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Plan for Evaluation of Reactor Pressure Vessel Surveillance Materials from Palisades Nuclear Generating Station

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February 2020

OAK RIDGE NATIONAL LABORATORY
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ORNL/TM-2020/1444

Light Water Reactor Sustainability Program

Performance Milestone Report: M2LW-20OR0402016

PLAN FOR EVALUATION OF REACTOR PRESSURE VESSEL SURVEILLANCE MATERIALS FROM PALISADES NUCLEAR GENERATING STATION

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ABBREVIATED TERMS

APT	atom probe tomography
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATR	Advanced Test Reactor
CVN	Charpy V-Notch
EFPD	effective full-power day
EFPY	effective full-power year
EOC	end of cycle
EOL	end of license
FY	fiscal year
HAZ	heat-affected zone
HSST	Heavy-Section Steel Technology
LAMDA	Low Activation Materials Development and Analysis
LWR	light-water reactor
LWRS	Light Water Reactor Sustainability
NDT	nil-ductility transition
PNGS	Palisades Nuclear Generating Station
PWR	pressurized water reactor
RPV	reactor pressure vessel
SANS	small-angle neutron scattering
SAXS	small-angle x-ray scattering
SRM	standard reference material
TEM	transmission electron microscopy
USE	upper shelf energy

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EXECUTIVE SUMMARY

The Palisades Nuclear Generating Station (PNGS), located in Michigan, is owned and operated by Entergy. It is a Combustion Engineering 2-loop pressurized water reactor (PWR) producing 805 MWe (2,565 MWth). The PNGS was built between 1967 and 1970, with approval to operate at full power in 1973; the plant's original license was due to expire on March 24, 2011. An application for 20-year extension was filed in 2005 with the Nuclear Regulatory Commission and was granted on January 18, 2007. Although the plant was scheduled for decommissioning by 2031, Entergy currently plans to close the PNGS in 2022. The PNGS included in its reactor pressure vessel (RPV) surveillance program a capsule, designated A-60, containing specimens of one of the vessel plates and a weld metal with nickel content of about 1.36 wt % and copper content of about 0.20 wt %. This capsule was irradiated to a fluence of 1.8×10^{20} n/cm^2. The capsule was removed from its surveillance position in 1995 and has been resident in the spent fuel pool since that time. The material is also of special interest because of its very high nickel content and because of the potential for development of NiMnSi (nickel-manganese-silicon) precipitates, dubbed "late blooming phases." The surveillance program also includes a capsule, designated T-150, dedicated specifically for thermal aging, which would provide results for at least 33 effective full power years, which is beyond the current thermal-aging database for such materials. Given that license extensions to 60 years of operation have been approved by the US Nuclear Regulatory Commission for most of the currently operating light water reactors in the United States, and that the first extension to 80 years was recently approved, there exists the probability that some RPVs will reach and possibly exceed a fast neutron fluence (> 1 MeV) of 1×10^{20} n/cm^2. This is a fluence regime with no US surveillance data and very little test reactor data, except for the Light Water Reactor Sustainability Program–sponsored University of California Santa Barbara Advanced Test Reactor (ATR) ATR-2 project. Thus, the materials in the A-60 capsule represent a valuable resource for directly exploring the effects of commercial surveillance irradiation on a typical plate and a high-nickel weld with similar materials irradiated in the ATR-2 test reactor project. This report provides background information for the surveillance program, previous results of surveillance materials testing, the preliminary plan for capsule retrieval and disassembly, and the plan for testing and microstructural examination of the mechanical test specimens of these unique materials to assess the features induced by very high irradiation fluence or very long thermal aging time.

1. INTRODUCTION

The Palisades Nuclear Generating Station (PNGS) is located on Lake Michigan, in Van Buren County's Covert Township, Michigan, on a 432-acre (175 ha) site 5 miles (8.0 km) south of South Haven, Michigan, USA. Palisades is currently owned and operated by Entergy. It is a Combustion Engineering 2-loop pressurized water reactor (PWR) producing 805 MWe (2,565 MWth) with a reactor pressure vessel (RPV) that weighs 425 tons and has steel walls 220 mm (8½ in.) thick. The PNGS was built between 1967 and 1970 and was granted approval to operate at full power in 1973 [1, 2]. The plant's original license was due to expire on March 24, 2011. An application for a 20-year extension was filed in 2005 with the Nuclear Regulatory Commission. It was granted on January 18, 2007, so the plant was then scheduled for decommissioning by 2031 [3, 4]. However, current information is that Entergy plans to close the PNGS in 2022 [5], although there is a possibility that it will operate longer.

The PNGS included in its surveillance program a surveillance capsule, designated A-60, containing specimens of a weld metal with nickel content of about 1.36 wt % and copper content of about 0.20 wt %. This capsule was irradiated to a fluence of 1.8×10^{20} n/cm^2. The capsule was removed from its surveillance position in 1995 and has been resident in the spent fuel pool since that time. The material is also of special interest because of its very high nickel content and because of the potential for development of NiMnSi (nickel-manganese-silicon) precipitates, dubbed "late blooming phases" [6, 7]. The surveillance program also includes a capsule, designated T-150, dedicated specifically for thermal aging. The plan for this task is to retrieve and disassemble the two capsules, test the mechanical test specimens, and examine some of the capsule materials microstructurally to assess the irradiation-induced features associated with these unique materials and conditions (very high fluence and very long thermal aging time).

2. BACKGROUND OF PALISADES SURVEILLANCE PROGRAM

Combustion Engineering, Inc., the PNGS designer, developed the RPV surveillance program and designed and supplied the surveillance capsules and specimens [8]. The program and materials were designed in accordance with ASTM Standard E 185-66, *Recommended Practice for Surveillance Tests on Structural Materials in Nuclear Reactors* [9]. The original program included ten capsules to monitor the effects of both neutron and thermal environments on the beltline materials of the RPV [8]. Six capsules were located at the beltline near the inside surface of the RPV; two capsules intended for accelerated neutron exposure (A-240 and A-60) were located on the outer wall of the core support barrel, thus, closer to the core. The remaining two capsules were located in a very low flux region above the core for monitoring the effects of thermal exposure (thus, designated thermal aging capsules). Figure 1 shows a schematic diagram of the capsule locations [10]. All ten capsules contained Charpy V-Notch (CVN) impact and tensile specimens of the surveillance base metal, weld metal, heat-affected-zone (HAZ), and standard reference materials. In addition to those ten capsules, two additional capsules, designated supplemental surveillance capsules, were produced and included three additional weld metal specimens representative of the three welds in the beltline region of the PNGS RPV. The two supplemental capsules were inserted into the reactor following cycle 11 in locations near the outer wall of the core support barrel for accelerated exposure; SA-60-1 was withdrawn at the end of cycle 13 [11]; SA-240-1 was withdrawn at the end of cycle 14 [12]. A statement from the PNGS Design Basis Document, DBD-2.10, Revision 4, explains the very high neutron fluence for the A-60 capsule: "The capsule in A-60 was found to have a broken extraction screw and it could not be removed until a later outage. By that time the accelerated fluence was many times the EOL fluence, and the capsule data were considered to be of no value."[1]

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[1] Excerpt from DBD-2.10, Revision 4 from Wes Stinson of PNGS to Randy Nanstad of ORNL, 01-28-2020.

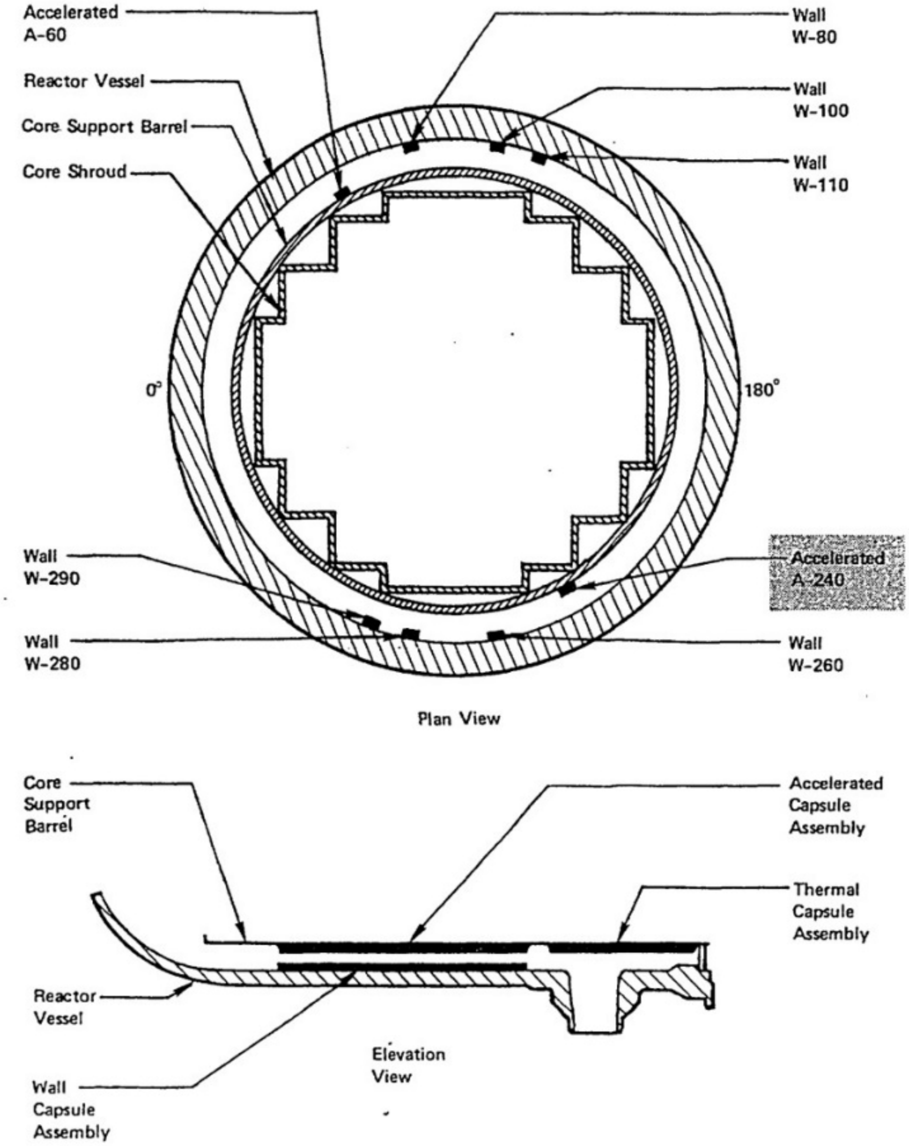

Figure 1. Arrangement of surveillance capsules in the PNGS reactor vessel [10].

The ten original capsules contain specimens made from (1) intermediate shell course plate D-3803-1 (Heat C1279-3), (2) HAZ material fabricated by welding intermediate shell plates D-3803-2 (Heat A0313-2) and D-3803-3 (Heat C1279-1) with a submerged-arc process using Linde 1092 flux, and (3) weld metal fabricated by welding intermediate shell plates D-3803-1 and D-3803-2 with a submerged arc process using Linde 1092 flux and with both a MIL-B4 electrode and a 1/16 in. diameter Nickel-200 wire feed (Heat 3277).[2] The materials and chemical compositions are shown in Table 1. For the PNGS surveillance program, the standard reference material (SRM) (also designated a correlation monitor material) is Heavy-Section Steel Technology (HSST) Plate 01; section MY of HSST Plate 01 was used for fabrication of the SRM CVN specimens. Each capsule assembly is comprised of four Charpy impact

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[2] This weld wire is representative of the three welds in the actual RPV beltline, but the heat number is not the same as any of the three.

specimen compartments and three compartments for tensile specimens and flux/temperature monitors [8]. Figure 2 shows a schematic diagram of a typical surveillance capsule assembly [10].

Table 1. Chemical compositions (wt %) of the PNGS reactor surveillance materials* [8].

Element**	**Plate for base metal surveillance specimens Heat C1279-3**	**Used to fabricate surveillance weld and HAZ, Heat A0313-2**	**Used to fabricate surveillance HAZ, Heat C1279-1**	**Weld fabricated for machining surveillance HAZ specimens**		**Weld fabricated for machining weld metal surveillance specimens Heat 3277**	
	Plate D-3803-1	**Plate D-3803-2**	**Plate D-3803-3**	**Weld D-3803-3/ D-3803-2 Root**	**Weld D-3803-3/ D-3803-2 Face**	**Weld D-3803-2/ D-3803-2 Root**	**Weld D-3803-2/ D-3803-1 Face**
Si	**0.23**	**0.32**	**0.24**	**0.24**	**0.25**	**0.25**	**0.22**
S	0.019	0.021	0.020	0.009	0.010	0.010	0.010
P	**0.011**	**0.12**	**0.010**	**0.011**	**0.012**	**0.011**	**0.011**
Mn	**1.55**	**1.43**	**1.56**	**1.08**	**1.03**	**1.01**	**1.02**
C	0.22	0.23	0.21	0.098	0.080	0.088	0.086
Cr	0.13	0.42	0.13	0.05	0.04	0.05	0.03
Ni	**0.53**	**0.55**	**0.53**	**0.43**	**1.28**	**0.63**	**1.27**
Mo	0.58	0.58	0.59	0.54	0.53	0.55	0.52
Al(T)	0.037	0.022	0.037	Nil	Nil	Nil	Nil
V	0.003	0.003	0.003	Nil	Nil	Nil	Nil
Cu	**0.25**	**0.25**	**0.25**	**0.25**	**0.20**	**0.26**	**0.22**

*Note: All three plates showed a drop-weight nil-ductility transition (NDT) temperature of –30°F (–34°C), but D-3803-1 plate was selected for the base metal surveillance material because it had the highest 41-J transition temperature, ~13°F (–11°C), in the as-received condition. The other two plates were used to fabricate weldments used for machining weld metal (with Plates D-3803-1 and D-3803-2) and heat-affected-zone specimens (with Plates D-3803-2 and D-3803-3) for the surveillance program. The face welds were made with a submerged arc process, using a MIL-B4 electrode and Linde 1092 flux, and with a 1/16 in. Nickel 200 additive [8].

