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Reactor Pressure Vessel Task of Light Water Reactor Sustainability Program: Assessment of High Value Surveillance Materials

June 2011

Prepared by

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Light Water Reactor Sustainability

Reactor Pressure Vessel Task of Light Water Reactor Sustainability Program: Assessment of High Value Surveillance Materials (including Palisades Capsule)

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1. INTRODUCTION

The reactor pressure vessel (RPV) in a light-water reactor (LWR) represents the first line of defense against a release of radiation in case of an accident. Thus, regulations that govern the operation of commercial nuclear power plants require conservative margins of fracture toughness, both during normal operation and under accident scenarios. In the unirradiated condition, the RPV has sufficient fracture toughness such that failure is implausible under any postulated condition, including pressurized thermal shock (PTS) in pressurized water reactors (PWR). In the irradiated condition, however, the fracture toughness of the RPV may be severely degraded, with the degree of toughness loss dependent on the radiation sensitivity of the materials. As stated in previous progress reports, the available embrittlement predictive models, e.g. [1], and our present understanding of radiation damage are not fully quantitative, and do not treat all potentially significant variables and issues, particularly considering extension of operation to 80y.

The major issues regarding irradiation effects are discussed in [2, 3] and have also been discussed in previous progress and milestone reports. As noted previously, of the many significant issues discussed, the issue considered to have the most impact on the current regulatory process is that associated with effects of neutron irradiation on RPV steels at high fluence, for long irradiation times, and as affected by neutron flux. It is clear that embrittlement of RPV steels is a critical issue that may limit LWR plant life extension. The primary objective of the LWRSP RPV task is to develop robust predictions of transition temperature shifts (TTS) at high fluence (ϕt) to at least 10^{20} n/cm^2 (>1 MeV) pertinent to plant operation of some pressurized water reactors (PWR) for 80 full power years. New and existing databases will be combined to support developing physically based models of TTS for high fluence-low flux ($\phi < 10^{11}$ n/cm^2-s) conditions, beyond the existing surveillance database, to neutron fluences of at least $1{\times}10^{20}$ n/cm^2 (>1 MeV).

This report provides the status for the Milestone L-11OR040202 Level M2, #M2L11OR04020205, "Complete assessment of other high value surveillance materials (including Palisades capsule)." This milestone is associated with procurement of materials from commercial power reactor surveillance programs for eventual inclusion in research reactor irradiation experiments, such as the UCSB ATR-2 experiment, and/or microstructural examination.

2. COMMERCIAL RPV SURVEILLANCE MATERIALS

2.1 MATERIALS FOR THE ATR-2 EXPERIMENT

To obtain high fluence data in a reasonable time (e.g., ~ one year), test reactor experiments must be performed in such a way to enable development of a mechanistic understanding of the effects of flux [2, 3]. As described previously, one such experiment is currently under preparation and will be performed as part of a Nuclear Energy University Program (NEUP) grant to the University of California, Santa Barbara (UCSB) in cooperation with ORNL within the LWRSP. The experiment (designated ATR-2) will be performed at the National Scientific User Facility at the Advanced Test Reactor, managed by the Idaho National Laboratory (INL).

A description of the ATR-2 experiment was provided in a previous progress report and will be summarized here. A so-called "Small I" location just inside the reflector of the ATR has been made available. This position will provide space for an irradiation capsule of about 20 mm diameter and 1.2 m long, and will be sufficient to allow for inclusion of more than 1800 small specimens (seven different geometries), including tensile, microhardness, fracture toughness, and specimens for microstructural examination (e.g., small-angle neutron scattering, atom probe, etc). The capsule will incorporate a thermal neutron shield and active temperature control with three major regions irradiated at 270, 290 and 310°C, and one small region at 250°C. The specimens will be irradiated at a flux of about 2×10^{12} n/cm^2 (>1 MeV) to a fluence of 1×10^{20} n/cm^2 and tested. The objective is to obtain a high f1uence, intermediate flux database to couple to a large body of existing data for a large set of common alloys (≥ 100) irradiated over a wide range of flux and fluence. Figure 2.1 shows the flux/fluence range for the ATR-2 experiment (red circles). The results from the experiment will allow for direct comparisons with two existing test reactor databases (IVAR and REVE).

