

Light Water Reactor Sustainability Program:

Zion Unit 1 Reactor Pressure Vessel Sample Acquisition: Phase 2 and Phase 3 Status Report

September 2016

Prepared by

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Zion Unit 1 Reactor Pressure Vessel Sample Acquisition: Phase 2 (Cutting Blocks) and Phase 3 (Machining Test Specimen) Status Report

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EXECUTIVE SUMMARY

The decommissioning of the Zion Units 1 and 2 Nuclear Generating Station in Zion, Illinois, presents a special and timely opportunity for developing a better understanding of materials degradation and other issues associated with extending the lifetime of existing nuclear power plants (NPPs) beyond 60 years of service. In support of extended service and current operations of the US nuclear reactor fleet, the Oak Ridge National Laboratory (ORNL), through the Department of Energy (DOE), Light Water Reactor Sustainability (LWRS) Program, is coordinating and contracting with Zion Solutions, LLC, a subsidiary of Energy Solutions, the selective procurement of materials, structures, and components, from the decommissioned reactors. As described in the report on harvesting Zion Unit 1 reactor pressure vessel (RPV) segments [1], the LWRS Program contracted with Energy Solutions to acquire materials, including segments of the Zion RPV to evaluate potential degradation issues associated with extended lifetime of existing NPPs. This report describes the status of the plan and work to cut seven blocks and machine specimens from the Zion Unit 1 RPV ORNL Beltline Weld Segment 1.

Zion Unit 1 RPV ORNL Beltline Weld Segment 1, which contains well-characterized base metal heat B7835-1 and a section of the well-characterized WF-70 beltline weld (between the lower and the intermediate shells) was harvested and shipped to the Energy Solutions Memphis Processing Facility (MPF) for cutting into seven blocks: five base metal and two beltline weld (Phase 2). As of September 22, 2016, all seven blocks were successfully cut and lifted out of Segment 1. The target shipping date to BWXT (Phase 3 / Zion RPV harvesting project) is the week of October 17th. The blocks in turn will be machined into mechanical test specimens and microstructural characterization samples at BWXT (Phase 3).

The through-wall mechanical test specimens, including Charpy V-Notch (CVN), tensile, and fracture toughness, machined from the beltline WF-70 weld and based metal heat B7835-1, having a peak fluence $< 1 \times 10^{19} \text{ n/cm}^2$ will be tested to evaluate the change in mechanical properties as function of depth (neutron fluence attenuation). These results will be used to assess current radiation damage models [2, 3].

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1. INTRODUCTION

1.1 BACKGROUND

As described in ORNL report, ORNL/TM-2016/240, “Report on the Harvesting and Acquisition of Zion Unit 1 Reactor Pressure Vessel Segments,” [1] components and structures in a NPP must withstand a very harsh operating environment, including extended time at temperature, under stress from operational loads, under neutron irradiation, and in corrosive media. Moreover, extending reactor service beyond 60 years will increase those demands and possibly introduce new modes of degradation [4]. Although the numerous modes of degradation are complex and vary depending on location and material, understanding and managing materials degradation is key for the continued safe and reliable operation of NPPs. As noted in the Expanded Materials Degradation Assessment (EMDA) [5], a comprehensive evaluation of potential aging-related degradation modes, an important component of understanding materials degradation is the examination of service-aged materials. And one important source of service-aged materials has been the Zion Harvesting Project [2]. This project is important because access to materials from active or decommissioned NPPs provide an invaluable resource for which there is limited operational data or experience to inform relicensing decisions and assessments of current degradation models to further develop the scientific basis for understanding and predicting long-term environmental degradation behavior.

The Zion Harvesting Project, in cooperation with Zion Solutions, LLC, a subsidiary of Energy Solutions, an international nuclear services company, is coordinating the selective procurement of materials, structures, components, and other items of interest to the LWRs Program and NRC from the Zion Station (a former nuclear generating facility), in support of extended service and current operations of the U.S. nuclear reactor fleet. The Zion Station is a decommissioned two unit, Westinghouse 4-loop PWR facility, with each unit capable of producing 1,040 MWe. The units were commissioned in 1973, permanently shut down in 1998, and placed into SAFSTOR (a method of decommissioning where a nuclear facility is placed and maintained in a condition that allows the facility to be safely stored and subsequently decontaminated to levels that permit release for unrestricted use) in 2010. Materials of high interest include low-voltage cabling, concrete core samples, through-wall-thickness sections of the RPV, and other structures and components of interest to researchers evaluating aging management issues [5].

A potentially life-limiting component in light-water reactors (LWR) is the RPV because replacement of the RPV is not considered a viable option [2]. Researchers studying the effects of radiation on RPV materials have long been interested in evaluating service-irradiated materials to validate physically-informed correlations of transition-temperature-shift predication models [6]. For those reasons, the LWRs Program proposed the acquisition of segments of the Zion Station Unit 1 RPV, cutting the segments into blocks from the well-characterized beltline weld [7 - 9] and base metal [13], and machining those blocks into mechanical (Charpy, compact tension, and tensile) test specimens and coupons for microstructural (transmission electron microscopy, atom probe tomography, small angle neutron scattering, and nano indentation) characterization.

