

CONNECTICUT YANKEE REACTOR VESSEL  
RADIATION SURVEILLANCE PROGRAM

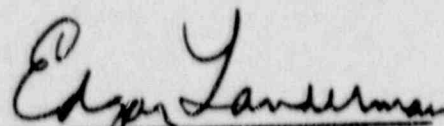
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### Abstract

The purpose of this program is to obtain information on the effects of radiation on the Connecticut Yankee reactor vessel materials under operating conditions.

Charpy V-notch impact specimens, tensile specimens and Wedge Opening Loading specimens were machined from three 10-1/2 inch shell plates from the center shell course adjacent to the core region of the Connecticut Yankee reactor vessel and weld metal from a weldment joining two upper shell course plates. The results of Charpy V-notch impact tests, tensile tests and Wedge Opening Loading tests on unirradiated Connecticut Yankee reactor vessel material are given.

Charpy impact, tensile and Wedge Opening Loading specimens will be inserted into eight material test capsules to be located between the thermal shield and the vessel wall and positioned opposite the center of the core. The identification of the specimens and their locations in the test capsules are given.

Post-irradiation testing of the Charpy impact specimens will provide a guide for establishing pressure-temperature limits of the plant considering the presently used conservative margin for the nil-ductility-transition temperature (NDTT) concepts. The post-irradiation test results on the Wedge Opening Loading specimens will provide applied stress values considering defect size and temperatures. The knowledge of these parameters could be used by design engineers to determine more specific limits for startup and operating procedures for nuclear reactors than those obtained with NDTT concepts.



## I. Purpose and Scope

The purpose and scope of this program is to obtain information on the effect of radiation on the Connecticut Yankee reactor vessel materials under actual operating conditions. It is known that radiation can produce shifts to higher temperatures for the ductile-to-brittle "transition" temperature.<sup>/1,2</sup> The transition temperature increase with service can be monitored by a surveillance program which consists of periodically checking of irradiated reactor vessel surveillance specimens. The nil-ductility transition temperature (NDTT) is defined as the temperature at which a drop weight test specimen is broken in a series of tests in which duplicate no-break performance occurs at a temperature 10°F higher, (from ASTM E208; Drop Weight Test to Determine Nil-Ductility-Transition Temperature of Ferritic Steels). The NDTT has been correlated with Charpy V-notch impact test results; for SA302 Grade B steel, the Charpy V-notch "fix" temperature which corresponds to the NDTT is the temperature at 30 ft-lbs.<sup>/3</sup> This relationship has been listed in the PB Document 151987 and Section III of the ASME Code for Nuclear Vessels.

The surveillance program is based on ASTM E185 (Recommended Practice for Surveillance Tests on Structural Materials in Nuclear Reactors). In addition to the transition temperature approach, a fracture mechanics approach utilizing Wedge Opening Loading (WOL) specimens will be used to evaluate the effects of radiation on the fracture toughness of the Connecticut Yankee reactor vessel materials.<sup>/4-10</sup>

Post-irradiation testing of the Charpy impact specimens will provide a guide for determining pressure-temperature limits of the plant considering the presently used conservative margin of NDT temperature concepts. Charpy impact test data will provide a

temperature shift of the NDT temperature with radiation exposure at the plant temperatures. These data can then be reviewed to verify or establish new pressure-temperature limits of the vessel during startup and cooldown since the Charpy specimens are most nearly indicative of the radiation exposure seen by the vessel. This will allow a check of the predicted shift in the NDT temperature. The post-irradiation test results on the WOL specimens will provide allowable stress values considering defect size and temperature and are expected to allow safe relaxation of startup and operating restrictions currently used to prevent brittle fracture of reactor pressure vessels. The present ASME Codes require specific allowable stresses in the design of reactor pressure vessels. These allowable stresses are based on safety factors of three or four depending on the code. In the case of designing against brittle fracture, the present transition temperature approach does not have a specified safety factor in the conventional sense based on stresses. The transition temperature approach provides a safety factor based on temperature differences. The fracture mechanics approach will provide an allowable stress criterion with engineering safety factors.

Eight materials test capsules will be located in the Connecticut Yankee reactor between the thermal shield and the vessel wall positioned opposite the center of the core. The test capsules will be contained in baskets attached to the thermal shield. The capsules will contain SA302 Grade B reactor vessel steel from three 10-1/2 inch thick shell plates from the Connecticut Yankee reactor vessel center shell course adjacent to the core region and also weld metal and heat affected zone (HAZ) metal. The thermal history or heat treatment given these plates is identical to the thermal history of the Connecticut Yankee reactor vessel material with the exception of the stress relieving treatment which was performed by WAPD and simulates the stress relieving treatment

received by the reactor vessel. In addition, correlation monitors made from fully documented specimens of SA302 Grade B material obtained through Subcommittee II of ASTM Committee E10 on Radioisotopes and Radiation Effects will be inserted in the capsules. This material was made available by the U. S. Steel Corporation. Data on the SA302 Grade B steel used for the correlation monitors have been summarized in a report on surveillance tests.<sup>11</sup>

The eight material test capsules will contain Charpy V-notch impact specimens, tensile specimens and WOL specimens from the three middle shell plates of the Connecticut Yankee reactor vessel and associated weld metal, and Charpy V-notch impact specimens of HAZ metal and the U.S. Steel correlation monitor material. Dosimeters to measure the integrated neutron flux and thermal monitors to measure temperature will also be contained in each of the eight material test capsules.

## II. Sample Preparation

### A. Pressure Vessel Material

The SA302 Grade B Connecticut Yankee reactor vessel material was supplied by Combustion Engineering from the three middle shell plates (W9807-2; W9807-4 and W9807-7). Data on the Connecticut Yankee pressure vessel plates are presented in Appendix A.

### B. Correlation Monitor Material

The SA302 Grade B material for the correlation monitors was supplied by the U.S. Steel Corporation from 6 inch thick plate. Data on the correlation monitor material are presented in Appendix B.



### C. Machining

Plate material was obtained from an end of each shell plate after the thermal heat treatment and prior to welding the three plates together to form the center shell course. All test specimens were machined from the 1/4 thickness location of the plate after stress relieving. The test specimen represent material taken at least one plate thickness (10-1/2") from the quenched edges of the plates. Specimens were machined from weld and heat affected zone metal from a stress relieved weldment joining plates W9807-1 and W9807-8.

#### 1. Charpy V-notch Impact Specimens, (Figure 1)

The base line of the notch of the Charpy V-notch impact specimens was machined perpendicular to the major surfaces of the plate. The longitudinal axis of the specimen was parallel to the rolling direction of the plate.

#### 2. Tensile Specimens, Item 2, (Figure 2)

All tensile specimens were machined with the rolling direction of the plate parallel to the longitudinal axis of the specimen.

#### 3. Wedge Opening Loading Specimens, Item 2, (Figure 3)

All WOL test specimens were machined with the simulated crack of the specimen perpendicular to the rolling direction and the major surfaces of the plate.

### D. Dosimeters

Five Type I capsules shown in Figure 4 will contain dosimeters of aluminum-cobalt (0.15% Co) wire (cadmium shielded and unshielded) and copper. The test specimens will serve as iron dosimeters. Three Type II capsules shown in Figure 5 will contain dosimeters of copper, pure nickel wire, aluminum-



cobalt wire (cadmium shielded and unshielded), neptunium-237 and uranium-238. The test specimens will also serve as iron dosimeters. The dosimeters will be used to measure the integrated flux at specific neutron energy levels.

#### E. Thermal Monitors

The capsules will contain two low melting point eutectic alloys to define more accurately the temperature attained by the test specimens during irradiation. The thermal monitors will be sealed in quartz tubes and then inserted in spacers located as shown in Figures 4 and 5. The two eutectic alloys and their melting points are:

2.5 Ag, 97.5 Pb

1.75 Ag, 0.75 Sn, 97.5 Pb

Melting point 579°F

Melting point 590°F

#### F. Capsule Loading

The five Type I and the three Type II capsules will be loaded with test specimens as shown in Figures 4 and 5 respectively and will be located in the reactor between the thermal shield and the vessel wall.

Each Type I capsule will contain 32 Charpy V-notch specimens; 8 Charpy specimens machined from each of the three Connecticut Yankee vessel plates, the remaining 8 Charpy specimens will be machined from correlation monitor material. In addition, each Type I capsule will contain 3 tensile specimens (one specimen from each of the three Connecticut Yankee plates) and 6 WOL specimens (2 specimens from each of the three Connecticut Yankee plates). Dosimeters of copper, Al-Co and Cd shielded Al-Co will be secured in holes drilled in spacers at the top, middle and bottom of each Type I capsule as shown in Figure 4.

Each Type II capsule will contain 32 Charpy V-notch specimens; 8 specimens will be machined from one of the three Connecticut Yankee plates, 8 specimens of weld metal, 8 specimens of HAZ metal and the remaining 8 specimens will be correlation monitors. In addition, each Type II capsule will contain 4 tensile specimens and 4 WOL specimens; two tensile specimens and two WOL specimens from one of the three Connecticut Yankee plates and the weld metal. Each Type II capsule will contain a dosimeter block shown in Figure 6 at the center of the capsule. Two cadmium oxide shielded capsules, one containing each of the two isotopes  $U^{238}$  and  $Np^{237}$  will be contained in the dosimeter block along with wires of Co-Al (cadmium shielded and unshielded) and nickel. The double containment afforded by the dosimeter assembly prevents loss and contamination by the  $Np^{237}$  and  $U^{238}$  and their activation products. Each dosimeter block will contain approximately .0 milligrams of  $Np^{237}$  and .0 milligrams of  $U^{238}$  contained in a 3/8 inch long by 1/4 inch O.D. sealed brass tube. Each tube will be placed in a 1/2 inch diameter hole in the dosimeter block (one  $Np^{237}$  and one  $U^{238}$  tube per block), and the space around the tube will be filled with cadmium oxide. After placement of this material, each hole will be blocked with two 1/16 inch aluminum spacers disc and an outer 1/8 inch steel cover discs which will be welded in place. The aluminum-cobalt and nickel wires will be inserted in their respective holes in the blocks and will be held secure by peening the hole opening closed. Dosimeters of Co, Ni-Co and Cd shielded Al-27 will also be secured in holes drilled in spacers located at the top and bottom of each Type II capsule as shown in Figure 5.

The specimen numbering system and location in the Type I and Type II capsules is shown in Tables I and II respectively and Figure 7.

G. Specimen Capsule

To prevent corrosion of the surface of the specimens during radiation, the specimens will be seal welded into a square austenitic stainless steel capsule. The capsules will be hydrostatically tested in demineralized water to collapse the can on the specimens to provide optimum thermal conductivity between the specimens and the reactor coolant. The capsules will be helium leak tested as a final inspection procedure. Fabrication details and testing procedures are listed in Figures 4 and 5.

III. Pre-Irradiation Testing

A. Charpy V-notch impact tests were performed on each Connecticut Yankee plate at  $-80^{\circ}\text{F}$ ,  $-40^{\circ}\text{F}$ ,  $-10^{\circ}\text{F}$ ,  $+10^{\circ}\text{F}$ ,  $+60^{\circ}\text{F}$ ,  $+110^{\circ}\text{F}$ ,  $+160^{\circ}\text{F}$ , and  $+212^{\circ}\text{F}$  to obtain a full Charpy V-notch transition curve. See Table III through Table V and Figures 8, 9 and 10. Charpy V-notch impact tests were performed on Weld metal and HAZ metal at  $-80^{\circ}\text{F}$ ,  $-40^{\circ}\text{F}$ ,  $-10^{\circ}\text{F}$ ,  $+10^{\circ}\text{F}$ ,  $+60^{\circ}\text{F}$ ,  $+120^{\circ}\text{F}$ ,  $+160^{\circ}\text{F}$  and  $+210^{\circ}\text{F}$  and the data are reported in Table VI and VII and Figures 11 and 12 respectively. The Charpy V-notch impact data for the correlation monitor material are shown in Table VIII and Figure 13.

B. Tensile Tests

Tensile tests were performed on each Connecticut Yankee plate and the weld metal at room temperature,  $200^{\circ}\text{F}$ ,  $400^{\circ}\text{F}$  and  $600^{\circ}\text{F}$  and the data are shown in Tables IX through XII and Figures 14 through 17.

C. Wedge Opening Loading

WOL tests were performed on each of the Connecticut Yankee plates and the weld metal at various temperature from  $-320^{\circ}\text{F}$



to -100°F. The fracture toughness stress intensity factor ( $K_{Ic}$ ) versus temperature was determined for each plate and is shown in Table VIII and Figures 10 through 21.

#### IV. Post-Irradiation Testing

Specimen capsules will be removed from the reactor only during normal refueling periods. The recommended schedule for removal of capsules follows:

<u>Capsule Type</u>	<u>Capsule Identification</u>	<u>Exposure Time</u>
II	A	(Replacement of 1st Region)
I	F	(Replacement of 2nd Region)
II	D	(Replacement of 4th Region)
I	E	10 years  Extra capsules for complementary testing or additional exposure.
I	B	
II	C	
I	U	
I	G	

Each specimen capsule upon removal after radiation exposure will be transferred to a post-irradiation test facility for disassembly of the capsule and testing of all specimens.