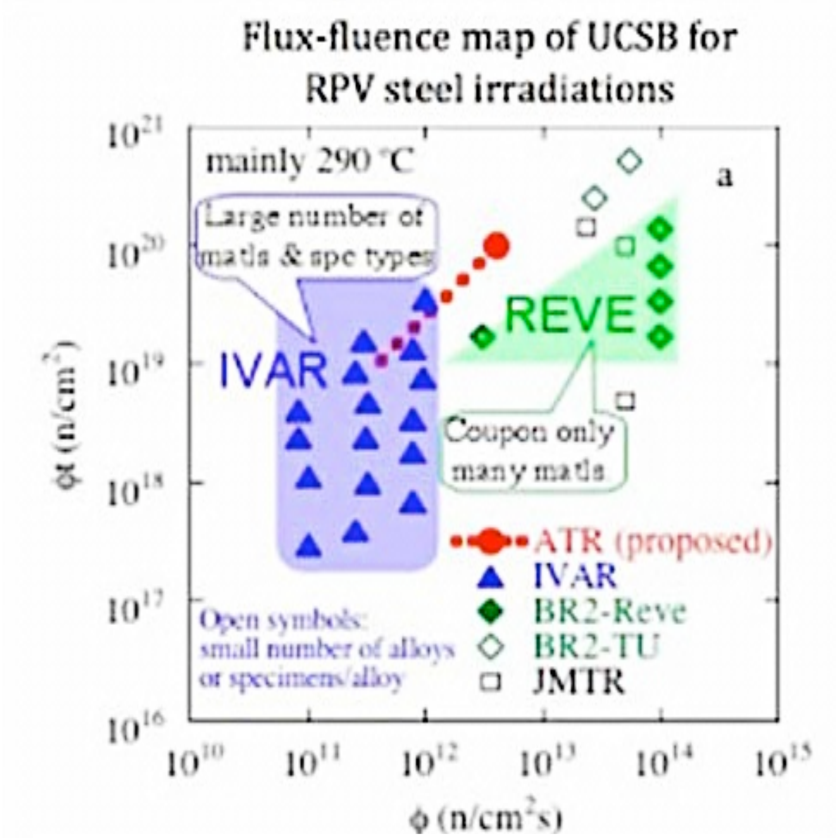

Figure 1. Schematic depiction of the flux/fluence range for the ATR-2 experiment, showing overlap of existing data from the IVAR and REVE databases.

Thus, a variety of relatively small specimens of many different RPV steels will be incorporated, including many materials that have been irradiated and tested in previous test reactor programs at different flux levels. Some of the materials are HSST Plate 02, HSSI Weld 73W, Midland Beltline Weld (WF-70), and other alloys from the UCSB IVAR project, etc.

Additionally, surveillance materials from various operating nuclear reactors will be included to enable a direct comparison of results from a test reactor at high flux and a power reactor at low flux. In collaboration with the nuclear power industry and Mr. William Server of ATI-Consulting, archival materials have been procured from various sources within the U.S. nuclear industry. Mr. Server contacted all the appropriate utilities to request material and, in one instance, visited the storage facility at Westinghouse in Pittsburgh to locate specific archive materials.

Table 2.1 shows the specific RPV surveillance materials that were previously identified as those that would provide results of particular interest. For the materials in Table 2.1, contacts have been made with the relevant nuclear utilities to obtain archival material for each case and the right hand column provides the status as of October 2010 in each case. These materials have been selected based not only on their chemical composition but also on their inclusion in capsules intended for relatively high fluence to allow for comparisons of results from surveillance conditions and the test reactor conditions in the ATR-2 and subsequent experiments.

Table 2.1. U.S. nuclear plant RPV surveillance materials identified for potential evaluation.