This report documents the status of Phase 2 and 3 of the Zion RPV project: The receipt of four Zion Unit 1 RPV segments at the Energy Solutions Memphis Processing Facility (MPF) where an RPV segment was cut into blocks. Specifically, Segment 1 of the Zion Unit 1 RPV containing well-characterized base metal heat B7835-1 and a section of the well-characterized WF-70 beltline weld (between the lower and the intermediate shells) was harvested and shipped to the MPF for cutting into blocks (Zion RPV Phase 2). Those blocks will be machined into mechanical and microstructural characterization samples (Zion RPV Phase 3) at BWXT (Lynchburg). Access to service-irradiated RPV welds and plate sections will allow through-wall attenuation studies to be performed, which will be used to assess current radiation damage models. [2, 3]

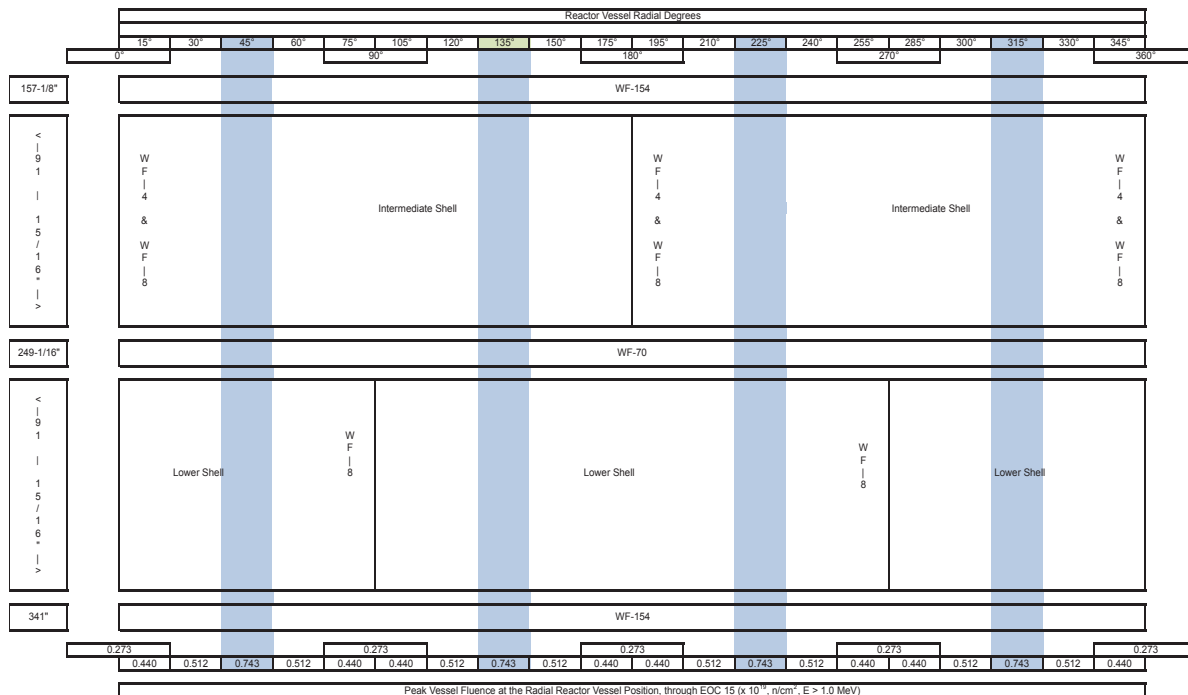


Figure 1. Peak vessel fluence along the circumferential weld of the Zion Unit 1 RPV through End of Cycle (EOC) 13 ($\times 10^{19}$ n/cm², $E > 1.0$ MeV) [10].

1.2 CIRCUMFERENTIAL FLUENCE

An important consideration in the evaluation of which RPV segments to harvest is the circumferential fluence. As shown at the bottom of in Figure 1, peak circumferential fluence varies by a factor of three over a 45° arc from the vertical weld positions to midway between the vertical weld positions. **Based on this variation, the optimum region of beltline weld to harvest would be a section midway between the upper (intermediate shell) and lower (lower shell) vertical welds.**

1.3 RPV SPECIFICATIONS

The Zion RPV has a total height without the head plate of approximately 419 inches (1,064 cm). The vessel wall has an inner diameter of 173 inches (439 cm) and thickness of 8.8 inches (22.4 cm) over the beltline region. The nozzle section is approximately 11 inches thick. Including cladding, the reactor vessel weighs about 700,000 lbs. (317,515 kg) and has a total activity of about 400 curies. The characterization results indicate that the vessel wall is class A waste.

The stainless steel cladding has a nominal thickness of 3/16 inch (~ 5mm). The total weight of the cladding within +/- 2 feet of the core is about 4,750 lbs (2,159 kg) and has a total activity of approximately 145 curies. If it were separate from the vessel wall, the cladding would be class B waste, but if it is integral with the ferritic steel wall, the assembly as a whole is class A. The RPV is composed of the head, nozzle ring section, three ring or shell sections composed of hemispherical plates with two vertical welds, and a bottom plate as shown in a preliminary segmentation plan with horizontal cuts along the three ring sections (nozzle, middle shell, and lower shell) and the bottom plate.

