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Technical Letter Report

Evaluation on the Feasibility of Using Ultrasonic Testing of Reactor Pressure Vessel Welds for Assessing Flaw Density/Distribution per 10 CFR 50.61a, *Alternate Fracture Toughness Requirements for Protection Against Pressurized Thermal Shock*

EJ Sullivan
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June 2014

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Summary

The U.S. Nuclear Regulatory Commission (NRC) completed a research program in which it was concluded that the risk of through-wall cracking due to a pressurized thermal shock (PTS) event is much lower than previously estimated. The NRC subsequently developed and promulgated an alternate PTS rule, described in the *Code of Federal Regulations*, Title 10, Part 50.61 (§50.61), "Fracture Toughness Requirements for Protection against Pressurized Thermal Shock Events." Use of the new rule by licensees is optional. The §50.61a rule differs from §50.61 in that it requires licensees who choose to follow this alternate method to use the results from periodic volumetric examinations required by the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code), Section XI, *Rules for Inservice Inspection (ISI) of Nuclear Power Plants*. Results from periodic ultrasonic testing (UT) of reactor vessel welds are evaluated in order to locate and size flaws of interest to the PTS rule.

This technical letter report (TLR) provides an assessment undertaken by Pacific Northwest National Laboratory (PNNL) at the request of the NRC to assess the capability of periodic ASME-required volumetric examinations of reactor vessels to characterize the density and distribution of flaws of interest for applying §50.61a on a plant-by-plant basis.

While performing this study, the NRC staff received certain UT performance information from the Electric Power Research Institute (EPRI). The information from EPRI is based on data gathered by the industry's Performance Demonstration Initiative (PDI), a program for qualifying UT personnel, procedures, and equipment. The security of the PDI database is maintained by EPRI and is not available for review by NRC staff at this time. The PDI database, while not collected under field conditions, may be the only source of data that could potentially be used to characterize the ability of Section XI UT methods to detect and size surface-connected flaw of interest to the PTS rule. A review of the results of some reactor vessel weld examinations demonstrated that UT examinations are capable of detecting flaws as small as 3 mm (0.118 inch) or possibly smaller. However, based on extensive reactor vessel fabrication flaw validation studies performed at PNNL, and recent investigations into standard ASME Code ultrasonic practices during inservice inspection, it appears that detection rates for small fabrication flaws may be lower than originally estimated and the ability to accurately determine the location and size of these small fabrication flaws remains unclear. This TLR provides an assessment of the reports and data received from EPRI and others.

Acronyms and Abbreviations

ACRS	Advisory Committee on Reactor Safeguards
ASME Code	American Society of Mechanical Engineers Boiler and Pressure Vessel Code
DAC	distance amplitude correction
EPRI	Electric Power Research Institute
FR	Federal Register
ID	inside diameter
ISI	inservice inspection
L	longitudinal
MRP	Materials Reliability Program
NDE	nondestructive examination
NRC	United States Nuclear Regulatory Commission
NRR	NRC Office of Nuclear Reactor Regulation
PDI	Performance Demonstration Initiative
PNNL	Pacific Northwest National Laboratory
PISC	Programme for the Inspection of Steel Components
POD	probability of detection
PTS	pressurized thermal shock
PVRUF	Pressure Vessel Research Users Facility
PWR	pressurized water reactor
RES	NRC Office of Nuclear Regulatory Research
RG	Regulatory Guide
RMSE	root mean square error
RPV	reactor pressure vessel
SAFT-UT	Synthetic Aperture Focusing Technique for Ultrasonic Testing
SAW	submerged arc welding
SMA	shielded metal arc
TVA	Tennessee Valley Authority
TWCF	through-wall crack frequency
TWE	through-wall extent
UT	ultrasonic testing or ultrasonic inspection or ultrasonic examination

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1.0 Introduction

Pressurized thermal shock (PTS) events are system transients in a pressurized water reactor in which there is a rapid operating temperature cool-down that results in cold vessel temperatures with or without repressurization of the vessel. The rapid cooling of the inside surface of the reactor pressure vessel (RPV) causes thermal stresses that can combine with stresses caused by high pressure. The aggregate effect of these stresses is an increase in the potential for fracture if pre-existing flaws are present in a material susceptible to brittle failure. The ferritic, low-alloy steel of the reactor vessel beltline adjacent to the core, where neutron radiation gradually embrittles the material over the lifetime of the plant, can be susceptible to brittle fracture.

The PTS rule, described in the *Code of Federal Regulations*, Title 10, Part 50.61 (§50.61), "Fracture Toughness Requirements for Protection against Pressurized Thermal Shock Events," establishes screening criteria to ensure that the potential for a reactor vessel to fail due to a PTS event is deemed to be acceptably low.

The U.S. Nuclear Regulatory Commission (NRC) completed a research program that concluded the risk of through-wall cracking due to a PTS event to be much lower than previously estimated. The NRC subsequently developed and promulgated an alternate PTS rule, §50.61a. Use of the new rule by licensees is optional. The §50.61a rule differs from §50.61 in that it requires licensees who choose to follow this alternate method to analyze the results from periodic volumetric examinations required by the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code), Section XI, *Rules for Inservice Inspection (ISI) of Nuclear Power Plants*.

This technical letter report provides an assessment undertaken by Pacific Northwest National Laboratory (PNNL) at the request of the NRC to assess the capability of periodic ASME-required volumetric examinations of reactor vessels to characterize the density and distribution of flaws of interest for applying §50.61a on a plant-by-plant basis.

2.0 Background

Pressurized thermal shock events are system transients in a pressurized water reactor (PWR) in which there is a rapid operating temperature cool-down that results in cold vessel temperatures with or without repressurization of the vessel (SECY-09-0059). The rapid cooling of the inside surface of the RPV causes thermal stresses that can combine with stresses caused by high pressure. The aggregate effect of these stresses is an increase in the potential for fracture if pre-existing flaws are present in a material susceptible to brittle failure. The ferritic, low-alloy steel of the reactor vessel beltline adjacent to the core, where neutron radiation gradually embrittles the material over the lifetime of the plant, can be susceptible to brittle fracture.

The PTS rule, §50.61, adopted on July 23, 1985 (50 FR 29937), establishes screening criteria to ensure that the potential for a reactor vessel to fail due to a PTS event is deemed to be acceptably low. These screening criteria effectively define a limiting level of embrittlement beyond which operation cannot continue without further plant-specific evaluation.

A licensee may not continue to use a reactor vessel with materials predicted to exceed the screening criteria in §50.61 without implementing compensatory actions or additional plant-specific analyses unless the licensee receives an exemption from the requirements of the rule. Acceptable compensatory actions are neutron flux reduction, plant modifications to reduce the PTS event probability or severity, and reactor vessel annealing. Currently, no operating PWR vessel is projected to exceed the §50.61 screening criteria before the expiration of its 40-year operating license. However, several PWR vessels are approaching the screening criteria, while others are likely to exceed the screening criteria during the extended period of operation of their first 20-year license renewal.

The NRC completed a research program that concluded that the risk of through-wall cracking due to a PTS event is much lower than previously estimated. This finding indicates that the screening criteria in §50.61 are overly conservative and may impose an unnecessary burden on some licensees.

The NRC subsequently developed a rule, §50.61a, published on January 4, 2010, entitled “Alternate Fracture Toughness Requirements for Protection Against Pressurized Thermal Shock Events” (75 FR 13). Use of the new rule by licensees is optional. The rule is applicable to licensees whose construction permits were issued before February 3, 2010, and whose reactor vessels were designed and fabricated to the ASME Code, 1998 Edition or earlier. This would include applicants for plants such as Watts Bar, Unit 2, who have not yet received an operating license.

The alternate methodology (§50.61a) differs from §50.61 in that it requires licensees who choose to follow this alternate method to analyze the results from periodic volumetric examinations required by the ASME Code, Section XI. These analyses are intended to determine if the actual flaw density and size distribution in the licensee’s reactor vessel beltline welds are bounded by the flaw density and size distribution values used in the PTS technical basis. The technical basis was developed using a flaw density, spatial distribution, and size distribution determined from experimental data, as well as from physical models and expert elicitation. Experimental data were obtained from samples of reactor vessel materials salvaged from cancelled plants (i.e., Pressure Vessel Research Users Facility [PVRUF], Midland, and Shoreham). When using ultrasonic testing (UT), which is the standard inservice volumetric examination method applied, 10 CFR 50.55a(g)(6)(ii)(C) requires licensees to implement performance demonstration requirements of the ASME Code, Section XI, Appendix VIII, Supplements 4 and 6. Supplement 4 contains qualification requirements for the reactor vessel weld examination volume from the clad-to-base metal interface through the inner 2.54 cm (1.0 inch), or 10 percent of the vessel thickness, whichever is larger. Supplement 6 contains qualification requirements for reactor vessel weld volumes other than those near the clad-to-base metal interface.

