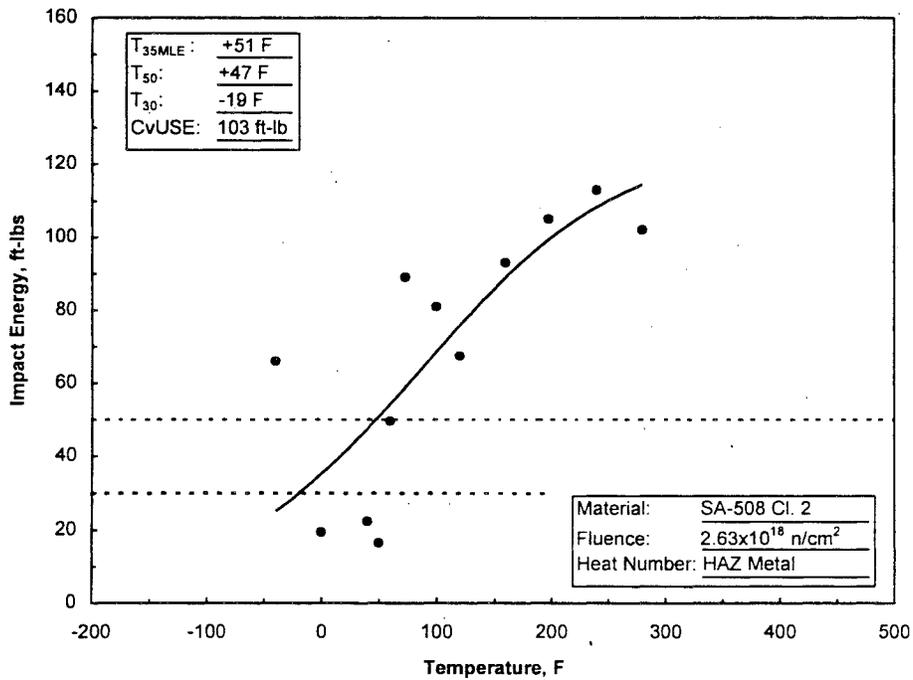
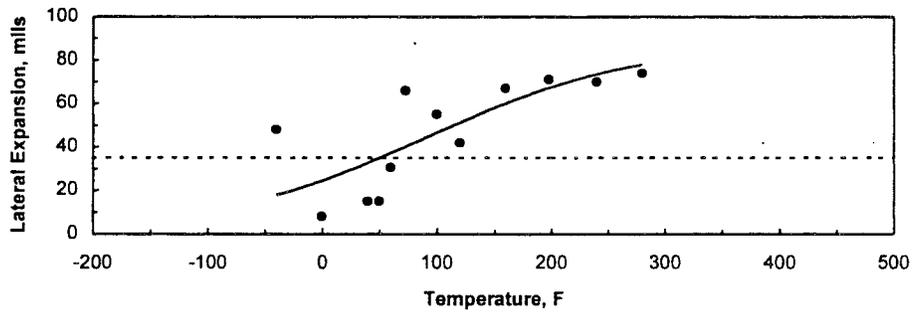
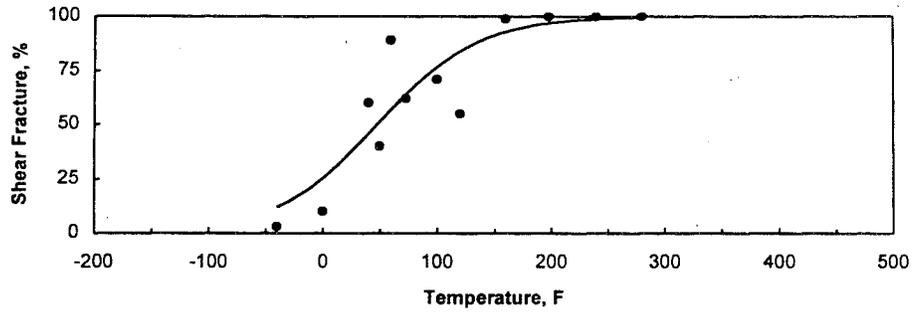
