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# Reactor Pressure Vessel Task of Light Water Reactor Sustainability Program: Milestone M2LW-13OR0402013, Progress Report on Status of Advanced Test Reactor-2 Reactor Pressure Vessel Materials Irradiation Project

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Light Water Reactor Sustainability

# Reactor Pressure Vessel Task of Light Water Reactor Sustainability Program: Milestone M2LW-13OR0402013, Progress Report on Status of Advanced Test Reactor-2 Reactor Pressure Vessel Materials Irradiation Project

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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 ($\phi t$) 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 $1\times10^{20}$ n/cm$^2$ (>1 MeV). All references to neutron flux and fluence in this report are for fast neutrons (>1 MeV).

The RPV task of the LWRS Program is working with various organizations to obtain archival surveillance materials from commercial nuclear power plants to allow for comparisons of the irradiation-induced microstructural features from reactor surveillance materials with those from similar materials irradiated under high flux conditions in test reactors. This report is submitted relative to the Level 2 Milestone (M2LW-13OR0402013), “Complete Progress Report on Status of Advanced Test Reactor-2 Reactor Pressure Vessel Materials Irradiation Project.”

# 2. BACKGROUND AND REVIEW

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, such an irradiation experiment is currently underway as part of the Idaho National Laboratory (INL) Advanced Test Reactor (ATR) National Scientific User Facility (NSUF). The experiment was awarded to University of California, Santa Barbara (UCSB) and its collaborator, ORNL, several years ago with full funding for the facility provided by DOE through the NSUF. A description of the UCSB ATR-2 experiment and materials was provided in previous progress reports [4, 5] and will be summarized briefly here.

In collaboration with UCSB the INL staff carried out conceptual design of the sophisticated instrumented irradiation test assembly. The INL staff carried out the engineering design, construction and insertion of the test assembly, which is currently responsible for operation of the UCSB

ATR-2 irradiation. The scientific experiment itself was designed by UCSB in collaboration with ORNL. The total of 172 alloys included in the experiment were acquired by UCSB and ORNL, including those contributed by Rolls Royce Marine (UK), Bettis Atomic Power Laboratory (US), and the Central Research Institute for the Electric Power Industry (Japan). Notably, the Rolls Royce contribution included a total of more than 50 new alloys. Additionally, surveillance materials from various operating nuclear reactors are included to enable a direct comparison of results from a test reactor at high flux and a power reactor at low flux. The specific surveillance materials were described in detail in [4, 5] and are summarized below. Fabrication of the specimens was primarily carried out by UCSB with the assistance of ORNL. The specimens were loaded into thin walled cups at UCSB and the cups were loaded into the test assembly at INL.

The irradiation is being carried out in the so-called “Small I” position in ATR just inside the pressure vessel and reflector. The test assembly has a 20 mm inside diameter and is ≈ 1.2 m long. The UCSB ATR-2 experiment includes ≈ 1625 small specimens in three basic geometries. These include: tensile specimens, for a large matrix of alloys; so-called multipurpose coupons that will support microhardness, shear punch and a wide variety of microstructural characterization studies (e.g., small-angle neutron scattering, atom probe, etc) for all the alloys; and, 20-mm diameter disc compact tension (DCT) fracture specimens for three alloys - the Palisades B weld and two UCSB forgings (C17 and LP). The DCT specimens are being irradiated at a nominal temperature of 290°C. The test assembly includes a thermal neutron shield and active temperature control with three major regions at nominal temperatures of 270, 290 and 310°C, and one small region at 250°C. The specimens are being irradiated at a peak flux of about $3.3\times10^{12}$ n/cm$^2$-s (>1 MeV) to a target fluence of $1\times10^{20}$ n/cm$^2$. 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 line). The results from the experiment will allow for direct comparisons with two existing test reactor databases (IVAR and REVE, shown in triangles and circles, respectively).