##### A. Charpy V-notch Impact Tests

The testing of the Charpy impact specimens from each of the three Connecticut Yankee vessel plates, the weld and HAZ metal, and the correlation monitor material in each capsule can be done singularly making it possible to perform Charpy impact tests at five different temperatures with three extra specimens to provide an optimum curve for each plate.

The initial Charpy specimen from the first capsule to be re-



moved should be tested at 110°F. The impact energy value for this test temperature should be compared with pre-irradiation test data. The testing temperatures for the remaining specimens should then be appropriately raised or lowered. The test temperatures of specimens from capsules exposed to longer irradiation periods should be determined by the test results for the previous capsule.

B. Tensile Tests

The two tensile specimens per plate from the Type II capsules should be tested at room temperature and the approximating operating temperature of the reactor (550°F). The one tensile specimen per plate from the Type I capsule should be alternately tested at room temperature and the approximate operating temperature of the reactor vessel shell (550°F).

C. Wedge Opening Loading Tests

The WOL specimens from each individual capsule should be tested at a temperature based on the transition temperature shift obtained from the associated Charpy impact specimens. A mean temperature of -150°F plus the transition temperature shift should be the initial test temperature.

D. Post-Irradiation Test Equipment

1. Milling machine or special cut-off wheel for opening capsules and dosimeter blocks.
2. Hot-cell tensile testing machine with
  - a. pin type adapter for pulling tensile tests
  - b. clevis and extensometer for pulling WOL specimens
3. Hot-cell Charpy impact testing machine.
4. NaI scintillation detector and pulse height analyzer for gamma counting of the specific activities of the dosimeters.

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## APPENDIX A

### Connecticut Yankee Pressure Vessel Plates

Combustion Engineering furnished sections from three middle shell plates of SA302 Grade B reactor vessel steel and a weldment from 10-1/2" thick Connecticut Yankee reactor vessel shell plate. This plate was produced by the Lukens Steel Company.

#### a) Chemistry (Per Cent)

<u>Plate No.</u>	<u>Lukens Heat No.</u>	<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Mo</u>	<u>Si</u>	<u>Cu</u>
W9807-2	A5892	0.20	1.42	0.010	0.014	0.47	0.26	0.10
W9807-4	A5877	0.20	1.37	0.010	0.021	0.47	0.19	0.12
W9807-7	A5911	0.20	1.46	0.013	0.010	0.48	0.22	0.12
W9807-1	A5887	0.20	1.28	0.016	0.016	0.47	0.20	0.10
W9807-8	B0716	0.20	1.29	0.012	0.017	0.47	0.17	0.11

#### b) Heat Treatment

The middle shell plates and weldment were heat treated by Combustion Engineering at 1550-1600°F and held at temperature for four hours and dip quenched, tempered at 1225°F for four hours and furnace cooled. Material cut from the middle shell plates was then stress relieved at 1150°F for 24 hours and furnace cooled at WAPD. The weldment was stress relieved at Combustion Engineering at 1150°F for 30 hours and furnace cooled.



## APPENDIX B

### U. S. Steel Corporation Correlation Monitor Material

The correlation monitor material SA302 Grade B was furnished by the U.S. Steel Corporation through Subcommittee II of ASTM Committee E10 on Radioisotopes and Radiation Effects. The specimens were machined from a 96 inch wide by 72 inch long by 6 inch thick plate which was melted using a fine-grain practice and a transverse to longitudinal rolling ratio of 1:1.

#### a) Chemistry (Per Cent)

<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Mo</u>	<u>Si</u>
0.24	1.34	0.011	0.023	0.51	0.23

#### b) Heat Treatment

The U.S. Steel material was heat treated at the U.S. Steel Homestead District Works as follows:

The six inch thick plate was charged into a furnace operating at 1100°F, heated at a maximum rate of 63°F per hour to 1650°F, held at temperature for four hours, and water quenched to 300°F. The plate was then recharged into a furnace operating at 700 to 750°F and heated at a maximum rate of 63°F per hour to 1200°F for 6 hours.



Table 1

Specimen Identification and Location in Connecticut Yankee  
Reactor Irradiation Test Capsules Type I

Location	Specimen Type	Capsule B	Capsule C	Capsule F	Capsule G	Capsule H
40,41 38,39	Charpy	C-8,Y-8 W-8,R-8	C-16,Y-16 W-16,R-16	C-24,Y-24 W-24,R-24	C-32,Y-32 W-32,R-32	C-40,Y-40 W-40,R-40
37	Tensile	C-1	C-2	C-3	C-4	C-5
35,36 33,34	Charpy	C-7,Y-7 W-7,R-7	C-15,Y-15 W-15,R-15	C-23,Y-23 W-23,R-23	C-31,Y-31 W-31,R-31	C-39,Y-39 W-39,R-39
32	WOL	C-2	C-4	C-6	C-8	C-10
31	WOL	C-1	C-3	C-5	C-7	C-9
29,30 27,28	Charpy	C-6,Y-6 W-6,R-6	C-14,Y-14 W-14,R-14	C-22,Y-22 W-22,R-22	C-30,Y-30 W-30,R-30	C-38,Y-38 W-38,R-38
26	WOL	Y-2	Y-4	Y-6	Y-8	Y-10
25	WOL	Y-1	Y-3	Y-5	Y-7	Y-9
23,24 21,22	Charpy	C-5,Y-5 W-5,R-5	C-13,Y-13 W-13,R-13	C-21,Y-21 W-21,R-21	C-29,Y-29 W-29,R-29	C-37,Y-37 W-37,R-37
19,20 17,18	Charpy	C-4,Y-4 W-4,R-4	C-12,Y-12 W-12,R-12	C-20,Y-20 W-20,R-20	C-28,Y-28 W-28,R-28	C-36,Y-36 W-36,R-36
16	WOL	W-2	W-4	W-6	W-8	W-10
15	WOL	W-1	W-3	W-5	W-7	W-9
13,14 11,12	Charpy	C-3,Y-3 W-3,R-3	C-11,Y-11 W-11,R-11	C-19,Y-19 W-19,R-19	C-27,Y-27 W-27,R-27	C-35,Y-35 W-35,R-35
10	Tensile	Y-1,W-1	Y-2,W-2	Y-3,W-3	Y-4,W-4	Y-5,W-5
8 6	Charpy	C-2,Y-2 W-2,R-2	C-10,Y-10 W-10,R-10	C-18,Y-18 W-18,R-18	C-26,Y-26 W-26,R-26	C-34,Y-34 W-34,R-34
4 2	Charpy	C-1,Y-1 W-1,R-1	C-9,Y-9 W-9,R-9	C-17,Y-17 W-17,R-17	C-25,Y-25 W-25,R-25	C-33,Y-33 W-33,R-33

Specimen Numbering Code

Plate W9807-2

Plate W9807-4

Plate W9807-7

Plate (ASTM, Correlation Monitor)

Table II

Specimen Identification and Location in Connecticut Yankee  
Reactor Irradiation Test Capsules Type II

<u>Location</u>	<u>Specimen Type</u>	<u>Capsule A</u>	<u>Capsule D</u>	<u>Capsule E</u>
40,41 38,39	Charpy	C-48,R-48 D-8,H-8	Y-48,R-56 D-16,H-16	W-48,R-64 D-24,H-24
36,37 34,35	Charpy	C-47,R-47 D-7,H-7	Y-47,R-55 D-15,H-15	W-47,R-63 D-23,H-23
32,33	Tensile	C-6,C-7	Y-6,Y-7	W-6,W-7
31	WOL	C-12	Y-12	W-12
29,30 27,28	Charpy	C-46,R-46 D-6,H-6	Y-46,R-54 D-14,H-14	W-46,R-62 D-22,H-22
26	WOL	C-11	Y-11	W-11
24,25 22,23	Charpy	C-45,R-45 D-5,H-5	Y-45,R-53 D-13,H-13	W-45,R-61 D-21,H-21
21	Dosimeter	11	12	13
19,20 17,18	Charpy	C-44,R-44 D-4,H-4	Y-44,R-52 D-12,H-12	W-44,R-60 D-20,H-20
16	WOL	D-2	D-4	D-6
14,15 12,13	Charpy	C-43,R-43 D-3,H-3	Y-43,R-51 D-11,H-11	W-43,R-59 D-19,H-19
11	WOL	D-1	D-3	D-5
9,10	Tensile	D-1,D-2	D-3,D-4	D-5,D-6
7,8 5,6	Charpy	C-42,R-42 D-2,H-2	Y-42,R-50 D-10,H-10	W-42,R-58 D-18,H-18
3,4 1,2	Charpy	C-41,R-41 D-1,H-1	Y-41,R-49 D-9,H-9	W-41,R-57 D-17,H-17

Specimen Numbering Code

C - Plate W9807-2

Y - Plate W9807-4

W - Plate W9807 -7

R - Plate (ASTM Correlation  
Monitor)

D - Weld Metal

E- Haz Metal

Table III

Pre-Irradiation Charpy V - Notch Impact Data for  
Connecticut Yankee Pressure Vessel Plate (W9807-2)

Test Temp. (°F)	Impact Energy (Ft-LBS)	Average Impact Energy (FT-LBS)	Fracture Appearance (% Shear)	Lateral Expansion (Mils)
-80	6.5	5.8	0	10
-80	5.0		0	3
-80	6.0		0	4
-40	30.5	34.0	10	25
-40	34.0		10	27
-40	37.5		10	30
-10	37.5	38.8	10	32
-10	43.0		10	36
-10	36.0		10	30
+10	43.5	53.8	10	36
+10	56.0		20	46
+10	62.0		20	52
+60	97.0	87.0	40	69
+60	84.0		30	59
+60	80.0		30	57
+110	132.0	120.0	100	70
+110	112.0		85	75
+110	116.0		85	86
+160	129.0	131.2	100	87
+160	129.0		100	90
+160	135.0		100	91
+212	137.0	134.7	100	93
+212	127.0		100	86
+212	140.0		100	85



Table IV

Pre-Irradiation Charpy V- Notch Impact Data for  
Connecticut Yankee Pressure Vessel Plate (W9807-4)

Test Temp (°F)	Impact Energy (FT-LBS)	Average Impact energy (FT-LBS)	Fracture Appearance (% Shear)	Lateral Expansion (Mils)
-80	3.5	3.3	0	2
-80	3.0		0	2
-80	3.5		0	2
-40	36.0	24.2	10	30
-40	25.5		10	22
-40	11.0		5	12
-10	18.5	33.2	5	16
-10	32.5		10	28
-10	41.5		10	34
-10	40.0		10	34
+10	57.0	48.8	15	46
+10	42.5		15	38
+10	47.0		15	38
+60	72.0	74.7	20	56
+60	78.0		20	62
+60	74.0		20	54
+110	109.0	103.3	70	78
+110	98.0		50	77
+110	103.0		70	75
+160	120.0	121.3	100	90
+160	126.0		100	84
+160	118.0		99	84
+212	125.5	126.0	100	82
+212	127.5		100	82
+212	125.0		100	86



Table V

Pre-Irradiation Charpy V-Notch Impact Data for  
Connecticut Yankee Pressure Vessel Plate (W9807-7)

Test Temp (°F)	Impact Energy (Ft-Lbs)	Average Impact Energy (Ft-Lbs)	Fracture Appearance (% Shear)	Lateral Expansion (Mils)
-80	4.0	4.5	0	2
-80	4.5		0	2
-80	5.0		0	2
-40	20.0	30.0	5	20
-40	27.5		5	27
-40	46.0		5	39
-40	26.5		5	24
-10	47.0	34.7	10	38
-10	35.0		10	30
-10	22.0		10	21
+10	56.5	52.7	20	48
+10	56.5		20	48
+10	45.0		20	35
+60	95.0	79.5	40	72
+60	68.5		40	54
+60	75.0		40	62
+110	108.5	116.5	70	79
+110	116.0		100	84
+110	125.0		100	86
+160	120.0	119.5	100	92
+160	118.0		100	88
+160	119.5		100	80
+212	118.0	121.0	100	91
+212	122.0		100	89
+212	123.0		100	93

Table VI

**Pre-Irradiation Charpy V-Notch Impact Data for  
Connecticut Yankee Pressure Vessel Weld Metal**

<u>Test Temp (°F)</u>	<u>Impact Energy (Ft-Lbs)</u>	<u>Average Impact Energy (Ft-Lbs)</u>	<u>Fracture Appearance (% Shear)</u>	<u>Lateral Expansion (Mils)</u>
-80	22.0	18.0	10	23
-80	13.0		10	12
-80	19.0		10	16
-40	36.5	39.0	20	32
-40	43.5		30	39
-40	37.0		30	34
-10	46.0	46.2	40	41
-10	37.5		40	36
-10	55.0		40	45
+10	53.0	58.7	50	49
+10	59.0		40	52
+10	64.0		50	46
+60	86.0	89.0	80	74
+60	90.0		90	77
+60	91.5		70	81
+120	96.0	100.2	100	81
+120	108.0		100	91
+120	96.5		95	86
+160	100.5	104.8	100	81
+160	105.0		100	87
+160	108.0		100	87
+210	102.5	105.7	100	87
+210	112.5		100	87
+210	102.0		100	87