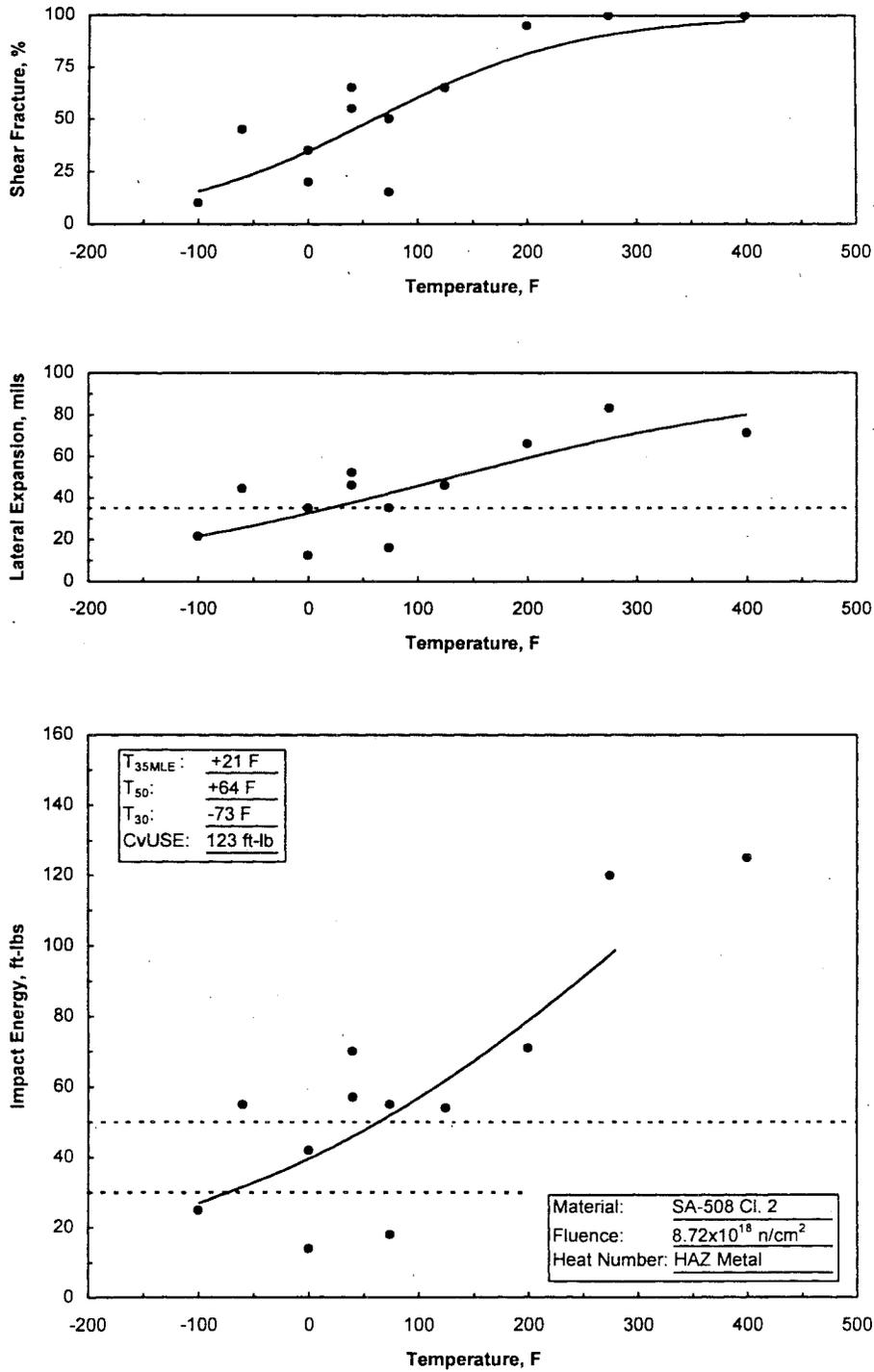
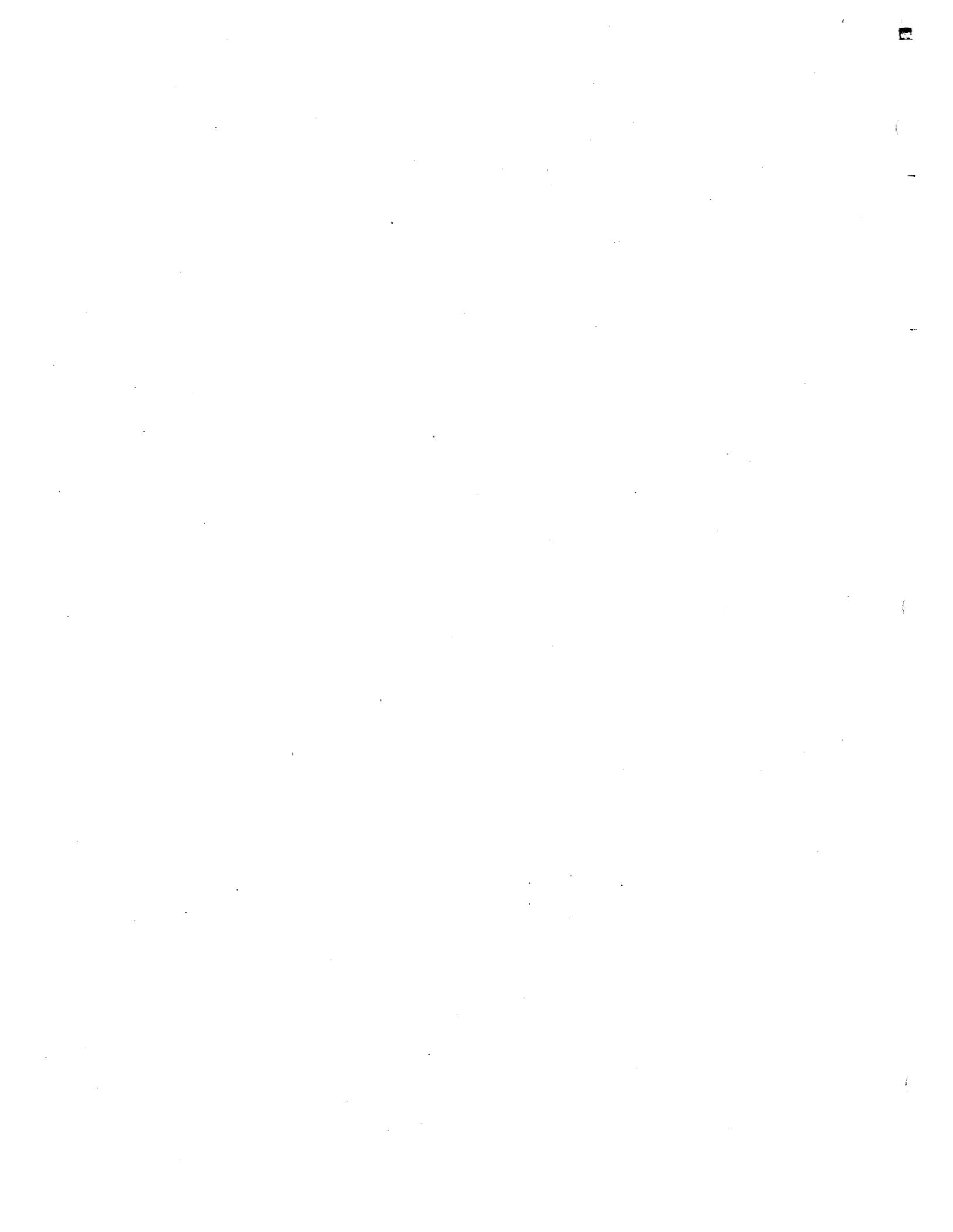