** Element symbols and composition values in bold font are for the major elements that cause radiation-induced embrittlement.

Prior to being machined into surveillance specimens, the surveillance plate material was given 1.75 h of interstage and 30 h of final heat treatment at 1,150 ± 25°F (621 ± 14°C). As described in references [8] and [13], both longitudinal and transverse CVN specimens were fabricated from the base metal, whereas tensile specimens were fabricated only in the longitudinal orientation. Longitudinal specimens were oriented with the major axis of the specimen parallel to the principal rolling direction of the plate and parallel to the surface of the plate. The CVN base metal specimens in the transverse orientation were oriented with the major axis of the specimen perpendicular to the principal rolling direction and parallel to the surface of the plate. All base metal CVN and tensile specimens were machined such that one long surface was at the ¼ thickness depth from the plate surface and with the other long surface either closer to the plate surface or closer to the mid-thickness of the plate. Appendix A [8] provides drawings showing removal locations for test specimens.

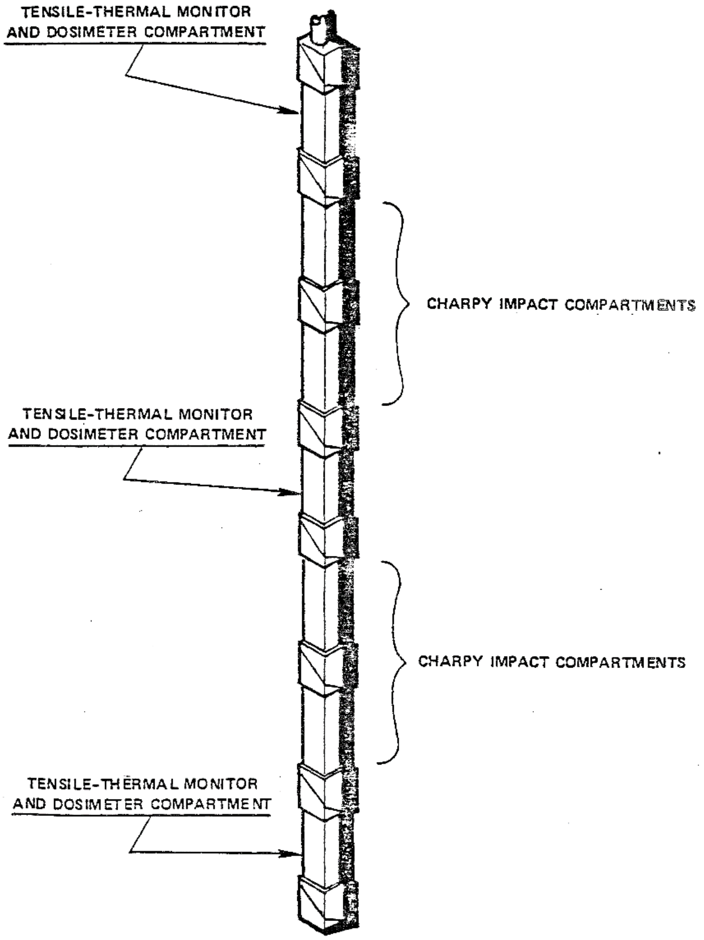


Figure 2. Schematic diagram of a typical surveillance capsule for the PNGS RPV [10].

Longitudinal weld metal CVN and tensile specimens were oriented with the major axis of the specimen parallel to the direction of the weld and parallel to the surface of the weld. Weld metal CVN and tensile specimens were machined from the regions of the weld at least 1.25 in. from the plate surface and without any part of the specimen being in the weld root region. Specimens from the HAZ were oriented with the major axis of the specimen perpendicular to the direction of the weld and parallel to the surface of the weld. For the SRM, longitudinal CVN specimens were machined, but no tensile specimens were machined.

The axis of the notch of all base metal and weld metal Charpy impact specimens was perpendicular to the surface of the plate or weld. The axis of the notch of all HAZ Charpy impact specimens was parallel to the surface of the plate. Thus, in current practice, base metal CVN specimens were fabricated in both the T-L and L-T orientations, while HAZ CVN specimens were fabricated in the T-L orientation. Drawings for the CVN and tensile specimens are provided in Appendix B [8]. Of the ten original capsules, six have been pulled and tested as shown in Table 2, four remain in the vessel, and one is stored in the spent fuel pool:

- Four irradiated capsules, W290, W110, W100, A240, were pulled and tested at fluences of 0.94, 1.64, 2.09, and 4.09 × 10^{19} n/cm^2, respectively [14]. The estimated time-weighted temperatures for those four capsules are 531, 533, 534, and 526°F (277, 278, 279, 274°C), respectively [10]. The fast neutron flux for capsule W100 is given at 3.935 × 10^{10} n/cm^2/s [14]. It is also notable that the variability in flux over the length of the capsule is less than 10% [11]. Capsules SA60-1 [11] and SA-240-1 [12] with three other welds (heats W5214, 34B009, 27204), were also pulled and tested.

- One thermal capsule (T-330) was pulled and tested at 4.975 effective full-power years (EFPY). It was noted in reference [15] that a fast neutron flux analysis of a tested specimen from this thermal capsule indicated a fast flux of six orders of magnitude less than that of an analyzed irradiated capsule, meaning a flux of about 10^5 n/cm^2/s. Such a flux for 33 EFPY would result in a fast fluence less than 1×10^{14} n/cm^2.
- Three irradiated surveillance capsules (W-80, W-280, and W-260) are currently inside the RPV with accumulated fast fluence of about 3×10^{19} n/cm^2.
- One irradiated surveillance capsule (A-60) with fast fluence of 1.87×10^{20} n/cm^2 (>1 MeV) is stored in the spent fuel pool (since June 1995).
- One thermal aging capsule (T-150) with aging time of 46 years (286,100 h = 32.7 EFPY) at ~533°F (279°C) is inside the RPV but above the core, so it is being exposed to extremely low irradiation as was the previously tested thermal capsule T-330.

Table 2. Irradiation information for the PNGS RPV surveillance capsules removed from the reactor (T after capsule name indicates specimens tested).

Capsule	Inserted*	Removed**	Irrad Time, s	Flux, n/cm^2/s	Fluence, n/cm^2	Displacement data	
						dpa/s	dpa
W290 T	12-31-1971	08-12-1983 EOC 5	1.642×10^8	5.74×10^{10}	0.94×10^{19}	8.17×10^{-11}	0.0134
W110 T	12-31-1971	06-05-1993 EOC 10	3.138×10^8	5.23×10^{10}	1.64×10^{19}	7.65×10^{-11}	0.0240
W100 T	12-31-1971	03-16-2003 EOC 16	5.344×10^8	3.935×10^{10}	2.09×10^{19}	5.66×10^{-11}	0.0302
A240 T	12-31-1971	01-06-1978 EOC 2	7.156×10^7	5.72×10^{11}	4.09×10^{19}	8.15×10^{-10}	0.0583
A60***	12-31-1971	05-22-1995 EOC 11	3.15×10^8	5.72×10^{11}	1.87×10^{20}	8.15×10^{-10}	0.2566
SA60-1 T***	08-21-1995	04-25-1998 EOC 13	6.64×10^7 Cycles 12 &13	2.26×10^{11}	1.50×10^{19}	3.26×10^{-10}	0.0216
SA240-1 T***	08-21-1995	10-15-1999 EOC 14	1.09×10^8 Cycles 12–14	2.18×10^{11}	2.38×10^{19}	3.03×10^{-10}	0.0330

*The reactor did not begin full power operation until 1973.
**EOC: End of cycle.
*** Flux for A60 assumed same as A240, fluence provided by PNGS, other values calculated.

All remaining capsules include CVN and tensile specimens of a high-copper/high-nickel weld and a high-copper/average-nickel plate, and CVN specimens of a weld HAZ and a correlation monitor plate with medium copper/medium nickel. The two supplemental accelerated capsules, SA60-1 and SA240-1, containing specimens of three weld metals (W5214, 34B009, and 27204) representative of those found in the core region, were removed at the end of cycle 13. Drawings of capsule placement indicated that SA-60-1 and SA240-1 were placed in the positions previously occupied by capsules A60 and A240. The specimens contained in SA-60-1 have been tested and reported in [10]; the capsule was pulled after cycle 13, with a reported neutron fluence of 1.5×10^{19} n/cm^2. The RPV task of the Light Water Reactor

Sustainability (LWRS) Program previously identified high-fluence data, high-nickel welds, and thermal aging as three of the major remaining issues for long-time operation of US commercial light water reactors (LWRs) [7, 16, 17]. Thus, although all capsules would provide useful data for supplementing the existing RPV surveillance database, we have identified the high-fluence A-60 capsule and the thermal aging T-150 capsule as high priority for the following major points:

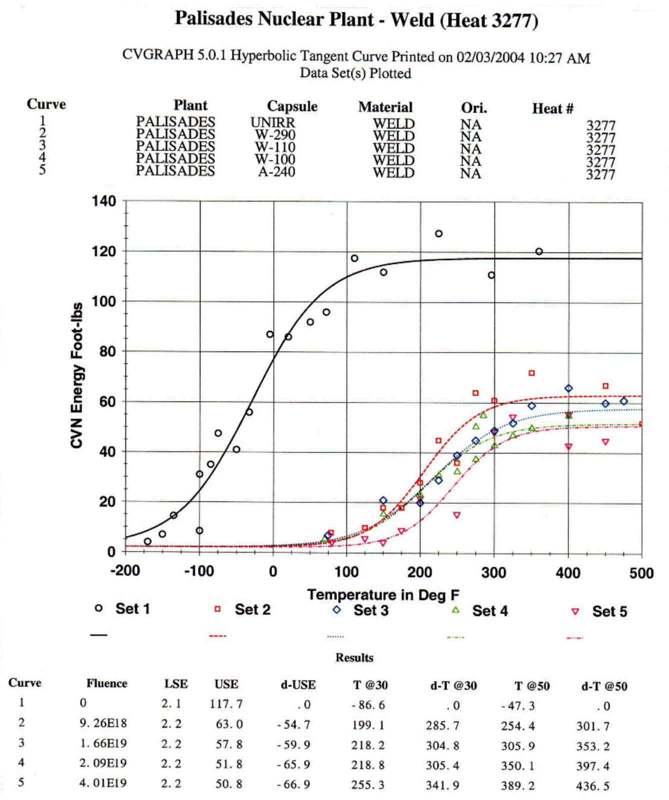
- These medium- and high-nickel materials at a very high fluence are of special interest for evaluation of the so-called “late-blooming phases” that have been shown to occur at relatively high fluences in high-nickel materials.

- The high-nickel/high-copper weld would complement the current Advanced Test Reactor (ATR) ATR-2 project [18, 19] with a wide range of materials, including very high-nickel materials, irradiated at fluences from 0.8 to 1.4×10^{20} n/cm^2 (> 1 MeV), as well as the research performed on the Ringhals reactor surveillance welds with 1.6 wt % nickel, but low copper [20].

- Data from the thermal capsule would provide thermal-aging data for typical RPV materials at a greater amount of aging time (> 33 EFPY) than currently available [21].

Figure 3 shows the CVN impact test results for the surveillance weld in the unirradiated condition and following exposure to four irradiation fluence conditions in the L-T orientation [10]. For the highest fluence (4.01×10^{19} n/cm^2), the 41-J (30 ft-lb) shift is 341.9°F (189.9°C), and with a 41-J transition temperature of 255.3°F (124.1°C). One past estimate [14] of the peak fluence at the RPV wall after 32 EFPY was 3.23×10^{19} n/cm^2, which would indicate (by linear interpolation) a 41-J transition temperature shift of about 327°F (164°C) and a 41-J transition temperature of 240.4°F (115.8°C) for the surveillance weld. As expected, based on chemical composition, the surveillance weld is demonstrated by such testing to be more radiation-sensitive than the base metal or the HAZ. Similar graphs for the other materials and for tensile data are provided in Appendices C, D, and E [10].

Figure 4, a revision of one in reference [21], provides a graph of thermal aging data, relative to thermal aging-induced ductile-brittle transition temperature shifts, for LWR RPV steels available worldwide. As shown, the available data for aging temperatures from 280 to 320°C are very limited, and nonexistent at aging times at or beyond the typical end of first license of 32 EFPY.



Palisades Nuclear Plant - Weld (Heat 3277)

CVGRAPH 5.0.1 Hyperbolic Tangent Curve Printed on 02/03/2004 10:27 AM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALISADES	UNIRR	WELD	NA	3277
2	PALISADES	W-290	WELD	NA	3277
3	PALISADES	W-110	WELD	NA	3277
4	PALISADES	W-100	WELD	NA	3277
5	PALISADES	A-240	WELD	NA	3277

Results

Curve	Fluence	LSE	USE	d-USE	T @30	d-T @30	T @50	d-T @50
1	0	2. 1	117. 7	. 0	- 86. 6	. 0	- 47. 3	. 0
2	9. 26E18	2. 2	63. 0	- 54. 7	199. 1	285. 7	254. 4	301. 7
3	1. 66E19	2. 2	57. 8	- 59. 9	218. 2	304. 8	305. 9	353. 2
4	2. 09E19	2. 2	51. 8	- 65. 9	218. 8	305. 4	350. 1	397. 4
5	4. 01E19	2. 2	50. 8	- 66. 9	255. 3	341. 9	389. 2	436. 5

Figure 3. CVN energy vs. test temperature for the PNGS surveillance weld in the unirradiated condition and following exposure to four different fluences (above fluences were revised slightly in 2011 [10]).