Table VII  
Pre-Irradiation Charpy V-Notch Impact Data for  
Connecticut Yankee Pressure Vessel Weld Heat Affected Zone Material

<u>Test Temp (°F)</u>	<u>Impact Energy (Ft-Lbs)</u>	<u>Average Impact Energy (Ft-Lbs)</u>	<u>Fracture Appearance (% Shear)</u>	<u>Lateral Expansion (Mils)</u>
-80	2.5	4.0	0	1
-80	6.5		0	5
-80	3.0		0	2
-40	6.0	13.5	10	6
-40	21.0		20	17
-10	22.5	26.7	10	22
-10	31.5		30	28
-10	26.0		30	25
10	29.0	31.0	10	27
10	33.0		30	30
60	65.5	53.8	60	53
60	42.0		40	39
120	67.5	61.8	90	59
120	56.0		90	54
160	99.5	88.0	100	79
160	85.0		100	71
160	79.5		100	69



Table VIII

Pre-Irradiation Charpy V-Notch Impact Data for  
ASTM SA302B Correlation Monitor Material (Supplied by U.S. Steel)

<u>Specimen No.</u>	<u>Test Temp. (°F)</u>	<u>Impact Strength (Ft-Lbs)</u>	<u>Fracture Appearance (% Shear)</u>	<u>Lateral Expansion (Mils )</u>
1	+100	62	85	58
2	+100	68	98	60
3	+ 80	50	70	48
4	+ 80	67	100	60
5	+ 60	33	45	35
6	+ 60	36	50	40
7	+ 40	26	45	26
8	+ 40	36	45	33
9	+ 20	23	35	23
10	+ 20	29	35	28
11	0	18	25	18
12	0	22	30	22
13	- 20	13	15	14
14	- 20	14	15	14
15	- 40	6	5	7
16	- 40	10	5	10
17	- 40	12	10	14
18	- 60	6	3	6
19	- 60	8	3	6
20	- 80	4	2	6
21	- 80	4	2	6



**Table IX**  
**Pre-Irradiation Tensile Properties of**  
**Connecticut Yankee Pressure Vessel Plate (W9807-2)**

Test Temp. °F	0.2% Offset Yield Strength PSI	Tensile Strength PSI	Elongation %	Reduction in Area %
Room	62,550	83,400	30.2	68.2
Room	<u>62,950</u>	<u>83,700</u>	<u>28.4</u>	<u>71.1</u>
Average	62,750	83,550	29.3	69.6
200	59,450	79,250	27.7	68.7
200	<u>59,450</u>	<u>78,950</u>	<u>26.6</u>	<u>65.2</u>
Average	59,450	79,100	27.2	67.0
400	55,250	74,700	25.3	66.7
400	<u>53,900</u>	<u>76,800</u>	<u>27.2</u>	<u>66.4</u>
Average	54,575	75,750	26.2	66.6
600	52,400	81,050	27.6	63.4
600	<u>52,500</u>	<u>78,900</u>	<u>30.0</u>	<u>62.3</u>
Average	52,450	79,975	28.8	62.8

Table X

Pre-Irradiation Tensile Properties of  
Connecticut Yankee Pressure Vessel Plate (W9807-4)

<u>Test Temp °F</u>	<u>0.2% Offset Yield Strength PSI</u>	<u>Tensile Strength PSI</u>	<u>Elongation %</u>	<u>Reduction in Area %</u>
Room	58,750	81,850	29.6	71.0
Room	<u>58,550</u>	<u>80,225</u>	<u>28.7</u>	<u>69.0</u>
Average	58,650	81,040	29.2	70.0
200	56,450	76,400	25.0	68.6
200	<u>56,450</u>	<u>76,400</u>	<u>24.7</u>	<u>68.6</u>
Average	56,450	76,400	24.8	68.6
400	53,800	76,400	21.9	71.3
400	<u>54,500</u>	<u>76,900</u>	<u>22.0</u>	<u>68.6</u>
Average	54,150	76,650	22.0	70.0
600	50,800	76,700	27.5	65.0
600	<u>51,200</u>	<u>71,550</u>	<u>27.3</u>	<u>65.0</u>
Average	51,100	74,125	27.4	65.0

Table XI

Pre-Irradiation Tensile Properties of  
Connecticut Yankee Pressure Vessel Plate (W9807-7)

Test Temp °F	0.2% Offset Yield Strength PSI	Tensile Strength PSI	Elongation %	Reduction in Area %
Room	61,920	81,610	25.9	69.6
Room	<u>61,530</u>	<u>81,190</u>	<u>28.5</u>	<u>75.4</u>
Average	61,725	81,400	27.4	72.5
200	58,450	76,950	24.1	65.3
200	<u>58,840</u>	<u>76,650</u>	<u>26.9</u>	<u>68.2</u>
Average	58,645	76,800	25.5	66.8
400	53,090	74,140	22.1	72.9
400	<u>53,270</u>	<u>74,270</u>	<u>22.1</u>	<u>66.1</u>
Average	53,180	74,205	22.1	69.5
600	53,530	76,660	26.4	62.8
600	<u>52,670</u>	<u>73,840</u>	<u>28.4</u>	<u>69.4</u>
Average	53,100	75,250	27.4	66.1



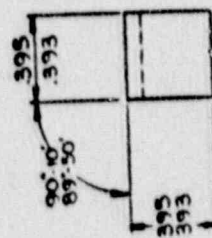
Table XIIPre-Irradiation Tensile Properties of  
Connecticut Yankee Pressure Vessel Weld Metal

<u>Test Temp °F</u>	<u>0.2% Offset Yield Strength PSI</u>	<u>Tensile Strength PSI</u>	<u>Elongation %</u>	<u>Reduction in Area %</u>
Room	69,600	81,800	27.7	70.0
Room	<u>69,950</u>	<u>83,350</u>	<u>33.2</u>	<u>70.8</u>
Average	69,775	82,575	30.4	70.4
200	67,200	79,760	26.7	70.1
200	<u>64,900</u>	<u>78,550</u>	<u>29.3</u>	<u>71.6</u>
Average	66,050	79,155	28.0	70.8
400	61,900	76,700	23.3	68.8
400	<u>61,900</u>	<u>77,850</u>	<u>24.2</u>	<u>69.1</u>
Average	61,900	77,275	23.8	69.0
600	59,250	79,150	24.3	62.4
600	<u>63,950</u>	<u>86,800</u>	<u>19.2</u>	<u>50.8</u>
Average	61,600	82,975	21.8	56.6



Table XIII  
Pre-Irradiation Fracture Toughness Properties of  
~~Pressure Vessel~~ Pressure Vessel Plate Materials  
included Weld Metal

Plate No.	Test Temp °F	Load lbs	$\bar{\sigma}_N$ lbs/in <sup>2</sup>	$G_{IC}$ in-lbs/in <sup>2</sup>	$K_{IC}$ ksi $\sqrt{in}$
W9807-2	-320	3,075	47,700	24.70	28.55
"	"	3,425	60,300	38.60	35.60
"	-250	3,300	47,420	26.75	29.70
"	"	3,900	62,460	44.90	38.50
"	-200	4,680	69,550	59.70	44.40
"	"	5,050	83,920	83.50	52.50
"	-150	6,600	96,330	127.00	64.60
"	"	4,500	79,210	71.40	48.50
W9807-4	-320	2,510	38,690	17.15	23.80
"	"	2,660	37,460	16.69	23.40
"	-200	2,925	52,510	29.25	31.05
"	"	3,300	49,055	28.60	30.70
"	-150	4,175	68,080	55.10	42.60
"	"	5,000	74,330	70.50	48.20
"	-100	6,625	93,400	125.80	64.40
"	"	5,625	83,620	95.20	56.00
W9807-7	-320	2,875	41,975	21.00	25.30
"	"	2,650	39,070	17.90	24.30
"	-200	5,725	85,090	93.40	55.50
"	"	5,175	78,370	76.20	50.25
"	-150	5,350	79,460	79.00	51.00
"	"	5,700	80,320	81.30	51.80
"	-100	7,275	110,120	169.50	74.70
"	"	7,300	98,250	143.00	68.70
Weld Metal	-320	2,540	63,890	28.55	30.60
"	"	4,200	72,570	57.30	44.60
"	-200	5,025	106,160	103.00	58.30
"	"	6,875	116,450	164.00	73.60
"	-150	5,825	115,580	135.00	66.80
"	"	6,925	129,300	187.50	78.60



A - REACTOR VESSEL MATERIAL AS SPECIFIED BY ENGINEER

08/ALL OVER UNLESS OTHERWISE SPECIFIED

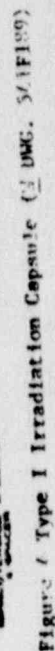
Figure 1 Charpy V-Notch Impact Specimen



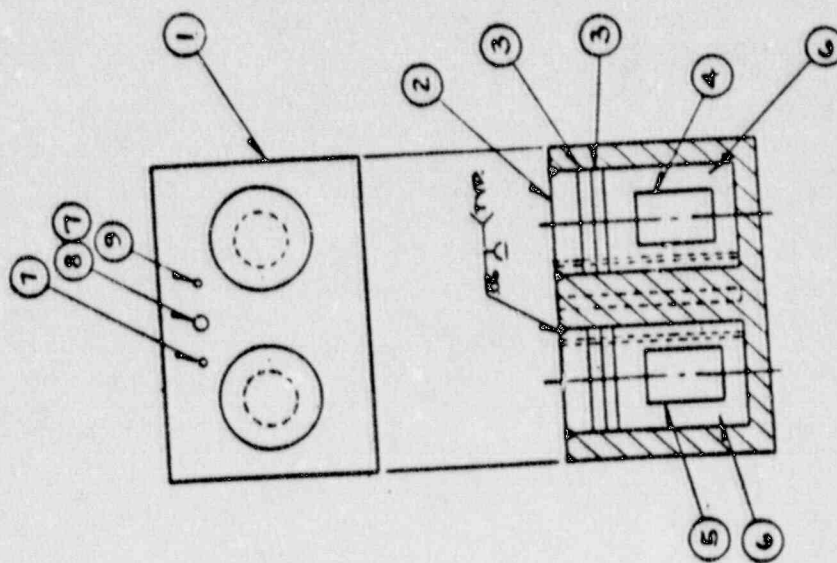












BILL OF MATERIAL				QCB CODE	
ITEM	QTY	DESCRIPTION	QCB CODE	QCB CODE	QCB CODE
1	1	BLOCK	1	1	1
2	1	PLATE	2	2	2
3	1	SPACER	3	3	3
4	1	NEPTUNIUM 137 SEALED CAPSULE	4	4	4
5	1	URANIUM 235 SEALED CAPSULE	5	5	5
6	1	CADMIUM OXIDE	6	6	6
7	1	COPALT SPECIMEN	7	7	7
8	1	CADMIUM SPECIMEN	8	8	8
9	1	NICKEL WIRE	9	9	9



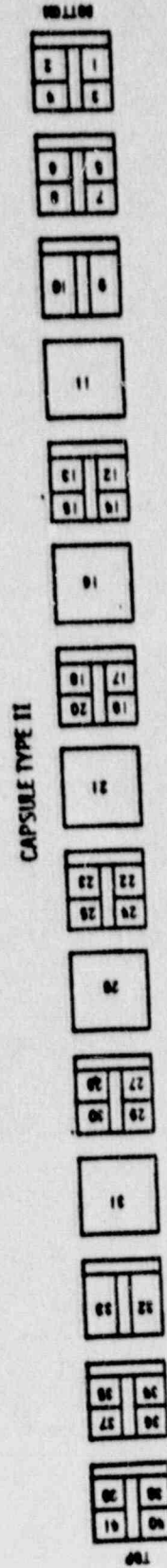
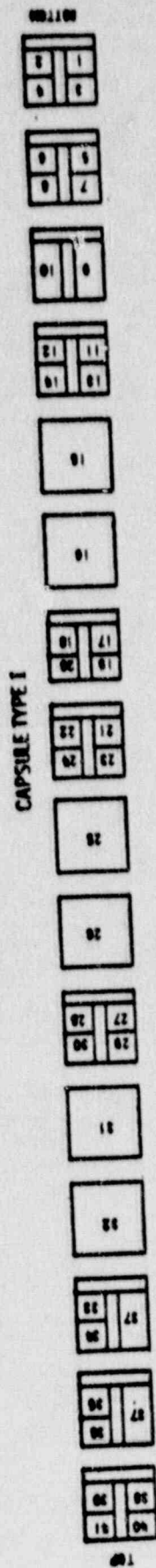


Figure 7 Location Reference Numbers for Connecticut Yankee  
Generator Surveillance Test Capsule Specimens