Figure D-12. North Anna Unit No. 1 Capsule U Surveillance Charpy Impact Data for Heat-Affected Zone Material - Refitted Using Hyperbolic Tangent Curve-Fitting Method -





APPENDIX E

Charpy V-Notch Shift Comparison: Hand-Drawn Curve Fitting vs. Hyperbolic Tangent Curve Fitting

**Table E-1. Comparison of Curve Fit Transition Temperature Shifts for
North Anna Unit No. 1 Surveillance Material,
Base Metal Forging 03, Heat No. 990400/292332,
Tangential Orientation**

Capsule	Fluence ($\times 10^{19}$ n/cm ²) (E > 1.0 MeV)	30 ft-lb Transition Temperature			
		Hand-Drawn Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	-6	---	-5	---
V	0.263	33	39	46	51
U	0.872	89	95	111	116

Capsule	Fluence ($\times 10^{19}$ n/cm ²) (E > 1.0 MeV)	50 ft-lb Transition Temperature			
		Hand-Drawn Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	12	---	23	---
V	0.263	80	68	84	61
U	0.872	112	100	145	122

Capsule	Fluence ($\times 10^{19}$ n/cm ²) (E > 1.0 MeV)	35 MLE Transition Temperature			
		Hand-Drawn Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	7	---	17	---
V	0.263	80	73	78	61
U	0.872	112	105	122	105

**Table E-2. Comparison of Curve Fit Transition Temperature Shifts for
North Anna Unit No. 1 Surveillance Material,
Base Metal Forging 03, Heat No. 990400/292332,
Axial Orientation**

Capsule	Fluence ($\times 10^{19}$ n/cm ²) (E > 1.0 MeV)	30 ft-lb Transition Temperature			
		Hand-Drawn Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	46	---	40	---
V	0.263	65	19	69	29
U	0.872	111	65	112	72

Capsule	Fluence ($\times 10^{19}$ n/cm ²) (E > 1.0 MeV)	50 ft-lb Transition Temperature			
		Hand-Drawn Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	85	---	84	---
V	0.263	130	45	123	39
U	0.872	165	80	165	81

Capsule	Fluence ($\times 10^{19}$ n/cm ²) (E > 1.0 MeV)	35 MLE Transition Temperature			
		Hand-Drawn Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	74	---	72	---
V	0.263	110	36	106	34
U	0.872	124	50	129	57

**Table E-3. Comparison of Curve Fit Transition Temperature Shifts for
North Anna Unit No. 1 Surveillance Material,
Weld Metal (Wire Heat 25531 / Flux Lot 1211)**

Capsule	Fluence ($\times 10^{19}$ n/cm ²) (E > 1.0 MeV)	30 ft-lb Transition Temperature			
		Hand-Drawn Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	-26	---	-44	---
V	0.263	52	78	44	88
U	0.872	49	75	-14	30

Capsule	Fluence ($\times 10^{19}$ n/cm ²) (E > 1.0 MeV)	50 ft-lb Transition Temperature			
		Hand-Drawn Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	25	---	17	---
V	0.263	96	71	90	73
U	0.872	125	100	95	78

Capsule	Fluence ($\times 10^{19}$ n/cm ²) (E > 1.0 MeV)	35 MLE Transition Temperature			
		Hand-Drawn Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	-13	---	-26	---
V	0.263	67	80	60	86
U	0.872	52	65	16	42

**Table E-4. Comparison of Curve Fit Transition Temperature Shifts for
North Anna Unit No. 1 Surveillance Material,
Heat-Affected-Zone Material**

Capsule	Fluence ($\times 10^{19}$ n/cm ²) (E > 1.0 MeV)	30 ft-lb Transition Temperature			
		Hand-Drawn Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	-51	---	-76	---
V	0.263	4	55	-19	57
U	0.872	49	100	-73	3

Capsule	Fluence ($\times 10^{19}$ n/cm ²) (E > 1.0 MeV)	50 ft-lb Transition Temperature			
		Hand-Drawn Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	2	---	-27	---
V	0.263	60	58	47	74
U	0.872	112	110	64	91

Capsule	Fluence ($\times 10^{19}$ n/cm ²) (E > 1.0 MeV)	35 MLE Transition Temperature			
		Hand-Drawn Curve Fit		Hyperbolic Tangent Curve Fit	
		Avg., °F	Shift, °F	Avg., °F	Shift, °F
Unirradiated	---	20	---	-9	---
V	0.263	65	45	51	60
U	0.872	90	70	21	30



APPENDIX F

Fluence Analysis Methodology

The primary tool used in the determination of the flux and fluence exposure to the Capsule W specimens is the two-dimensional discrete ordinates transport code DORT.^[F-1]

The North Anna Unit No. 1 Capsule W was located at the 25° location for cycles 1 through 13. The power distributions in the cycle 1 - 13 irradiation were symmetric both in θ and Z. That is, the axial power shape is roughly the same for any angle and, conversely, that the azimuthal power shape is the same for any height. This means that the neutron flux at some point (R, θ , Z) can be considered to be a separable function of (R, θ) and (R, Z). Therefore, the cycle 1 - 13 irradiation can be modeled using the standard FTI synthesis procedures.^[F-2]

Figure F-1 depicts the analytical procedure that is used to determine the fluence accumulated over cycles 1 - 13. As shown in the figure, the analysis is divided into seven tasks: (1) generation of the neutron source, (2) development of the DORT geometry models, (3) calculation of the macroscopic material cross sections, (4) synthesis of the results, and (5-7) estimation of the calculational bias, the calculational uncertainty, and the final fluence. Each of these tasks is discussed in greater detail in the following sections.

F.1. Generation of the Neutron Source

The time-average space and energy-dependent neutron source for cycles 1 - 13 was calculated using the SORREL^[F-3] code. The effects of burnup on the spatial distribution of the neutron source were accounted for by calculating the cycle average fission spectrum for each fissile isotope on an assembly-by-assembly basis, and by determining the cycle-average specific neutron emission rate. This data was then used with the normalized time weighted average pin-by-pin relative power density (RPD) distribution to determine the space and energy-dependent neutron source. The azimuthal average, time average axial power shape in the peripheral assemblies was used with the fission spectrum of the peripheral assemblies to determine the neutron source for the axial DORT run. These two neutron source distributions were input to DORT as indicated in Figure F-1.

F.2. Development of the Geometrical Models

The system geometry models for the mid-plane (R, θ) DORT were developed using standard FTI interval size and configuration guidelines. The R θ model for the cycle 1 -13 analysis extended radially from the center of the core to a point approximately 20 cm into the water of the shield tank, and azimuthally from the major axis to 45°. The surveillance capsule was modeled explicitly in the R θ model and the axial (R, Z) DORT geometry model was developed

using FTI procedures for axial modeling and the Virginia Power interval structure in the axial direction. The axial model extended from core plate to core plate. The geometrical models either met or exceeded all guidance criteria concerning interval size that are provided in U.S. NRC Draft Regulatory Guide DG-1053.^[F-4] In all cases, cold dimensions were used. The geometry models were input to the DORT code as indicated in Figure F-1. These models will be used in all subsequent Code of Federal Regulation, Title 10, Part 50 (10 CFR 50), Appendix H^[F-5] and pressure-temperature curve analyses that may be performed by FTI for North Anna Unit No. 1.