The technical basis for the rule also indicates that flaws buried deeper than 2.54 cm (1.0 inch) from the clad-to-base metal interface or 10 percent of the vessel thickness, whichever is greater, are not as susceptible to brittle fracture as similarly sized flaws located closer to the inner surface. Therefore, the rule does not require the comparison of the density of these flaws, but still requires large flaws, if discovered, to be evaluated for contributions to through-wall crack frequency (TWCF) if they are within the inner three-eighths of the vessel thickness. The limitation for flaw acceptance, specified in ASME Code, Section XI, Table IWB-3510-1, approximately corresponds to the threshold for flaw sizes that can make a significant contribution to TWCF if present in reactor vessel material at this depth. Therefore, the rule requires that flaws exceeding the size limits in ASME Code, Section XI, Table IWB-3510-1, be evaluated for contribution to TWCF in addition to the other evaluations for such flaws that are prescribed in the ASME Code.

The technical basis for the rule concludes that flaws as small as 2.54 mm (0.1 inch) in through-wall extent (TWE) contribute to TWCF, and nearly all of the contributions come from flaws located within 2.54 cm (1 inch) of the inner diameter surface of the reactor vessel. The PTS event produces high cooling within the inner vessel wall with associated high tensile thermal stresses and low fracture toughness in this region. Thus, small flaws near the clad inner surface are of primary concern. For weld flaws that exceed the sizes prescribed in the rule, the risk analysis indicates that a single flaw can be expected to contribute a significant fraction of the 1×10^{-6} per reactor year limit on TWCF. Therefore, if any flaws that exceed the sizes prescribed in the rule are found in a reactor vessel, they must be assessed individually.

The numerical values in Table 2, *Allowable Number of Flaws in Welds*, and Table 3, *Allowable Number of Flaws in Plates and Forgings*, of the rule represent the number of flaws in each size range that were derived from the technical basis. An explanation of Tables 2 and 3 is contained in Appendix A of this technical letter report. To ensure the applicability of the rule at a specific plant, it must be verified that weld, plate, and/or forging flaw distributions in the RPV at the subject plant are consistent with those assumed in the technical basis of §50.61a. If one or more larger flaws are found in a reactor vessel, they must be evaluated to ensure that they are not causing the TWCF to exceed the regulatory limit. The rule, in effect, requires that the smallest flaws that must be sized are 1.9 mm (0.075 inch) in TWE. For each flaw detected that has a TWE equal to, or greater than, 1.9 mm (0.075 inch), the licensee shall document the dimensions of the flaw, its orientation, its location within the reactor vessel, and its depth from the clad-to-base metal interface.

The flaw sizes in Tables 2 and 3 represent actual flaw dimensions, while the results from the ASME Code examinations are estimated dimensions. The available information indicates that, for most flaw sizes in Tables 2 and 3, qualified inspectors will oversize flaws. Comparing oversized flaws to the size and density distributions in Tables 2 and 3 is conservative and acceptable, but not necessary. The rule permits licensees to adjust the flaw sizes estimated by inspectors qualified under the ASME Code, Section XI, Appendix VIII, Supplement 4 and Supplement 6. The NRC determined that, in addition to inherent ultrasonic flaw sizing uncertainties, licensees should be allowed to consider other types of nondestructive examination (NDE) uncertainties, such as probability of detection (POD) of flaws, and errors associated with estimating flaw density and location measurements, because these issues may also affect the ability of a licensee to demonstrate compliance with the rule. As a result, the language in §50.61a(e) allows licensees to account for the effects of NDE-related uncertainties in meeting the flaw size and density requirements of Tables 2 and 3. The methodology to account for these uncertainties must be based on statistical data collected from ASME Code inspector qualification tests, or any other tests that measure the difference between the actual flaw size and the size determined from the applied NDE; for example, ultrasonic examination. Verification that a licensee's flaw size and density distribution are upper bounded by the distribution of Tables 2 and 3 is required to confirm that the risk associated with PTS is acceptable. Collecting, evaluating, and using data from ASME Code inspector qualification tests requires extensive engineering judgment. Therefore, the methodology used to adjust flaw sizes to account for the effects of NDE-related uncertainties must be reviewed and approved by the Director of the NRC, Office of Nuclear Reactor Regulation (NRR).

Paragraph §50.61a(e)(2) requires licensees to verify that flaws detected at the clad-to-base metal interface do not open to the inside surface of the vessel by using a surface or visual examination technique capable of detecting and characterizing service-induced cracking in the reactor vessel cladding. Flaws open to the inside surface of the vessel could have a substantial effect on the TWCF and, when such flaws are verified to exist, licensees are required by §50.61a(e)(4) to demonstrate that the reactor vessel will have a TWCF of less than 1×10^{-6}.

3.0 Statement of Problem

In the NRC Commission voting record for the final 10 CFR 50.61a rule, Commissioner Jaczko indicated that the recommendations of the Advisory Committee on Reactor Safeguards (ACRS) should be addressed by the staff. Specifically, Commissioner Jaczko indicated that to aid in the implementation of the rule, the staff should undertake an effort to verify and document the capability of NDE procedures that are used to characterize the flaw distributions in reactor vessels.

The ACRS provided its conclusions and recommendations on the proposed final rule on alternate fracture toughness requirements in a March 13, 2009, letter to R.W. Borchardt, NRC Executive Director of Operations (ACRS 2009). In its letter, the ACRS included the following comments and recommendation relative to the NDE requirements in the rule.

> “The flaw distribution used in the PTS Reevaluation Project is largely based on a detailed evaluation of the flaws in two pressure vessels from cancelled plants, one of them a boiling water reactor. The materials and fabrication processes for these vessels were representative, and the flaw distributions derived from these vessels should be broadly applicable. Nevertheless, we support the requirement of the rule that applicants perform inspections and analyses to verify that the flaw distributions in their vessels are consistent with those used in the detailed study of three plants.
>
> “The flaws of concern for PTS are smaller in size than those usually addressed in American Society of Mechanical Engineers Section XI inspections of the vessel. Based on discussions with the staff and industry NDE experts, the staff believes that current inspection capabilities are sufficient to characterize the flaw distributions of interest, but no documentation of this conclusion is available. This is not an obstacle to the issuance of the rule, but the availability of such documentation will be helpful in the implementation of the rule. We encourage the staff to pursue a study, either through RES or through a cooperative effort with industry, to verify and document this conclusion.”

NRR, through the Office of Nuclear Regulatory Research (RES), asked PNNL to assess the issue of UT capability in regards to the PTS rule.

To assess UT reliability as an input to the PTS rule, NRC requested that the following items be investigated and reported:

1. Assess the ability of current inservice inspection (ISI)-UT techniques, as qualified through ASME Code, Appendix VIII, Supplements 4 and 6, to detect small fabrication or inservice-induced flaws located in RPV welds and adjacent base materials.
2. Determine the ability of these qualified UT techniques to distinguish between “crack-like” or “non-crack-like” ultrasonic reflectors.
3. Determine to what extent the qualified UT techniques can accurately resolve, locate, and size (both through-wall and length) these reflectors.

4. Evaluate, based on the available information, the capability of UT to provide flaw density/distribution inputs for making RPV weld assessments in accordance with 10 CFR 50.61a.
5. Provide insights and expectations regarding these flaw density/distributions that may assist NRR in regulatory decision-making.

As noted in the Background section, licensees must verify that any flaws detected at the clad-to-base metal interface do not open to the inside surface of the vessel by using a surface or visual examination technique capable of detecting and characterizing service-induced cracking in the reactor vessel cladding. In addition to assessing UT in this report, the capability of visual and surface examination techniques for performing this verification is also briefly discussed.

4.0 Approach

PNNL undertook the following efforts to assess UT capabilities by reviewing available data and reports, and evaluating their applicability to the problem. In addition, several industry NDE experts were interviewed to elicit their input with regard to the aforementioned questions posed by NRR.