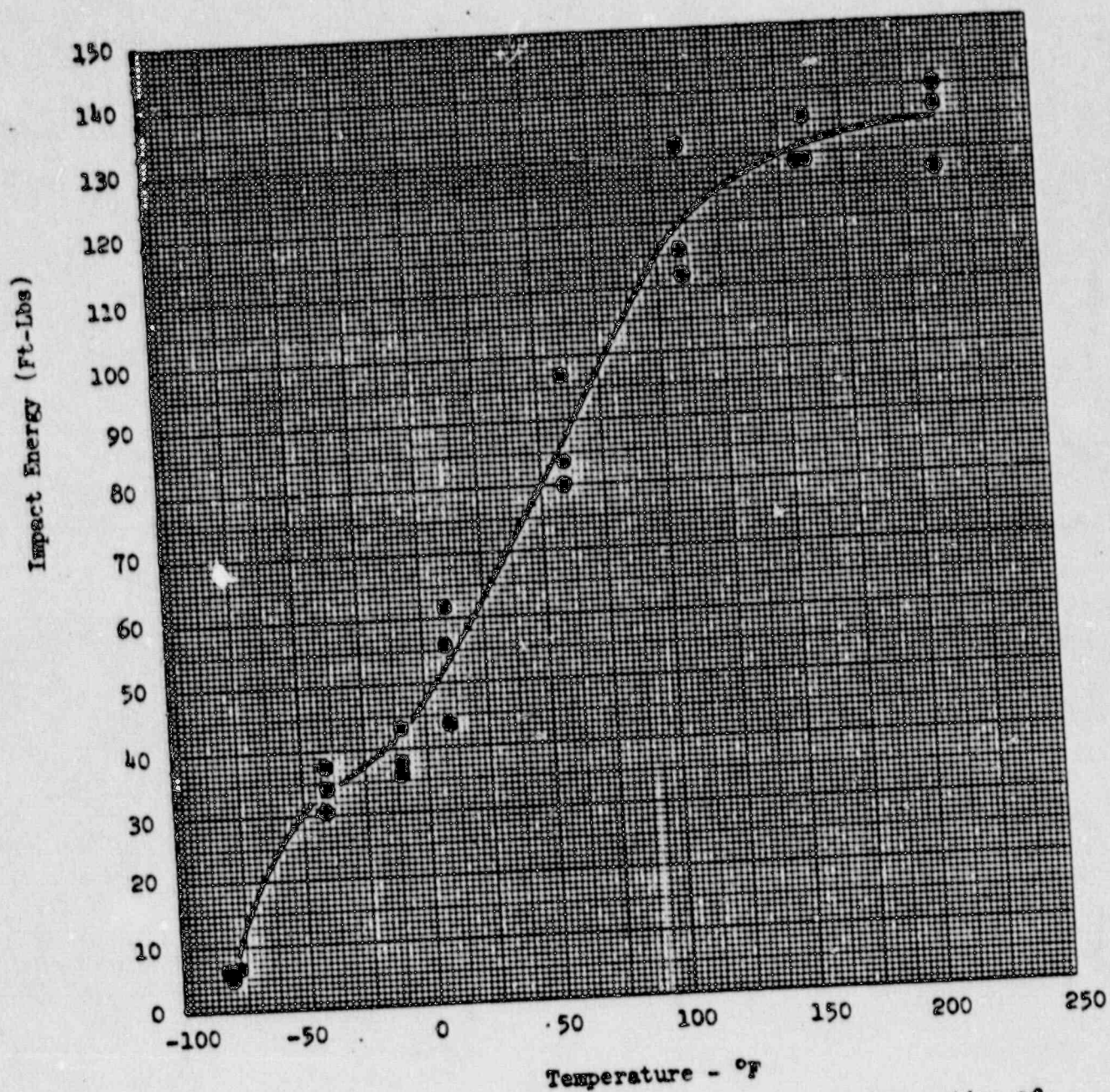


Figure 8 Pre-Irradiation Charpy V-Notch Impact Properties of Connecticut Yankee Pressure Vessel - Plate (W9807-2)



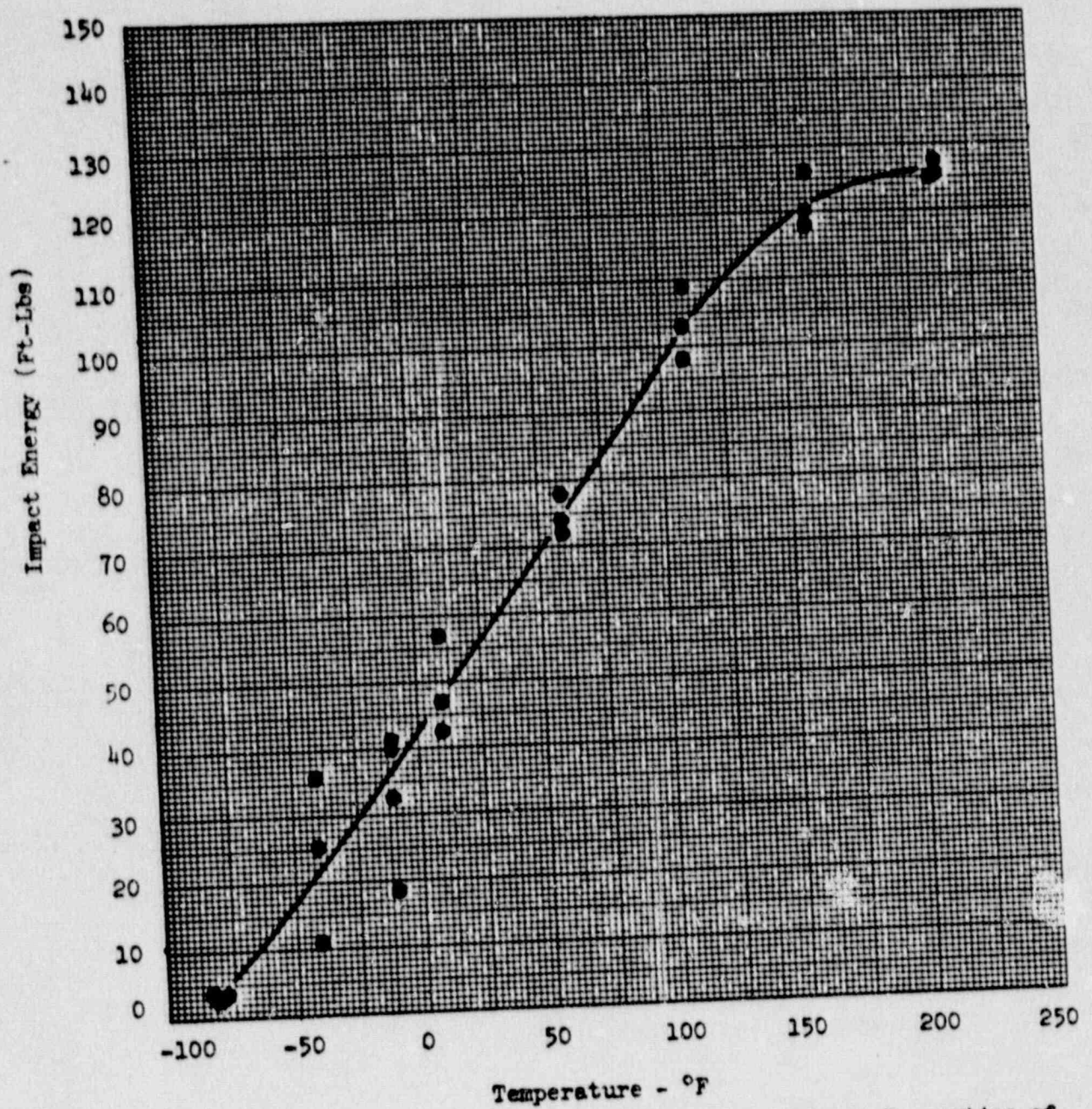


Figure 9 Pre-Irradiation Charpy V-Notch Impact Properties of Connecticut Yankee Pressure Vessel - Plate (W9807-4)



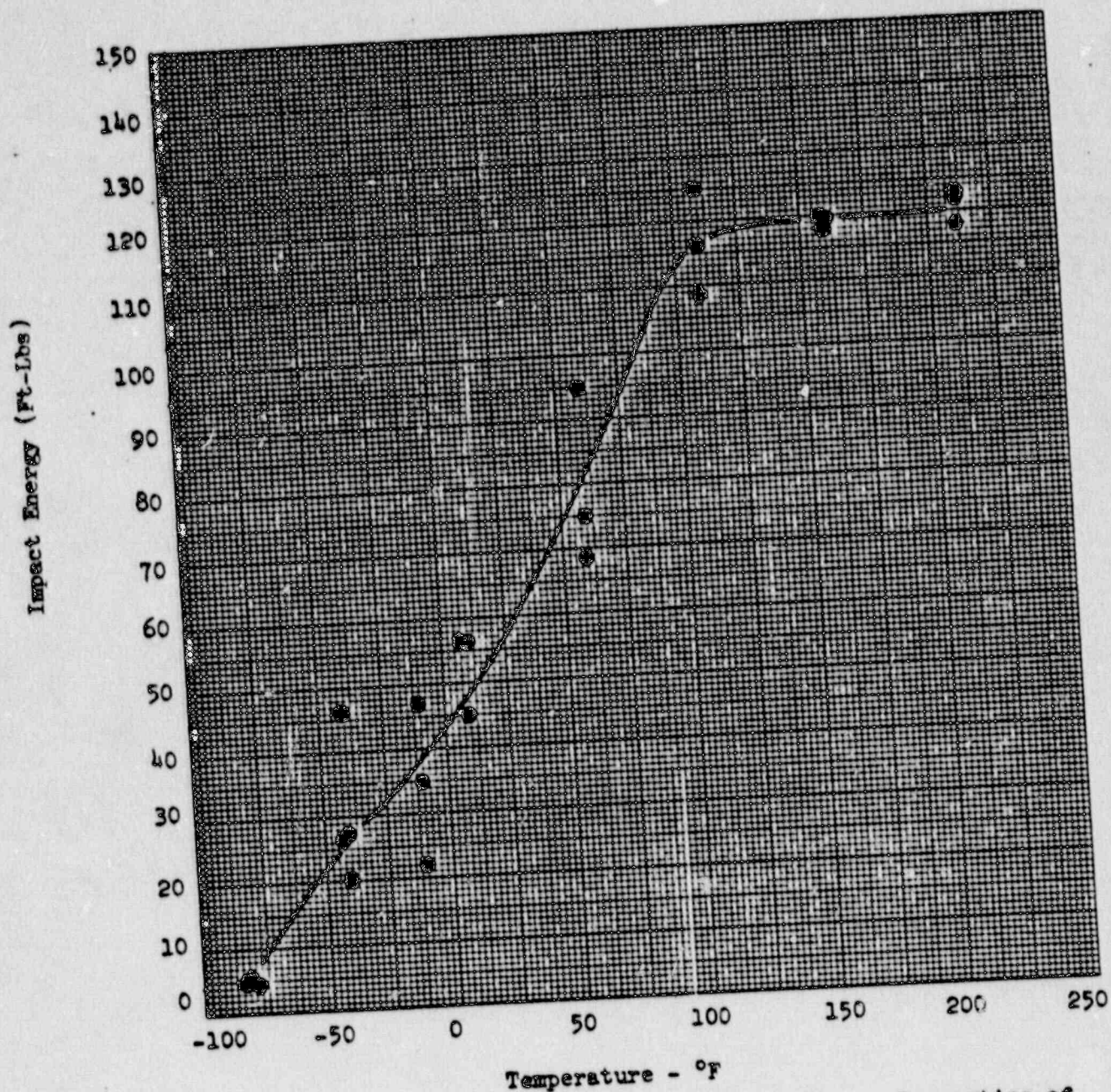


Figure 10 Pre-Irradiation Charpy V-Notch Impact Properties of  
Connecticut Yankee Pressure Vessel - Plate (W9807-7)