F.3. Calculation of Macroscopic Material Cross Sections

In accordance with DG-1053, the BUGLE-93^[F-6] cross section library was used. The GIP^[F-7] code was used to calculate the macroscopic energy-dependent cross sections for all materials used in the analysis – from the core out through the cavity and into the concrete and from core plate to core plate. The ENDF/B6 dosimeter reaction cross sections were used to generate the response functions that were used to calculate the DORT-calculated “saturated” specific activities.

F.4. DORT Analyses

The cross sections, geometry, and appropriate source were combined to create a set of DORT models (R θ and RZ) for the cycle 1 - 13 analysis. Each DORT run utilized a cross section Legendre expansion of three (P_3), seventy directions (S_{10}) for the R θ and forty-eight directions (S_8) for the RZ, and the appropriate boundary conditions. A theta-weighted flux extrapolation model was used, and all other requirements of DG-1053 that relate to the various DORT parameters were either met or exceeded for all DORT runs.

F.5. Synthesized Three Dimensional Results

The DORT analyses produce two sets of two-dimensional flux distributions, one for a vertical cylinder and one for the radial plane. The vertical cylinder, which will be referred to as the RZ plane, is defined as the plane bounded axially by the upper and lower grid plates and radially by the center of the core and a vertical line located 20 cm into the water biological shield. The horizontal plane, referred to as the R θ plane, is defined as the plane bounded radially by the center of the core and a point located 20 cm into the water and azimuthally by the major axis and the adjacent 45° radius. The vessel flux, however, varies significantly in all three cylindrical-coordinate directions (R, θ , Z). This means that if a point of interest is outside the planes of both the R-Z DORT and the R- θ DORT, the true flux cannot be

determined from either DORT run. Under the assumption that the three-dimensional flux is a separable function,^[F-2] both two-dimensional data sets were mathematically combined to estimate the flux at all three-dimensional points (R, θ , Z) of interest. The synthesis procedure outlined in DG-1053 forms the basis for the FTI flux-synthesis process.

F.6. Calculated Activities and Measured Activities

The calculated activities for each dosimeter type “d” were determined using the following equation:

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

where:

C_d	...	calculated specific activity for dosimeter “d” in μCi of product isotope per gram of target isotope
$\phi_g(\bar{r}_d)$...	three dimensional flux for dosimeter “d” at position for energy group “g”
RF_g^d	...	dosimeter response function for dosimeter “d” and energy group “g”
B_d	...	bias correction factors for dosimeter “d”
NSF	...	non-saturation correction factor (NSF).

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

The power history data in Table F-2 was used to determine the non-saturation factors for each of the dosimeter product isotopes for cycles 1 - 13.

A photofission factor was applied to correct for the fact that some of the ^{137}Cs atoms present in the dosimeter were produced by (γ , f) reactions and were not accounted for in DORT analysis. The short half life and impurity correction factors were insignificant and were not applied.

F.7. C/M Ratios

To start, the following explanation will define the meanings of the terms “measurements” (M) and “calculations” (C) as used in this analysis.^[F-2]

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



- **Calculations:** The calculational methodology produces two primary results – the calculated dosimeter activities and the neutron flux at all points of interest. The meaning of the term “calculations” as used by FTI is the calculated dosimeter activity. The calculated activities are determined in such a way that they are directly comparable to the measurement values, but without recourse to the measurements. That is, the calculated values are determined by the DORT calculation and are directly comparable to the measurement values. ENDF/B6 based dosimeter reaction cross sections^[F-8] and response functions were used in determining the calculated values for each individual dosimeter. In summary, it should be stressed that the calculation values in the FTI approach¹ are independent of the measurement values.

F.8. Uncertainty

The North Anna Unit No. 1 fluence predictions are based on the methodology described in the FTI “Fluence and Uncertainty Methodologies” topical report, BAW-2241P, Revision 1.^[F-2]

The time-averaged fluxes, and thereby the fluences throughout the reactor and vessel, are calculated with the DORT discrete ordinates computer code using three-dimensional synthesis methods. The basic theory for synthesis is described in Section 3.0 of BAW-2241P, Revision 1 and the DORT three-dimensional synthesis results are the bases for the fluence predictions using the FTI “Semi-Analytical” (calculational) methodology.

The uncertainties in the North Anna Unit No. 1 fluence values have been evaluated to ensure that the greater than 1.0 MeV calculated fluence values are accurate (with no discernible bias) and have a mean standard deviation that is consistent with the FTI benchmark database of

uncertainties. Consistency between the fluence uncertainties in the updated calculations for North Anna Unit No. 1 cycles 1 through 13 and those in the FTI benchmark database ensures that the vessel fluence predictions are consistent with the 10 CFR 50.61,^[F-9] Pressurized Thermal Shock (PTS) screening criteria and the Regulatory Guide 1.99, Revision 2^[F-10] embrittlement evaluations.

The verification of the fluence uncertainty for the North Anna Unit 1 reactor includes:

- estimating the uncertainties in the cycles 1 - 13 dosimetry measurements,
- estimating the uncertainties in the cycles 1 - 13 benchmark comparison of calculations to measurements, and
- estimating the uncertainties in the cycles 1 - 13 pressure vessel fluence
- determining if the specific measurement and benchmark uncertainties for cycles 1 - 13 are consistent with the FTI database of generic uncertainties in the measurements and calculations.

The embrittlement evaluations in Regulatory Guide 1.99, Revision 2 and those in 10 CFR 50.61 for the PTS screening criteria apply a margin term to the reference temperatures. The margin term includes the product of a confidence factor of 2.0 and the mean embrittlement standard deviation. The factor of 2.0 implies a very high level of confidence in the fluence uncertainty as well as the uncertainty in the other variables contributing to the embrittlement. The 12 dosimeter measurements from the North Anna Unit No. 1 Capsule W analysis would not directly support this high level of confidence. However, the North Anna Unit No. 1 Capsule W dosimeter measurement uncertainties are consistent with the FTI database. Therefore, the calculational uncertainties in the updated fluence predictions for North Anna Unit No. 1 are supported by 728 additional dosimeter measurements and thirty-nine benchmark comparisons of calculations to measurements as shown in Appendix A of BAW-2241P, Revision 1. The calculational uncertainties are also supported by the fluence sensitivity evaluation of the uncertainties in the physical and operational parameters, which are included in the vessel fluence uncertainty.^[F-2] The dosimetry measurements and benchmarks, as well as the fluence sensitivity analyses in the topical are sufficient to support a 95 percent confidence level, with a confidence factor of ± 2.0 , in the fluence results from the "Semi-Analytical" methodology.