1. The results of a multi-year program performed in the late 1990s to develop a validated flaw density and distribution for RPV welds and base metal were reviewed. This work involved UT, radiography, and metallurgical examinations of blocks removed from reactor vessels that were fabricated for nuclear power plants that were not put into service. A summary of relevant information is provided below.
2. The results of examinations of RPVs performed under the Programme for the Inspection of Steel Components (PISC) II were also reviewed. These examinations assessed and compared the capabilities of various UT techniques used to inspect heavy section vessel mockups. A summary of relevant examination results is provided below.
3. PNNL reviewed Materials Reliability Program (MRP)-207 (Spanner 2006), an Electric Power Research Institute (EPRI)-sponsored report prepared by WesDyne, which contains reanalyzed UT data from the Beaver Valley Nuclear Plant, Unit 2. The data was acquired with techniques that met the requirements of the ASME Code prior to implementation of Section XI, Appendix VIII, performance demonstration qualification requirements. The method of reanalysis of the data called for recording and measuring all indications interpreted as a valid flaw regardless of the amplitude of the indication. The analysis of this report is discussed below.
4. NRC interacted with the Tennessee Valley Authority (TVA) to obtain the results of a reactor vessel examination performed at Browns Ferry, Unit 3, in the mid-1990s. This examination was referred to as a “Spirit of Appendix VIII” examination. The procedures that were used for this examination included steps requiring the recording of indications of small flaws, such as flaws that are of concern for PTS. PNNL reviewed and analyzed the examination results, which are discussed below. The results of this examination are non-proprietary, while the procedures used by the inspection vendor to conduct the examinations are considered proprietary.
5. Results were obtained from Westinghouse on RPV inspections conducted at 13 plants performed with procedures qualified in accordance with the requirements of Section XI, Appendix VIII. PNNL reviewed and analyzed these results, which are discussed below. These results are non-proprietary.
6. RPV inspection vendors (WesDyne and IHI Southwest) were contacted. Some useful information was learned during discussions with these vendors. Insights from these discussions are discussed below.
7. NRC contacted EPRI to determine if any analyses exist of detection/flaw sizing results from the EPRI Performance Demonstration Initiative (PDI) database. PNNL was provided with EPRI Report 1007984, *Reactor Pressure Vessel Inspection Reliability Performance Demonstrations* (Becker 2004). EPRI has not performed analyses to update the information in this report. The results of these analyses are discussed below.

8. PNNL searched for, but has not identified, any data concerning RPV inside-diameter (ID) surface conditions on beltline welds, and the effect of these surface conditions on UT flaw detection and characterization. Likewise, data regarding the ability of ASME-qualified UT techniques to distinguish between “crack-like” and “non-crack-like” indications, and to accurately locate non–surface-connected flaws, have not been identified. Thus far, the findings indicate that performance data on ASME-qualified UT techniques were developed primarily using crack-like reflectors connected to the clad-to-base metal interface.

In addition to assessing UT, PNNL undertook a limited effort to assess the capability of visual and surface examination to verify that any flaws detected at the clad-to-base metal interface do not open to the inside surface of the vessel.

4.1 PNNL Validation Program on Vessel Flaw Density and Distribution

4.1.1 Overview of Reactor Vessel Fabrication

The shell courses of many PWR vessels, including PVRUF, were fabricated from rolled and welded plate (Schuster et al. 1998). The PVRUF vessel, which was never put into service, was fabricated by Combustion Engineering and was completed in 1982. It was constructed from A533B alloy steel. The shell courses of a smaller number of vessels were fabricated out of forged rings by piercing a large ingot of A508 steel and rolling it until a ring of the proper shape was obtained.

For the rolled and welded construction practice, the first step in the fabrication sequence was to hot-form plates into 120° segments. Three 120° segments were then welded together into a shell course. The shell courses were typically clad on the ID surface with austenitic stainless steel using either the multiple wire or strip cladding submerged arc welding (SAW) process. Three shell courses typically made up the cylindrical portion of a PWR. Following welding of the shell courses, a manually applied cladding layer was deposited on the zone around the weld to link the cladding already existing on the two shell courses.

Full-thickness welding was used to assemble the shell courses, the nozzle forgings, and the flange forgings. The most frequently used technique was automated SAW. Manual welding with the shielded metal arc (SMA) technique was used frequently for complex configurations, for repairs of base material, or for areas of weld buildup. Welding from the inside to the outside surface results in a small volume of material at the root of the weld that has to be removed and repaired to eliminate unacceptable weld root conditions. Manual SMA welding was also used to fill this volume of “back-gouged” metal, which was typically 2.54-mm (1-inch) thick. Forged vessel rings were joined in a similar fashion as stated above, except that the shell courses were one-piece ring forgings. This construction technique avoided longitudinal weldments and generally required between three and five forged rings to construct the cylindrical region of a reactor vessel. The forged material used most extensively was A508 Class 2 steel.

All interior surfaces of the PWR vessel were clad with austenitic stainless steel to inhibit general corrosion and the buildup of radioactive oxides. Three cladding processes were used. Automatic SMA with an SMA electrode was used when possible due to its high deposition rate. The process used either multiple wires or strip electrodes of Type 305 or Type 309 stainless steel. In areas where an automatic process was not possible, SMA or gas tungsten arc welding was utilized.

4.1.2 Research Protocols and Methods

The research performed to develop a validated flaw density and distribution was published in NUREG/CR-6471, Volumes 1–3. Volume 1 (Schuster et al. 1998) describes the nondestructive evaluation of fabrication flaw indications obtained from ultrasonic examinations performed from the PVRUF vessel's inside, cladded surface. This volume also contains results of applying a Synthetic Aperture Focusing Technique for Ultrasonic Testing (SAFT-UT), radiographic, and destructive examination of blocks removed from the Midland RPV. The Midland RPV was constructed from forged rings.

Volume 2 (Schuster et al. 2000) reports the research performed on material removed from the PVRUF vessel to validate the presence and characteristics of the fabrication flaw density and distribution. The methodology used by PNNL researchers to produce validated flaw rates included weld-normal UT, radiography of 25-mm- (0.98-inch-) thick plates, and destructive examination, including metallography of 25-mm (0.98-inch) cubes. The report shows the data obtained by the validation research and describes the validated flaw density and distribution that was obtained from the data.

Volume 3 (Schuster et al. 1999) documents the results of SAFT-UT examination of vessel material removed from the canceled Shoreham nuclear power station. The report gives the number and characteristics of the flaw indications detected and sized in the nondestructive examination.

SAFT-UT has an advantage over physical focusing techniques in that the resulting image is full-volume focused over the entire inspection area. Traditional physical focusing techniques provide focused images only over a limited zone at the depth of focus of the lens. SAFT-UT provides better characterization of flaws because of its increased flaw resolution.

Weld-normal inspection involved removing weld metal specimens by making through-wall cuts parallel to the weld, creating ultrasonic inspection surfaces by machining a cut on each specimen, and performing a SAFT-UT examination using UT beams normal to the weld metal. This inspection mode is very sensitive to discontinuities that have TWE.

4.1.3 Major Findings Related to Inspections and Validation Efforts Performed to Determine Density and Distribution of Flaws

As noted above, NUREG/CR-6471, Volume 1 (Schuster et al. 1998), reported the results of SAFT-UT inspections made from the PVRUF vessel's inside clad surface. Twenty linear meters of weldment were inspected by SAFT-UT, including the entire beltline weld of the vessel. Ten different inspection modes were used to produce complementary information on the size, type, location, and density of the indications of flaws in the vessel. There were 2500 detectable indications in the SAFT-UT inspections of the PVRUF vessel. The largest number of these indications, 982, was found at the clad-to-base metal interface, but 978 of these were measured by SAFT-UT to be less than 2 mm (0.08 inch) in TWE. In the near-surface zone, the inner 25 mm (0.98 inch) of the vessel, the weld metal contained 98 detectable planar indications, 87 of which were less than 2 mm (0.08 inch) in TWE.

Because of the level of work required to validate the inspection results, the Volume 2 research was performed on blocks removed from the vessel rather than on all the weldment examined as part of the Volume 1 work.