2. SEGMENTATION PLAN

Segmentation Plan: Based on information provided by Mr. Dan E. Pryor, Manager, Reactor Vessel Segmentation, Zion Solutions, the vessel was cut, using an oxy-propylene torch into 17 segments over four levels as shown in figure 2. Level 1, which includes the inlet and outlet nozzles, was cut into eight 45° segments of 157.5" (400 cm) in height. Level 2 was also cut into eight 45° segments of 157.5" (400 cm) in height and 72.9" (185.2 cm) in length as measured from end to end of the outer diameter. Because the vessel could not be rotated 22.5° after the nozzle segments were cut due to the location of the overhead bridge, the level 2 segments, which include most of the intermediate shell and a portion of the lower shell and the well-characterized WF-70 beltline weld, the vertical cuts were made along the same lines as the vertical nozzle cuts, i. e., at the two vertical welds of the intermediate shell, directly above the vertical welds of the lower shell, and in the middle of the peak circumferential flange. Moreover, four segments (1, 2, 7, and 8) also contained the well-characterized base metal B7835-1 in the upper shell (Figure 2, Figure 3, and Figure 4). The beltline pieces cut from the vessel are 8.8 inches thick including a 3/16th inch stainless steel cladding on the internal surface. Each piece weighs approximately 28,000 lbs. (12,727 kg).

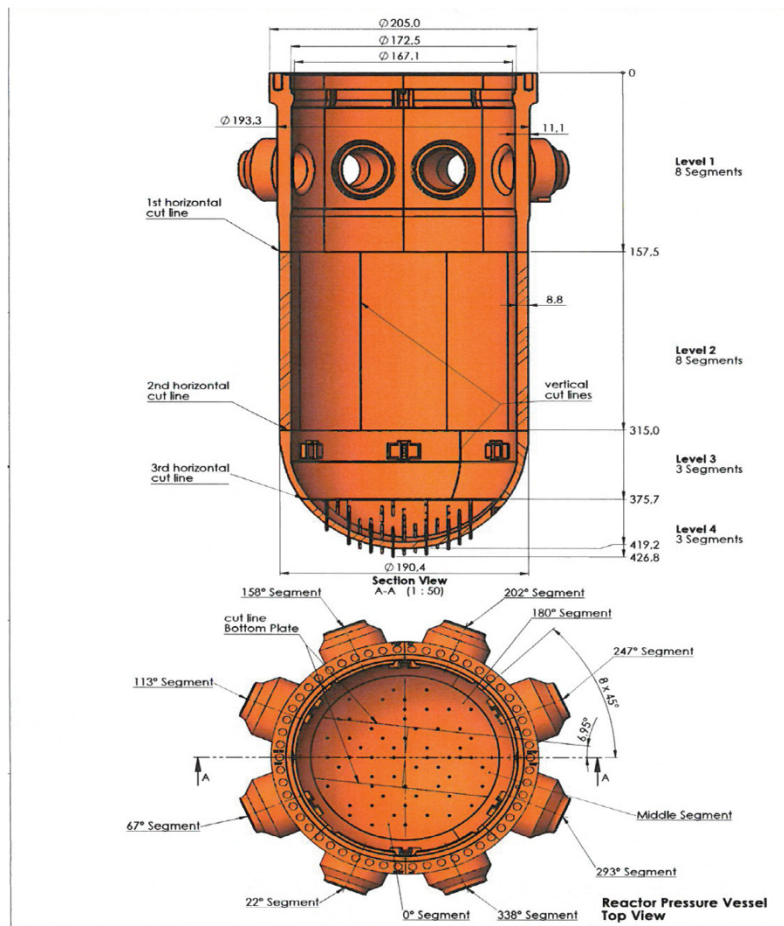


Figure 2. The 2014 RPV Segmentation Plan for the Zion Unit 1 vessel. The black lines are the proposed cut plan. There are eight vertical cuts in the nozzle region and eight vertical cuts in the Level 2 intermediate and lower shell area [11].

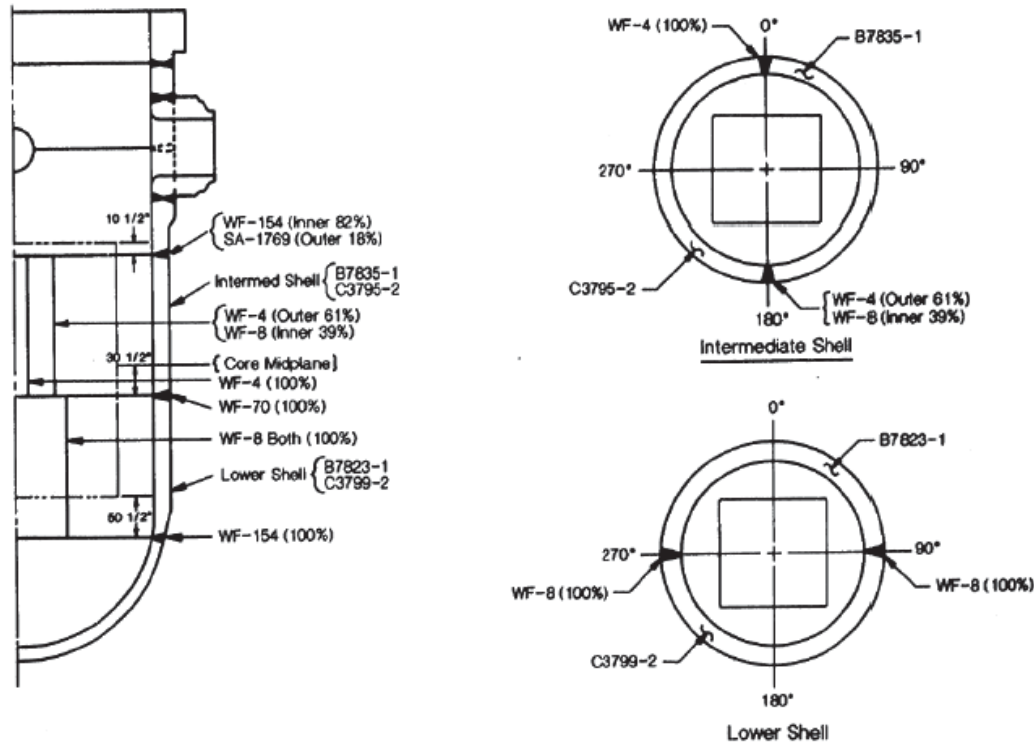


Figure 3. Location of materials (weld and base metal) used in the fabrication of the Zion Unit 1 beltline (intermediate shell to lower shell), two vertical welds above the beltline, and base metal heats [12].