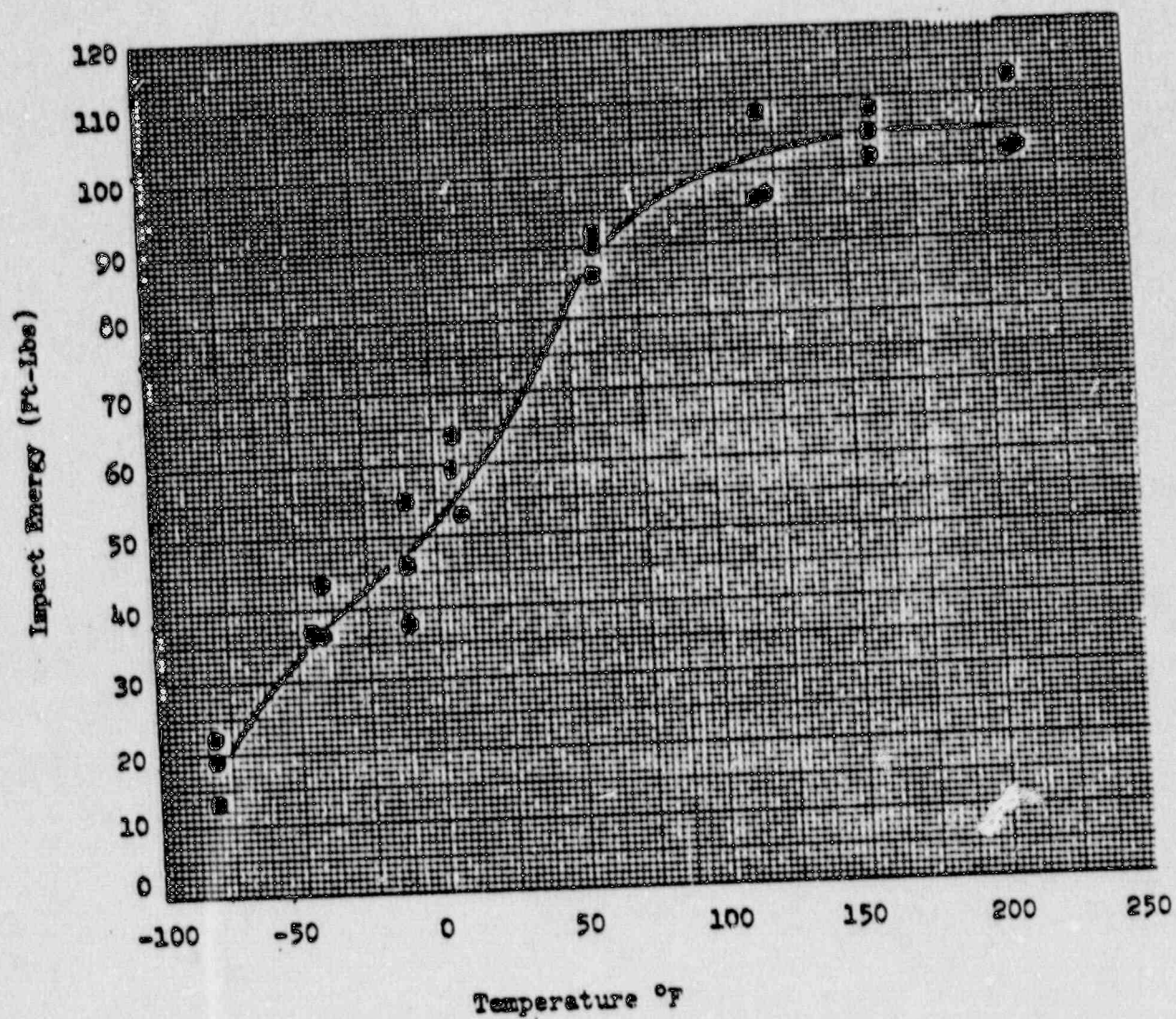


Figure 11 Pre-Irradiation Charpy V-Notch Impact Properties of Connecticut Yankee Pressure Vessel - Weld Metal



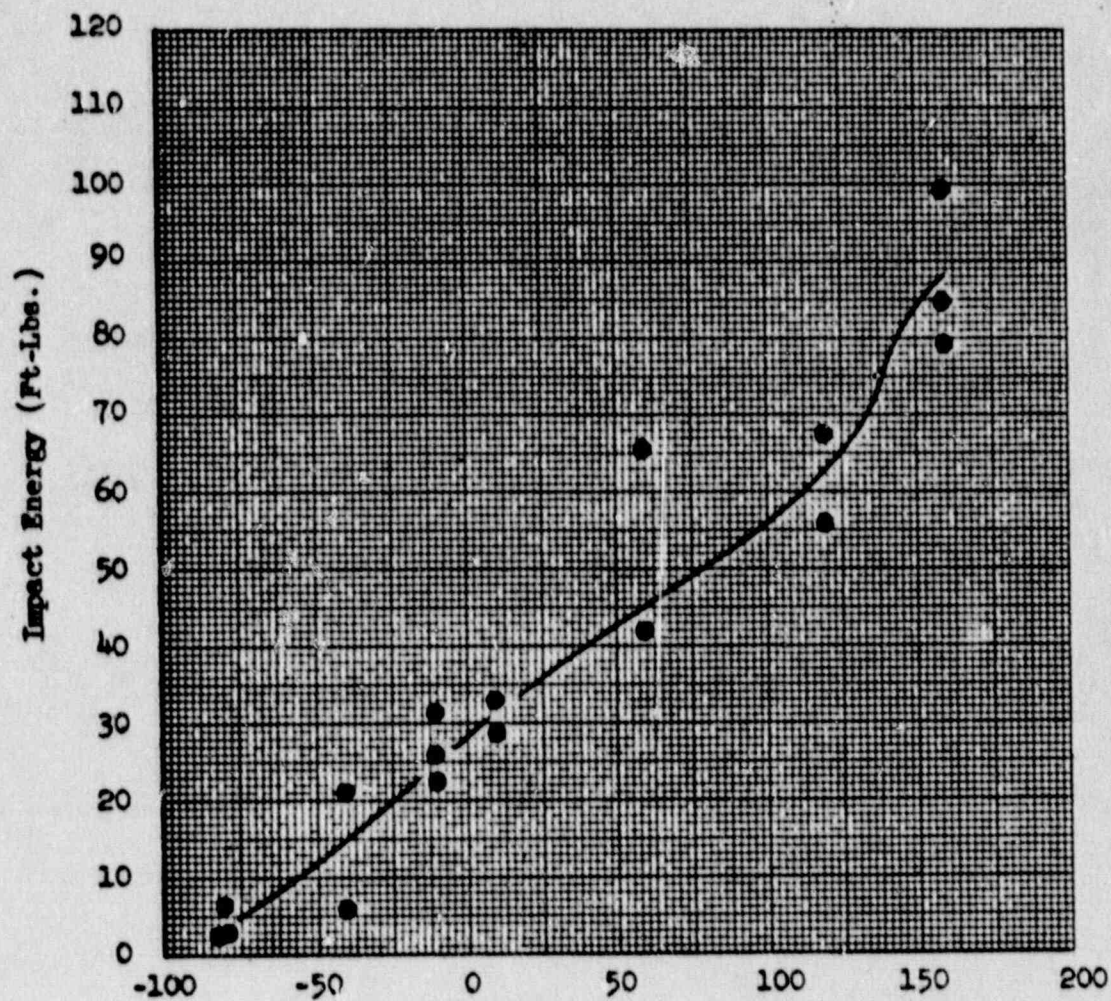


Figure 12 Pre-irradiation Charpy V-Notch Impact Properties of Connecticut Yankee Pressure Vessel Weld Heat Affected Zone Material



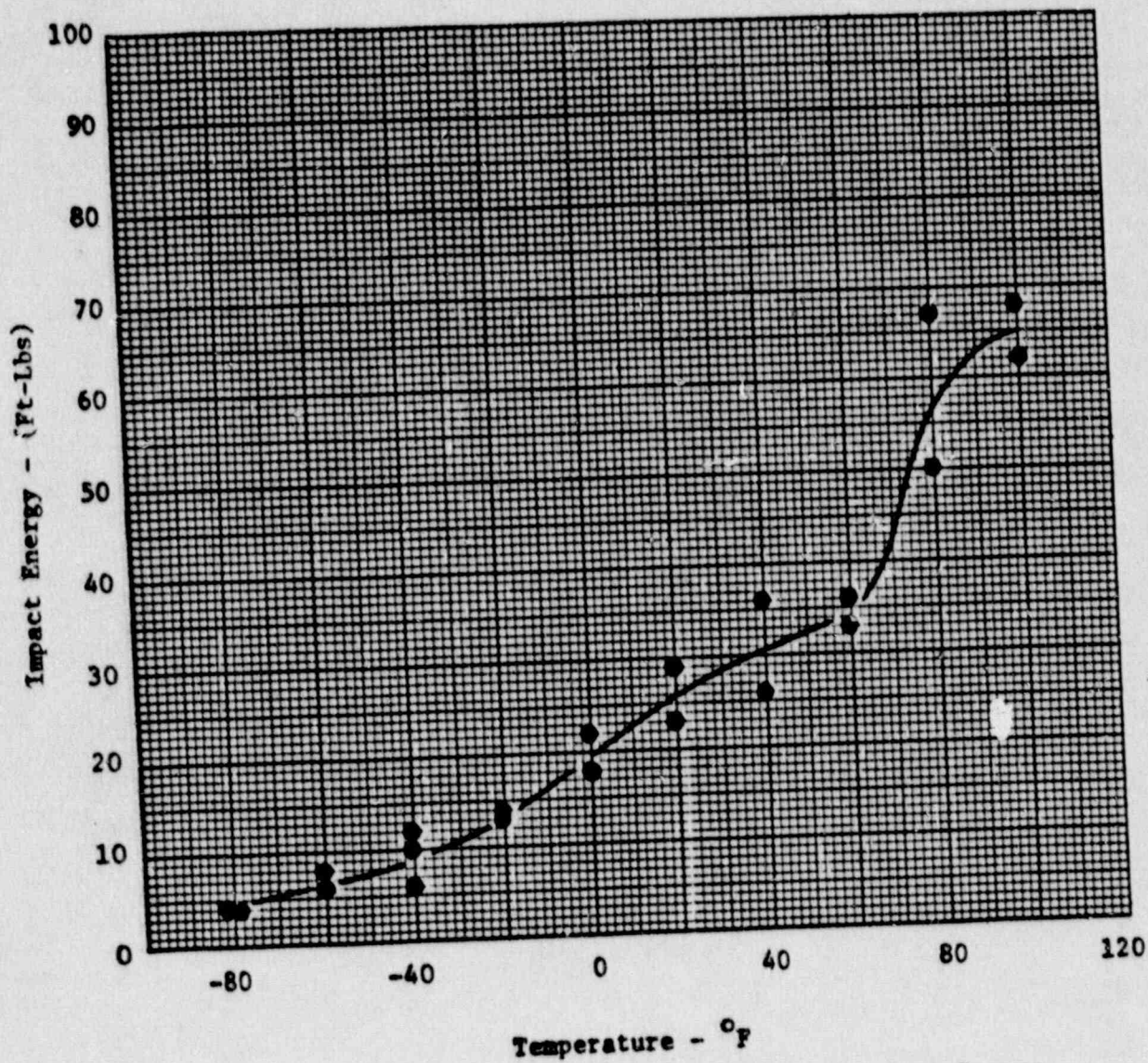


Figure 13 Pre-Irradiation Charpy V-Notch Impact Properties of U.S. Steel SA302B Correlation Monitor Material

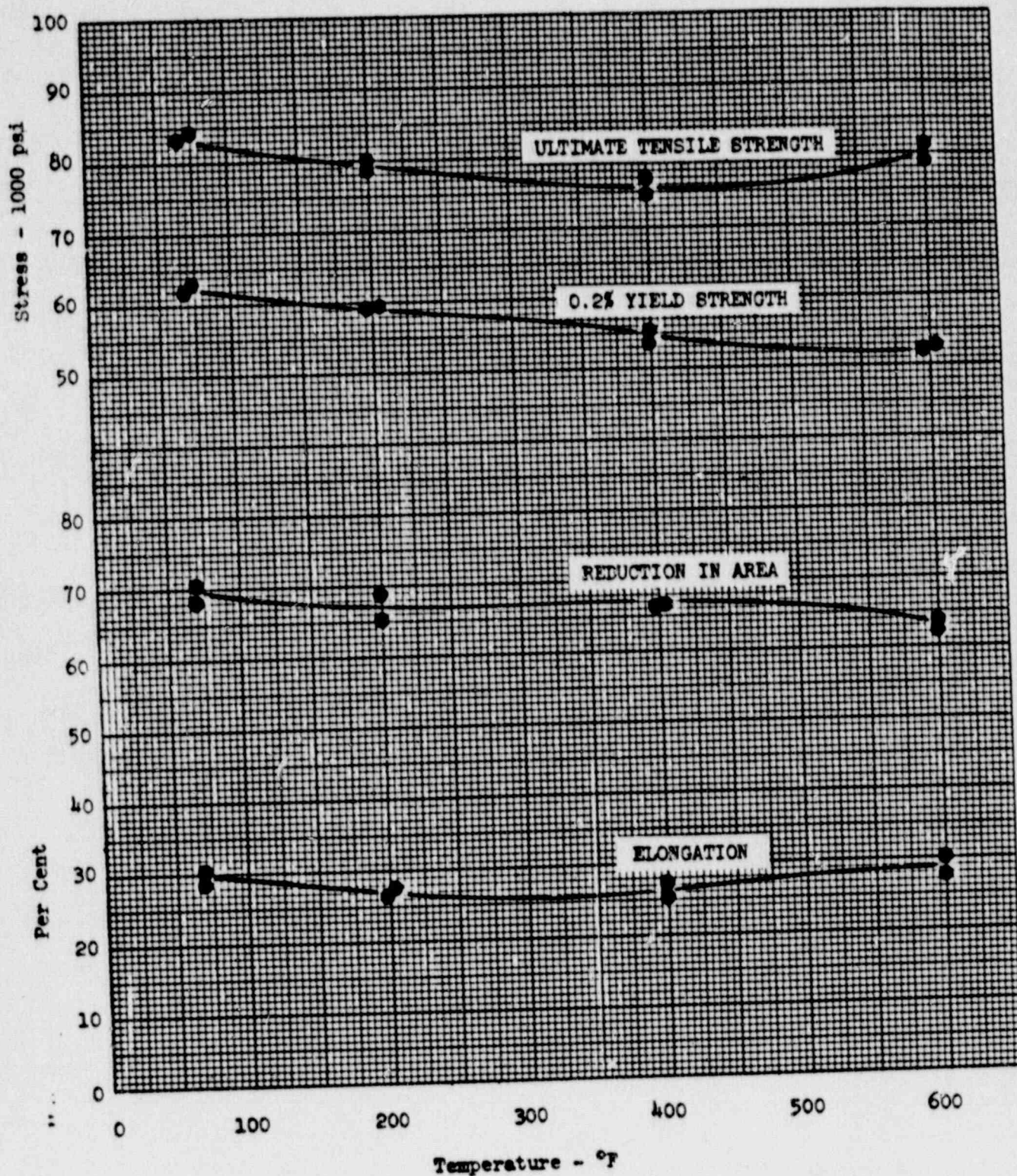


Figure 14 Pre-Irradiation Tensile Properties of Connecticut Yankee Pressure Vessel - Plate (W9807-2)