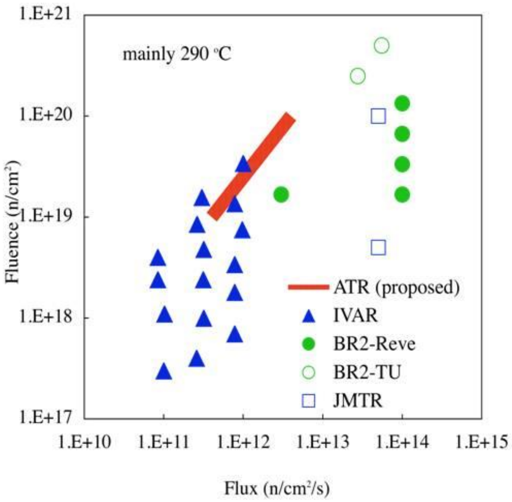

**Figure 2.1. Schematic depiction of the flux/fluence range for the ATR-2 experiment, showing overlap of existing data from the IVAR and REVE databases.**

Thus, a variety of relatively small specimens of many different RPV steels have been 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 are included to enable a direct comparison of results from a test reactor at high flux and power reactors at low fluxes. A variety of surveillance materials were identified as those that would provide results of particular interest to the ATR-2 experimental objectives. These materials were identified 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. From the group of materials identified as potential candidates, and with the major assistance of Mr. William Server of ATI-Consulting, we were able to procure nine specific RPV surveillance materials for inclusion in the ATR-2 capsule and they are shown in Table 2.1 below.

**Table 2.1. 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"**<br>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.

In summary, a variety of relatively small specimens of many different RPV steels are being irradiated in UCSB ATR-2, including many materials that have been irradiated and tested in previous test reactor and surveillance programs at different flux levels.

The UCSB ATR-2 irradiation test assembly was completed in late spring of 2011 and was successfully installed in the ATR on May 26, 2011. The irradiation began on June 7, 2011 and was anticipated to achieve its target fluence of $1\times10^{20}$ n/cm$^2$ (E>1 MeV) in the autumn of 2012. Thermocouple monitors during the course of the irradiation campaign have shown that the specimens are generally being irradiated at or close to their target temperatures.

# 3. CURRENT STATUS OF THE ATR-2 EXPERIMENT

A number of delays in operation of the ATR have pushed the completion of the ATR-2 irradiation campaign deep into 2013. Chief among these is the Powered Axial Locator Mechanism (PALM) cycle, which is occasionally performed by the ATR for complex transient testing and which can simulate multiple start-up and shutdown cycles of tests for fuels and materials [6]. The PALM tests normally last from a few hours to a couple of days, but some experiments must be removed from the reactor when a PALM test is performed. This is the case for the ATR-2 capsule which must be removed in anticipation of the PALM cycle experiment. Additional delays have now scheduled the PALM cycle for the end of March, 2013.

At the time of the ATR shutdown, the average neutron fluence (>1 MeV) for the ATR-2 capsule was $6.34\times10^{19}$ n/cm$^2$, with a peak fluence of $8.76\times10^{19}$ n/cm$^2$. Thus, a decision was made to have the capsule reinserted following the PALM cycle. This decision compelled design of a mock up experiment to load and remove the capsule. The ATR experiment team designed such an experiment and the necessary tool, and performed a mock up experiment. Recently, a mockup of the ATR-2 test train was placed in the ATR tank and was successfully transferred through the drop chute into the canal. A new tool was designed to grip the bottom of the experiment without damaging the thin walled tubing. The mockup test demonstrated that the new tool could maintain the correct orientation of the experiment needed to complete the transfer. Subsequently, the real test train was successfully transferred to the canal using the same process that was practiced with the mockup. The experiment will remain in the canal through the PALM cycle, then it will be transferred back into the ATR for additional cycles. The ATR-2 Experiment Manager reported that the team performing this work did an excellent job in transferring the capsule.

Based on the projected cycle times, the average and peak fluences would be 8.71 and $1.20\times10^{19}$ n/cm$^2$ after two additional cycles, while they would be 1.01 and $1.40\times10^{19}$ n/cm$^2$ after three additional cycles, respectively. The additional times estimated for this are 133 and 210 days for two and three cyles, respectively, depending on reactor operating efficiency. Three additional cycles would then put the completion of the ATR-2 irradiation campaign at about the end of 2013. A recent telecom with the various participants who have provided materials/specimens for the experiment resulted in a decision to reinsert the capsule for an additional two cycles of irradiation, with a decision to be made at that time regarding a third cycle.

Following completion of the irradiation campaign, the ATR-2 capsule will reside in the canal until ready for shipment to ORNL, with details of capsule disassembly yet to be determined.

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