3. ZION RPV PHASE 1: HARVESTING OBJECTIVES AND TASKS

3.1 OBJECTIVES

The initial objective of the harvesting project (Zion RPV Phase 1) was to harvest a segment containing the well-characterized WF-70 beltline weld and the well-characterized base metal heat B7835-1 and an adjoining section, with the same beltline and base metal materials, that overlaps one of four high circumferential fluence regions along the vertical cut (Figure 2, Figure 3, and **Error! Reference source not found.**4). Due to the estimated costs to cut 8 blocks from two segments and machine specimens from 5 of the blocks, a revised objective was developed, after the segments had been loaded into boxes, to obtain only one segment (Segment 1) of the Zion NPP Unit 1 RPV and to cut seven blocks and to machine four of the blocks into WF-70 beltline weld and base metal B7835-1 specimens for laboratory testing. Data from surveillance specimens containing similar WF-70 weld materials and base metal B-7835-1 are available in the literature for a comparison of hardening and changes in fracture toughness [13].

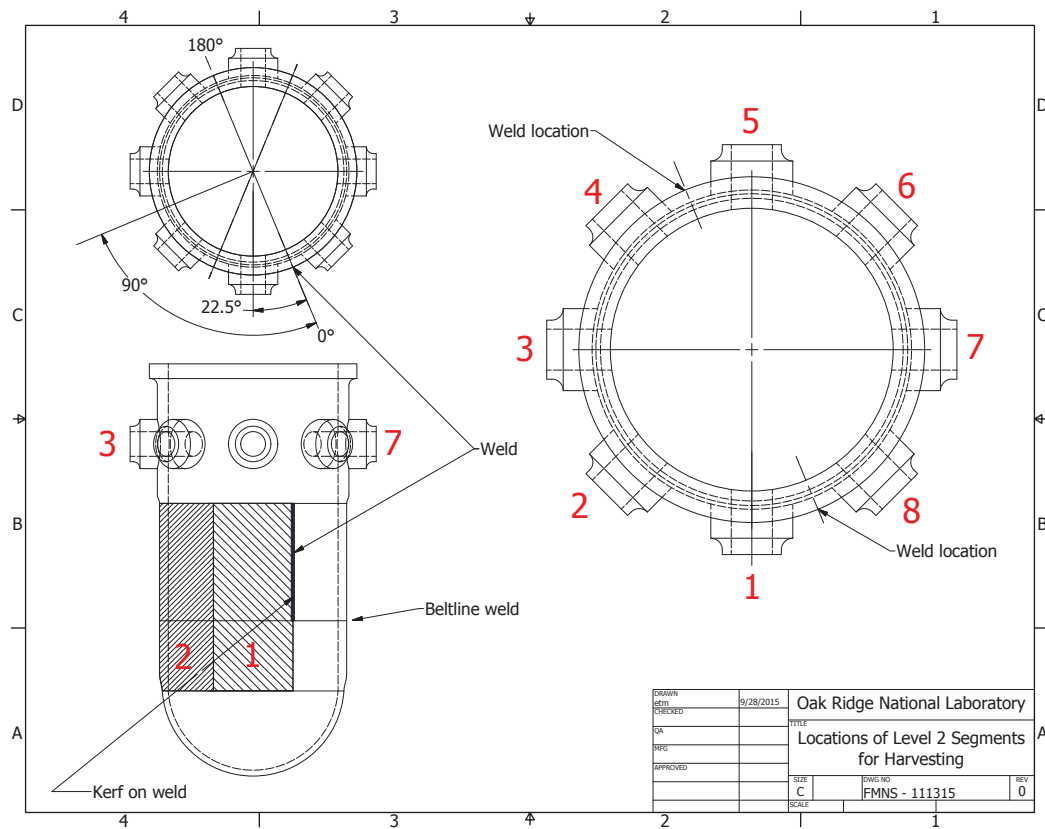


Figure 4. Identification of Level 2 segments (1, 2, 5, and 6) collected as part of process to harvest Segment 1. Segment 1 (as well as Segments 2, 7, & 8) contains the well-characterized base metal B7835-1 (intermediate shell) and a section of the well-characterized WF-70 beltline weld [11].

3.2 TASK 1

Harvest ORNL BW1 RPV Segment: Verifying that the RPV did not rotate a few degrees after cutting and removal of the nozzle shell segments, harvest one segment (Segment 1, Figures 2, Figure 3, and Figure 4) containing base metal B7835-1 and a section of the WF-70 beltline weld (between the lower and the intermediate shells). The right edge (as viewed from the outer wall) of this segment begins at the 0° position / WF-4 vertical weld. This segment is paired with Segment 5 to provide shielding during shipping.