Plant/Capsule	Fluence (E19)	Base Metal Heat	Cu	Ni	Weld	Flux/Heat	Cu	Ni	Comments
Farley1-Z	8.47	SA-533B-1	0.14	0.55	Linde	0091 (33A277)	0.14	0.19	Test reactor data exist for this weld wire heat (low Cu weld MTR program - Hawthorne et al.); archive Farley-1 material **has been located at Westinghouse**; other weldments from this same weld wire heat are **potentially** available ffrom Maine Yankee and Calvert Cliffs-1 archives at another Westinghouse/CE storage location if ever needed; non-irradiated Master Curve data exist for this weld wire heat; **formal approval from utility has been received, and material has been cut and will be shipped to ORNL from Westinghouse**
Farley1-V	7.14								
Farley1-W	4.75								
Farley1-X	3.06								
Farley2-Y	6.79	SA-533B-1 (C7466-1)	0.2	0.6	SMAW	(BOLA)	0.03	0.9	Test reactor data may exist for the weld metal from low Cu weld program (TBD); archive Farley-2 plate and weld metal material has been found (one 1/2-T CT for weld metal and twelve 1/2-T CTs for base metal); also other archive was located at Westinghouse, but will require further work to determine usability; **formal approval from utility has been received and some 1/2-T CT specimens have been shipped to ORNL from Westinghouse**
Farley2-Z	4.92								
Farley2-X	2.98								
Farley2-V	13.6 (2019)								
VC Summer-Z	6.54	SA-533B-1	0.1	0.51	Linde	124 (4P4784)	0.05	0.91	Key comparison of Linde 124 weld with SMAW weld from Farley-2; archive Summer weld metal located (six 1/2-T CTs); also other archive was located at Westinghouse, but will require further work to dertermine usability; **formal approval from utility has been received and material 1/2-T CT specimens have been shipped to ORNL from Westinghouse**
VC Summer-W	4.63								
VC Summer-Y	4.63 (2016)								
Kewaunee-T	5.62	SA-508-2 (122X208VA1 or 123X167VA1)	0.06	0.75	Linde	1092 (1P3571)	0.22	0.72	Same weld wire heats between Kewaunee and MY; fracture toughness data exist from Capsules T and S; **archive material for Kewaunee weld and forging have been located at Westinghouse ; utility approval has been received; pieces of materials will be shipped to ORNL from Westinghouse**
Kewaunee-S	3.67								
Kewaunee-N	9.2 (2022)								
MY-A35	6.11	SA-533B-1	0.1	0.53			0.36	0.78	Test reactor data exist for this weldment; also fracture toughness data exist from Capsule A-35; archive material has been located at Westinghouse (untested CVN specimen(s); utility approval has been received; **specimens have been shipped to ORNL from Westinghouse**

BV2-X	5.6	SA-533B-1 (B9004-2)	0.05	0.56	Linde	0091	0.08	0.07	Low copper plate to be compared with Farley-2 higher copper plate; archive material has been located at Westinghouse, **utility approval has been received, and a piece is is being cut and will be shipped to ORNL from Westinghouse**
BV2-W	3.63								
BV2-Y (2014)	6.0								
Robinson2-X	4.49	SA-302	0.12	N/A	Linde	124	0.34	0.66	Backup
Robinson2-T	3.87								
Robinson2-U (2011)	3.87								
Prairie Is1-R	4.48	SA-508-3	0.06	0.72	SMIT	89	0.13	0.09	Backup
Prairie Is1-S	4.02								
Prairie Is1-S (2011)	5.16								
Prairie Is2-R	4.38	SA-508-3	0.09	0.7	SMIT	89	0.08	0.07	Backup
Prairie Is2-P	4.17								
Prairie Is2-P (2014)	5.2								
Palisades-A240	4.01	SA-302B Mod.	0.25	0.53	Linde	1092	0.23	1.2	Need to get untested Capsule A60 to ORNL; **ORNL is pursuing rental of shiping container from Westinghouse;** older tested specimens probably have been discarded; heat code needs confirmation
Palisades - A60	>10								
Palisades-W80 (2019)	3.06								
Palisades - SA240	2.38	NA					0.307	1.045	Different weld wire heat; fracture toughness data exist
Palisades - SA60	1.5								
Diablo Canyon1 - V	1.37	SA-533B-1	0.08	0.46	Linde	1092	0.21	0.98	Original surveillance program, possibly another capsule will be tested in 2010/2011
Diablo Canyon Supplemental Capsules B, C, & D	TBD	NA				1092			Same weld heat as above, but slightly different chemistry
						80			WW7
						80			W8A/B
						0091			W9A/B
						124			72WP; still researching if capsule with DC-1 will be tested in 2010 or 2011, non-irradiated archive available form ORNL
Turkey Point 4	3.0 and higher with future capsules	NA			Linde	80 (71249)	0.29	0.6	Irradiated data from several sources including B&WOG and Point Beach 1**; material being shipped from Florida Power and Light to ORNL to be cut from archive block**