The FTI generic uncertainty in the capsule dosimetry measurements has been determined to be unbiased and has an estimated standard deviation of 7.0 percent for the qualified set of dosimeters. The North Anna Unit No. 1 cycle 1 - 13 dosimetry measurement uncertainties

were evaluated to determine if any biases were evident and to estimate the standard deviation. The dosimetry measurements were found to be appropriately calibrated to standards traceable to the National Institute of Standards and Technology and are thereby unbiased by definition. The mean measurement uncertainties associated with cycle 1 - 13 are as follows:

<u>Cycle</u>	<u>σ_M (%)</u>
1 - 13	5.06

This value was determined from Equation 7.6 in BAW-2241P, Revision 1 and indicate that there is consistency with the FTI database. Consequently, when the FTI database is updated, the North Anna Unit No. 1 cycle 1 - 13 dosimetry measurement uncertainties may be combined with the other 728 dosimeters. Since the cycle 1 - 13 measurements are consistent with the FTI database, it is estimated that North Anna Unit No. 1 dosimeter measurement uncertainty may be represented by the FTI database standard deviation of 7.0 percent. Based on the FTI database, there appears to be a 95 percent level of confidence that 95 percent of the North Anna Unit No. 1 Capsule W dosimetry measurements, for fluence reactions above 1.0 MeV, are within ± 14.2 percent of the true values.

The FTI generic uncertainty for benchmark comparisons of capsule dosimetry calculations relative to the measurements indicates that any benchmark bias in the greater than 1.0 MeV results is too small to be uniquely identified. The estimated standard deviation between the calculations and measurements is 9.9 percent. This implies that the root mean square deviation between the FTI calculations of the North Anna Unit No. 1 dosimetry and the measurements should be approximately 9.9 percent in general and bounded by ± 20.04 percent for a 95 percent confidence interval with thirty-nine independent benchmarks.

The weighted mean values of the ratio of calculated dosimeter activities to measurements (C/M) for North Anna Unit No. 1 Capsule W have been statistically evaluated using Equation 7.15 from BAW-2241P, Revision 1. The standard deviations in the benchmark comparisons are as follows:

<u>Cycle</u>	<u>$\sigma_{C/M}$ (%)</u>
1 - 13	3.0

This standard deviation indicates that the benchmark comparisons are consistent with the FTI database. Consequently, when the FTI database is updated, the cycle 1 - 13 benchmark uncertainties may be included with the other thirty-nine benchmark uncertainties in BAW-2241P, Revision 1. The consistency between the cycle 1 - 13 benchmark uncertainties and those in the FTI database indicates that North Anna Unit No. 1 fluence calculations for cycles 1 - 13 have no discernible bias in the greater than 1.0 MeV fluence values. In addition, the consistency indicates that the fluence values can be represented by the FTI reference set which includes a standard deviation of 7.0 percent at dosimetry locations. That is

$$\sigma_{\text{capsule fluence}} \leq 7.00\%$$

$$\sigma_{\text{pressure vessel fluence}} \leq 10.00\%$$

Table F-1. Bias Correction Factors

Dosimeter Type	Bias
Activation	Short Half Life
Fission	Photofission Impurities

Table F-2. North Anna Unit 1 Monthly Power History

Cycle 1				
Month	Year	Average Power (MW)	Maximum Power (MW)	Relative Power
April	1978	347	2775	0.12505
May	1978	1141	2775	0.41117
June	1978	2303	2775	0.82991
July	1978	2353	2775	0.84793
August	1978	2633	2775	0.94883
September	1978	1995	2775	0.71892
October	1978	2350	2775	0.84685
November	1978	2631	2775	0.94811
December	1978	2584	2775	0.93117
January	1979	2298	2775	0.82811
February	1979	2384	2775	0.85910
March	1979	2478	2775	0.89297
April	1979	0	2775	0.00000
May	1979	2439	2775	0.87892
June	1979	2703	2775	0.97405
July	1979	2672	2775	0.96288
August	1979	2747	2775	0.98991
September	1979	1948	2775	0.70198
October	1979	0	2775	0.00000
November	1979	0	2775	0.00000
December	1979	0	2775	0.00000

Table F-2. (Cont'd.) North Anna Unit 1 Monthly Power History

Cycle 2				
Month	Year	Average Power (MW)	Maximum Power (MW)	Relative Power
January	1980	561	2775	0.20216
February	1980	2131	2775	0.76793
March	1980	2711	2775	0.97694
April	1980	2370	2775	0.85405
May	1980	1956	2775	0.70486
June	1980	1804	2775	0.65009
July	1980	2631	2775	0.94811
August	1980	2739	2775	0.98703
September	1980	2622	2775	0.94486
October	1980	2475	2775	0.89189
November	1980	2492	2775	0.89802
December	1980	1851	2775	0.66703
January	1981	0	2775	0.00000
February	1981	0	2775	0.00000
March	1981	0	2775	0.00000

Table F-2. (Cont'd.) North Anna Unit 1 Monthly Power History

Cycle 3				
Month	Year	Average Power (MW)	Maximum Power (MW)	Relative Power
April	1981	1931	2775	0.69586
May	1981	2769	2775	0.99784
June	1981	2686	2775	0.96793
July	1981	2631	2775	0.94811
August	1981	2564	2775	0.92396
September	1981	2681	2775	0.96613
October	1981	533	2775	0.19207
November	1981	2506	2775	0.90306
December	1981	2753	2775	0.99207
January	1982	2603	2775	0.93802
February	1982	2614	2775	0.94198
March	1982	2772	2775	0.99892
April	1982	2395	2775	0.86306
May	1982	1190	2775	0.42883
June	1982	0	2775	0.00000
July	1982	0	2775	0.00000
August	1982	0	2775	0.00000
September	1982	0	2775	0.00000
October	1982	0	2775	0.00000
November	1982	0	2775	0.00000