Tables 4.1–4.3 below are reproduced from NUREG/CR-6471, Volume 2 (Schuster et al. 2000), and show the validated distribution of flaws in three regions of interest. The flaws listed in Table 4.1 are characterized as *crack* and *lack of fusion.*

Table 4.1. Flaws in Weld Metal of the Inner 25 mm (0.98 inch) of the PVRUF Vessel

Jan. 2000	< 3 mm	3 mm	4 mm	5 mm	6 mm	7 mm	8 mm	Total ≥ 3 mm
Crack LOF	190	7	2	2				11

Table 4.2. Flaws in Cladding and at the Clad-to-Base Metal Interface

Jan. 2000	< 3 mm	3 mm	4 mm	5 mm	6 mm	7 mm	8 mm	Total ≥ 3 mm
Crack LOF	1200	3	1					4

Quoting from Volume 2, "Table 4.2 shows the size distribution of slag inclusions and lack of fusion found in the cladding and at the clad-to-base metal interface. These flaws were confirmed from the rough machine cuts through the PVRUF material. Figure 3.79 shows a photograph of the 4-mm flaw found in the cladding [roughly horizontal flaw between about 4.2 and 4.6 mm on the scale]. Other rough machine cuts showed such flaw indications to be lack of fusion with slag." This is reproduced as Figure 4.1 below.

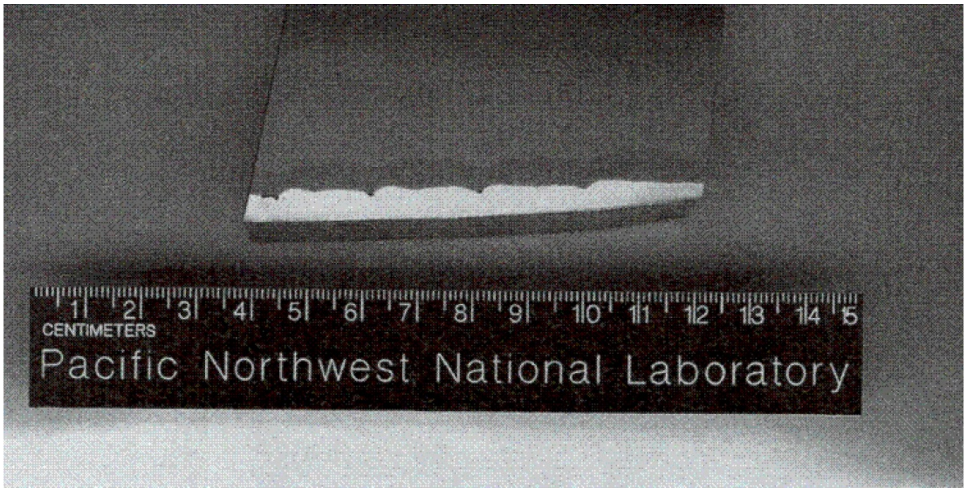

Figure 4.1. Photograph of PVRUF Specimen Showing Inclusions at the Clad-to-Base Metal Interface (Figure 3.79 from NUREG/CR-6471, Volume 2)

Table 4.3. Indications in Base Metal of the Inner 25 mm (0.98 inch) of the PVRUF Vessel

Jan. 2000	< 3 mm	3 mm	4 mm	5 mm	6 mm	7 mm	8 mm	Total ≥ 3 mm
Indications	180	10	3					13

Table 4.3 shows the size distribution for the base metal flaw indications that remain after the validation research. The validation of flaw indications in PVRUF included testing of only two near-surface zone base metal indications with the remaining indications listed in Table 4.3.

It is interesting to note from Tables 4.1 and 4.2 that there were many more small flaws that were located at or originated at the clad-to-base metal interface than flaws within the weld metal of the inner 25 mm (0.98 inch) of the vessel.

The results of the PVRUF flaw-validation research led to a number of significant conclusions. The validated flaws were mostly small, 3 mm (0.12 inch) or smaller in TWE. The fusion surface between the weld and the base metal contained a high concentration of planar discontinuities. Radiographic testing showed that 75% of these fusion surface flaws were linear indications, and metallographic testing showed lack of fusion with slag. The remaining 25% were taken to be inclusions and porosity. The largest confirmed flaw in the machine-made weld metal was shown to be 7 mm (0.28 inch) in TWE.

The largest flaws, greater than 8 mm (0.31 inch) in TWE, were all associated with repairs. These larger flaws were complex, and included a combination of cracks, lack of fusion, slag, and porosity. These repair flaws were found on the fusion surface of the repair with the base metal.

NUREG/CR-6471, Volume 2 (page 6.1) stated that, “Metallurgical analysis of (the larger) PVRUF flaw specimens show that the fabrication flaws are composed of a mixture of cracks, lack of fusion, contamination, and porosity. It follows from this that significant fabrication flaws can have an ultrasonic straight beam response.” However, it is our understanding that Appendix VIII procedures can be qualified without zone-focused straight beams being applied to assist in detection of these fabrication flaws.

Figures 4.2–4.4 below from NUREG/CR-6471, Volume 2, are included to show some typical flaw configurations from metallurgical analyses performed under the PNNL flaw validation program.

It should be noted that the flaws in the PVRUF vessel, although crack-like in nature, were not ideal planar cracks as conservatively assumed in fracture mechanics calculations. Treatment of the PVRUF flaws in such a manner would tend to over-estimate the structural significance of the observed flaws. In many cases, the crack-like flaws did not have highly sharpened crack tips. In other cases, in particular for the largest flaws associated with repairs to welds, the flaws had complex morphologies consisting of only partially linked lack-of-fusions, porosity, slag, and other sources of contamination. Modeling such flaws as planar cracks for purposes of structural integrity evaluation is conservative. Also, because the UT signals from these crack-like flaws may contain specular reflections, they may be easier to detect than tip-diffracted signals from planar cracks of similar size. UT examinations demonstrated to meet the requirements of Section XI, Appendix VIII, are qualified using procedure demonstration blocks and test blocks that contain primarily surface-connected planar flaws. It is expected that examinations performed using Appendix VIII, Supplements 4 and 6, procedures will detect rounded flaws, crack-like flaws, and planar flaws. However, the procedures are not qualified to distinguish between the different flaw types.

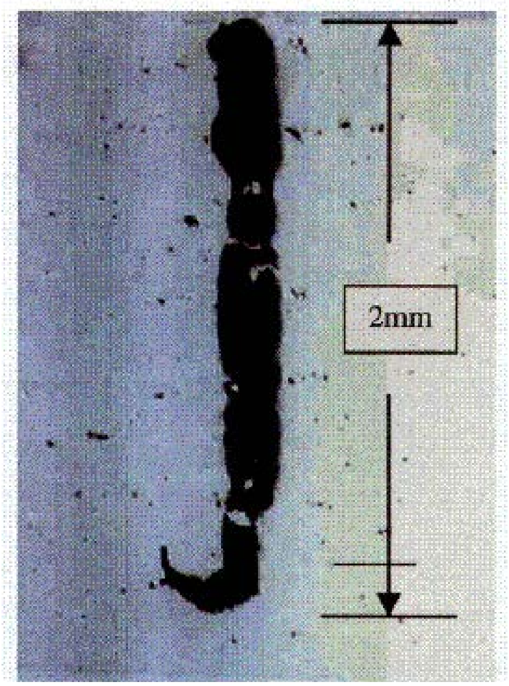

Figure 4.2. Micrograph of 2-mm Fusion Surface Flaw at Maximum Extent as Machined. This flaw is characterized as lack-of-fusion. (Figure 3.53 from NUREG/CR-6471, Volume 2.)