NOTES:

Blue indicates primary materials of interest

Yellow indicates capsules of interest

Capsules with dates after the fluence are planned values assuming the coordinated PWR surveillance program

Two outcomes of that activity were the shipping of pieces of some materials to ORNL by Dr. Brian Burgos of Westinghouse and Mr. Scott Boggs of Florida Power and Light (Turkey Point Unit 4 weld). They are shown in Table 2.2 below. Small specimens (thin wafers) have been machined from all of these surveillance materials and shipped to UCSB for punching of discs and inclusion in the UCSB ATR-2 experiment capsule. The ATR-2 experiment was inserted into the reactor and began irradiation on June 6, 2011. It is expected to achieve the target fluence in about one year.

Table 2.2. List of archival surveillance materials supplied by Westinghouse and Florida Power and Light for the ATR-2 experiment.

Plant	Material	Heat Number	Specimen Provided
Farley Unit 2	SMAW	BOLA	One (1) 1/2T-CT **"CW25"**
Farley Unit 2	SA533B-1	C7466-1	Two (2) 1/2T-CT **"CT29"** and **"CL28"**[(a)]
V.C. Summer	Linde 124 Weld	4P4784	One (1) 1/2T-CT **"CW26"**
Kewaunee	Linde 1092 Weld	1P3571	0.5" x 3" x 1.5" slice of weldment (weld marked)
Maine Yankee	Linde 1092 Weld	1P3571	Two (2) untested tensile **"4KL"** and **"3J2"** Two (2) broken Charpy halves from specimen **"372"**
Farley Unit 1	Weld	33A277	
Beaver Valley Unit 2	Plate	B9004-1	Block 5×2.25×2.375 in.
Kewaunee	Forging, SA 508-2	B6307-1	Block 3.19×0.875×0.55 in.
Turkey Point Unit 4	Linde 80 Weld, SA-1094	Weld wire heat #71249 and Linde 80 flux lot 8457.	Block 3.375x4.25x8.625 in. (Block returned following machining of specimens)

Notes:

(a) "CT" refers to transverse orientation and "CL" refers to longitudinal orientation.

2.2. MATERIALS FROM THE GINNA REACTOR

The Nuclear Plant Life Extension Demonstration (NPLED) Project is a partnership between the Department of Energy (DOE), the Electric Power Research Institute (EPRI) and Constellation Energy, owner of the Ginna Nuclear Plant. The NPLED will investigate the technical issues and demonstrate analysis methods to achieve nuclear plant life extension to 80 years. Many issues have been identified that are of mutual interest within the partnership, and the methods to investigate the issues will be determined through the DOE LWRS Program and the EPRI Long Term Operation (LTO) Project. Constellation Energy's Ginna and Nine Mile Point nuclear power stations will both be used as the pilot plant sites due to their age (~40 y) and representation of the PWR and BWR technologies. For the RPV task, materials from the Ginna PWR RPV are of the highest interest due to their higher irradiation fluence and demonstrated irradiation-induced embrittlement from the RPV surveillance program.