The process used to obtain Segment 1 was as follows:

- The beltline weld was located on the outer wall of the RPV and photographic evidence of the location of the segment provided.
- Segments, ~ 13' x 6' (157.5" x 72.9" x 8.8") of the RPV extending from just below the circumferential weld between the nozzle section and the intermediate shell to just above the circumferential weld between the lower shell and the bottom plate were cut using an oxy-propane torch (Figure 5). The selected segment, Segment 1, contains base metal B7835-1 and a section of the WF-70 beltline weld. The right edge (as viewed from the outer wall of the RPV) begins at the 0° / WF-4 vertical weld.



Figure 5. Vertical cut using an oxy-propane torch of a Zion Unit 1 RPV Level 2 Segment [11].

- c) The cut segment (Segment 1) was removed using a gripper crane and positioned onto the down-ender frame to allow proper positioning in the shipping box. The first segment is loaded face up and the matching (opposite side segment: segment 5) is loaded face down to provide clam-shell shielding in the same manner as used to ship the other RPV sections to the Energy Solutions, Clive, Utah site.

4. TRANSPORTATION OF ZION RPV SEGMENTS

Transportation of Segments: Due to the size and weight of the four Zion Unit 1 RPV Level 2 beltline sections, (~ 13' x 6' or 157.5" x 72.9" x 8.8" thick including a 3/16 in SS cladding on the internal surface, weighing ~ 28,000 lbs. each) in two large steel boxes with a combined weight of ~ 180,000 lbs, a rail car was used to ship the RPV segments to the Energy Solutions, MPF site on March 31, 2016 for cutting Segment 1 into blocks for eventual machining. On April 12, 2016, the railcar containing the four segments arrived at the Energy Solutions MPF site and was received, inspected, and temporarily stored while a revised contract with the Energy Solutions for cutting seven blocks from the Zion Unit 1 RPV Segment 1 was finalized. The cutting phase of the project began on June 20, 2016.

5. PHASE 2: BLOCK CUTTING PLAN [1]

Objectives for Cutting the Segments into Blocks for Machining: The objective was to cut one segment (ORNL BW 1) of the Zion NPP Unit 1 RPV into 7 blocks of welds and base metal and to package those blocks for shipment to a vendor that will machine the blocks into test specimens including Charpy V-Notch (CVN), tensile, and fracture toughness. The cutting waste and remaining unused segments will be packaged and shipped to the Energy Solutions, Clive, Utah site.

Plan Scope: ORNL BW1 RPV (Segment 1), which was harvested from the Zion Unit 1 NPP and includes the WF-70 beltline weld and base metal B7835-1 (Figure 2, Figure 3, and Figure 4) shall be cut into blocks (**Fig. 6**) varying in length from approximately 5.7 x 2.0 x 8.5 inches to 7.6 x 3.0 x 8.5 inches to 11.25 x 3.0 x 8.5 inches. Three types of blocks shall be cut and are designated as “C,” “F,” and “CF.” The “C” block is designated for machining Charpy V-notch, SS-3 tensile specimens and coupons for chemical and microstructural characterization. The “F” block is designated for machining compact tension specimens for Fracture toughness testing. The “CF” block is designated for alternating rows of Charpy and compact tension specimens for Fracture toughness testing.

Task 1 Identification of the welds: Prior to cutting the “C,” “CF,” and “F” blocks, the location of the center line of the welds shall be identified using chemical etching or other suitable techniques on the outer wall of the segment. An ORNL technical representative will be on site to assist Energy Solution MPF staff in the identification of the weld.

Task 2: ORNL BW1 RPV Segment Cutting Plan: Two “C” blocks, one “CF” block and four “F” blocks shall be cut from ORNL BW1 RPV Segment (Zion Solutions RPV Segment 1, fig. **Error! Reference source not found.**6) containing a portion of the WF-70 beltline weld and base metal heat B7835-1 and no vertical weld.

- One “CF” block (11.25 x 3.0 x 8.5 inches) and one “C” block (7.6 x 3.0 x 8.5 inches each), separated only by the kerf, shall be cut from and centered on the WF-70 beltline weld. The “CF” block shall be cut ~ 4” from the left edge of the vertical cut, as shown in Figure 6.. The “C” block (7.6 x 3.0 x 8.5 inches) and four “F” blocks (5.7 x 2.0 x 8.5 inches each), separated only by the kerf, shall be cut from the base metal above the beltline weld “CF” block that is located closest to left vertical edge of the segment as viewed from the external side of the RPV segment and ~ 4” (depends upon actual vertical cut location) from the left edge. The first “C” block cut from the base metal shall be at least 2” above the beltline weld “CF” block.
- An ORNL technical representative will be on site to assist Energy Solutions MPF staff in the identification of the weld to insure that the block is centered on the weld.
- The Vendor shall use the most cost and time effective methods to reduce excess material from the segment prior to final cutting of the 4 “F,” 2 “C” blocks, and “CF” block.
- Each of the seven (7) blocks shall be uniquely numbered for identification, orientation, and tracking.