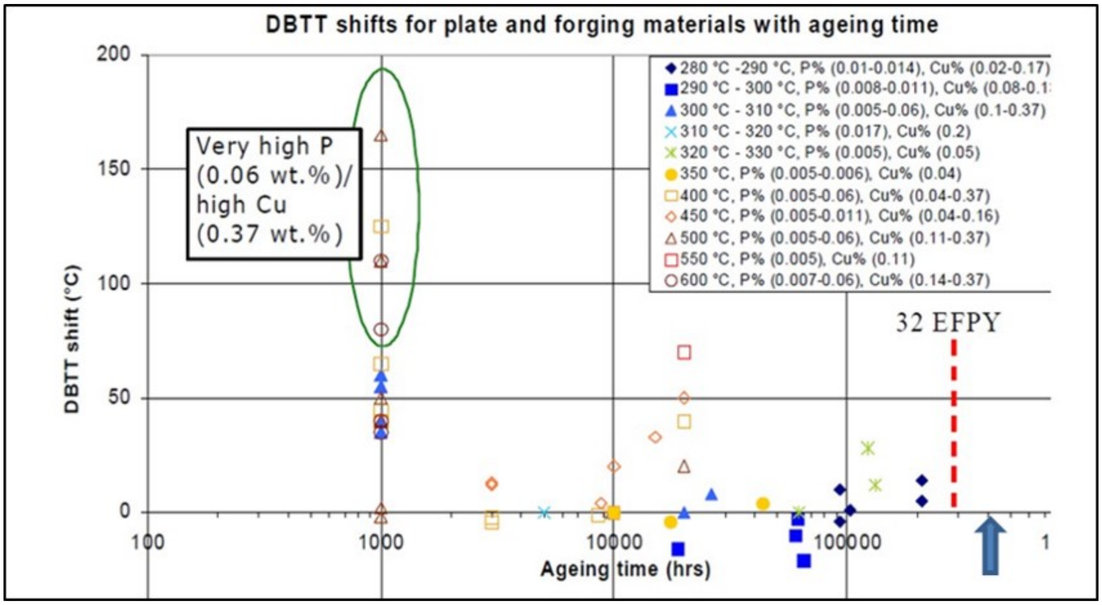
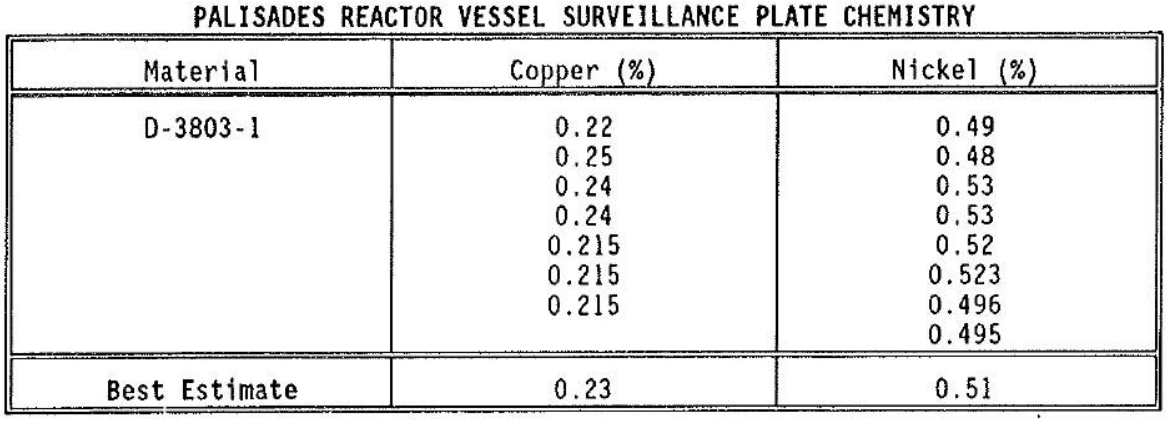


Figure 4. Thermal aging data in international database for LWR RPV steels (the blue arrow represents the approximate thermal aging time of about 33 EFPY (286,100 h) for capsule T-150 if removed from the RPV in 2020.

3. DESCRIPTION OF MATERIALS AND SPECIMENS FOR ORNL EVALUATION

PNGS included in its surveillance program a surveillance capsule, designated A-60, containing Charpy impact and tensile specimens of base metal (A302 grade B modified, heat C1279-3, Plate No. D-3803-1), a surveillance weld and an HAZ weld (both fabricated with RACO 3 weld wire heat 3277 with Ni200 nickel addition, Linde 1092 flux), and a standard reference (correlation monitor) material, HSST Plate 01. Tables 3 and 4 from PNGS provide previous elemental measurements for the materials.[3] As shown in Table 3, the plate has an average copper content of 0.23 wt % and an average nickel content of 0.51 wt %. Table 4 shows that the surveillance weld has an average nickel content of 1.36 wt % ($\sigma = \pm 0.32$) and copper content of about 0.25 wt % and that the HAZ weld has an average nickel content of 1.10 wt % and copper content of 0.25 wt %. These welds were fabricated with a nickel cold-wire feed process to enhance the nickel contents; that process also results in a very large scatter in the nickel contents of both welds. This scatter in nickel content will require specific measurements of each specimen fabricated for microstructural examination. The HAZ weld metal will not be tested, but the chemical composition is of importance to evaluation of the HAZ test results due to potential compositional dilution effects during welding.

Table 3. Copper and nickel measurements for the PNGS reactor vessel surveillance plate.



PALISADES REACTOR VESSEL SURVEILLANCE PLATE CHEMISTRY

Material	Copper (%)	Nickel (%)
D-3803-1	0.22	0.49
	0.25	0.48
	0.24	0.53
	0.24	0.53
	0.215	0.52
	0.215	0.523
	0.215	0.496
		0.495
Best Estimate	0.23	0.51

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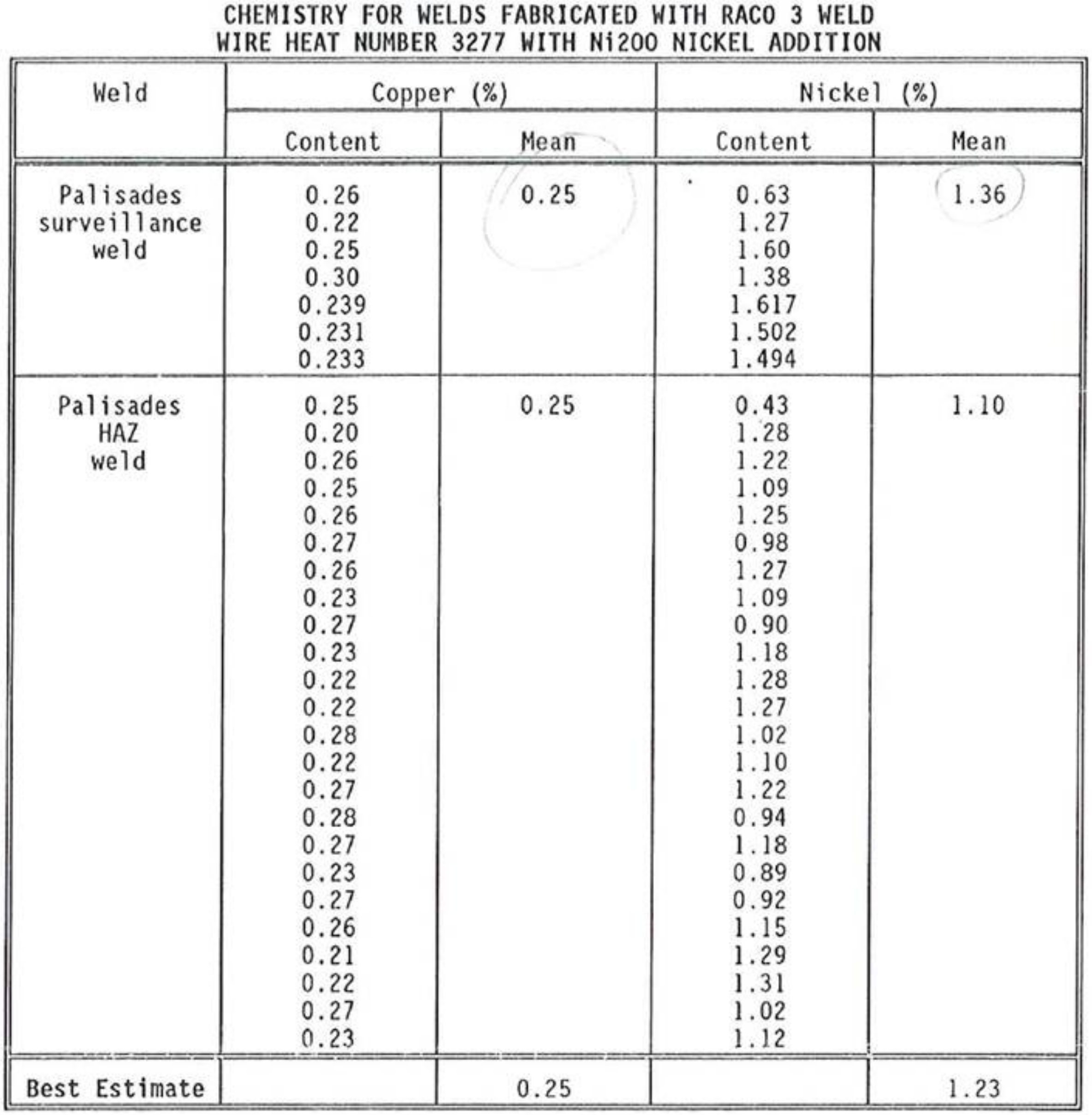
[3] Information regarding the materials in the Palisades Nuclear Plant (now PNGS) A-60 capsule provided in two Letters from John R. Kneeland, Jr. (Consumers Power Co.) to Randy K. Nanstad (ORNL), 2 May, and 22 May 1995.

Table 4. Copper and nickel measurements for the PNGS reactor vessel surveillance weld and HAZ weld.



CHEMISTRY FOR WELDS FABRICATED WITH RACO 3 WELD
WIRE HEAT NUMBER 3277 WITH Ni200 NICKEL ADDITION

Weld	Copper (%)		Nickel (%)	
	Content	Mean	Content	Mean
Palisades surveillance weld	0.26	0.25	0.63	1.36
	0.22		1.27	
	0.25		1.60	
	0.30		1.38	
	0.239		1.617	
	0.231		1.502	
	0.233		1.494	
Palisades HAZ weld	0.25	0.25	0.43	1.10
	0.20		1.28	
	0.26		1.22	
	0.25		1.09	
	0.26		1.25	
	0.27		0.98	
	0.26		1.27	
	0.23		1.09	
	0.27		0.90	
	0.23		1.18	
	0.22		1.28	
	0.22		1.27	
	0.28		1.02	
	0.22		1.10	
	0.27		1.22	
	0.28		0.94	
	0.27		1.18	
	0.23		0.89	
	0.27		0.92	
	0.26		1.15	
	0.21		1.29	
	0.22		1.31	
	0.27		1.02	
	0.23		1.12	
Best Estimate		0.25		1.23

The mechanical test specimen contents of the A-60 capsule are provided in Table 5, as are the various radiation and thermal monitors. As described in Section 2, the A-60 capsule was irradiated in an accelerated neutron flux position at the outer side of the core support barrel to a fluence of 1.8 × 10^{20} n/cm^2. This capsule was located in a similar position (separated by 180°) as that of a previously tested capsule (A-240). The average fluence for the specimens in capsule A-240 was given as 4.09 × 10^{19} n/cm^2 after being resident in the reactor for 825.08 effective full power days (EFPD) [14]; thus, the fast flux was about 5.69 ×10^{11} n/cm^2/s and likely is essentially the same for capsule A-60. Capsule A-60 was removed from its surveillance position during the fuel outage of May 1995 and has been resident in the spent fuel pool since that time. The intent of this task is to retrieve the capsule, test the tensile and Charpy impact specimens, and examine some of them microstructurally with various techniques, including atom probe tomography and small-angle neutron scattering (SANS) to assess the irradiation-induced features of this unique material condition (very high fluence and high copper/high nickel) and potential for development of NiMnSi late blooming phases, even in the presence of high copper content. This specific weld is unique within the US commercial nuclear reactor fleet and does not represent the specific conditions of any other US nuclear reactors; however, it is of considerable value from a research perspective when combined with information from other high-nickel materials and other materials with lower nickel contents irradiated at high flux in test reactors to enable further understanding of neutron flux effects.

Table 5. Contents of PNGS Capsules A-60 and T-150.

Material/Monitor	Charpy Specimens[1]		Tensile Specimens[1]		Other
	A-60	T-150	A-60	T-150	
Plate, A302 grade B modified, heat C1279-3, Plate No. D-3803-1	12 L-T	12 L-T 12 T-L	3 L	3L	
Surveillance Weld RACO 3 weld wire heat 3277 with Ni200 nickel addition, Linde 1092 flux	12 L-T	12 L-T	3 L	3L	
HAZ, from weld using Plates D-3803-3 and D-3803-2	12 L-S	12 L-S	3 L	3L	
SRM, HSST Plate 01, A533, grade B, class 1	12 L-T	None	None	None	
Iron attenuation monitor					15
Temperature monitors Total of 12					3: 92.5% Pb, 5.0% Sn, 2.5% Ag 3: 90.0% Pb, 5.0% Sn, 5.0% Ag 3: 97.5% Pb, 2.5% Ag 3: 92.5% Pb, 0.75% Sn, 1.75% Ag
Spectrum monitors Total of 21					3: uranium powder 3: titanium 3: iron 3: sulfur in quartz 3: cadmium shielded uranium powder 3: cadmium shielded nickel 3: cadmium shielded copper

[1] Charpy specimens are L-T orientation for base metal, weld metal, and SRM, but L-S for HAZ; tensile specimens are longitudinal orientation (L) in all cases.

The thermal capsule, T-150, contains a similar specimen complement as that of capsule A-60 (except it has no SRM specimens and does have both LT and TL CVN specimens of base metal), but has been resident in the reactor since initial operation (currently about 32 EFPY). Testing and evaluation of the thermal aged specimens from that capsule would provide data for about 33 EFPY, beyond the available aging time in the international database.

Table 6 provides a summary of the primary chemical elements responsible for radiation sensitivity in the four materials available in the surveillance capsules. The surveillance weld, with relatively high copper and very high nickel, is the material of primary interest.

Table 6. Summary of primary radiation-sensitive elements for the PNGS surveillance materials.