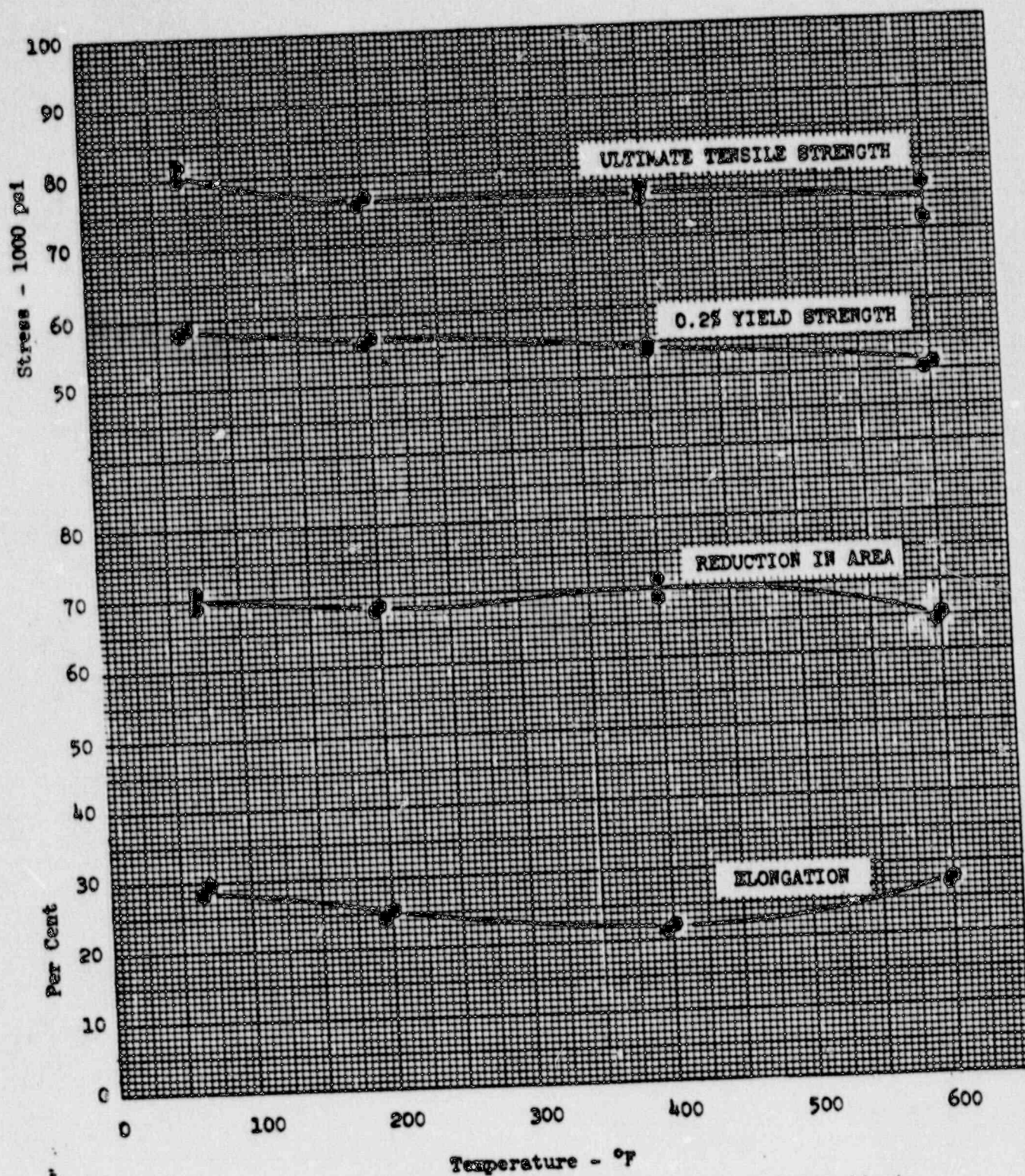


Figure 15 Pre-Irradiation Tensile Properties of Connecticut Yankee Pressure Vessel - Plate (W9807-4)



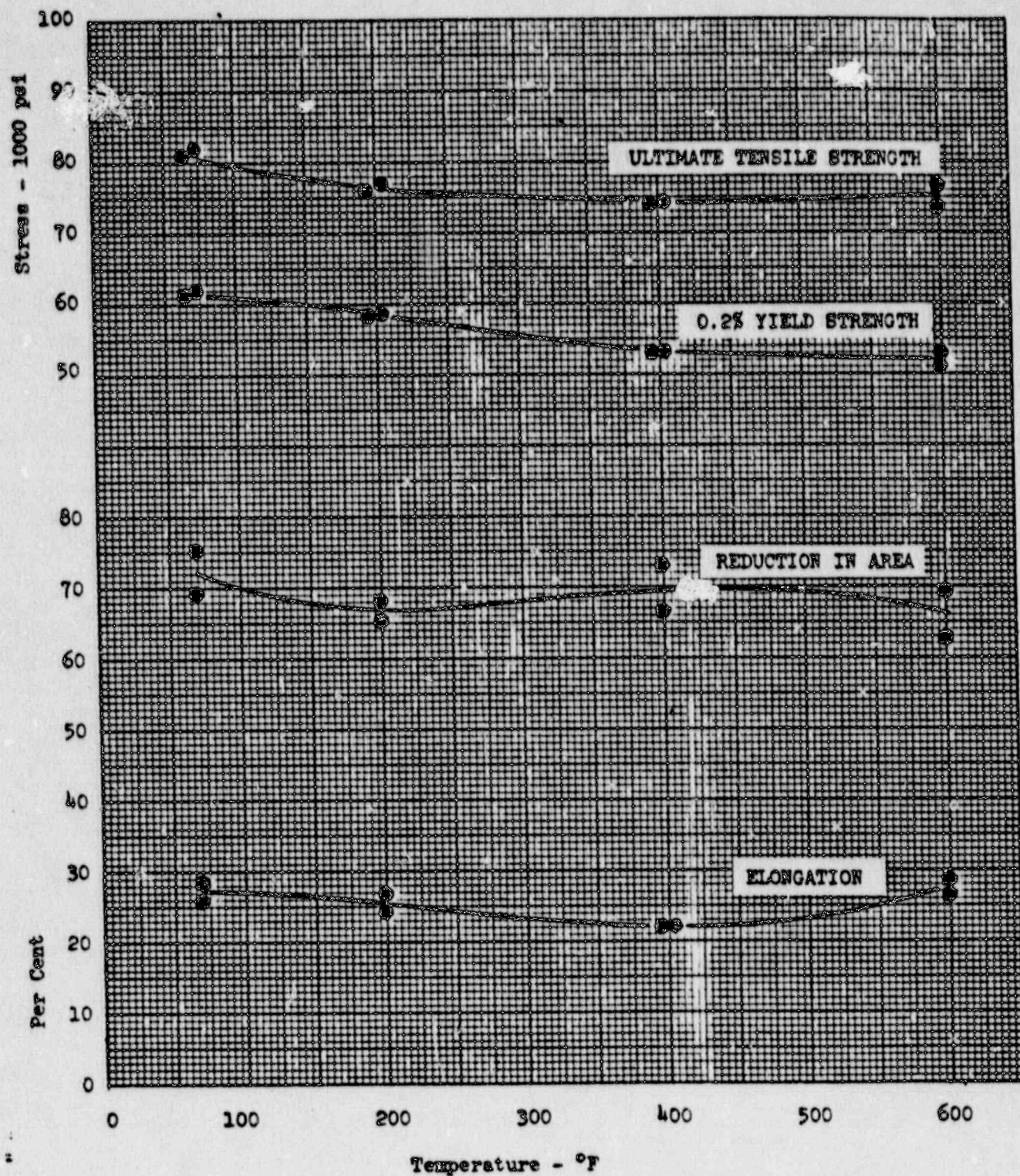


Figure . Pre-Irradiation Tensile Properties of Connecticut  
Yankee Pressure Vessel - Plate (W9807-7)

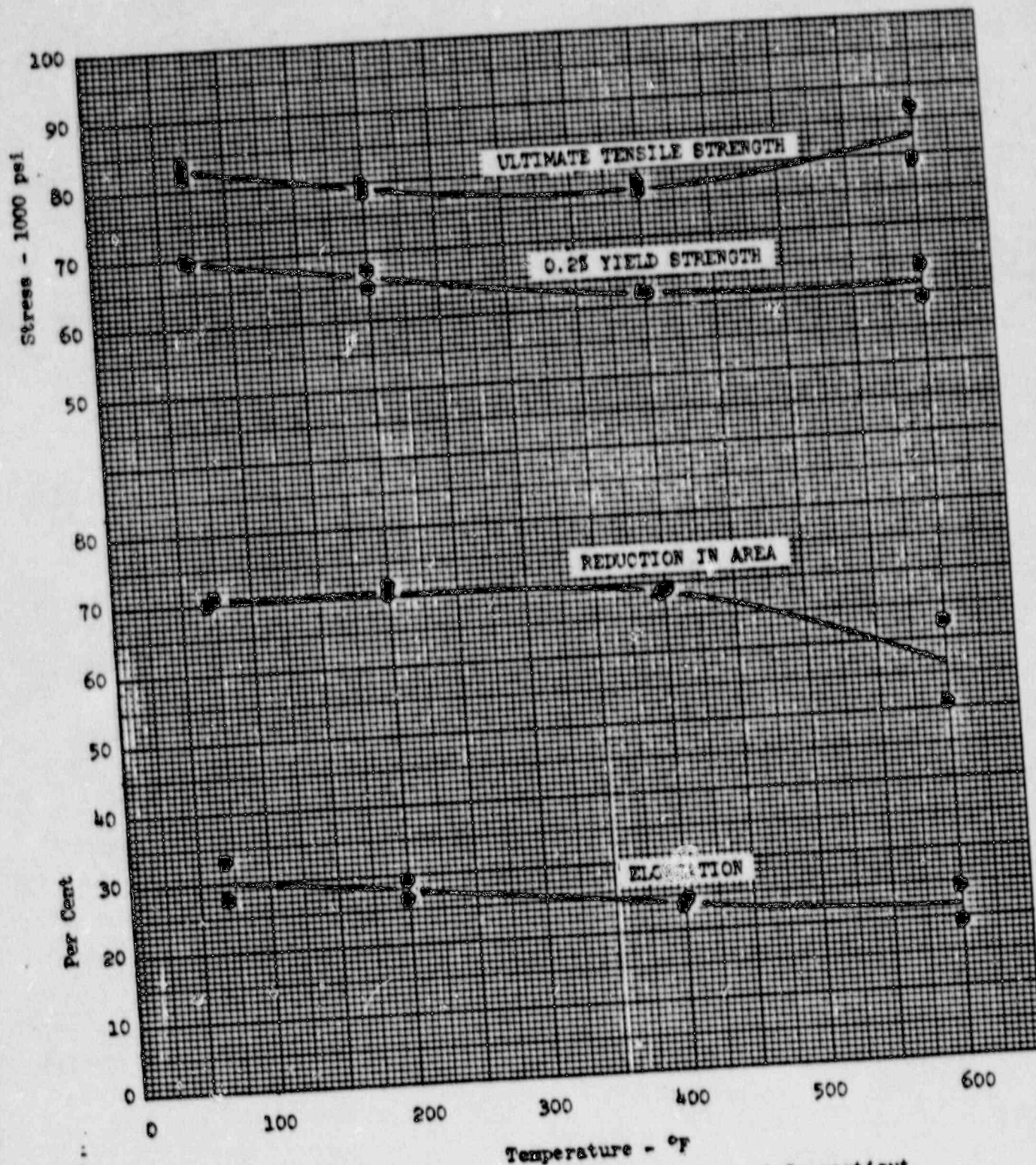
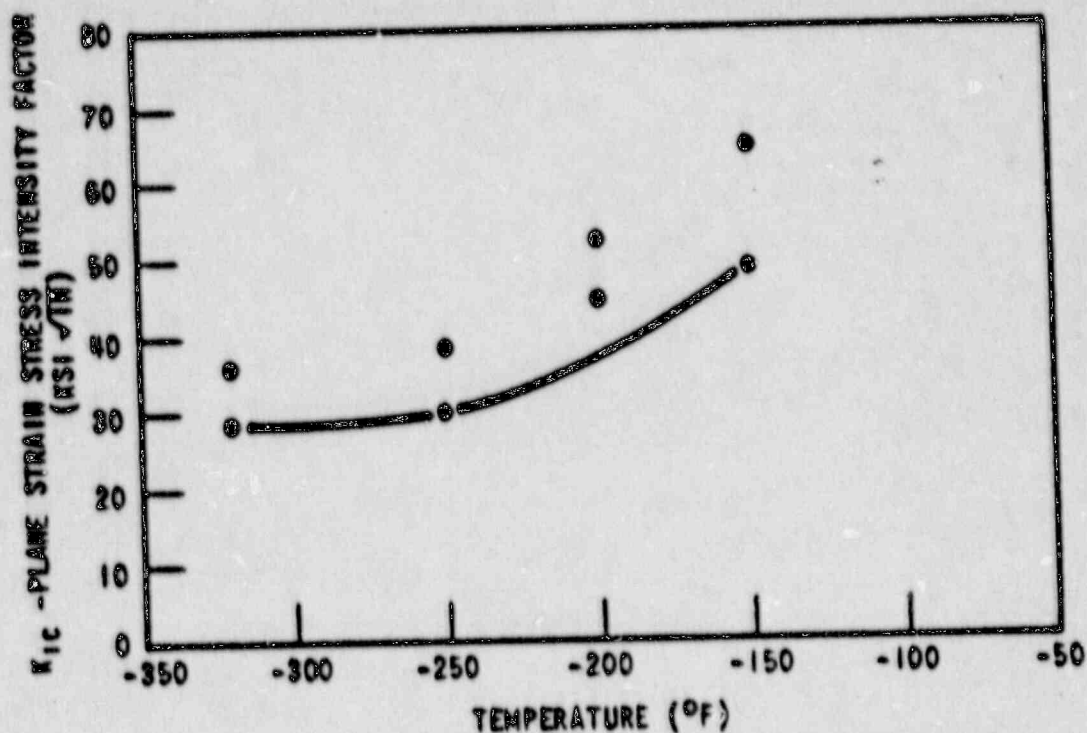