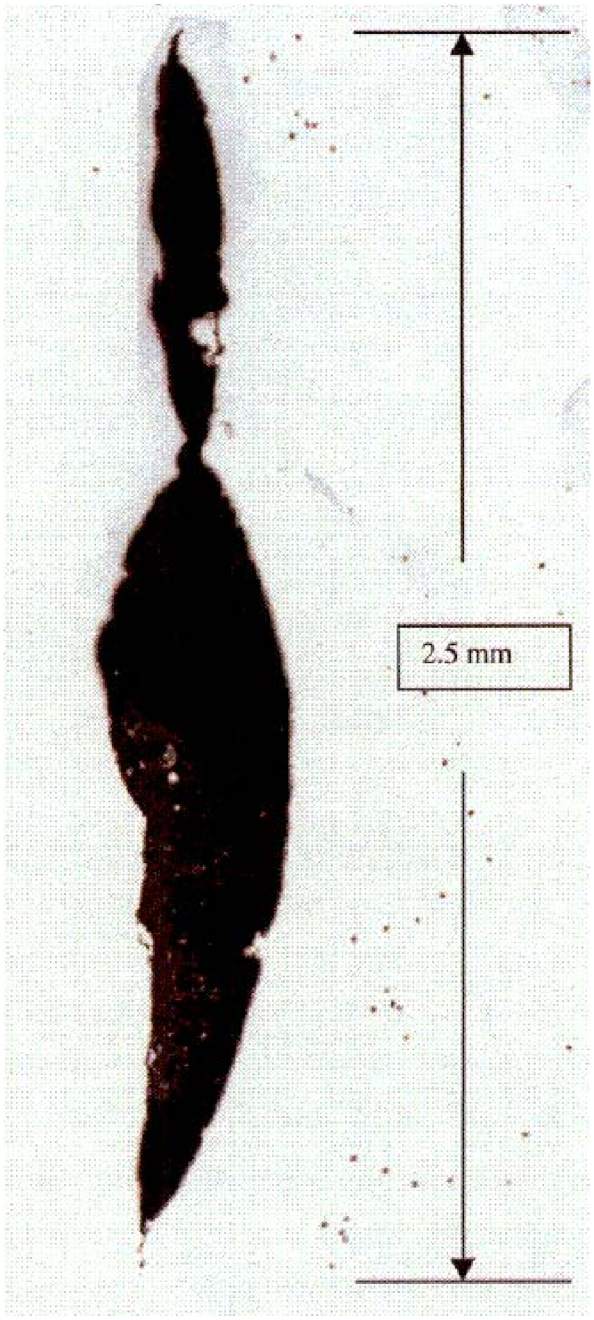

Figure 4.3. Micrograph of a Cross Section of One Weld Flaw from a Large Cluster (of inter-bead flaws). The through-wall extent of the flaw is 2.5 mm. The flawed area contains slag. Crack-like tips are visible on both flaw ends. (Figure 3.55 from NUREG/CR-6471, Volume 2.)

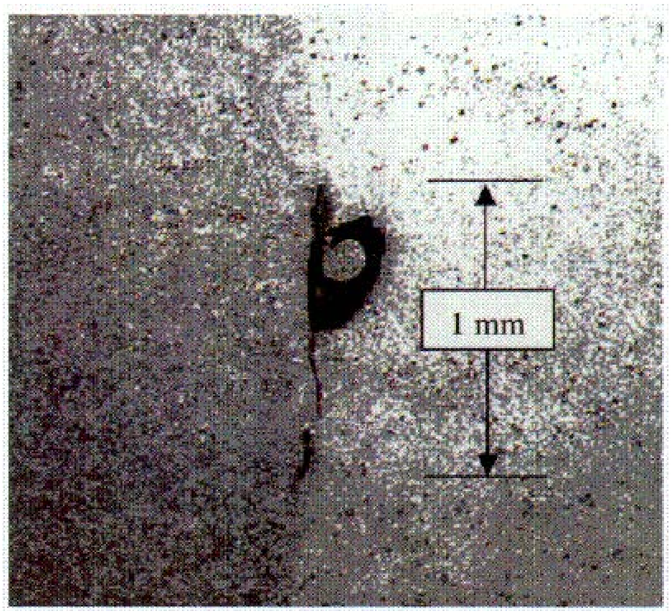

Figure 4.4. Micrograph of Small Flaw (shown to be inter-run slag). Flaw has vertical extent of 1.0 mm and planar features between the weld beads. (Figure 3.57 from NUREG/CR-6471, Volume 2.)

As reported in NUREG/CR-6471, Volume 1 (Schuster et al. 1998), blocks of approximately 1.2 m (4 feet) of circumferential weldment were removed from the Midland reactor vessel, inspected by SAFT-UT, and destructively examined. Most of the indications were measured to be less than 2 mm (0.08 inch) in TWE. Based on destructive analysis that was performed on blocks removed from the Midland vessel, the flaws were found to be mainly slag inclusions.

4.2 Review of PISC-II Data

PNNL reviewed the results of examinations of RPV specimens performed under the Programme for the Inspection of Steel Components II and published by the NRC (Heasler et al. 1993). This report provided an analysis of UT performance data that was gathered during the PISC-II international round-robin testing of RPV welds. Teams from several European countries as well as the United States and Japan participated in this multi-year study. A total of 45 teams and approximately 429 inspections were listed in the computer database that resulted from the PISC-II study. In the PNNL report, more formal statistical procedures were applied to the computerized data than provided in the final PISC-II report (Nichols and Crutzen 1988). Some of the major conclusions from the PNNL analysis were:

- There was no significant difference in detection and sizing performance between U.S. and other PISC-II participants using similar procedures.
- Team-to-team variability was a large factor in both detection and sizing performance.

- The detection performance demonstration requirements proposed by ASME, Section XI, [Appendix VIII], clearly screened inspection capability well; that is, screened out poor performance. As an example, only those teams that used special inspection techniques for the clad region had a high chance of successfully passing an ASME-type test. However, sizing techniques used by PISC–II participants would not have been successful in passing new sizing performance demonstration requirements adopted by ASME Section XI.

The plots of POD for smooth, rough, and volumetric flaws show that for a given flaw depth, POD for volumetric flaws is the highest, followed by POD for rough flaws, followed by POD for smooth flaws.

Figure 4.5 is a POD plot from the PNNL analysis of a manual, 10% distance amplitude correction (DAC) procedure. We have only included this plot for volumetric flaws, because the flaws in the PISC–II RPV mockups in the range of flaw sizes in Tables 2 and 3 of §50.61a were primarily volumetric flaws. The 10% DAC procedure appeared to provide the best performance for volumetric flaws. The volumetric flaws are believed to be actual fabrication flaws resulting from welding of plates. Data points that show anomalous variation from the regression line are indicated with an “H” (for high) or an “L” (for low). It should be noted that the number of volumetric flaws in the range of flaw sizes of interest is limited. Also, improvements in inspection procedures were made as a result of the recommendations from PISC; for example, all PWR RPV inspections are conducted with encoded data gathering procedures. Improvements in inspection techniques being used in the field were made in the years following PISC–II in anticipation of the implementation of Appendix VIII. Procedures developed following PISC–II would likely yield higher POD than the procedures used during the PISC-II exercises. This discussion would suggest that Appendix VIII-qualified techniques would have POD values for volumetric flaws higher than shown in Figure 4.5, but as noted above, the POD for planar flaws would be expected to be lower than for volumetric flaws.

We have not presented any information on PISC-II sizing uncertainty because the information provided in the referenced reports was for a larger flaw size range than of interest for the current evaluation. Also, the conclusions of the PNNL study noted that the sizing techniques used by PISC-II participants would not have been successful in passing new sizing performance demonstration requirements adopted by ASME Section XI.

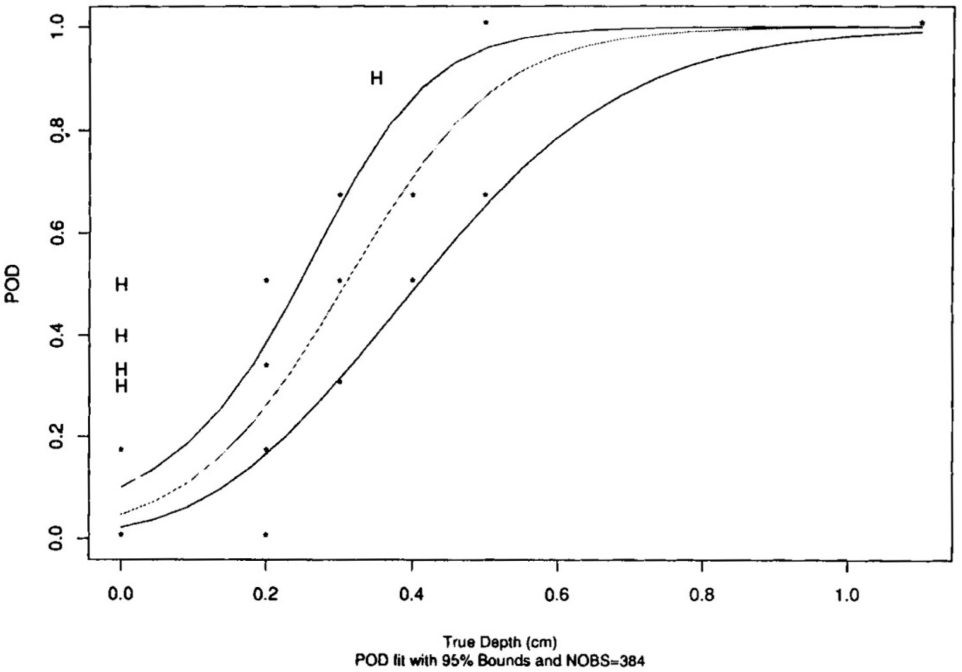

Figure 4.5. POD vs. Flaw Depth, Base Material: Manual 10% DAC Procedure – Volumetric Flaws (from Heasler et al. 1993 – Appendix B)