Material	Heat designation	Chemical composition, wt %				Chemistry Factor* 2
		Copper	Nickel	Manganese	Silicon	
Base metal, plate A302B, Mod.	C1279-3	0.23	0.51	1.37	0.18	154
Surveillance weld, Linde 1092	3277	0.25	1.36	1.23	0.20	214**
Heat-affected-zone	3277	0.25	1.10	1.23	0.20	211
Correlation monitor, A533B-1 Plate	HSST Plate 01	0.17	0.66	1.46	0.19	129

*Source: U. S. Nuclear Regulatory Commission, *Radiation Embrittlement of Reactor Vessel Materials*, Regulatory Guide 1.99, Rev. 2, 1988.

** The chemistry factor is limited by the maximum nickel content of 1.20 wt % in R.G. 1.99-2.

4. PLAN FOR RETRIEVAL AND DISASSEMBLY OF SURVEILLANCE CAPSULES

Given the announced plans for shutdown of the PNGS, numerous discussions have been held with responsible staff members at the PNGS who had indicated their willingness to provide capsule A-60 to ORNL for evaluation. The recent discussions also included the desire of ORNL to retrieve the remaining thermal capsule (T-150) for evaluation. Preliminary discussions to ascertain capability have also been held with some organizations that have indicated interest in retrieval of the capsule from the spent pool, loading it into a shipping cask, and shipping it to a site for disassembly. Based on discussions with PNGS staff, it is likely that a shipping cask with capacity for a full-length surveillance capsule assembly will be required. At this early stage in planning, it is also likely that the capsule will be disassembled by an organization with such experience and that the test specimens will be shipped to ORNL for testing and evaluation; however, there may be the option for some testing by the capsule disassembly organization. Appendix F provides drawings of the individual compartments for tensile and CVN specimens in the surveillance capsule.[4] it is known that there are no costs associated with the operations to be performed by the PNGS staff. Appendix G provides a table of all the PNGS surveillance capsules (given the best information currently available) indicating the irradiation exposure information, the materials included in each capsule, and the current status/locations of the capsules and specimens.

5. PLAN FOR TESTING AND EVALUATION OF SURVEILLANCE SPECIMENS

5.1 CAPSULE A-60

As shown in Table 5, there are 12 CVN specimens available for all four materials, and 3 tensile specimens available for the base metal, weld metal, and HAZ. No tensile specimens are available for the SRM. CVN specimens are in the L-S orientation for the HAZ material, but in the L-T orientation for the other three materials; all tensile specimens are longitudinal.

5.1.1 Tensile Testing

Tentative plans are for tensile testing to be performed at ORNL, although testing at the facility where the capsule disassembly takes place may be considered. If testing is performed at ORNL, radioactivity

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[4] Drawings provided in Letter from John R. Kneeland, Jr. (Consumers Power Co.) to Randy K. Nanstad (ORNL), 22 May 1995.

measurements will be performed to determine if the tests could be performed in the Low Activation Materials Development and Analysis (LAMDA) Laboratory or if the activities require testing in the ORNL hot cells. Because only three specimens are available, all tensile specimens will be tested at room temperature in accordance with ASTM Standard E-8 [22]. Figure 5 shows the surveillance data for the weld metal for each of the four fluences and at the temperatures tested, indicating a very high amount of hardening (yield strength increase) at the highest fluence. The curves shown are exponential fits based on fitting of yield strength vs. temperature data for this class of material provided in Section II, Part D of the ASME Boiler and Pressure Vessel Code [23], which provided reasonable trends for changes in yield strength vs. temperature, neglecting the potential effects of changes in strain hardening that tend to occur in the irradiation cases. Moreover, such fitting was also used to make estimates of some yield strength values where testing had not been performed.

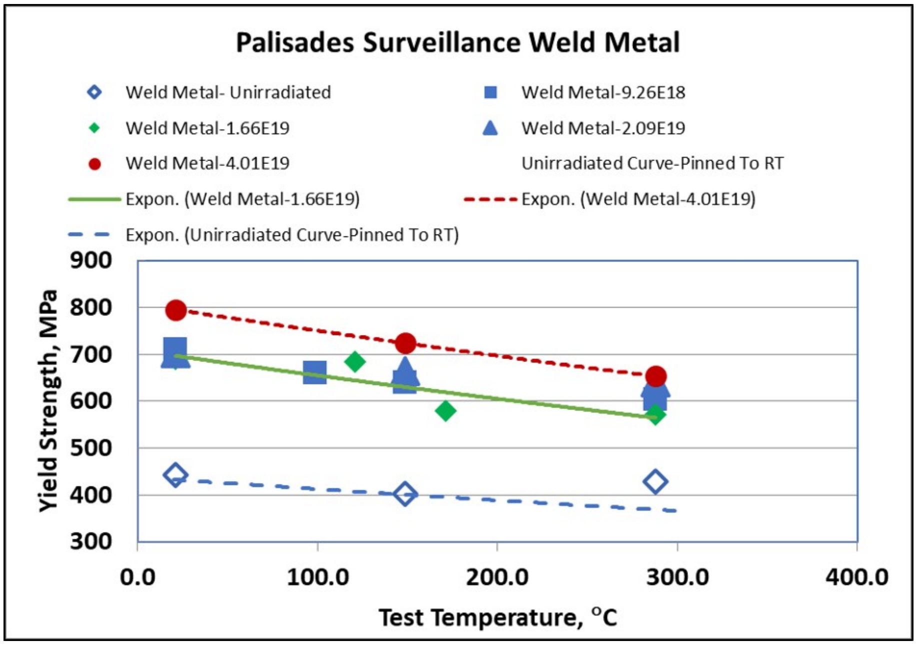

Figure 5. Yield strength data for PNGS surveillance weld metal in unirradiated condition and at four irradiation fluences. Curve fits are shown only for the unirradiated, and two indicated fluences. Four values are the result of interpolation/extrapolation as discussed in the text.

For the weld metal case, the yield strengths at 149°C for the unirradiated condition, at 21°C for 9.26×10^{18} n/cm^2, for 21°C for 1.66×10^{19} n/cm^2, and at 149°C for 4.01×10^{19} n/cm^2, are estimated based on such fitting. Thus, having values of yield strength at room temperature for all five conditions, the irradiation-induced increases in yield strength were calculated; the results are shown in Figure 6, which also shows the fluence for the tensile specimens in Capsule A-60 at 1.87×10^{20} n/cm^2. Additional graphs are provided in Appendices C, D, and E for the weld metal, base metal, and HAZ, respectively.

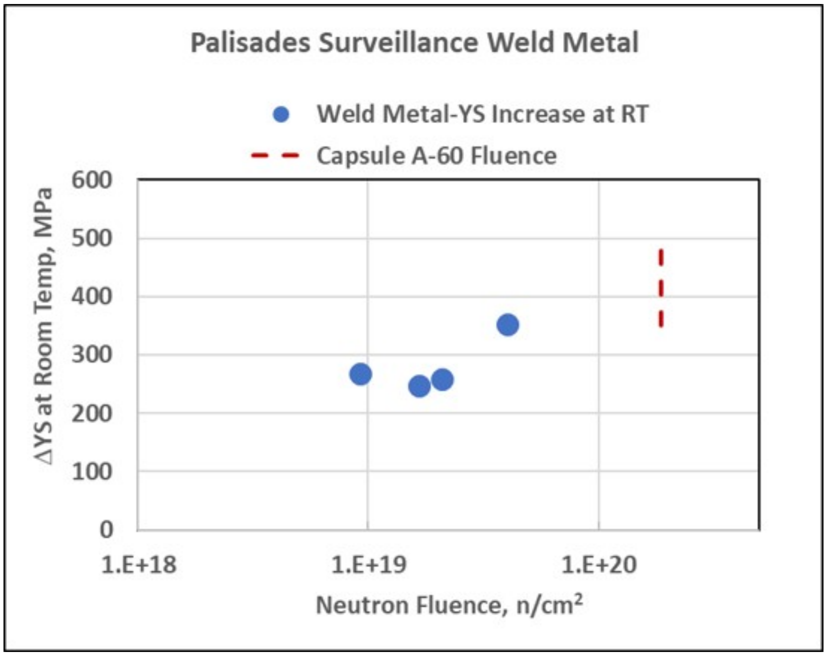

Figure 6. Increase in yield strength vs. fluence for the PNGS surveillance weld metal.

5.1.2 Charpy impact and fracture toughness testing

Current plans are for CVN testing to be performed at ORNL. Because the surveillance specimens were removed from the reactor more than 25 years ago, radioactivity measurements will be performed to determine if the tests could be performed in an annex of the LAMDA Laboratory or if the activities require testing in the ORNL hot cells. Testing will be conducted at a range of temperatures, in accordance with ASTM Standard E23 [24], to allow construction of absorbed energy vs. temperature curves, such as those shown in Fig. 3, with the primary objectives to determine the 41-J transition temperature (T_{41J}) and upper-shelf energy (USE) for each tested material. Given values of T_{41J} for the five conditions available from the surveillance program, the irradiation-induced increases (ΔT_{41J}) were calculated; the results are shown in Figure 7, which also shows the fluence for the Charpy impact specimens in Capsule A-60 at 1.87×10^{20} n/cm^2. Similar graphs are provided in Appendix C for the base metal and HAZ. Additionally, machining and testing of mini-Compact Tension specimens of weld metal, either from tested weld metal CVNs or from the weld metal portion of selected HAZ specimens, will be performed in accordance with ASTM Standard E1921 [25], with the primary objective to determine the fracture toughness reference temperature (T_0). The results from these tests will provide a valuable comparison of fracture toughness and Charpy impact reference temperatures for this highly irradiated material.

5.1.3 Microstructural characterization, chemical analyses, and other testing

Microhardness testing will be performed on each material to provide data for correlation of irradiation-induced microhardness changes with both yield strength and CVN transition temperature changes. Microstructural and chemical evaluation, optical metallography, transmission electron microscopy (TEM) and atom probe tomography (APT) of the weld metal will be performed. To provide a full comprehensive analysis of the irradiation-induced microstructural changes, dependent on available funding, additional microstructural analysis with SANS and small-angle x-ray scattering (SAXS) will be performed in collaboration with the University of California, Santa Barbara and Brookhaven National Laboratory. Moreover, similar microstructural evaluations of base metal and HAZ materials would be performed to provide valuable comparisons of microstructural evolution at high fluence in materials with significantly different nickel contents.

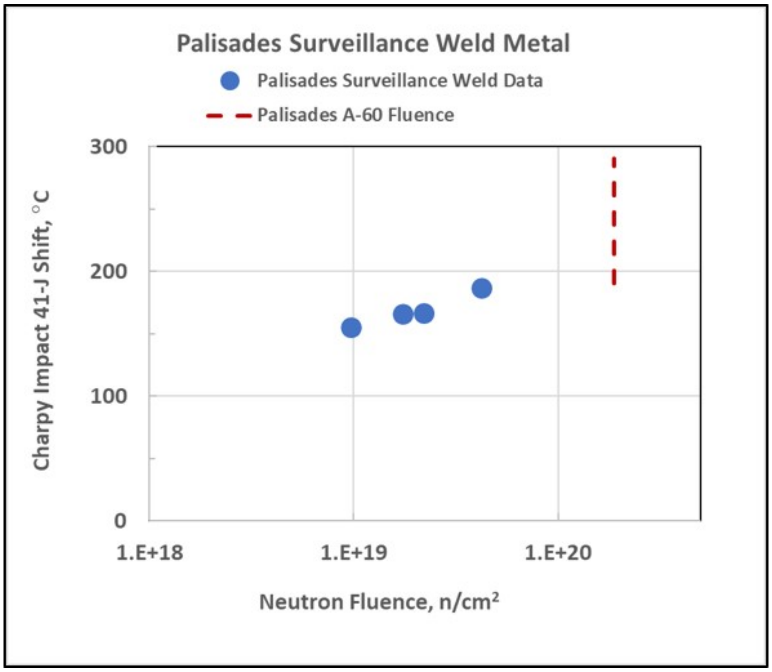

Figure 7. Increase (shift) in Charpy impact 41-J temperature for the Palisades surveillance weld metal.

5.1.4 Dosimetry and irradiation temperature evaluations

Dosimetry evaluations have been reported in the various surveillance reports [10, 11, 12, 13, 14] and, because the capsule has been out of the reactor for about 25 years, the evaluations will only be considered for this program if the tensile and Charpy impact test results indicate significant uncertainties regarding the irradiation fluence. The temperature monitors are not considered reliable enough to provide an accurate determination of the exposure temperature, and, as with the dosimetry, irradiation temperature evaluations have been reported in the surveillance reports.

5.2 CAPSULE T-150

As shown in Table 5e 24 CVN specimens are available for the base metal (two orientations), 12 CVN specimens for each of the weld metal and HAZ, and 3 tensile specimens for all the materials except for the SRM. No CVN or tensile specimens are available for the SRM. CVN specimens are in the L-S orientation for the HAZ material, the L-T orientation for the weld material, both the L-T and T-L orientations for the base metal; all tensile specimens are longitudinal. As discussed in Section 2 and shown in Figure 4, the current data are very sparse for thermal aging of RPV materials at typical operating temperatures, and data from Capsule T-150 would provide data for time beyond those in the current database.

5.2.1 Tensile testing

Current plans are for tensile testing to be performed at ORNL. Radioactivity measurements will be performed to determine our assumption that the tests could be performed in an annex of the LAMDA Laboratory; it is anticipated that will be confirmed because the thermal aging capsule was located in a very low neutron flux field. All tensile specimens will be tested at room temperature in accordance with ASTM Standard E-8 [22].