Table F-2. (Cont'd.) North Anna Unit 1 Monthly Power History

Cycle 4				
Month	Year	Average Power (MW)	Maximum Power (MW)	Relative Power
December	1982	6	2775	0.00216
January	1983	0	2775	0.00000
February	1983	0	2775	0.00000
March	1983	1374	2775	0.49514
April	1983	2769	2775	0.99784
May	1983	2287	2775	0.82414
June	1983	2620	2775	0.94414
July	1983	2484	2775	0.89514
August	1983	2756	2775	0.99315
September	1983	2559	2775	0.92216
October	1983	616	2775	0.22198
November	1983	2595	2775	0.93514
December	1983	2769	2775	0.99784
January	1984	724	2775	0.26090
February	1984	1859	2775	0.66991
March	1984	2767	2775	0.99712
April	1984	2769	2775	0.99784
May	1984	2639	2775	0.95099
June	1984	0	2775	0.00000
July	1984	0	2775	0.00000
August	1984	0	2775	0.00000

Table F-2. (Cont'd.) North Anna Unit 1 Monthly Power History

Cycle 5				
Month	Year	Average Power (MW)	Maximum Power (MW)	Relative Power
September	1984	264	2775	0.09514
October	1984	2173	2775	0.78306
November	1984	2148	2775	0.77405
December	1984	2700	2775	0.97297
January	1985	2661	2775	0.95892
February	1985	2706	2775	0.97514
March	1985	2459	2775	0.88613
April	1985	2769	2775	0.99784
May	1985	2775	2775	1.00000
June	1985	2750	2775	0.99099
July	1985	2775	2775	1.00000
August	1985	1277	2775	0.46018
September	1985	1843	2775	0.66414
October	1985	2448	2775	0.88216
November	1985	2656	2775	0.95712

Table F-2. (Cont'd.) North Anna Unit 1 Monthly Power History

Cycle 6				
Month	Year	Average Power (MW)	Maximum Power (MW)	Relative Power
December	1985	422	2775	0.15207
January	1986	1091	2775	0.39315
February	1986	2534	2775	0.91315
March	1986	2581	2775	0.93009
April	1986	2769	2775	0.99784
May	1986	2589	2775	0.93297
June	1986	2567	2775	0.92505
July	1986	2772	2775	0.99892
August	1986	1657	2794	0.59306
September	1986	281	2893	0.09713
October	1986	2757	2893	0.95299
November	1986	2780	2893	0.96094
December	1986	2766	2893	0.95610
January	1987	2890	2893	0.99896
February	1987	2890	2893	0.99896
March	1987	2881	2893	0.99585
April	1987	2595	2893	0.89699
May	1987	0	2893	0.00000

Table F-2. (Cont'd.) North Anna Unit 1 Monthly Power History

Cycle 7				
Month	Year	Average Power (MW)	Maximum Power (MW)	Relative Power
June	1987	278	2893	0.09609
July	1987	518	2893	0.17905
August	1987	0	2893	0.00000
September	1987	0	2893	0.00000
October	1987	772	2893	0.26685
November	1987	2132	2893	0.73695
December	1987	1987	2893	0.68683
January	1988	668	2893	0.23090
February	1988	1915	2893	0.66194
March	1988	2245	2893	0.77601
April	1988	2890	2893	0.99896
May	1988	2890	2893	0.99896
June	1988	2873	2893	0.99309
July	1988	2861	2893	0.98894
August	1988	2335	2893	0.80712
September	1988	2890	2893	0.99896
October	1988	2838	2893	0.98099
November	1988	2893	2893	1.00000
December	1988	2745	2893	0.94884
January	1989	2821	2893	0.97511
February	1989	2297	2893	0.79399
March	1989	0	2893	0.00000
April	1989	0	2893	0.00000
May	1989	0	2893	0.00000
June	1989	0	2893	0.00000

Table F-2. (Cont'd.) North Anna Unit 1 Monthly Power History

Cycle 8				
Month	Year	Average Power (MW)	Maximum Power (MW)	Relative Power
July	1989	2074	2893	0.71690
August	1989	2893	2893	1.00000
September	1989	2890	2893	0.99896
October	1989	2890	2893	0.99896
November	1989	2867	2893	0.99101
December	1989	1357	2893	0.46906
January	1990	2717	2893	0.93916
February	1990	2890	2893	0.99896
March	1990	2893	2893	1.00000
April	1990	2893	2893	1.00000
May	1990	2870	2893	0.99205
June	1990	2887	2893	0.99793
July	1990	2890	2893	0.99896
August	1990	2887	2893	0.99793
September	1990	2867	2893	0.99101
October	1990	2430	2893	0.83996
November	1990	1941	2893	0.67093
December	1990	1501	2893	0.51884
January	1991	1244	2893	0.43000
February	1991	0	2893	0.00000

Table F-2. (Cont'd.) North Anna Unit 1 Monthly Power History

Cycle 9				
Month	Year	Average Power (MW)	Maximum Power (MW)	Relative Power
March	1991	2419	2893	0.83616
April	1991	2881	2893	0.99585
May	1991	1374	2893	0.47494
June	1991	2890	2893	0.99896
July	1991	1533	2893	0.52990
August	1991	2725	2893	0.94193
September	1991	2887	2893	0.99793
October	1991	2890	2893	0.99896
November	1991	2893	2893	1.00000
December	1991	2123	2893	0.73384
January	1992	0	2893	0.00000
February	1992	0	2893	0.00000
March	1992	2109	2893	0.72900
April	1992	2728	2893	0.94297
May	1992	2745	2893	0.94884
June	1992	2745	2893	0.94884
July	1992	2725	2893	0.94193
August	1992	2728	2893	0.94297
September	1992	2583	2893	0.89284
October	1992	2106	2893	0.72796
November	1992	1678	2893	0.58002
December	1992	1319	2893	0.45593
January	1993	1131	2893	0.39094
February	1993	0	2893	0.00000
March	1993	0	2893	0.00000