4.3 MRP-207, Reanalysis of Reactor Vessel Examination Data from the 1996 Beaver Valley, Unit 2, Vessel Examination

This study consisted of a reanalysis of the process data from the 1996 ten-year ISI examination of the Beaver Valley, Unit 2, reactor vessel. The examination was performed by WesDyne in September 1996 using remotely operated scanning tools delivering ultrasonic transducers in the contact method to the vessel inside surface. The 1996 examination was performed in accordance with the ASME Code, Section XI, 1983 Edition through the summer 1983 Addenda and Regulatory Guide (RG) 1.150, “Ultrasonic Testing of Reactor Vessel Welds During Preservice and Inservice Examinations.” This RG was based on prescriptive approaches to performing UT. It was withdrawn by the NRC in 2007, because it was superseded by 10 CRR 50.55a(g)(6)(ii)(C)(1). This regulation implemented the requirements of the ASME Code, Section XI, Appendix VIII, “Performance Demonstration for Ultrasonic Examination Systems.”

The purpose of the reanalysis was to provide an updated estimate of the indication population and sizes using recent methods of analysis, to the extent practical with the 1996 acquired data. The following conditions applied: the reanalysis included all shell welds, including flange-to-shell and lower shell-to-lower head circumferential welds; the depth of indications reanalyzed was intended to be to about 6 cm (2.5 inches) deep from the clad-to-base metal interface; and the data was reanalyzed to record and measure all indications that were interpreted as valid flaws regardless of amplitude.

A large number of small fabrication defects were detected by contact UT methods after the vessel was assembled and had undergone hydrostatic testing. The greatest population was detected in lower long seam L11. As a result, the entire length of the long seam weld to a depth of about 10.2 cm (4 inches) was removed. Prior to weld repair, several samples were taken for metallurgical analysis of the flaws. The flaws were determined to be small shrinkage voids in the weld metal, inclined at an angle as to be preferentially reflective for UT beams directed normal to the weld direction. The analysis concluded that the flaws were individually small and posed no threat to vessel integrity, and the remaining welds having identical indications were left un-repaired. From destructive analysis, the maximum actual observed size was 0.254-cm (0.10-inch) TWE and 0.13-cm (0.5-inch) long. The metallurgical analysis also indicated that individual flaws were invariably arrayed so their reflections could combine to yield medium-to-high–amplitude ultrasonic indications. Consequently, many of the high-amplitude indications were not caused by single imperfections but resulted from stacks of small flaws oriented so their reflections would combine and be interpreted as a single imperfection.

WesDyne indicated that the majority of the solidification shrinkage defects were around 5.08-cm (2-inches) deep, so the primary detection and sizing transducers of greatest use were the 2.0-MHz single-element shear wave units at 45 and 60 degrees. The 70-degree longitudinal (L) wave unit was calibrated for the under-clad region. The dual-element, 45-degree L wave transducer at 4 MHz had a focal depth of 22–mm (0.87-inch) metal path. With short focal depths, neither L wave transducer type was especially effective on deeper inclusions. WesDyne indicated that at 2 MHz, the resolution of the single shear wave units was good for diffraction and flaw feature measurement. Based on procedure development work at WesDyne, flaw features may be detected and measured using diffraction or satellite features when the flaw is greater than about 3 mm (0.125 inch) in diameter for a round flaw and top to bottom for planar reflectors. WesDyne commented that the indication responses from the Beaver Valley, Unit 2, vessel did not have the anticipated sizing measurement points and were largely single response targets indicative of small flaws below the measurement threshold noted above.

A total of 132 indications were observed, which was an increase of 33 indications over the 1996 total of 99. Many of the new indications recorded were in the 5–15% DAC range and were categorized as not recordable in the prior examination. Based on the metallurgical analyses during the vessel fabrication and procedure development work, WesDyne assigned a defect size of 3 mm (0.125 inch) to indications that had no measurable features in the UT data.

Chapter 4 of the MRP-207 report (Spanner 2006) indicates that, “A review of the defect coordinates would indicate that all recorded flaws are within the weld metal portion of the examination volume, or so close to the weld metal that they can be reasonably assumed to be in the weld.” It is not clear how this conclusion was reached. For example, drawings in Attachment 1 show that the elevation of center of weld C-2 is 327.7 cm (129.0 inches) to the top of the vessel and the vertical width of weld C-2 is 4.14 cm (1.63 inches) at the outside surface of the vessel. This is expected to be the widest vertical dimension of the weld. Table 3-2 lists the elevations of the indications in circumferential weld C-2 as ranging from 325.6 cm (128.2 inches) to 332.2 cm (130.8 inches), or a difference in elevation of 6.6 cm (2.6 inches), which considerably exceeds the width of the weld. Table 3-2 lists all the indications in weld C-2 as being parallel to the plane of the weld. Other tables in Chapter 3 show similar discrepancies with the statement from Chapter 4 quoted above. These values may indicate that not all of the recorded flaws are in the welds unless some of the recorded flaws are located in weld repairs that extend into the base metal. Otherwise, there may have been inaccuracies involved in locating indications.

The alternative PTS rule requires that results from periodic volumetric examinations required by the ASME Code, Section XI, *Rules for Inservice Inspection (ISI) of Nuclear Power Plants*, be analyzed to determine if the actual flaw density and size distributions in the licensee's reactor vessel beltline weld metal and base metal are bounded by the flaw density and size distribution values used in the PTS technical basis. The discussion in the preceding paragraph points out the potential difficulty in the field with determining the location of indications in either the weld metal or base metal, particularly if the size and location of weld repairs is not completely known.

It is of interest to compare the rule maximum values from Table 2 (included later in Table 4.5 below) from §50.61a, *Allowable Number of Flaws in Welds*, with the results of the WesDyne reanalysis. In most cases, the TWE of the flaws used in this comparison were the estimated flaw depths from MRP-207. In a few cases where the analyst concluded that use of an estimated flaw depth was not warranted, the measured flaw depth from the 1996 examination was used. The estimated or default flaw depth used in MRP-207 was 3 mm (0.125 inch). Where included in the MRP-207 tables, the default sizing is considered more reliable than the 1996 amplitude-drop measurements. Amplitude-drop measurements tend to oversize reflections from flaws that are smaller than the UT beam width. PNNL included all flaws with a peak depth of 2.54 cm (1 inch) or less. As discussed in Section 2.0, Background, the flaws to be considered under the requirements §50.61a are limited to a depth of approximately 2.54 cm (1 inch) from the clad-to-base metal interface or 10 percent of the vessel thickness, whichever is greater. For Beaver Valley, Unit 2, 2.54 cm (1 inch) is greater than 10 percent of the vessel thickness. This comparison only included the beltline welds. The welds considered were the intermediate-to-lower shell circumferential weld (C-3), the intermediate shell long seam weld at 45° (L-9), the intermediate shell long seam weld at 225° (L-10), the lower shell long seam weld at 135° (L-11), and the lower long seam weld at 335° (L-12).

Nineteen flaws were identified in these welds within 2.54 cm (1 inch) from the clad-to-base metal interface. Table 4.4 provides a list of these 19 flaws with their peak depth, TWE in inches, and the applicable bin or bins from §50.61a Table 2.

To make the comparison between the number of flaws allowed by §50.61a and the reanalyzed data from Beaver Valley, Unit 2, the number of inches of weld length in the inspection volume is needed. MRP-207 contains sufficient information to determine that the length of welds C-3, L-9, L-10, L-11, and L-12 was approximately 2.29 cm (903 inches). Table 4.5 shows this comparison.