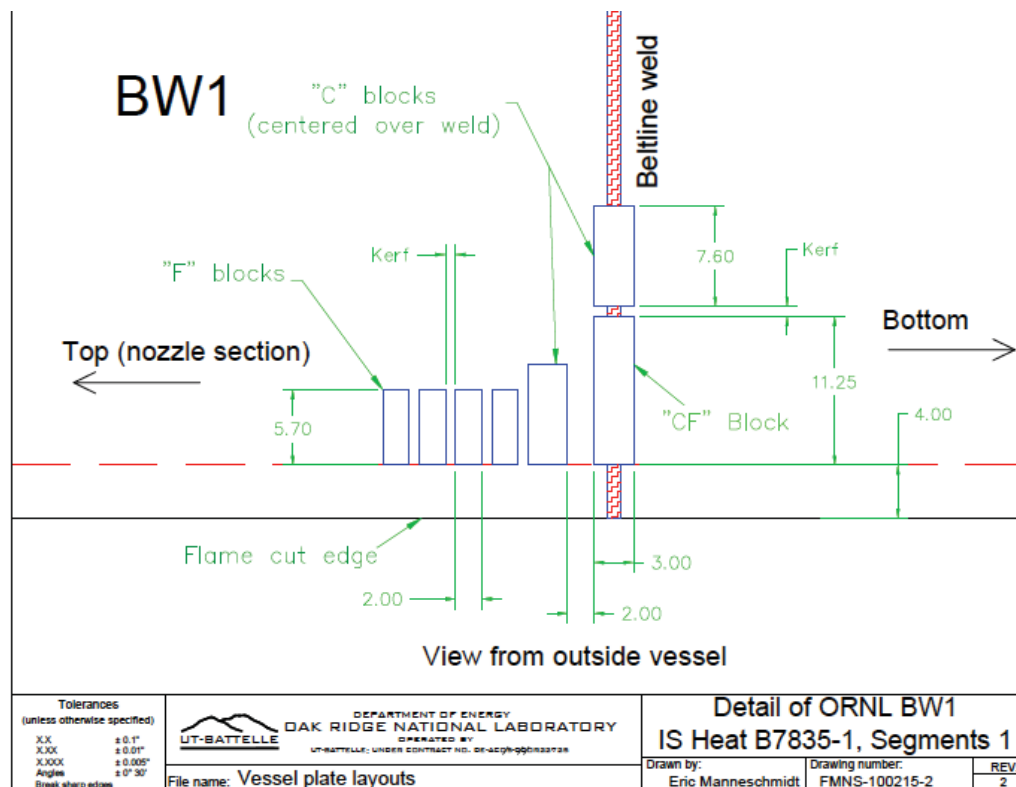


Figure 6. Expanded view of the location of 5 base metal and 2 beltline blocks to be cut from Zion Unit 1 ORNL BW1 RPV Segment 1.

6. ZION RPV PHASE 2: BLOCK CUTTING STATUS

Upon implementation of the “Block Cutting” contract (Zion RPV Phase 2), the box containing Zion Unit 1 RPV Segments 1 and 5 was opened and the ~ 14 ton, 45° ORNL Beltline Weld Segment 1 was lifted and transferred from the rail car to the designated MPF C-zone cutting location by crane, placed on the cutting stand (Fig. 7) for cutting into blocks and the activity verified. At the conclusion of the work, the uncut portion of Segment 1 along with the cutting waste will be stored in the steel box containing Segment 5 and placed into the railcar with the box containing Segments 2 and 6 for eventual shipment as waste to Clive, Utah. The cut blocks will, in turn, be shipped to a third party vendor to be machined into test specimens and coupons for eventual laboratory testing.

The process of cutting the blocks from the well-characterized beltline weld and base metal above the weld began with locating the exact position of the beltline weld and a determination of the slope across the outer diameter of the segment. Due to the high probability that the oxy-propane flame cut along the vertical direction may have obscured the weld, two 1” holes were drilled approximately 6” above and below the estimated position of the beltline weld and 2.75” from either edge of the segment (Figs 8 and 9) and a wire saw placed through the holes to cut out two small sections in order to provide fresh surfaces to locate the exact position of the weld and to determine what the slope (if any) of the weld line is on the segment. Following the removal of the two small sections, chemical etching, using a 10% Nital (nitric acid / alcohol) solution, revealed the weld cross-section and position (Fig 10) approximately 2” below the estimated position.



Figure 7. Segment 1 on the cutting frame at the Energy Solutions MPF.

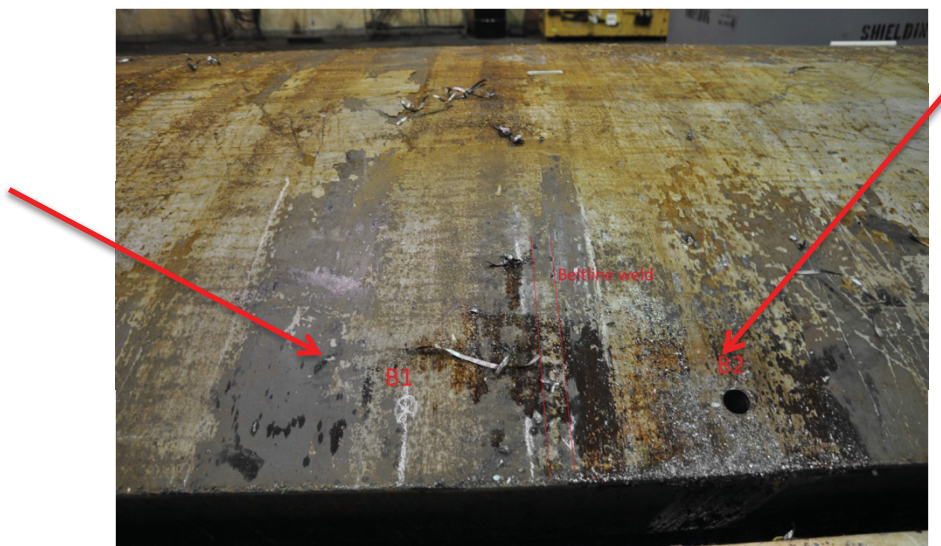


Figure 8. Location of holes for wire saw to cut a fresh section to identify beltline weld.