Figure " Pre-Irradiation Tensile Properties of Connecticut Yankee Pressure Vessel - Weld Metal





PRE-IRRADIATION FRACTURE TOUGHNESS OF  
CONNECTICUT YANKEE PRESSURE VESSEL  
PLATE (W9807-2)

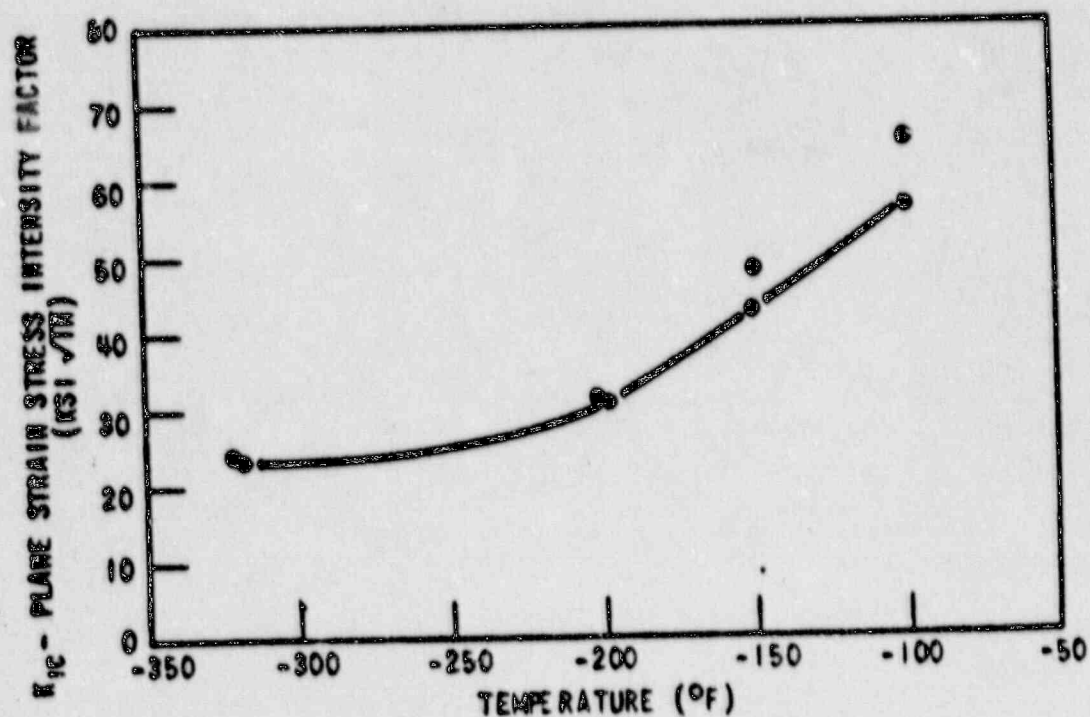


Figure 1:  
PRE-IRRADIATION FRACTURE TOUGHNESS OF  
CONNECTICUT YANKEE PRESSURE VESSEL  
PLATE (W9807-4)



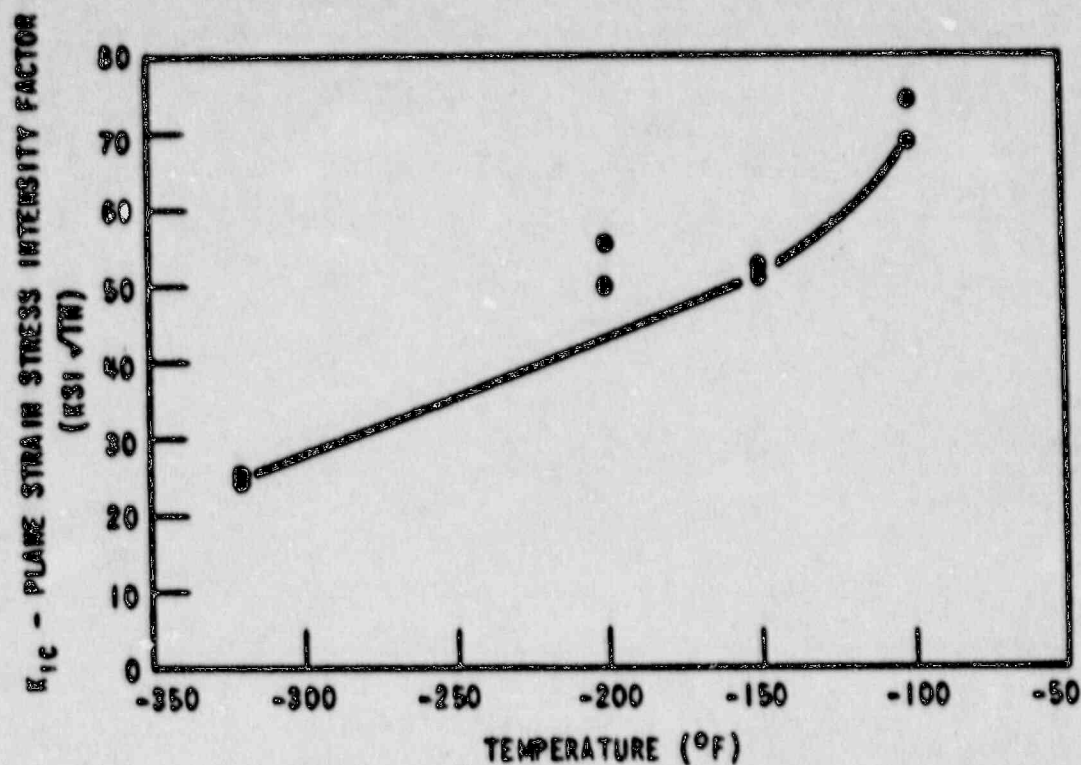


Figure 20

PRE-IRRADIATION FRACTURE TOUGHNESS OF  
CONNECTICUT YANKEE PRESSURE VESSEL  
PLATE (W9807-7)

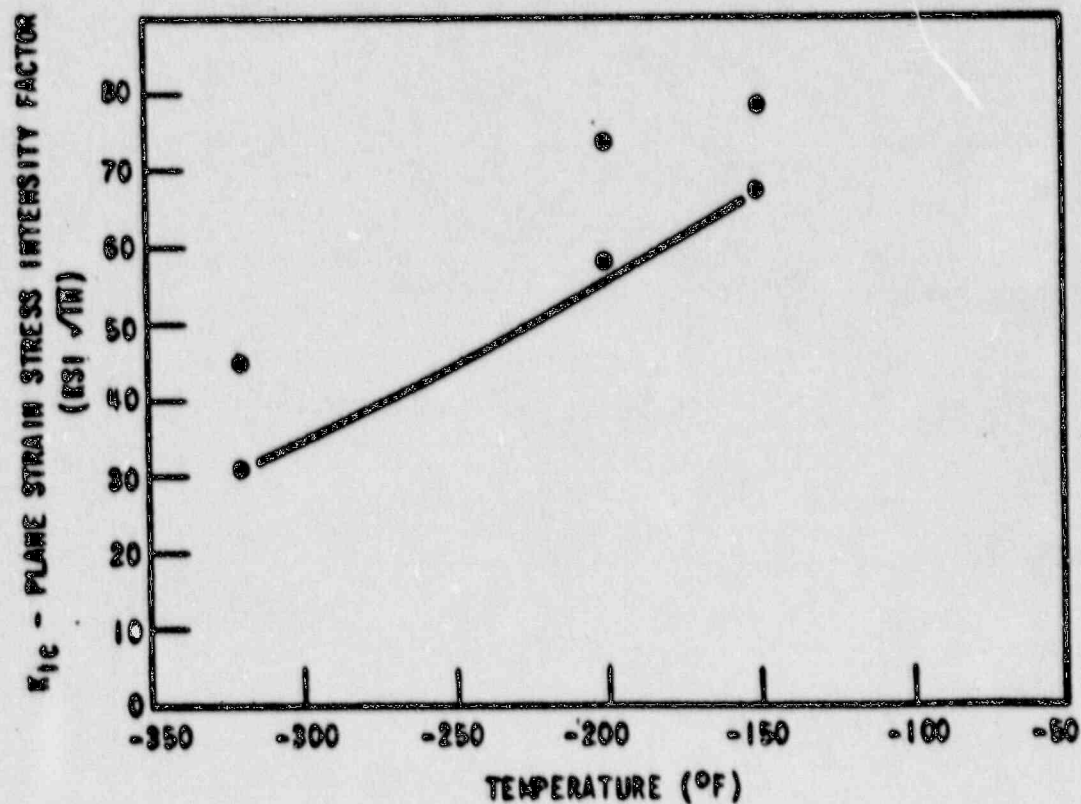


Figure 21

PRE-IRRADIATION FRACTURE TOUGHNESS OF  
CONNECTICUT YANKEE PRESSURE VESSEL  
WELD METAL

# ATTACHMENT 4

## CAPSULE REMOVAL HISTORY

<u>Capsule</u>	<u>Type</u>	<u>Date</u>	<u>EFY</u>	<u>fluence (n/cm<sup>2</sup>)</u>
A	II	April 1970	2	$2.07 \times 10^{18}$
F	I	April 1971	3	$4.04 \times 10^{18}$
H	I	October 1977	9	$1.79 \times 10^{19}$
D	II	September 1981	11	$2.22 \times 10^{19}$

## SCHEDULE FOR FUTURE REMOVAL

B	I	25
C	I	Standby
E	II	Standby
G	I	Standby

EXAMINATION AND EVALUATION OF CAPSULE A  
FOR THE CONNECTICUT YANKEE REACTOR  
PRESSURE-VESSEL SURVEILLANCE PROGRAM

by

D. R. Ireland and V. G. Scotti

SUMMARY

The irradiation conditions and the irradiation-induced changes in mechanical properties of the Connecticut Yankee reactor pressure vessel have been determined from evaluation of specimens contained in the first surveillance capsule to be removed after 1.9 equivalent full-power years of operation. The irradiation temperature was between 550 and 580 F.

The capsule obtained a fluence of  $2.07 \times 10^{18}$  nvt ( $> 1$  Mev), which is less, by more than a factor of five, than the predicted capsule exposure at the time of this first refueling. The projected first appreciable change in the mechanical properties of the reactor pressure-vessel wall will occur after approximately 5 full-power years of operation.

The measured changes in nil ductility transition temperature (NDTT) for base metal, weld metal, and HAZ metal were consistent with those observed for other surveillance programs involving similar materials and irradiation conditions. A relatively well-defined trend band for change in NDTT with increasing exposure to fast neutron damage was determined from the results of this program and those for the other programs. The upper-bound curve of this trend band indicates the projected 30-year (end of life) change in NDTT will be 145 F. Since this value is agreeably lower than the previously expected value of 260 F, consideration might be given to extension of the end-of-life period. The tensile and yield strengths of the base metal and weld metal increased as expected, but according to current design considerations these changes will not affect operating pressures. Modified pressure-temperature relationships, based on the projections from the  $\Delta$ NDTT results of this program, are presented.