Based on the Beaver Valley, Unit 2, UT data reanalysis, as shown in Table 4.5, the number of indications found per 1000 inches (2540 cm) of weld length with TWE between 0.075-inch (1.9 mm) and 0.475-inch (12 mm) was 21.05 [19 ÷ (903÷ 1000)] as compared to the §50.61a Table 2 allowable of 166.7 flaws; the number of indications found per 1000 inches (2540 cm) of weld length with TWE between 0.125-inch (3.2 mm) and 0.475-inch (12 mm) was 19.94 [18 ÷ (903 ÷ 1000)] as compared to an allowable of 90.80 flaws; and the number of indications found per 1000 inches (2540 cm) of weld length with TWE between 0.175-inch (4.5 mm) and 0.475-inch (12 mm) was 1.11 [1 ÷ (903 ÷ 1000)] as compared to an allowable of 22.82 flaws. No indications were found that would fall within the remainder of the bins in Table 2 from §50.61a. It can be seen that the allowable flaw density bounds the flaw density determined from the Beaver Valley, Unit 2, reanalysis. It is possible that there were more fabrication flaws in the inspection volume than detected in the 1996 examination. For example, as noted above, the metallurgical analysis indicated that individual fabrication flaws were invariably stacked so their reflections could combine to yield medium-to-high amplitude ultrasonic indications in the 1977 post-hydro manual examination data. Also, many of the high-amplitude indications were not caused by single imperfections but resulted from stacks of small flaws oriented so their reflections would combine and be interpreted as a single imperfection. It is therefore possible that UT was detecting many of the flaws in the vessel welds but did not have the resolution to distinguish rows of small lack-of-fusion flaws or clusters of shrinkage voids.

Table 4.4. Beaver Valley, Unit 2, Table of Flaws within 1 inch of the Clad-to-Base Metal Interface

Weld	Peak Depth, in. (mm)	TWE, in. (mm)	Bin TWE Range, in.(a)
L-9	0.7 (17.8)	0.125 (3.2)	0.075 to 0.475 and 0.125 to 0.475
L-9	1.0 (25.4)	0.125 (3.2)	0.075 to 0.475 and 0.125 to 0.475
L-9	0.83 (21.1)	0.125 (3.2)	0.075 to 0.475 and 0.125 to 0.475
L-9	0.25 (6.35)	0.125 (3.2)	0.075 to 0.475 and 0.125 to 0.475
L-9	0.93 (23.6)	0.125 (3.2)	0.075 to 0.475 and 0.125 to 0.475
L-9	0.4 (10.2)	0.125 (3.2)	0.075 to 0.475 and 0.125 to 0.475
L-9	0.11 (2.8)	0.12 (3.0)	0.075 to 0.475
L-9	0.97 (24.6)	0.125 (3.2)	0.075 to 0.475 and 0.125 to 0.475
L-9	1.0 (25.4)	0.125 (3.2)	0.075 to 0.475 and 0.125 to 0.475
L-9	0.5 (12.7)	0.125 (3.2)	0.075 to 0.475 and 0.125 to 0.475
L-10	0.5 (12.7)	0.125 (3.2)	0.075 to 0.475 and 0.125 to 0.475
L-12	0.99 (25.2)	0.11 (2.8)	0.075 to 0.475
L-12	1.0 (25.4)	0.125 (3.2)	0.075 to 0.475 and 0.125 to 0.475
L-12	0.93 (23.6)	0.18 (4.6)	0.075 to 0.475 and 0.125 to 0.475 and 0.175 to 0.475
L-12	1.0 (25.4)	0.125 (3.2)	0.075 to 0.475 and 0.125 to 0.475
L-12	0.94 (23.9)	0.125 (3.2)	0.075 to 0.475 and 0.125 to 0.475
L-12	0.94 (23.9)	0.125 (3.2)	0.075 to 0.475 and 0.125 to 0.475
L-12	0.91 (23.1)	0.13 (3.3)	0.075 to 0.475 and 0.125 to 0.475
L-12	0.73 (18.5)	0.125 (3.2)	0.075 to 0.475 and 0.125 to 0.475

Note: No flaws within 1 inch (2.54 cm) of the clad-to-base metal interface were found in welds C-3 and L-11.
(a) Metric conversions are: 0.075 in. (1.9 mm); 0.125 (3.2 mm); 0.175 in. (4.4 mm); 0.475 in. (12 mm)

Table 4.5. Allowable Number of Flaws in Welds (Table 2 from §50.61a) Compared with the Results of the Beaver Valley, Unit 2, Reanalysis

Through-Wall Extent, in. (mm)		Number of Flaws per 1000 inches of Weld Length in the Inspection Volume that are Greater Than or Equal to TWE_{MIN} and Less Than TWE_{MAX}	
TWE_{MIN}	TWE_{MAX}	Rule Maximum	Beaver Valley, Unit 2
0 (0)	0.075 (1.9)	No Limit	None Reported
0.075 (1.9)	0.475 (12)	166.70	21.05
0.125 (3.2)	0.475 (12)	90.80	19.94
0.175 (4.5)	0.475 (12)	22.82	1.11
0.225 (5.7)	0.475 (12)	8.66	0.0
0.275 (7)	0.475 (12)	4.01	0.0
0.325 (8.3)	0.475 (12)	3.01	0.0
0.375 (9.5)	0.475 (12)	1.49	0.0
0.425 (10.8)	0.475 (12)	1.00	0.0
0.475 (12)	Infinite	0.00	0.0

MRP-207 (Spanner 2006) makes the point that the procedures used for this examination in 1996 differ from the procedures qualified per Appendix VIII and that it would be speculative to comment on how the results of the data reanalysis may change under Appendix VIII procedures. The NRC required licensees to implement Appendix VIII, Supplements 4 and 6, effective November 22, 2001. Because an ASME Code-required examination was performed at Beaver Valley, Unit 2, in 1996, it is likely that a (next interval) Code examination to the requirements of Appendix VIII, Supplements 4 and 6, has also been performed since 1996. Because Supplement 4 and 6 examinations use procedures that record/encode data, this data would be expected to be available for review. As §50.61a is based on UT procedures qualified to satisfy the requirements of Appendix VIII, it would be of value for this study to review the results of an examination of this vessel performed using procedures qualified to Appendix VIII requirements. Reviewing this data would enable a comparison of the sensitivity of the qualified procedures versus the pre-Appendix VIII procedures.

4.4 Browns Ferry, Unit 3, "Spirit of Appendix VIII" Examination

In 1993 the Tennessee Valley Authority performed an examination of the Browns Ferry, Unit 3, reactor vessel that was referred to as a "Spirit of Appendix VIII" examination. The procedures that were used for this examination were developed prior to the adoption by the NRC of requirements to implement Appendix VIII. TVA provided information on the results of the 1993 reactor vessel examination in a letter to the NRC dated September 2, 2010 (Krich 2010). Enclosures 1, 2, and 3 provided copies of the vendor's (General Electric's, GE's) examination procedures. The examination was performed by GE using GERIS 2000 equipment. The current owner of these procedures (GE-Hitachi) considers the examination procedures to be proprietary in nature, and requested through Enclosure 4 that such information be withheld from public disclosure. It is fair to note, however, that the recording threshold used during the examination was different than the requirements of Section XI applicable in 1993, or the guidance in RG 1.150, and resulted in a larger number of flaws that had to be evaluated against Section XI criteria.

Enclosure 5 provided copies of examination reports and associated records including examination summary sheets, examination data sheets, indication data sheets, and indication evaluation sheets. The search units used by GE consisted of 0° longitudinal, 70° longitudinal, and 45° and 60° shear wave probes. To develop a flaw density and distribution, PNNL reviewed the information in Enclosure 5 and summarized the data on indications detected and sized.

The Browns Ferry, Unit 3, reactor vessel has six circumferential shell welds and five sets of vertical welds between the six circumferential shell welds. PNNL used the data from the UT examinations of four of the circumferential welds, omitting the flange-to-shell weld and the shell-to-lower head weld. PNNL also used data from four sets of vertical shell welds. The vertical welds omitted were the uppermost vertical welds in the nozzle region. The beltline weld region that TVA identified includes portions of the lower two sets of vertical welds and the circumferential weld immediately above the shell-to-lower head weld. Although some of the welds PNNL analyzed are outside of what TVA identified as the beltline region, these welds were included because they have geometries that are similar to the configurations of the beltline region welds. Because it appears that other pre-Appendix VIII data like the Browns Ferry, Unit 3, examination data are not available, and because the welding techniques for all the shell welds would be expected to be the same, PNNL included a larger sample of fabrication welds than the welds in the beltline region.