Figure 9. Drilling holes for wire saw to cut fresh surfaces to identify the beltline.



Figure 10. With small section removed from the flame cut edge, chemical etching revealed the location of the beltline weld.

Once the position and slope were determined, a thin metal template was placed over the segment and aligned with the beltline weld (Fig. 11). The template was designed based on the location of the blocks relative the beltline weld and base metal as seen in Fig. 6 and included the location of cut lines for the blocks that includes the kerf and the location of 13 holes as seen in Fig. 12. The holes were used for inserting the diamond wire to cut the 2 beltline weld and 5 base metal blocks from Segment 1 as shown in Fig. 13. With the completion of Cut 11 (Fig. 12), the CF block was removed from Segment 1 (Fig. 14) using a lift magnet in a similar manner as shown in Fig. 15. Similarly, the remaining blocks were successfully cut and lifted out from Segment 1 (Figs. 16-19) by the end of the shift on September 22, 2016. The target shipping date to the machining vendor (Phase 3 / Zion RPV harvesting project) is the week of October 17th.

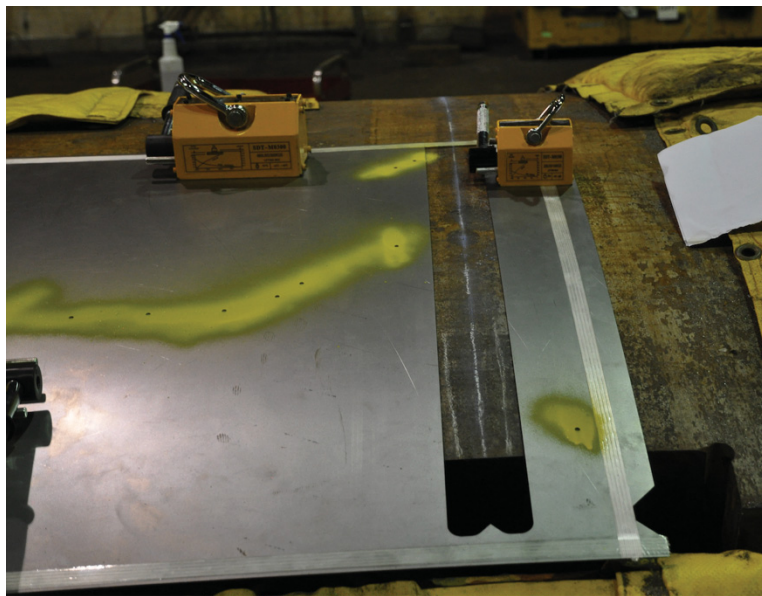


Figure 11. Thin-metal template, with the holes marked for transference to the RPV segment, was aligned with the beltline weld (chalk line). The holes will be used to thread the wire saw to cut the blocks.

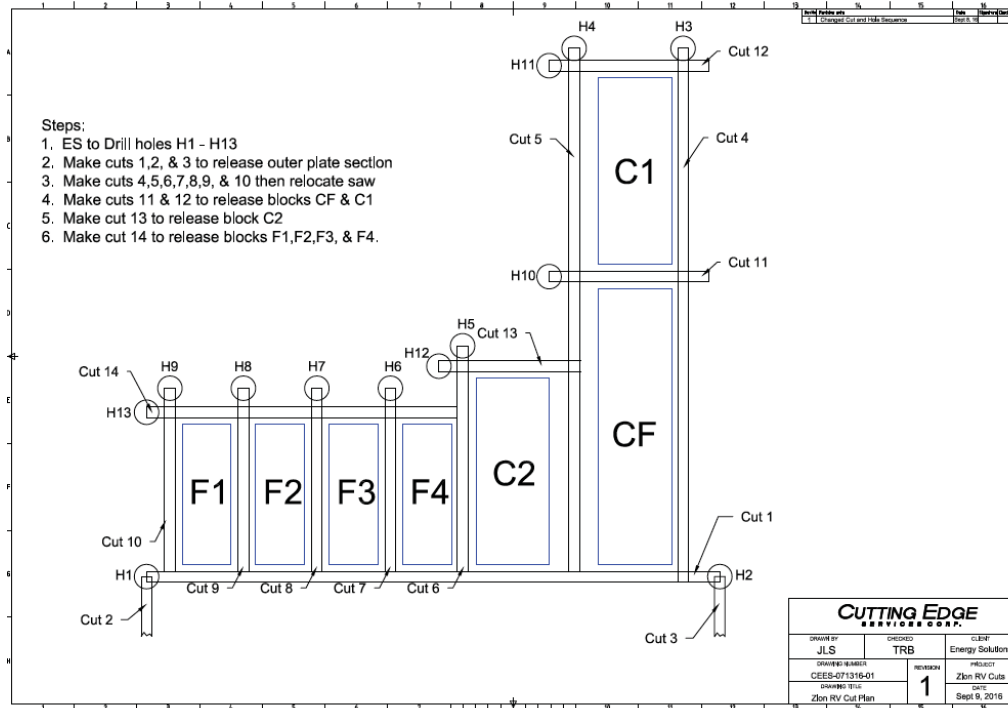


Figure 12. Cut plan (based on Figure 6) noting the blocks (blue outline), the wire saw access holes and cut lines with kerf.



Figure 13. Wire saw cuts parallel to the beltline weld.



Figure 14. CF block with orientation marked (Y axis is perpendicular to the beltline weld with the arrow pointing to the top of the segment and the X axis is parallel to the beltline weld with the arrow pointing to away from the high fluence edge).