5.2.2 Charpy impact and fracture toughness testing

Current plans are for Charpy impact and fracture toughness testing to be performed at ORNL. As for the tensile specimens, radioactivity measurements will be performed to confirm that the tests could be performed in an annex of the LAMDA Laboratory due to their expected very low activity. Testing will be conducted at a range of temperatures, in accordance with ASTM Standard E23 [24], to allow construction of absorbed energy vs. temperature curves, such as those shown in Figure 3, with the primary objectives to determine the 41-J transition temperature (T_{41J}) and USE for each tested material. A secondary goal for the base metal is to compare specimen orientation effects on T_{41J} and ΔT_{41J}. Additionally, if the CVN testing indicates substantial thermal aging embrittlement, machining and testing of mini-compact tension specimens of weld metal, either from tested weld metal CVNs or from the weld metal portion of selected HAZ specimens, will be performed to provide a valuable comparison of fracture toughness and Charpy impact reference temperatures for this highly thermally aged material.

5.2.3 Microstructural characterization, chemical analyses, and other testing

Microhardness testing will be performed on each material to provide data for correlation of irradiation-induced microhardness changes with both tensile yield strength and CVN transition temperature changes. Microstructural and chemical evaluation, optical metallography, TEM and APT of the weld metal will be performed. To provide a full comprehensive analysis of the thermal aging-induced microstructural changes, dependent on available funding, additional microstructural analysis with SANS and SAXS will be performed in collaboration with the University of California, Santa Barbara, and Brookhaven National Laboratory. Moreover, similar microstructural evaluations of base metal and HAZ materials would be performed to provide valuable comparisons of microstructural evolution after long-time thermal aging in materials with significantly different nickel contents.

5.2.4 Dosimetry and irradiation temperature evaluations

Dosimetry for Capsule T-150 is irrelevant due to its location in a very low-flux position in the reactor. Although the temperature monitors are not considered reliable enough to provide an accurate determination of the exposure temperature, they will be examined as was done for the previous thermal capsule to provide a best estimate of the aging temperature.

6. ESTIMATED SCHEDULE, COST, AND MATERIAL DISPOSITION

Once the project is initiated, progress will be reported as part of the LWRS Program monthly reporting schedule. Additionally, it is anticipated that progress reports will be submitted in conformance with a milestone schedule not yet determined, although one such report per year is currently envisioned. The PNGS has provided a preliminary estimate of the third quarter of fiscal year (FY) 2021 for the probable retrieval of capsule A-60, and, although that schedule is not firm, a rough estimate of scheduling would envision disassembly of the capsule during the fourth quarter of FY 2021, shipping and receipt of specimens to ORNL during the first quarter of FY 2022, initiation of mechanical property specimen testing during the third quarter of FY 2022, completion of all testing by end of third quarter of FY 2023, completion of microstructural analysis in mid-FY 2024, and a final report submitted at the end of FY 2024. The schedule for retrieval, shipping, disassembly, and evaluations of capsule T-150 is currently anticipated to be about one year following that for capsule A-60. Selected broken specimens of all irradiated and thermal aged materials will be sent to the National Scientific User Facility Library at Idaho National Laboratory for potential testing and evaluations by other interested organizations.

The costs estimated for this project are preliminary as there are no contracts between ORNL and any other parties nor requests for official quotes. Additionally, due to a relatively recent decision by PNGS, the thermal capsule T-150 will not be available until FY 2022 or later; thus, the cost and schedule are only being developed for the A-60 irradiated surveillance capsule. No costs are associated with the operations to be performed by the PNGS staff. A preliminary cost estimate will include (1) retrieval of capsule from Palisades, shipping of capsule to vendor, disassembly of capsule, and shipping of irradiated specimens to ORNL; (2) testing and analysis of the irradiated specimens by ORNL; and (3) reporting of results. The cost for the thermal capsule T-150 would be substantially less than the estimate for Capsule A-60 because the specimens are not irradiated and would not require testing and analysis in hot cells.

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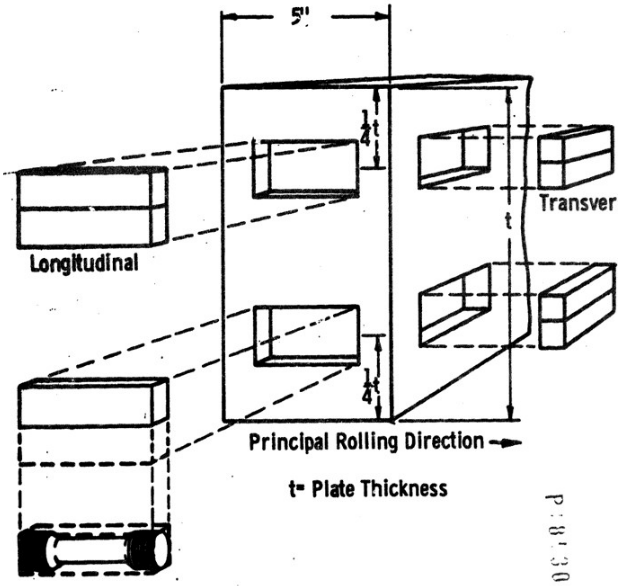
APPENDIX A. DRAWINGS OF REMOVAL LOCATIONS FOR MACHINING OF TENSILE AND CVN SPECIMENS [8]



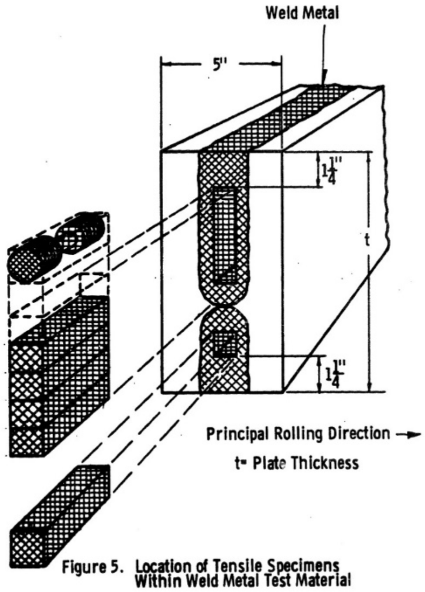
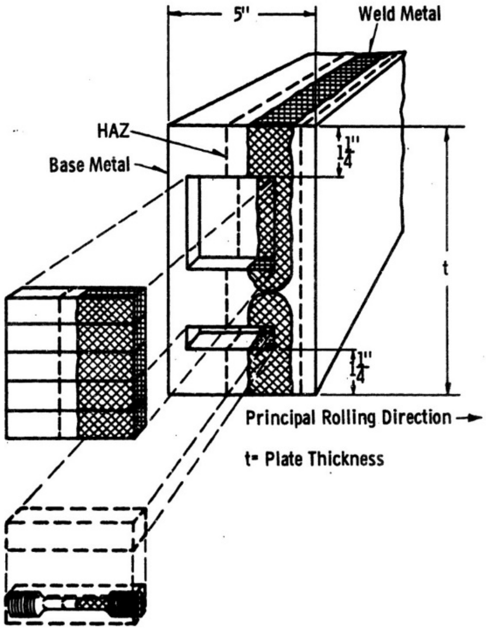
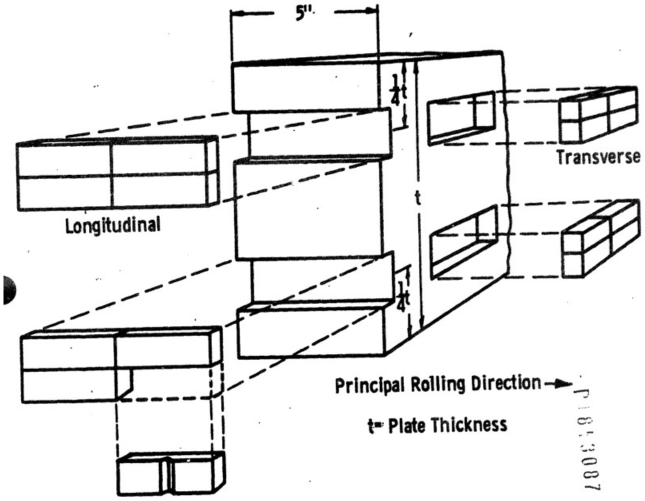
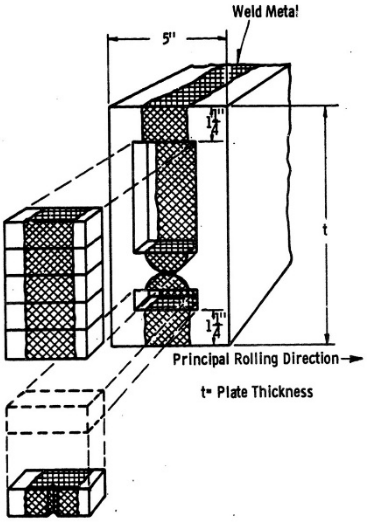
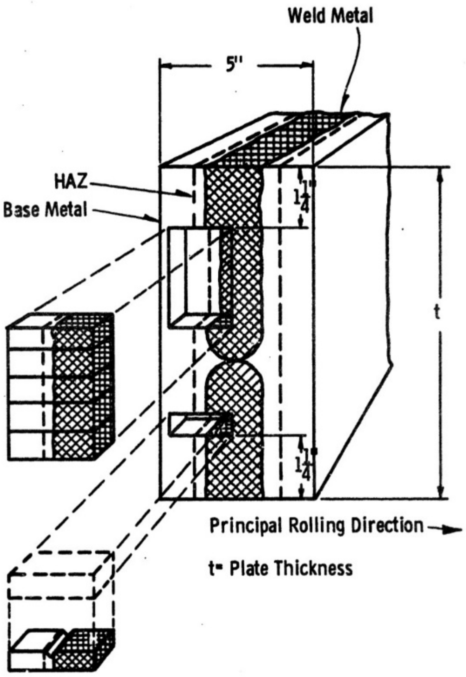


Figure 5. Location of Tensile Specimens Within Weld Metal Test Material

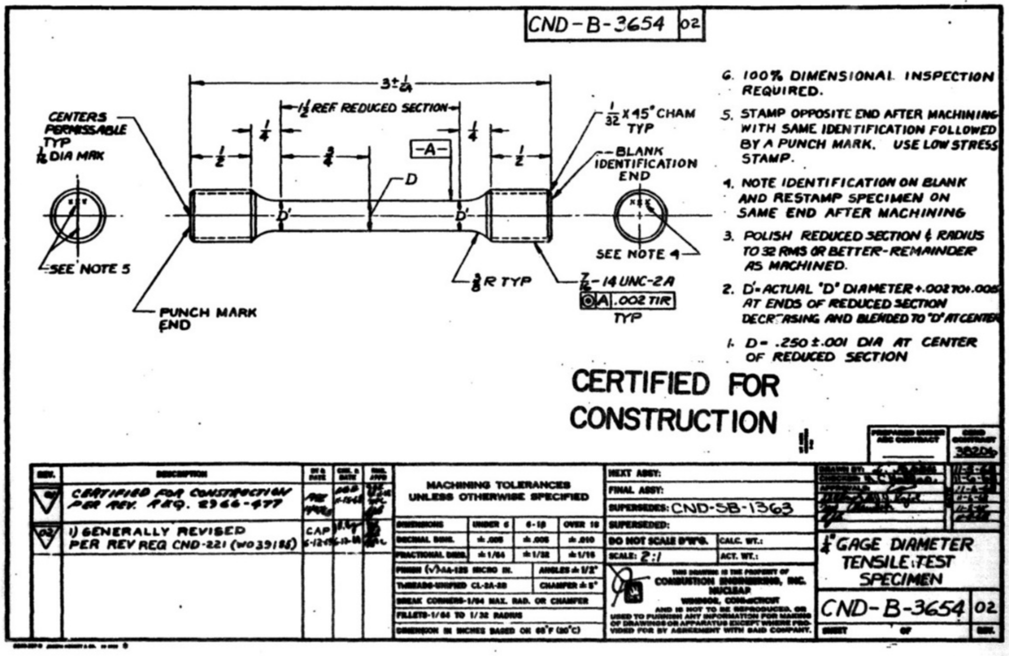


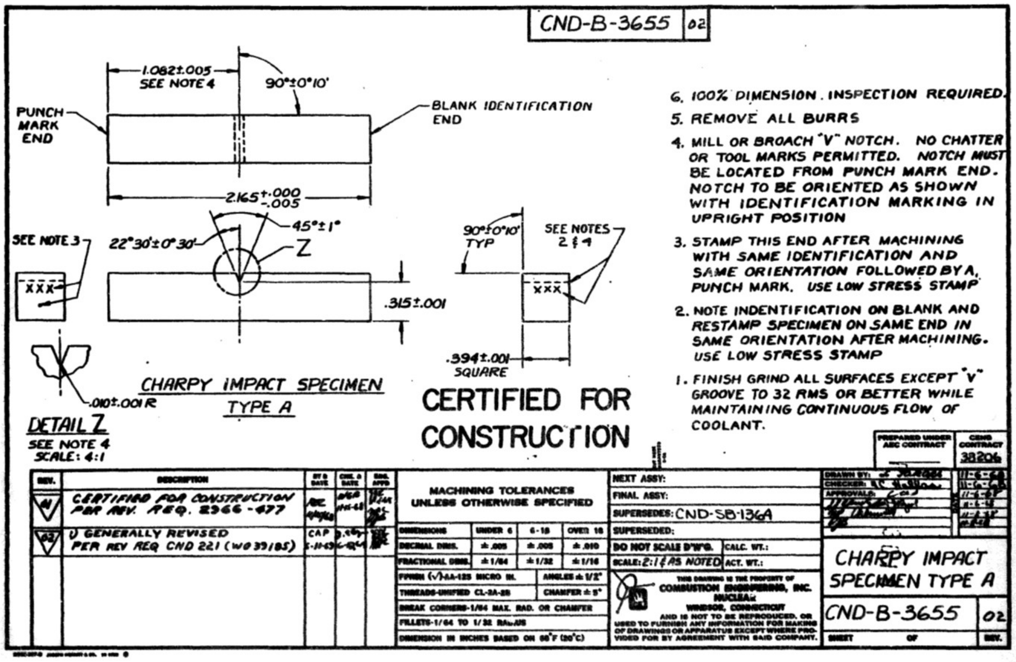

5"
1/4 t
1/4 t
t
Longitudinal
Transverse
Principal Rolling Direction
t= Plate Thickness
P81-3087