Table F-2. (Cont'd.) North Anna Unit 1 Monthly Power History

Cycle 10				
Month	Year	Average Power (MW)	Maximum Power (MW)	Relative Power
April	1993	2309	2893	0.79813
May	1993	2893	2893	1.00000
June	1993	2890	2893	0.99896
July	1993	2890	2893	0.99896
August	1993	2893	2893	1.00000
September	1993	2893	2893	1.00000
October	1993	2890	2893	0.99896
November	1993	2893	2893	1.00000
December	1993	2893	2893	1.00000
January	1994	2893	2893	1.00000
February	1994	2893	2893	1.00000
March	1994	2893	2893	1.00000
April	1994	2890	2893	0.99896
May	1994	2893	2893	1.00000
June	1994	2867	2893	0.99101
July	1994	2447	2893	0.84583
August	1994	1950	2893	0.67404
September	1994	1661	2893	0.57414

Table F-2. (Cont'd.) North Anna Unit 1 Monthly Power History

Cycle 11				
Month	Year	Average Power (MW)	Maximum Power (MW)	Relative Power
October	1994	2471	2893	0.85413
November	1994	2890	2893	0.99896
December	1994	2893	2893	1.00000
January	1995	2722	2893	0.94089
February	1995	2893	2893	1.00000
March	1995	2873	2893	0.99309
April	1995	2893	2893	1.00000
May	1995	2893	2893	1.00000
June	1995	2893	2893	1.00000
July	1995	2890	2893	0.99896
August	1995	2893	2893	1.00000
September	1995	2893	2893	1.00000
October	1995	2893	2893	1.00000
November	1995	2893	2893	1.00000
December	1995	2803	2893	0.96889
January	1996	2317	2893	0.80090
February	1996	1987	2893	0.68683

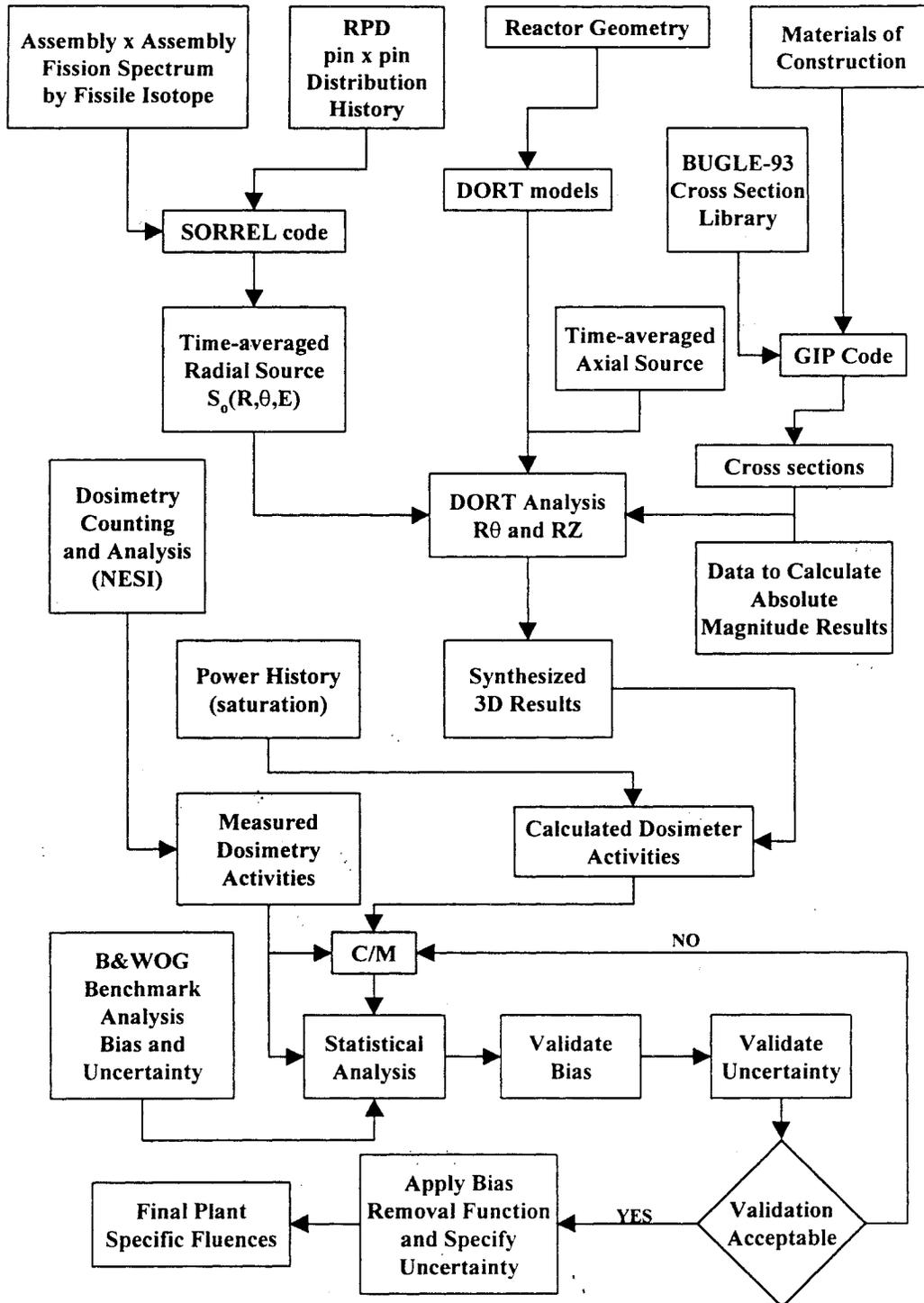
Table F-2. (Cont'd.) North Anna Unit 1 Monthly Power History

Cycle 12				
Month	Year	Average Power (MW)	Maximum Power (MW)	Relative Power
March	1996	2572	2893	0.88904
April	1996	2893	2893	1.00000
May	1996	2893	2893	1.00000
June	1996	2893	2893	1.00000
July	1996	2893	2893	1.00000
August	1996	2685	2893	0.92810
September	1996	2893	2893	1.00000
October	1996	2745	2893	0.94884
November	1996	2893	2893	1.00000
December	1996	2893	2893	1.00000
January	1997	2893	2893	1.00000
February	1997	2893	2893	1.00000
March	1997	2893	2893	1.00000
April	1997	2893	2893	1.00000
May	1997	2855	2893	0.98686