EXAMINATION AND EVALUATION OF CAPSULE F  
FOR THE CONNECTICUT YANKEE REACTOR  
PRESSURE-VESSEL SURVEILLANCE PROGRAM

PART A. PRIMARY INVESTIGATION

by

J. S. Perrin, J. W. Sheckherd, and V. G. Scotti

SUMMARY

The irradiation conditions and the irradiation-induced changes in mechanical properties of the Connecticut Yankee reactor pressure vessel (SA 302 Grade B) have been determined from evaluation of specimens contained in the second surveillance capsule, which was removed after 2.6 equivalent full-power years of operation. The irradiation temperature was between approximately 550 and 590 F, and the capsule obtained a fluence of  $4.04 \times 10^{18}$  nvt ( $> 1$  Mev).

The measured changes in nil ductility transition temperature (NDTT) for the base-metal plates were consistent with those observed for other surveillance programs involving similar materials and irradiation conditions. A relatively well defined trend band for change in NDTT with increasing exposure to fast neutron damage was determined from the results of this program and those from the other programs. The upper-bound curve of this trend band indicates the projected 30-year (end of life) change in NDTT will be 225 F, which is in good agreement with the original predicted shift of 260 F. The yield and ultimate tensile strengths of the base metal increased as expected. The present investigation shows that the Connecticut Yankee pressure vessel base-metal plate mechanical properties are changing with irradiation in a manner in agreement with the changes expected when the pressure vessel was designed and constructed.

A considerable amount of supplementary data was obtained in this program. The results of these evaluations are presented in Part B of this report. This work included fracture-mechanics evaluations of base-metal WOL specimens, acoustic emission studies of the WOL specimens, and instrumented impact test evaluation of the Charpy specimens.

## SECTION 1

### SUMMARY OF RESULTS

The analysis of the reactor vessel material contained in surveillance capsule H from the Connecticut Yankee Power Plant reactor pressure vessel led to the following conclusions:

- The capsule received an average fast fluence of  $1.79 \times 10^{19}$  neutrons/cm<sup>2</sup> ( $E > 1$  Mev).
- The fast fluence of  $1.79 \times 10^{19}$  n/cm<sup>2</sup> ( $E > 1$  Mev) resulted in a 45°F increase in the 50 ft-lb reference nil-ductility transition temperature (RTNDT) of the intermediate pressure vessel shell plate W9807-2. Plate W9807-4 exhibited a 67°F shift in the 50 ft-lb nil-ductility transition temperature while plate W9807-7 exhibited a shift of 51°F.
- The transition temperature (30 ft-lb) increases for the plate material are essentially the same as those obtained for the second capsule irradiated at  $4.04 \times 10^{18}$  neutrons/cm<sup>2</sup>.
- Supplemental tests, performed on weld metal identical to that used to fabricate the intermediate to lower shell circumferential weld, showed an increase in the 50 ft-lb reference nil ductility transition temperature of 140°F after receiving an average fast fluence of  $1.40 \times 10^{19}$  n/cm<sup>2</sup>. Tests performed on the surveillance weld metal after irradiation in a test reactor to  $3.0 \times 10^{19}$  n/cm<sup>2</sup> resulted in a 160°F increase. The irradiated upper shelf energy of the two welds was approximately 85 ft-lb showing an average decrease of 20 ft-lb.
- The irradiated properties of the plate and the weld metal are acceptable to provide for continued safe operation of the Connecticut Yankee Power Plant.

## **SECTION 1**

### **SUMMARY OF RESULTS**

The analysis of the reactor vessel material contained in the fourth reactor vessel material surveillance capsule which was removed from the Connecticut Yankee reactor pressure vessel after approximately 10.5 effective full power years of operation led to the following conclusions:

- The capsule received an average fast neutron fluence ( $E > 1 \text{ Mev}$ ) of  $2.22 \times 10^{19} \text{ n/cm}^2$  compared to a calculated fluence of  $2.39 \times 10^{19} \text{ n/cm}^2$ .
- Irradiation of base metal plate material to  $2.22 \times 10^{19} \text{ n/cm}^2$  resulted in a  $43^\circ \text{C}$  increase in the 41-Joule transition temperature when compared with unirradiated values. This transition temperature increase, when compared with increases of  $44$  and  $37^\circ \text{C}$  obtained for earlier capsules irradiated to  $0.471$  and  $1.58 \times 10^{19} \text{ n/cm}^2$  respectively indicates that the base material is experiencing a saturation of radiation damage.
- Reactor vessel submerged arc weld metal irradiated to  $2.22 \times 10^{19} \text{ n/cm}^2$  showed a 41-Joule transition temperature increase of  $61^\circ \text{C}$  which was only  $8^\circ \text{C}$  higher than the increase obtained on weld metal irradiated at  $0.239 \times 10^{19} \text{ n/cm}^2$ . The small transition temperature increase for these two irradiation fluence levels indicate that saturation of radiation damage is occurring for the weld metal.
- Comparisons of the 41-Joule transition temperature increases for the Connecticut Yankee materials with Regulatory Guide 1.99 Revision 1 predictions show that the increases after irradiation to  $2.22 \times 10^{19} \text{ n/cm}^2$  are significantly less than predicted.
- End-of-life projected maximum fast neutron fluences for the reactor vessel based on 27 effective full power years of operation at 1825 MWt are as follows:



<u>Vessel Location</u>	<u>Fast Neutron Fluence (n/cm<sup>2</sup>)</u>	
	<u>Calculated</u>	<u>Measured</u>
Inner Surface	$6.3 \times 10^{19}$	$5.9 \times 10^{19}$
1/4 Thickness	$2.9 \times 10^{19}$	$2.7 \times 10^{19}$
3/4 Thickness	$4.1 \times 10^{19}$	$3.8 \times 10^{19}$

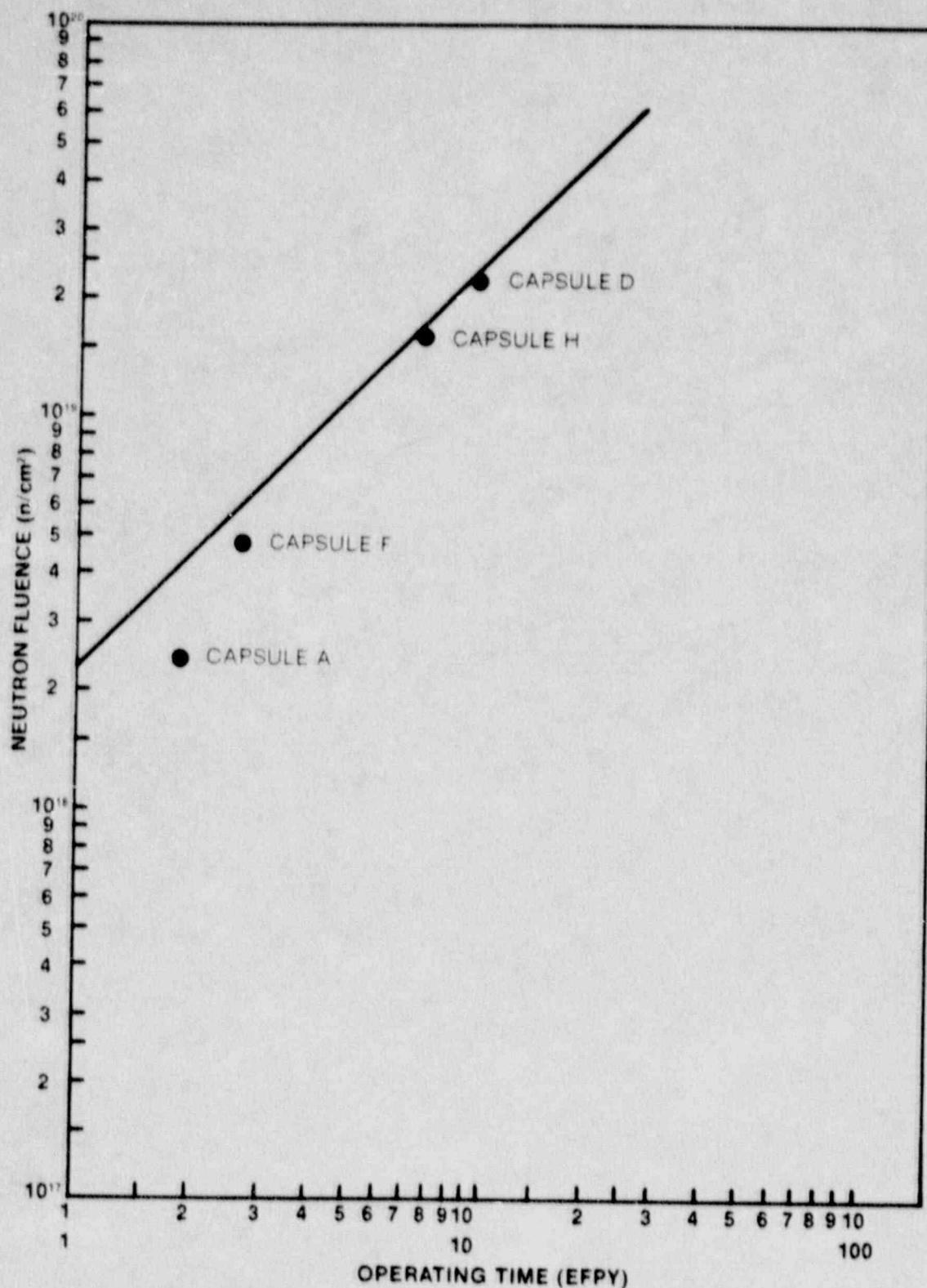


Figure 6-8. Comparison of measured and calculated Fast Neutron Fluence ( $E > 1.0$  Mev) within the surveillance capsules.

ATTACHMENT 5



## HADDAM NECK PLANT

TABLE A

ART VALUES (°F)

LOCATION	CHEMICAL Vt. % Cu	CONTENT Vt. % Ni	INITIAL RT/ BDT	MARGIN	f-FLUENCE (E> 1 MeV) $10^{19}$ n/cm <sup>2</sup>		SURFACE ART		SURFACE ART EXP. DATE
					@22 EFPT	@32 EFPT	@22 EFPT	@32 EFPT	
Nozzle Course V9807-6	0.11	0.20	34	34	1.664	2.42	138.70	144.76	
Intermed. Course V9807-7	0.12	0.20	-3	34	5.21	7.58	125.49	129.83	
Lower Course V9807-3	0.12	0.20	20	34	2.6	3.78	138.15	144.04	
V9807-5	0.15	0.20	10	34	2.6	3.78	144.48	151.51	
Weld (Longitud- inal)	0.22	0.10	-56	56	4.3	6.26	143.34	150.91	

ATTACHMENT 6

CALCULATION OF FLUENCE @ 32 EFPY W/O THERMAL SHIELD

LOCATION	(X10 <sup>19</sup> ) FLUENCE @ 16 EFPY	+	(X10 <sup>19</sup> ) FLUENCE FOR NEXT 16 EFPY *	=	(X10 <sup>19</sup> ) FLUENCE @ 32 EFPY
W9807-6	1.210		3.994		5.204
W9807-7	3.789		12.50		16.29
W9807-3	1.891		6.242		8.133
W9807-5	1.891		6.242		8.133
Weld	3.127		10.32		1.344

- \* 1. Fluence values are increased by a factor of three to conservatively account for impact of thermal shield removal per (W) recommendation.
2. Fluence values are also increased by 10% to conservatively account for impact of zircaloy clad core per B&W analysis, by S. Q. King, dated December 22, 1989.



ATTACHMENT 7

CONNECTICUT YANKEE  
PROJECTED ART VALUES ( $^{\circ}\text{F}$ ) @ 32 EFPY  
WITH THERMAL SHIELD REMOVED

LOCATION	CHEMICAL CONTENT		INITIAL RT/ NDT	MARGIN	(1) f=FLUENCE ( $E \geq 1 \text{ MeV}$ ) $10^{19} \text{ n/cm}^2$			SURFACE ART @32 EFPY	1/4 T ART @32 EFPY	3/4 T ART @32 EFPY
	Wt.% Cu	Wt.% Ni			SURFACE	1/4 T	3/4 T			
Nozzle Course W9807-6	0.11	0.20	34	34	5.20	2.70	0.728	155.42	146.43	124.48
Intermed. Course W9807-7	0.12	0.20	-3	34	16.3	8.48	2.28	135.39	130.96	112.94
Lower Course W9807-3	0.12	0.20	20	34	8.13	4.23	1.14	153.56	145.66	123.41
W9807-5	0.15	0.20	10	34	8.13	4.23	1.14	162.88	153.44	126.88
Weld (Longitud- inal)	0.22	0.10	-56	56	13.4	6.97	1.88	161.35	152.78	122.58

(1) Calculated via  $f=f_0 (e^{-0.24x})$ , where  $x$  = wall thickness

@ CY,  $x = 10.78125$ ,  $1/4T = 2.7$