Weld Metal
5"
1 1/4"
1 1/4"
t
Principal Rolling Direction
t= Plate Thickness

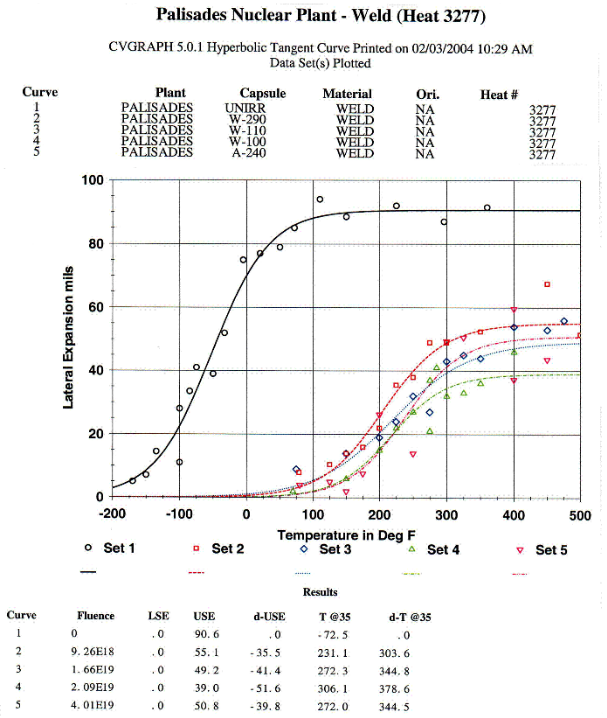

Weld Metal
5"
HAZ
Base Metal
1 1/4"
1 1/4"
t
Principal Rolling Direction
t= Plate Thickness

APPENDIX B. DRAWINGS OF CVN IMPACT AND TENSILE SPECIMENS FOR THE PALISADES RPV SURVEILLANCE PROGRAM [8]





APPENDIX C. GRAPHS OF TENSILE AND CVN SURVEILLANCE TEST RESULTS FOR PNGS SURVEILLANCE WELD METAL [10] AND ORNL DATA PLOTS



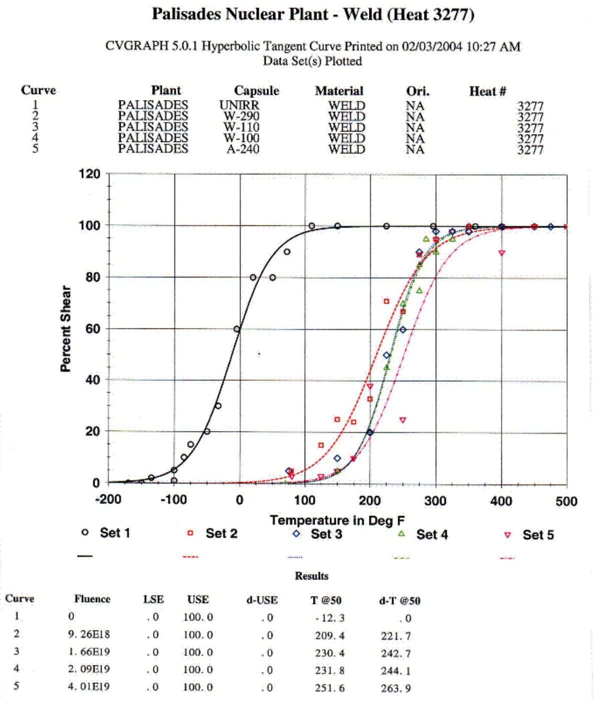
Palisades Nuclear Plant - Weld (Heat 3277)

CVGRAPH 5.0.1 Hyperbolic Tangent Curve Printed on 02/03/2004 10:29 AM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALISADES	UNIRR	WELD	NA	3277
2	PALISADES	W-290	WELD	NA	3277
3	PALISADES	W-110	WELD	NA	3277
4	PALISADES	W-100	WELD	NA	3277
5	PALISADES	A-240	WELD	NA	3277

Results

Curve	Fluence	LSE	USE	d-USE	T @35	d-T @35
1	0	. 0	90. 6	. 0	- 72. 5	. 0
2	9. 26E18	. 0	55. 1	- 35. 5	231. 1	303. 6
3	1. 66E19	. 0	49. 2	- 41. 4	272. 3	344. 8
4	2. 09E19	. 0	39. 0	- 51. 6	306. 1	378. 6
5	4. 01E19	. 0	50. 8	- 39. 8	272. 0	344. 5



Palisades Nuclear Plant - Weld (Heat 3277)

CVGRAPH 5.0.1 Hyperbolic Tangent Curve Printed on 02/03/2004 10:27 AM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALISADES	UNIRR	WELD	NA	3277
2	PALISADES	W-290	WELD	NA	3277
3	PALISADES	W-110	WELD	NA	3277
4	PALISADES	W-100	WELD	NA	3277
5	PALISADES	A-240	WELD	NA	3277

Results

Curve	Fluence	LSE	USE	d-USE	T @50	d-T @50
1	0	. 0	100. 0	. 0	- 12. 3	. 0
2	9. 26E18	. 0	100. 0	. 0	209. 4	221. 7
3	1. 66E19	. 0	100. 0	. 0	230. 4	242. 7
4	2. 09E19	. 0	100. 0	. 0	231. 8	244. 1
5	4. 01E19	. 0	100. 0	. 0	251. 6	263. 9

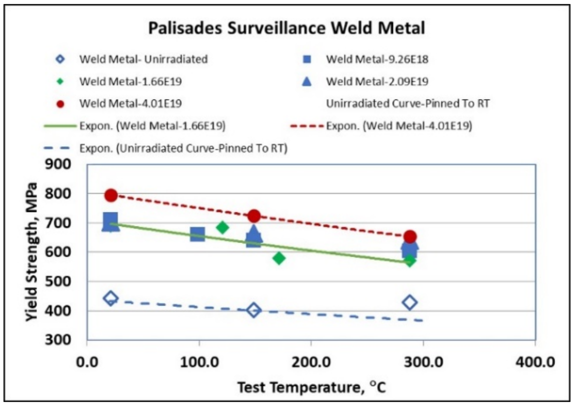


Figure C1. Tensile yield strength data after fitting measured surveillance data and estimating data at other temperatures for PNGS weld metal.

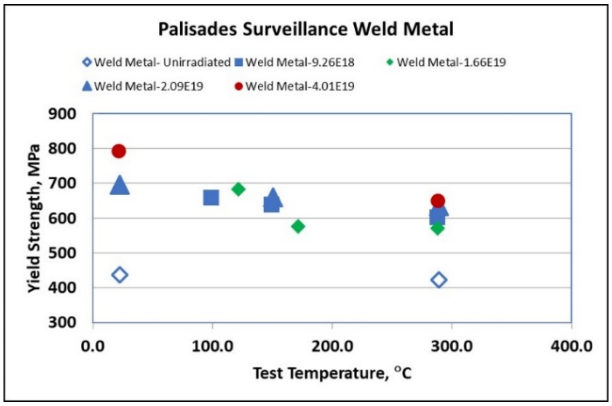
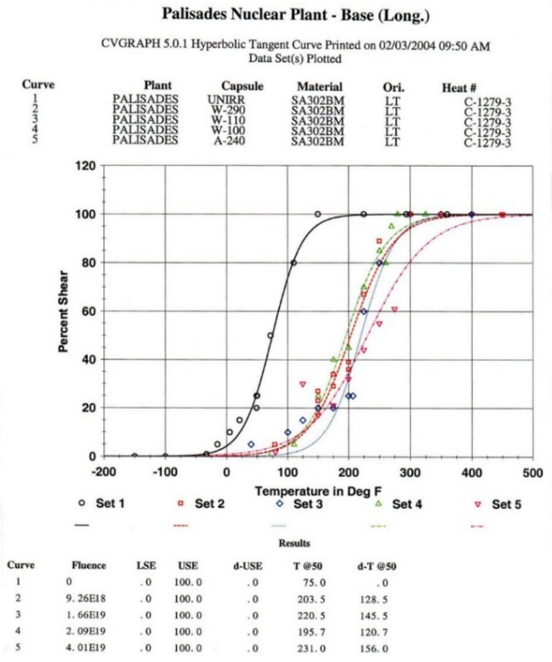


Figure C2. Measured surveillance tensile yield strength data for PNGS weld metal.

APPENDIX D. GRAPHS OF TENSILE AND CVN SURVEILLANCE TEST RESULTS FOR PNGS SURVEILLANCE BASE METAL [10] AND ORNL DATA PLOTS



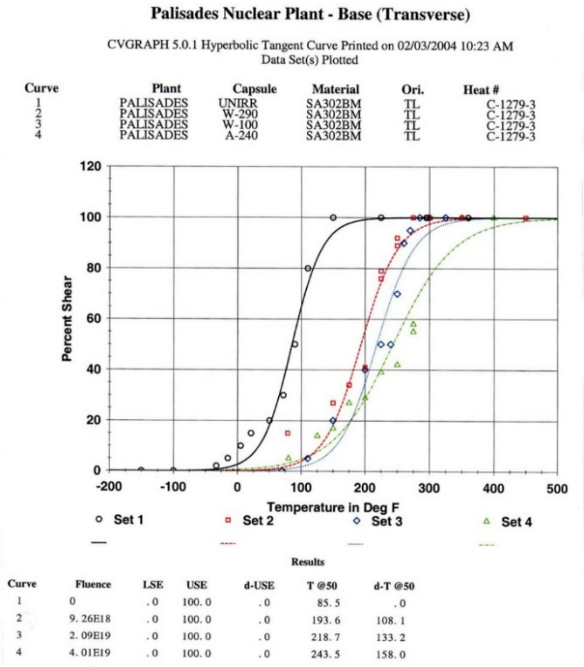
Palisades Nuclear Plant - Base (Long.)

CVGRAPH 5.0.1 Hyperbolic Tangent Curve Printed on 02/03/2004 09:50 AM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALISADES	UNIRR	SA302BM	LT	C-1279-3
2	PALISADES	W-290	SA302BM	LT	C-1279-3
3	PALISADES	W-110	SA302BM	LT	C-1279-3
4	PALISADES	W-100	SA302BM	LT	C-1279-3
5	PALISADES	A-240	SA302BM	LT	C-1279-3

Results

Curve	Fluence	LSE	USE	d-USE	T @50	d-T @50
1	0	. 0	100. 0	. 0	75. 0	. 0
2	9. 26E18	. 0	100. 0	. 0	203. 5	128. 5
3	1. 66E19	. 0	100. 0	. 0	220. 5	145. 5
4	2. 09E19	. 0	100. 0	. 0	195. 7	120. 7
5	4. 01E19	. 0	100. 0	. 0	231. 0	156. 0



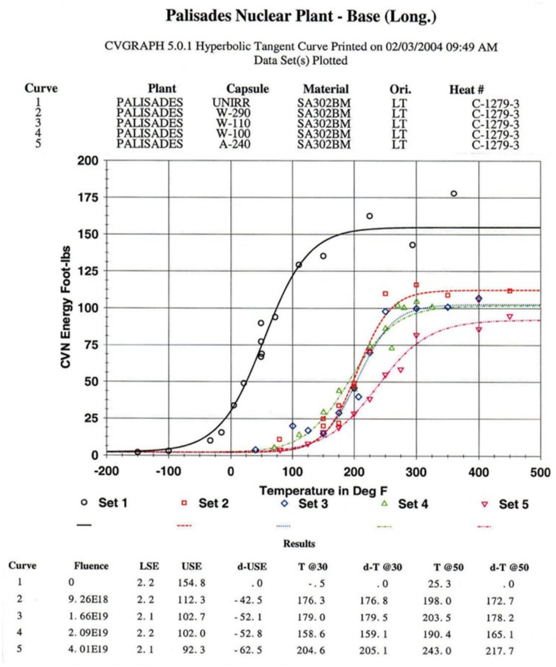
Palisades Nuclear Plant - Base (Transverse)

CVGRAPH 5.0.1 Hyperbolic Tangent Curve Printed on 02/03/2004 10:23 AM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALISADES	UNIRR	SA302BM	TL	C-1279-3
2	PALISADES	W-290	SA302BM	TL	C-1279-3
3	PALISADES	W-100	SA302BM	TL	C-1279-3
4	PALISADES	A-240	SA302BM	TL	C-1279-3

Results

Curve	Fluence	LSE	USE	d-USE	T @50	d-T @50
1	0	. 0	100. 0	. 0	85. 5	. 0
2	9. 26E18	. 0	100. 0	. 0	193. 6	108. 1
3	2. 09E19	. 0	100. 0	. 0	218. 7	133. 2
4	4. 01E19	. 0	100. 0	. 0	243. 5	158. 0



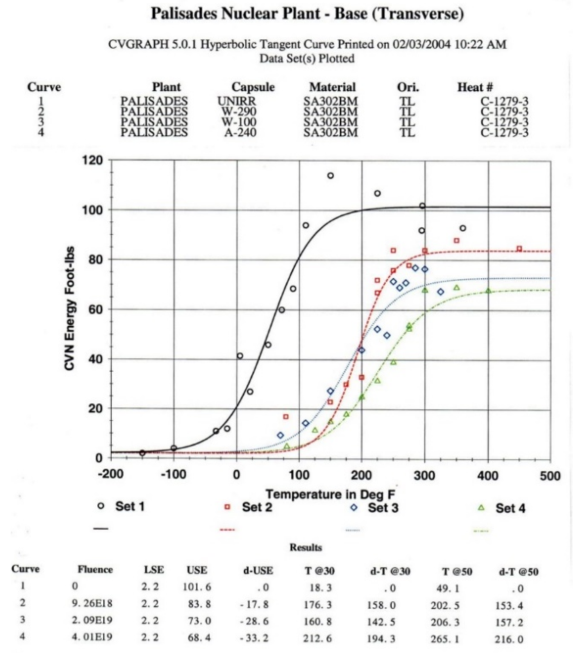
Palisades Nuclear Plant - Base (Long.)