The Ginna RPV was fabricated with a Linde 80 weld metal and this material was included in the surveillance program. The weld metal chemical composition is 0.24% Cu, 0.52% Ni, and 1.30%

Mn (all wt%). Four capsules were removed and tested over the course of reactor operation with neutron fluences ranging from 5.0×10^{18} n/cm^2 to 3.7×10^{19} n/cm^2 and with Charpy impact 30 ft-lb shifts from 148 to 221°F. The tested specimens are located at the Westinghouse hot cell facility. The intent is to obtain pieces of the tested specimens for microstructural examination using atom probe tomography and small-angle neutron scattering.

2.3 MATERIALS FROM THE ZION REACTORS

The LWRS Program, in cooperation with EPRI, the NRC, and Westinghouse, is engaged in discussions with Zion Solutions, Inc., owner of the Zion Nuclear Plant, Units 1 and 2. These two reactors have been shut down since 1998, having operated for only about 15 effective full power years. A number of specific recommendations have been made by the RPV task of the LWRS Program relative to information provided by Zion Solutions, Inc. These recommendations are provided below:

- Previously tested surveillance specimens will be sectioned and evaluated by microstructural techniques such as atom probe tomography and small-angle neutron scattering.
    - Capsule U from Zion 1 at 0.9×10^{19}n/cm^2 both base metal and weld metal
    - Capsule Y from Zion 2 at 1.5×10^{19} n/cm^2; both base metal and weld metal
    - Note: Surveillance welds with heat 72105 used different welding flux than for RPV weld.
- Untested surveillance specimens from Zion 2 will be obtained and tested.
    - Capsule X from Zion 2 at 1.4×10^{19} n/cm^2; test specimens and perform microstructural investigations, e.g., atom probe tomography and small-angle neutron scattering.
    - Note: Surveillance welds with heat 72105 used different welding flux than for the RPV weld.
- Large sections of the RPVs will be sectioned to machine specimens from the Linde 80 (weld wire 72105) weld (RPV peak fluence $< 1\times10^{19}$ n/cm^2):
    - First, determine through-thickness variation in chemical composition (especially Cu).
    - Perform CVN and tensile tests to compare with surveillance results.
    - Perform CVN, tensile, and K_{Jc} testing through thickness to evaluate attenuation.
    - Zion 2 weld metal showed a Charpy 30 ft-lb shift of 225°F at 1.5×10^{19} n/cm^2.
- Possibly perform similar investigations with base metals to evaluate flux effects and attenuation effects. The Zion 2 base metal showed a Charpy 30 ft-lb shift of 121°F at 1.5×10^{19} n/cm^2.
- Thermal annealing of RPV materials may be performed to compare with the same materials irradiated in test reactors.
- Proposals by others have been made to perform non-destructive examination on the RPV prior to segmentation.

The DOE, NRC, EPRI, and Industry have all expressed similar interests for uses of the Zion RPV materials, and a coordinated research plan is still under development.

2.4 MATERIALS FROM THE RINGHALS REACTORS

Dr. Pal Efsing of Vattenfall AB in Sweden has provided small samples of surveillance materials removed from tested Charpy impact specimens. All the surveillance specimens are from low-copper high-nickel weld metals in Ringhals Units 3 and 4, both pressurized water reactors. Table 2.3 provides the chemical composition for the materials, showing nickel contents of about 1.6 wt%

nickel and copper contents of 0.08 wt% or less. Table 2.4 provides the irradiation temperature, neutron flux and fluence for each specimen. The samples provided by Vattenfall are slices from Charpy impact specimens and are about 10×10×0.4 mm thick. These specimens will be used to prepare samples for atom probe tomography and small-angle neutron scattering to characterize the microstructure relative to irradiation-induced precipitates and other defects. These materials are of high interest because they have relatively low copper and high nickel contents, and have been irradiated to relatively high neutron fluences. This again relates to the issue of late-blooming nickel-manganese-silicon phases, especially since these materials have low copper contents.