Table F-2. (Cont'd.) North Anna Unit 1 Monthly Power History

Cycle 13				
Month	Year	Average Power (MW)	Maximum Power (MW)	Relative Power
June	1997	2430	2893	0.83996
July	1997	2829	2893	0.97788
August	1997	2890	2893	0.99896
September	1997	2893	2893	1.00000
October	1997	2893	2893	1.00000
November	1997	2887	2893	0.99793
December	1997	2893	2893	1.00000
January	1998	2893	2893	1.00000
February	1998	2803	2893	0.96889
March	1998	2890	2893	0.99896
April	1998	2893	2893	1.00000
May	1998	2893	2893	1.00000
June	1998	2879	2893	0.99516
July	1998	2612	2893	0.90287
August	1998	2893	2893	1.00000

Figure F-1. Fluence Analysis Methodology for North Anna Unit No. 1 Capsule W



F.9. References

- F-1. Ed. M. A. Rutherford, N. M. Hassan, et al., "DORT, Two Dimensional Discrete Ordinates Transport Code," BWNT-TM-107, Framatome Technologies, Inc., Lynchburg, Virginia, May 1995.
- F-2. J. R. Worsham III, "Fluence and Uncertainty Methodologies," BAW-2241P, Revision 1, Framatome Technologies, Inc., Lynchburg, Virginia, April 1999.
- F-3. L. A. Hassler and N. M. Hassan, "SORREL, DOT Input Generation Code User's Manual," NPGD-TM-427, Revision 8, Framatome Technologies, Inc., Lynchburg, Virginia, July 1992.
- F-4. U.S. Nuclear Regulatory Commission, "Calculational and Dosimetry Methods for Determining Pressure Vessel Neutron Fluence," Draft Regulatory Guide DB-1053, June 1996.
- F-5. Code of Federal Regulation, Title 10, Part 50, "Domestic Licensing of Production and Utilization Facilities," Appendix H, Reactor Vessel Material Surveillance Program Requirements.
- F-6. D. T. Ingersoll, et al., "BUGLE-93, Production and Testing of the VITAMIN-B6 Fine Group and the BUGLE-93 Broad Group Neutron/Photon Cross-Section Libraries Derived from ENDF/B-VI Nuclear Data," ORNL-DLC-175, Radiation Safety Information Computational Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, April 1994.
- F-7. L. A. Hassler and N. M. Hassan, "GIP Users Manual for B&W Version, Group Organized Cross Section Input Program," NPGD-TM-456, Revision 11, Framatome Technologies, Inc., Lynchburg, Virginia, August 1994.
- F-8. J. R. Worsham, "BUGLE-93 Response Functions," FTI Document 32-1232719-00, Framatome Technologies, Inc., Lynchburg, Virginia, June 1995.
- F-9. Code of Federal Regulations, Title 10, "Domestic Licensing of Production and Utilization Facilities," Part 50.61, "Fracture Toughness Requirements for Protection Against Pressurized Thermal Shock," Federal Register, December 19, 1995.
- F-10. U.S. Nuclear Regulatory Commission, "Radiation Embrittlement of Reactor Vessel Materials," Regulatory Guide 1.99, Revision 2, May 1998.



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VIRGINIA ELECTRIC AND POWER COMPANY
NORTH ANNA POWER STATION UNIT 1
ANALYSIS OF REACTOR VESSEL MATERIALS SURVEILLANCE CAPSULE W

10 CFR 50 Appendix H, "Reactor Vessel Material Surveillance Program Requirements," requires reactor vessel materials surveillance capsule analysis results to be submitted to the NRC within one year of the date of capsule withdrawal. Pursuant to 10 CFR 50 Appendix H, Virginia Electric and Power Company is providing an analysis report for North Anna Unit 1 Reactor Vessel Materials Surveillance Capsule W. This surveillance capsule was withdrawn on September 22, 1998 during the North Anna Unit 1 Cycle 13/14 refueling outage. This Capsule W analysis is included as an attachment to this letter.

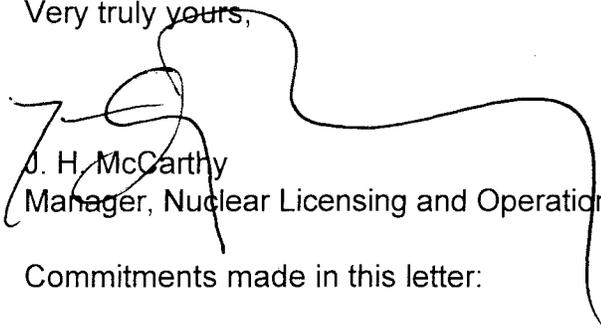
When new information concerning the condition of the reactor vessel beltline materials becomes available, it is necessary to evaluate this information to determine if currently applicable reactor vessel integrity analyses and plant operational limitations must be revised. An evaluation is presently being prepared to assess the impact of North Anna Unit 1 Capsule W analysis results on the currently applicable (a) reactor coolant system pressure/temperature (P/T) operating limits, (b) the Low Temperature Overpressure Protection System (LTOPS) setpoints and system enable temperature, and (c) the 10 CFR 50.61 Pressurized Thermal Shock (PTS) evaluation. A preliminary evaluation prepared by the engineering services contractor as part of the Capsule W analysis indicates that the Capsule W results will not adversely impact the current licensing basis P/T limits, LTOPS setpoints, and PTS evaluation. Thus, no Technical Specification change is currently required. Virginia Power is continuing to evaluate the Capsule W analysis results and will submit a detailed evaluation of the Capsule W results to the NRC by November 30, 1999. It is anticipated that the NRC will use the submittal to update the Reactor Vessel Integrity Database (RVID).

1008/1

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PDR ADOCK 05000338
P PDR

If you have any questions concerning this request, please contact us.

Very truly yours,



J. H. McCarthy
Manager, Nuclear Licensing and Operations Support

Commitments made in this letter:

Submit a detailed analysis report of Capsule W results to NRC by November 30, 1999.

Attachment

cc: U. S. Nuclear Regulatory Commission
Region II
Atlanta Federal Center
61 Forsyth St., SW, Suite 23T85
Atlanta, Georgia 30303

Mr. J. E. Reasor
ODEC
Innsbrook Corporate Center
4201 Dominion Blvd.
Glen Allen, Va. 23060

Mr. M. J. Morgan
NRC Senior Resident Inspector
North Anna Power Station