CVGRAPH 5.0.1 Hyperbolic Tangent Curve Printed on 02/03/2004 09:49 AM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALISADES	UNIRR	SA302BM	LT	C-1279-3
2	PALISADES	W-290	SA302BM	LT	C-1279-3
3	PALISADES	W-110	SA302BM	LT	C-1279-3
4	PALISADES	W-100	SA302BM	LT	C-1279-3
5	PALISADES	A-240	SA302BM	LT	C-1279-3

Results

Curve	Fluence	LSE	USE	d-USE	T @30	d-T @30	T @50	d-T @50
1	0	2. 2	154. 8	. 0	-. 5	. 0	25. 3	. 0
2	9. 26E18	2. 2	112. 3	-42. 5	176. 3	176. 8	198. 0	172. 7
3	1. 66E19	2. 1	102. 7	-52. 1	179. 0	179. 5	203. 5	178. 2
4	2. 09E19	2. 2	102. 0	-52. 8	158. 6	159. 1	190. 4	165. 1
5	4. 01E19	2. 1	92. 3	-62. 5	204. 6	205. 1	243. 0	217. 7



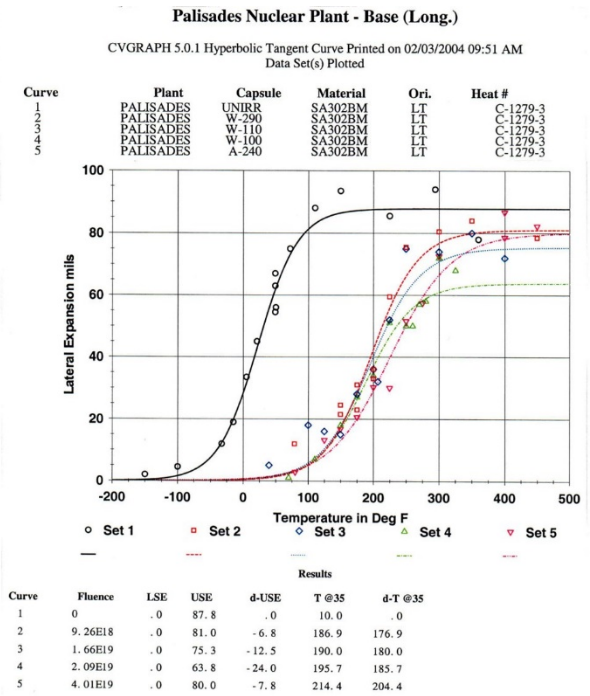
Palisades Nuclear Plant - Base (Transverse)

CVGRAPH 5.0.1 Hyperbolic Tangent Curve Printed on 02/03/2004 10:22 AM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALISADES	UNIRR	SA302BM	TL	C-1279-3
2	PALISADES	W-290	SA302BM	TL	C-1279-3
3	PALISADES	W-100	SA302BM	TL	C-1279-3
4	PALISADES	A-240	SA302BM	TL	C-1279-3

Results

Curve	Fluence	LSE	USE	d-USE	T @30	d-T @30	T @50	d-T @50
1	0	2. 2	101. 6	. 0	18. 3	. 0	49. 1	. 0
2	9. 26E18	2. 2	83. 8	- 17. 8	176. 3	158. 0	202. 5	153. 4
3	2. 09E19	2. 2	73. 0	- 28. 6	160. 8	142. 5	206. 3	157. 2
4	4. 01E19	2. 2	68. 4	- 33. 2	212. 6	194. 3	265. 1	216. 0



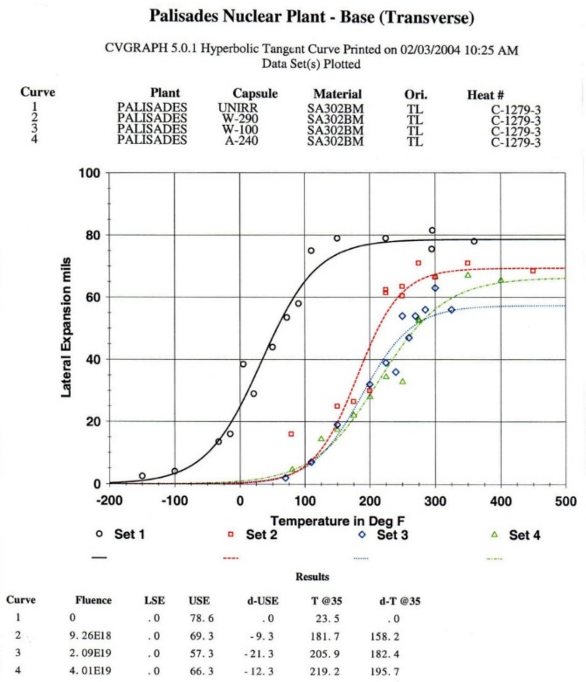
Palisades Nuclear Plant - Base (Long.)

CVGRAPH 5.0.1 Hyperbolic Tangent Curve Printed on 02/03/2004 09:51 AM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALISADES	UNIRR	SA302BM	LT	C-1279-3
2	PALISADES	W-290	SA302BM	LT	C-1279-3
3	PALISADES	W-110	SA302BM	LT	C-1279-3
4	PALISADES	W-100	SA302BM	LT	C-1279-3
5	PALISADES	A-240	SA302BM	LT	C-1279-3

Results

Curve	Fluence	LSE	USE	d-USE	T @35	d-T @35
1	0	.0	87.8	.0	10.0	.0
2	9.26E18	.0	81.0	-6.8	186.9	176.9
3	1.66E19	.0	75.3	-12.5	190.0	180.0
4	2.09E19	.0	63.8	-24.0	195.7	185.7
5	4.01E19	.0	80.0	-7.8	214.4	204.4



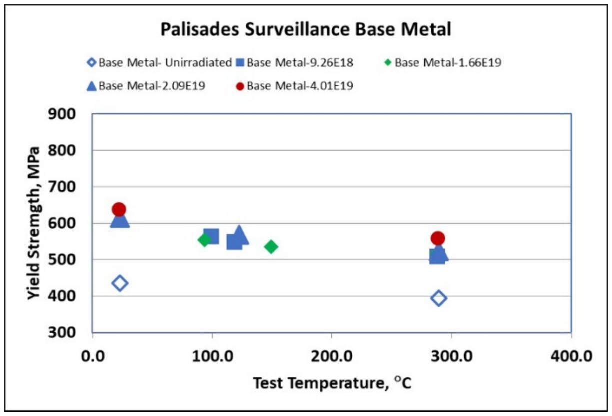
Palisades Nuclear Plant - Base (Transverse)

CVGRAPH 5.0.1 Hyperbolic Tangent Curve Printed on 02/03/2004 10:25 AM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALISADES	UNIRR	SA302BM	TL	C-1279-3
2	PALISADES	W-290	SA302BM	TL	C-1279-3
3	PALISADES	W-100	SA302BM	TL	C-1279-3
4	PALISADES	A-240	SA302BM	TL	C-1279-3

Results

Curve	Fluence	LSE	USE	d-USE	T @35	d-T @35
1	0	.0	78.6	.0	23.5	.0
2	9.26E18	.0	69.3	-9.3	181.7	158.2
3	2.09E19	.0	57.3	-21.3	205.9	182.4
4	4.01E19	.0	66.3	-12.3	219.2	195.7



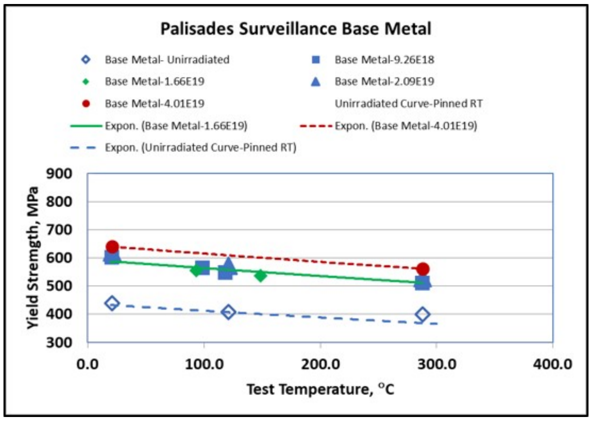


Figure D1. Tensile yield strength data after fitting measured surveillance data and estimating data at other temperatures for PNGS base metal.

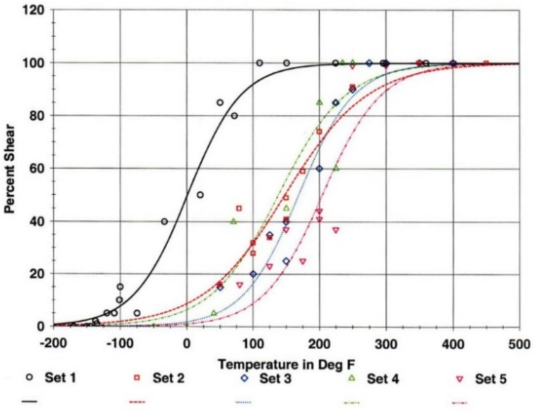
Figure D2. Measured surveillance tensile yield strength data for PNGS base metal.

APPENDIX E. APPENDIX E GRAPHS OF TENSILE AND CVN SURVEILLANCE TEST RESULTS FOR PNGS SURVEILLANCE [10] AND ORNL DATA PLOTS

Palisades Nuclear Plant - Heat Affected Zone

CVGRAPH 5.0.1 Hyperbolic Tangent Curve Printed on 02/03/2004 10:31 AM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALISADES	UNIRR	SA302BM	NA	C-1279-1
2	PALISADES	W-290	SA302BM	NA	C-1279-1
3	PALISADES	W-110	SA302BM	NA	C-1279-1
4	PALISADES	W-100	SA302BM	NA	C-1279-1
5	PALISADES	A-240	SA302BM	NA	C-1279-1



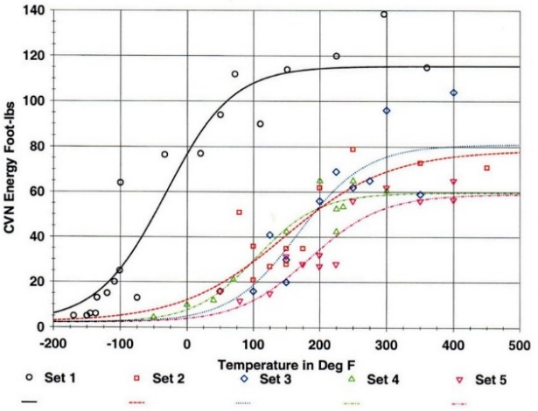
Results

Curve	Fluence	LSE	USE	d-USE	T @50	d-T @50
1	0	. 0	100. 0	. 0	1. 0	. 0
2	9. 26E18	. 0	100. 0	. 0	148. 1	147. 1
3	1. 66E19	. 0	100. 0	. 0	169. 0	168. 0
4	2. 09E19	. 0	100. 0	. 0	137. 9	136. 9
5	4. 01E19	. 0	100. 0	. 0	204. 7	203. 7

Palisades Nuclear Plant - Heat Affected Zone

CVGRAPH 5.0.1 Hyperbolic Tangent Curve Printed on 02/03/2004 10:31 AM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALISADES	UNIRR	SA302BM	NA	C-1279-1
2	PALISADES	W-290	SA302BM	NA	C-1279-1
3	PALISADES	W-110	SA302BM	NA	C-1279-1
4	PALISADES	W-100	SA302BM	NA	C-1279-1
5	PALISADES	A-240	SA302BM	NA	C-1279-1



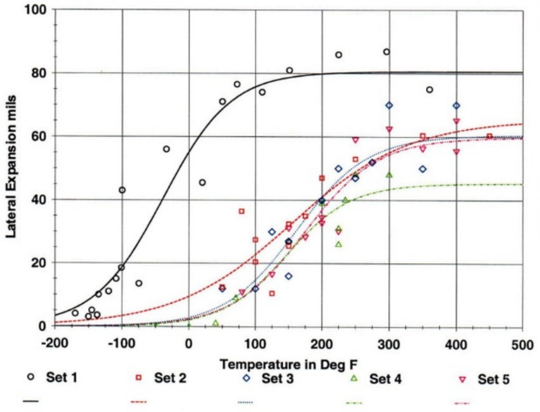
Results

Curve	Fluence	LSE	USE	d-USE	T @30	d-T @30	T @50	d-T @50
1	0	2. 1	115. 5	. 0	- 89. 6	. 0	- 48. 9	. 0
2	9. 26E18	2. 2	78. 6	- 36. 9	104. 5	194. 1	188. 3	237. 2
3	1. 66E19	2. 2	81. 0	- 34. 5	137. 1	226. 7	190. 1	239. 0
4	2. 09E19	2. 2	59. 7	- 55. 8	101. 4	191. 0	179. 2	228. 1
5	4. 01E19	2. 2	59. 1	- 56. 4	183. 5	273. 1	275. 8	324. 7

Palisades Nuclear Plant - Heat Affected Zone

CVGRAPH 5.0.1 Hyperbolic Tangent Curve Printed on 02/03/2004 10:33 AM
Data Set(s) Plotted

Curve	Plant	Capsule	Material	Ori.	Heat #
1	PALISADES	UNIRR	SA302BM	NA	C-1279-1
2	PALISADES	W-290	SA302BM	NA	C-1279-1
3	PALISADES	W-110	SA302BM	NA	C-1279-1
4	PALISADES	W-100	SA302BM	NA	C-1279-1
5	PALISADES	A-240	SA302BM	NA	C-1279-1



Results

Curve	Fluence	LSE	USE	d-USE	T @35	d-T @35
1	0	. 0	80. 6	. 0	- 52. 9	. 0
2	9. 26E18	. 0	65. 5	- 15. 1	167. 0	219. 9
3	1. 66E19	. 0	60. 5	- 20. 1	178. 4	231. 3
4	2. 09E19	. 0	45. 3	- 35. 3	205. 9	258. 8
5	4. 01E19	. 0	59. 8	- 20. 8	193. 1	246. 0

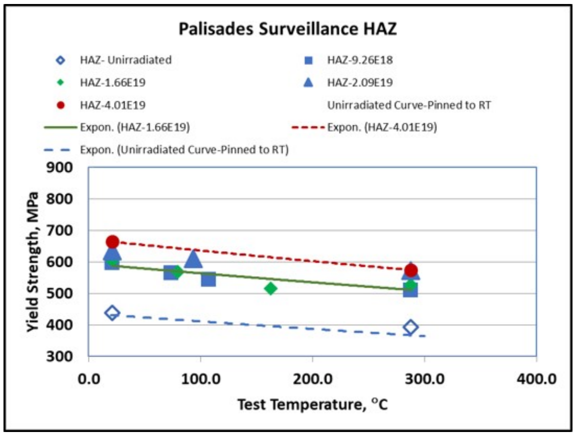


Figure E1. Tensile yield strength data after fitting measured surveillance data and estimating data at other temperatures for PNGS HAZ.