Figure 15. Lift magnet used to remove the cut blocks.



Figure 16. F4 and C2 blocks with orientations marked.



Figure 17. F3 block with orientation marked.



Figure 18. F1 and F2 blocks with orientations marked.



Figure 19. C1 block with orientation marked.

7. ZION RPV PHASE 3: CURRENT MACHINING PLAN SUMMARY

The summary of the revised machining plan for one (1) base metal “C” block, one (1) beltline weld “CF” block, and two (2) base metal “F” blocks is listed below.

Summary of samples to be machined from one “C” block (base metal)

239 = [(17x15)-16] Charpy specimens

128 = (16 x 8) SS3 tensile specimens

64 = (2 x 2 x 16) coupons (for microstructural characterization)

Summary of samples to be machined from one “CF” block (weld)

180 = (20 x 9) Charpy specimens

144 = (9 x 2 x 8) SS3 tensile specimens

72 = (2 x 2 x 18) coupons (for microstructural characterization)

80 = (10 x 8) 0.4T C(T)

Summary of samples to be machined from 2 “F” blocks (base metal):

112 = 56 (4 x 14) 1/2 T C(T) x 2 “F” blocks

Summary of samples to be machined by type:

Charpy specimens (239 base metal + 180 weld) = **419**

SS3 tensile specimens (128 base metal + 144 weld) = **272**

Coupons (64 base metal + 72 weld) = **136**

Fracture toughness (112, 1/2T base metal + 80, 0.4T weld) = **192**

8. CURRENT TEST PLANS

Through Wall Attenuation Study of Welds and Base Metal Test and Research Plan: The through-wall mechanical test specimens, including Charpy V-Notch (CVN), tensile, and fracture toughness, machined from the beltline WF-70 weld and based metal heat B7835-1, having a peak fluence $< 1 \times 10^{19}$ n/cm² will be tested to evaluate the change in mechanical properties as function of depth (neutron fucose attenuation).

The specimen dimensions will be as follows:

- CVN (Charpy V-Notch) / Size: 10 x 10 x 55 mm
- Tensile / Size: SS-3 (.076 x 4.95 x 25.4 mm) cut from a 10 x 10 x 55 mm Charpy block, and
- Fracture toughness (compact tension) / Size: 0.5 T C(T) and 0.4 T C(T)

In addition to specimens for mechanical testing, through-thickness chemical characterization (at least, Cu, Ni, Mn, P), hardness distribution, and various microstructural characterization techniques such as Atom Probe Tomography (APT), Small Angle Neutron Scattering (SANS), and Positron Annihilation Spectroscopy (PALS) will be performed.

The test plans are as follows:

1. Determine the through-thickness variation in chemical composition of the weld (especially Cu).
2. If the chemical composition, especially the Cu content, is relatively uniform, perform CVN and tensile tests and compare results with surveillance results.
3. Perform CVN (see Fig. 16), tensile, hardness, and K_{Ic} testing through thickness to evaluate attenuation effects.
4. Microstructural characterization (Atom probe, SANS, SEM, TEM, and nano indentation) will be performed through thickness to evaluate attenuation effects using specimens obtained from 10 x 10 x 0.5 mm coupons.
5. Similar testing (3 and 4) through the thickness of base metal will also be performed in collaboration with CRIEPI as part of the CNWG program with Japan.
6. Thermal annealing of these RPV materials may also be performed to compare with the same weld metal (WF-70) previously irradiated in test reactors & annealed.

Specimens centered in weld

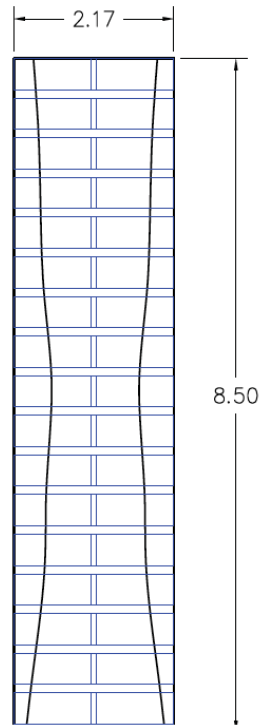


Figure 20. Detailed C1 block layout for Charpy Specimens. Figure derived from reference [2].

9. SUMMARY

This report documents the receipt of four segments of the Zion Unit 1 RPV to the Energy Solutions MPF, the successful cutting into seven blocks: two from the beltline weld and five base metal (Phase 2), and plans to ship the blocks to BWXT for machining into test specimens (Phase 3) for eventual laboratory testing. Specifically, Segment 1 of the Zion Unit 1 RPV containing well-characterized base metal B7835-1 heat and a section of the well-characterized WF-70 beltline weld (between the lower and the intermediate shells) was shipped for cutting into blocks. As of September 22, 2016, all seven blocks were successfully cut and lifted out from Segment 1. The target shipping date to BWXT (Phase 3 / Zion RPV harvesting project) is the week of October 17th. The blocks in turn will be machined into mechanical test specimens and microstructural characterization samples at BWXT (Phase 3) in FY 2017.

Data from RPV surveillance specimens containing similar WF-70 weld materials are available in the literature for a comparison of hardening and changes in fracture toughness and microstructure [7-9]. Similarly, data from surveillance specimens containing B7835-1 plate material are available for a comparison of hardening and changes in fracture toughness [13]. Access to service-irradiated RPV welds and plate sections will allow through-wall attenuation studies to be performed, which will be used to assess current radiation damage models [2, 3].

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