Table 2.3. Chemical compositions of RPV surveillance materials from Ringhalls Units 3 and 4.

Matl	C	Si	Mn	P	S	Cr	Mo	Ni	Cu
Unit R3	0.052	0.21	1.46	0.009	0.006	0.07	0.54	1.58	0.08
Unit R4	0.068	0.14	1.35	0.0015	0.004	0.04	0.5	1.66	0.05
ASME 1971	<0.27	0.15-0.35	0.50-0.90	<0.025	<0.025	0.25-0.45	0.55-0.90	0.55-0.90	0.05

Table 2.4. Neutron exposure data for RPV surveillance materials from Ringhalls Units 3 and 4.

Specimen	Reactor	Capsule	Material	Temp, ϒC	Fluence	EFPY	Calculated Flux
E46,3A	R3	W	Weld	284	4.34E+19	10.4	1.32E+11
E54,3A	R3	W	Weld	284	4.34E+19	10.4	1.32E+11
E6,3A	R3	U	Weld	284	6.39E+19	13.8	1.47E+11
E63,3A	R3	X	Weld	284	6.39E+19	13.8	1.47E+11
E56,5	R3	X	Weld	284	6.39E+19	13.8	1.47E+11
E16,3B	R3	U	Weld	284	6.39E+19	13.8	1.47E+11
E56,3A	R3	X	Weld	284	6.39E+19	13.8	1.47E+11
N27,3B	R4	V	Weld	284	3.30E+19	6.3	1.66E+11
N27,3A	R4	V	Weld	284	3.30E+19	6.3	1.66E+11
N11,3A	R4	U	Weld	284	6.03E+19	12.8	1.49E+11
N18,3B	R4	U	Weld	284	6.03E+19	12.8	1.49E+11

2.5 MATERIALS FROM THE PALISADES REACTOR

The Palisades Nuclear Plant (PNP) included in its surveillance program a surveillance capsule, designated A-60, containing some specimens of a weld metal with nickel content of about 1.36wt% and copper content of about 0.20 wt %. This particular capsule was irradiated to a fluence of 1.8×10^{20} n/cm^2. The capsule was removed from its surveillance position in the early 1990s 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 atom probe tomography and small-angle neutron scattering to assess the irradiation-induced features of this rather unique material condition (very high fluence). The material is also of special interest because of its very high nickel content and potential for development of NiMnSi late blooming phases.

Discussions have been held with the responsible persons at the PNP who have indicated their willingness to provide the capsule for evaluation. Discussions have also been held staff members of Westinghouse regarding retrieval of the capsule from PNP with one of their new shipping casks that can handle a full length surveillance capsule assembly. The preliminary plan is for Westinghouse to retrieve the capsule and ship it to the Westinghouse hot cell facility, disassemble the capsule to retrieve the specimens, and ship the specimens to ORNL for evaluation. This plan is currently in negotiation with Westinghouse.

3. SUMMARY AND CONCLUSIONS

Of the many significant issues discussed for RPVs, the issue considered to have the most impact on the current regulatory process is that associated with effects of neutron irradiation on RPV steels at high fluence, for long irradiation times, and as affected by neutron flux. It is clear that embrittlement of RPV steels is a critical issue that may limit LWR plant life extension. The primary objective of the LWRSP RPV task is to develop robust predictions of transition temperature shifts (TTS) at high fluence (ϕt) to at least 10^{20} n/cm^2 (>1 MeV) pertinent to plant operation of some pressurized water reactors (PWR) for 80 full power years. The RPV task of the LWRS Program is working with various organizations to obtain archival surveillance materials from commercial nuclear power plants. Materials from U.S. plants have been procured and specimens have been machined and inserted in the UCSB ATR-2 irradiation experiment. Materials have been obtained from the Ringhals Units 3 and 4 reactors surveillance program for microstructural examination. Negotiations are currently underway to obtain surveillance materials from the Ginna Nuclear Plant, the Zion Nuclear Plant, Units 1 and 2, and the Palisades Nuclear Power Plant.

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