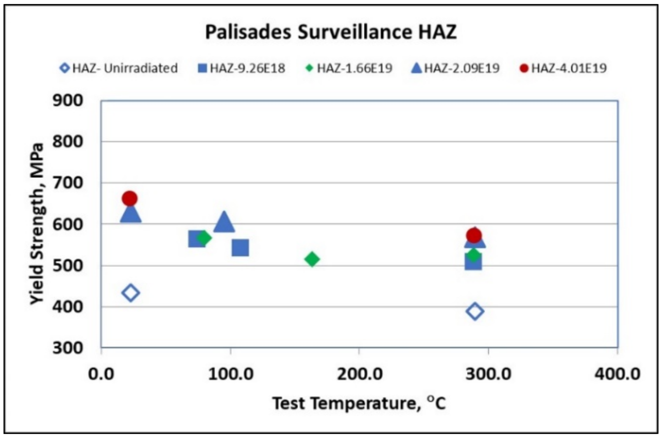
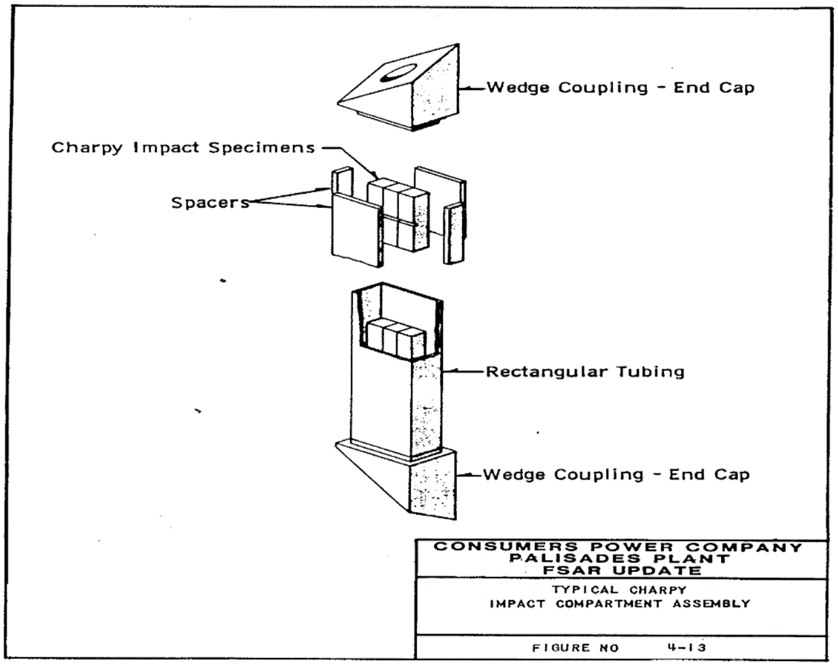


Figure. E2. Measured surveillance tensile yield strength data for PNGS HAZ.

APPENDIX F. DRAWINGS OF SPECIMEN COMPARTMENTS IN THE PNGS RPV SURVEILLANCE CAPSULES

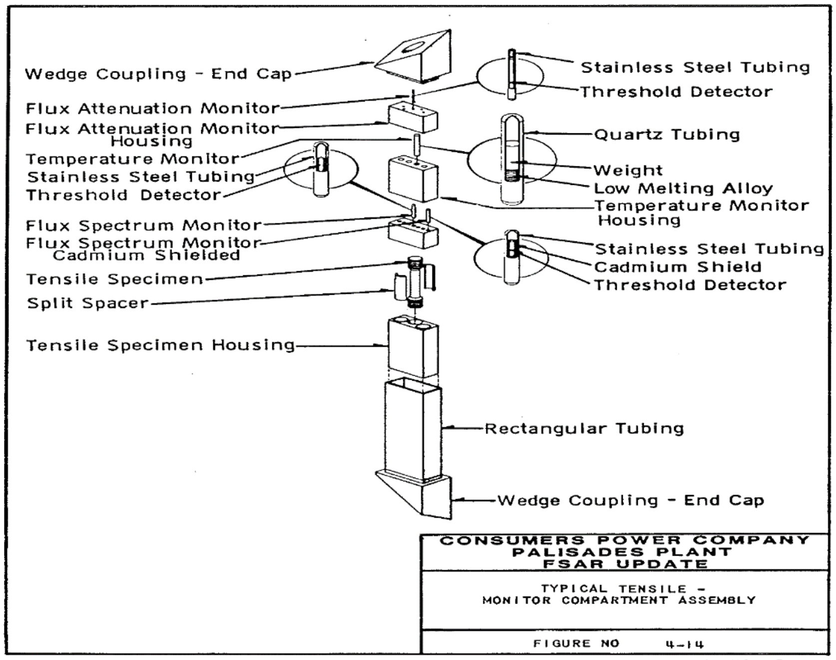


CONSUMERS POWER COMPANY
PALISADES PLANT
FSAR UPDATE

TYPICAL CHARPY
IMPACT COMPARTMENT ASSEMBLY

FIGURE NO 4-13

REVISION NO 0



CONSUMERS POWER COMPANY
PALISADES PLANT
FSAR UPDATE

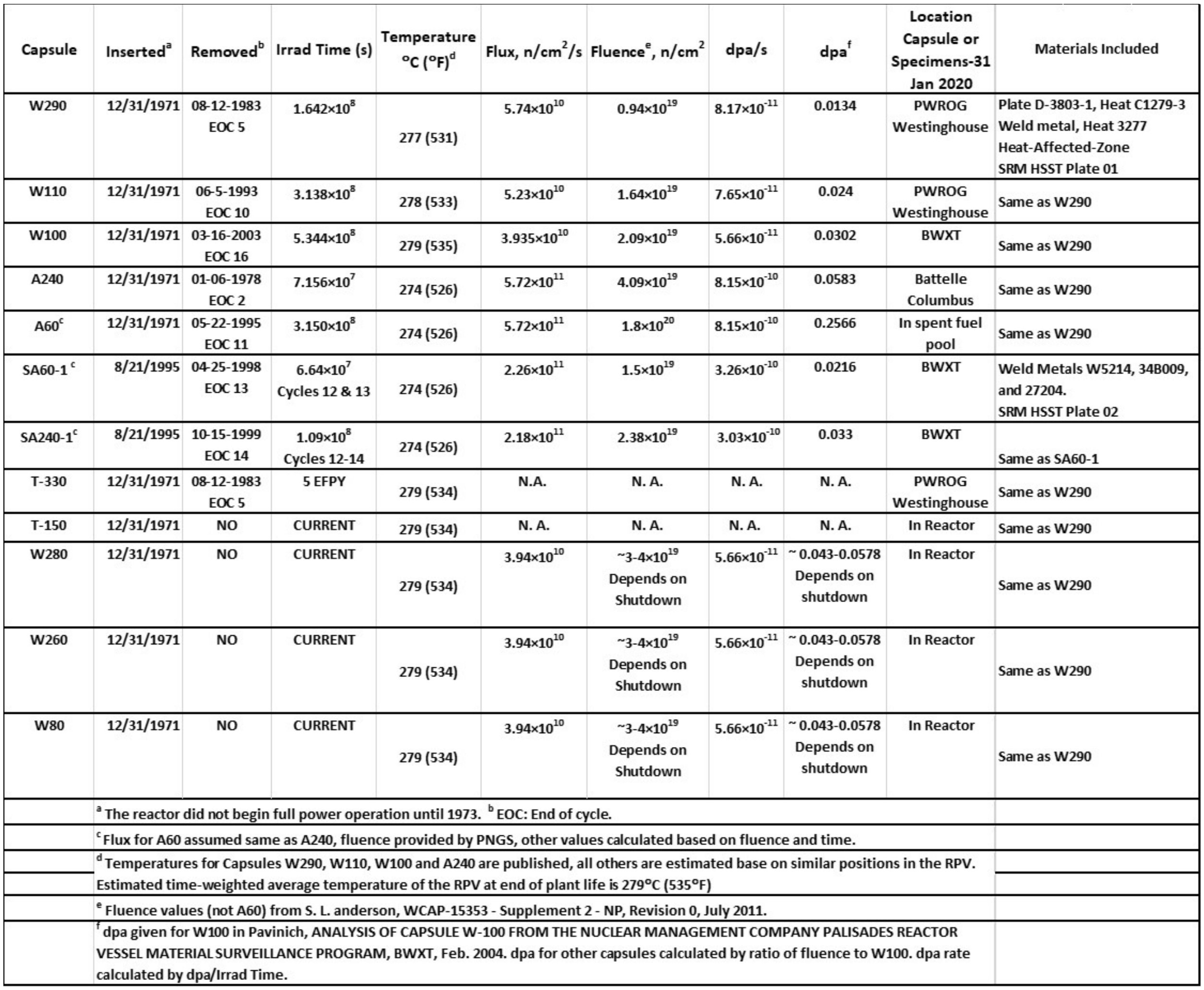
TYPICAL TENSILE -
MONITOR COMPARTMENT ASSEMBLY

FIGURE NO 4-14

REVISION NO 0

APPENDIX G. STATUS OF ALL PNGS RPV SURVEILLANCE CAPSULES AND TEST SPECIMENS

(Values in tables are best available estimates)



Capsule	Inserted[a]	Removed[b]	Irrad Time (s)	Temperature °C (°F)[d]	Flux, n/cm^2/s	Fluence[e], n/cm^2	dpa/s	dpa[f]	Location Capsule or Specimens-31 Jan 2020	Materials Included
W290	12/31/1971	08-12-1983 EOC 5	1.642×10^{8}	277 (531)	5.74×10^{10}	0.94×10^{19}	8.17×10^{-11}	0.0134	PWROG Westinghouse	Plate D-3803-1, Heat C1279-3 Weld metal, Heat 3277 Heat-Affected-Zone SRM HSST Plate 01
W110	12/31/1971	06-5-1993 EOC 10	3.138×10^{8}	278 (533)	5.23×10^{10}	1.64×10^{19}	7.65×10^{-11}	0.024	PWROG Westinghouse	Same as W290
W100	12/31/1971	03-16-2003 EOC 16	5.344×10^{8}	279 (535)	3.935×10^{10}	2.09×10^{19}	5.66×10^{-11}	0.0302	BWXT	Same as W290
A240	12/31/1971	01-06-1978 EOC 2	7.156×10^{7}	274 (526)	5.72×10^{11}	4.09×10^{19}	8.15×10^{-10}	0.0583	Battelle Columbus	Same as W290
A60[c]	12/31/1971	05-22-1995 EOC 11	3.150×10^{8}	274 (526)	5.72×10^{11}	1.8×10^{20}	8.15×10^{-10}	0.2566	In spent fuel pool	Same as W290
SA60-1 [c]	8/21/1995	04-25-1998 EOC 13	6.64×10^{7} Cycles 12 & 13	274 (526)	2.26×10^{11}	1.5×10^{19}	3.26×10^{-10}	0.0216	BWXT	Weld Metals W5214, 34B009, and 27204. SRM HSST Plate 02
SA240-1[c]	8/21/1995	10-15-1999 EOC 14	1.09×10^{8} Cycles 12-14	274 (526)	2.18×10^{11}	2.38×10^{19}	3.03×10^{-10}	0.033	BWXT	Same as SA60-1
T-330	12/31/1971	08-12-1983 EOC 5	5 EFPY	279 (534)	N.A.	N. A.	N. A.	N. A.	PWROG Westinghouse	Same as W290
T-150	12/31/1971	NO	CURRENT	279 (534)	N. A.	N. A.	N. A.	N. A.	In Reactor	Same as W290
W280	12/31/1971	NO	CURRENT	279 (534)	3.94×10^{10}	~3-4×10^{19} Depends on Shutdown	5.66×10^{-11}	~ 0.043-0.0578 Depends on shutdown	In Reactor	Same as W290
W260	12/31/1971	NO	CURRENT	279 (534)	3.94×10^{10}	~3-4×10^{19} Depends on Shutdown	5.66×10^{-11}	~ 0.043-0.0578 Depends on shutdown	In Reactor	Same as W290
W80	12/31/1971	NO	CURRENT	279 (534)	3.94×10^{10}	~3-4×10^{19} Depends on Shutdown	5.66×10^{-11}	~ 0.043-0.0578 Depends on shutdown	In Reactor	Same as W290

[a] The reactor did not begin full power operation until 1973. [b] EOC: End of cycle.

[c] Flux for A60 assumed same as A240, fluence provided by PNGS, other values calculated based on fluence and time.

[d] Temperatures for Capsules W290, W110, W100 and A240 are published, all others are estimated base on similar positions in the RPV. Estimated time-weighted average temperature of the RPV at end of plant life is 279°C (535°F)

[e] Fluence values (not A60) from S. L. anderson, WCAP-15353 - Supplement 2 - NP, Revision 0, July 2011.

[f] dpa given for W100 in Pavinich, ANALYSIS OF CAPSULE W-100 FROM THE NUCLEAR MANAGEMENT COMPANY PALISADES REACTOR VESSEL MATERIAL SURVEILLANCE PROGRAM, BWXT, Feb. 2004. dpa for other capsules calculated by ratio of fluence to W100. dpa rate calculated by dpa/Irrad Time.

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