PNNL prepared a density and distribution of the flaws found in these reactor vessel welds based on the following considerations. The total length of the four circumferential welds included in the analysis was approximately 80.1 m (3154 inches) and the length of the four sets of vertical welds included in the analysis was approximately 34.1 m (1342 inches). The total length of welds included in the flaw density and distribution was approximately 114.2 m (4497 inches). As discussed in Section 2.0, Background, the flaws to be considered under the requirements of §50.61a are limited to a depth of approximately 2.54 cm (1 inch) from the clad-to-base metal interface or 10 percent of the vessel thickness, whichever is greater. For Browns Ferry, Unit 3, 2.54 cm (1 inch) is greater than 10 percent of the vessel thickness. Sixty flaws were identified within 2.54 cm (1 inch) from the clad-to-base metal interface. The majority of these flaws were not connected to the clad-to-base metal interface. TVA provided the percentage of inspection coverage for each weld. Inspection coverage refers to the percentage of any given weld that has been examined in accordance with Code requirements. Sometimes the required coverage is not achieved because of obstacles or component geometry. Taking inspection coverage for each weld into account, the number of flaws used in the density and distribution was 67.91 flaws.

The depth or TWE sizing techniques used in this inspection included the ASME, Section XI, 50% DAC method, NRC RG 1.150 20% beam-spread correction methods, and sizing from tip-diffracted signals. For small flaws, the amplitude drop and beam-spread depth sizing techniques used in the 1993 Browns Ferry, Unit 3, RPV examination would typically produce relatively large measurements because, for flaws of this size, these techniques tend to measure the size of the sound beam, not the size of the flaw. The analyst's current procedures may require depth sizing using tip diffraction, an accurate technique, and require identifying the TWE as 3.2 mm (0.125 inch) if there are no tip responses present.

Contrary to the case seen for Beaver Valley, Unit 2, discussed in Section 4.3, no recent reanalysis of the Browns Ferry, Unit 3, 1993 data has been performed. Accordingly, PNNL used the depth sizes recorded on the indication data sheets when tip-diffraction techniques were used. There were several indications sized by tip-diffracted signals as having a TWE less than 3.2 mm (0.125 inch). PNNL used the TWE reported for these small indications. When amplitude drop or beam-spread depth-sizing techniques were used, PNNL assumed a default TWE of 3.2 mm (0.125 inch). For indications located within 2.54 cm (1 inch) of the clad-to-base metal interface and recorded as having "no determinable through-wall dimension," PNNL assigned the default depth of 3.2 mm (0.125 inch), similar to the estimated TWE value discussed in Section 4.3.

All flaws shown in the indication data sheets were assumed to be located in the weld. The TVA submittal does not make any statements regarding the location of flaws in the welds or base metal. It may have been possible to use information on the data sheets to infer flaw location, but it was judged that the effort and uncertainties involved would outweigh the benefits for this exercise. Table 4.6 shows the allowable number of flaws in welds (Table 2 from §50.61a) and the results of the Browns Ferry, Unit 3, analysis.

Table 4.6. Allowable Number of Flaws in Welds (Table 2 from §50.61a) Compared with the Results of the Browns Ferry, Unit 3, Analysis

Through-Wall Extent, in., (mm)		**Number of Flaws per 1000 inches of Weld Length in the Inspection Volume that are Greater Than or Equal to TWE_{MIN} and Less Than TWE_{MAX}**	
TWE_{MIN}	**TWE_{MAX}**	**Rule Maximum**	**Browns Ferry, Unit 3**
0 (0)	0.075 (1.9)	No Limit	0.0
0.075 (1.9)	0.475 (12)	166.70	15.01
0.125 (3.2)	0.475 (12)	90.80	14.83
0.175 (4.5)	0.475 (12)	22.82	6.44
0.225 (5.7)	0.475 (12)	8.66	5.28
0.275 (7)	0.475 (12)	4.01	4.09
0.325 (8.3)	0.475 (12)	3.01	3.11
0.375 (9.5)	0.475 (12)	1.49	1.29
0.425 (10.8)	0.475 (12)	1.00	0.79
0.475 (12)	Infinite	0.00	0.97

It can be seen that, for most of the Browns Ferry, Unit 3, reactor vessel weld flaw density bins, the allowable flaw density, or rule maximum, bounds the flaw density determined from the Browns Ferry, Unit 3, analysis. The density for the second and third bins is approximately an order of magnitude lower than the maximum flaw densities allowed by the rule. For the successive bins, the densities are comparable to the allowable maxima. For flaws greater than or equal to 8.3 mm (0.325 inch) and less than 12 mm (0.475 inch), the number of flaws per 1000 inches slightly exceeds the allowable number of flaws. For the last bin, flaws greater than or equal to 12 mm (0.475 inch), the number of flaws per 1000 inches is 0.97, which exceeds the §50.61a Table 2 maximum of 0 flaws for that bin. The rule requires that for any flaws that cause the limits of the rule in Table 2 or Table 3 to be exceeded, the licensee shall perform analyses to demonstrate that the reactor vessel will have a TWCF of less than 1×10^{-6} per reactor year.

For Browns Ferry, the only large differences in density between the examination and analysis results and the allowable limits are in the second and third bins in Tables 2 and 3 from §50.61a, the bins that include the smallest flaws. It is possible that there were more fabrication flaws in the inspection volume than detected in this 1993 examination. The sensitivity of the examination of the Browns Ferry, Unit 3, vessel may not have been sufficient to detect a large percentage of the 2–3 mm (0.08–0.12 inch) flaws that may have been present in the weld material and base metal.

4.5 Results of RPV Inspections Conducted at 13 PWR Plants

By letter dated September 7, 2011, from N. A. Palm and M. G. Semmler to A. A. Csontos of the NRC staff (Palm and Semmler 2011), Westinghouse provided results obtained from examinations of reactor vessel beltline welds at 13 PWR plants. The examinations were conducted by WesDyne using procedures qualified in accordance with the requirements of Section XI, Appendix VIII. PNNL reviewed and analyzed these results, which are discussed below.

The letter contains tables of results obtained for each of the 13 plants. The information on the first table for each plant includes a listing of the welds examined; for example, the intermediate-to-lower shell circumferential weld, the date of the last inspection, the number of recordable indications, and the number of reportable flaws. There were no reportable flaws for any of the 13 plants. The information on the second table for each plant includes each weld examined, each indication detected in the weld, the orientation of each flaw, and the location and sizing dimensions for each indication detected.

The following table contains a summary of the data reported by Palm and Semmler (2011) from the second table for each of the 13 plants. Surface flaws or scratches were omitted from this table.

Table 4.7. Summary Information on Indications Detected by RPV Weld Examinations at Thirteen PWRs

Plant	**Number of Recordable Indications**	**Number of Recordable Indications within 1 inch (25.4 mm) of the Clad-to-Base Metal (C-to-BM) Interface**	**Range in Through-Wall-Extents of Indications in the Third Column, mm (in.)[(b)]**	**Kay Range in Lengths of Indications in the Third Column, mm (in.)**	**Number of Indications in the Third Column Connected to the C-to-BM Interface**
A	2	1	5.6 (0.22)	40.6 (1.6)	0
B	2	2	3.2–5.6 (0.125–0.22)	15.2–28 (0.6–1.1)	(a)
C	1	1	3.2 (0.125)	25.4 (1)	0
D	1	0	N/A	N/A	0
E	4	4	5–15.2 (0.2–0.6)	20.3–24 (0.8–0.95)	0
F	26	1	3.6 (0.14)	132.8 (5.23)	0
G	3	2	1.5–4 (0.06–0.16)	12.7 (0.5)	0
H	1	1	4.6 (0.18)	28 (1.1)	0
I	3	1	3.6 (0.14)	12.7 (0.5)	0
J	8	3	5.6–8.6 (0.22–0.34)	40.6–53.3 (1.6–2.1)	0
K	119	10	2.3–10.9 (0.09–0.43)	10.4–1927 (0.41–75.86)	0
L	0	N/A	N/A	N/A	N/A
M	54	7	2.3–6.6 (0.09–0.26)	20.3–173 (0.8–6.82)	0

(a) One indication was reported to have a measured ligament to the inside clad-to-base metal interface of 1.65 mm (0.065 inch). The uncertainties in this measurement are likely larger than the measurement itself. This indication may actually be connected to the clad-to-base metal interface.

(b) Several flaws were recorded as having TWEs less than 2.54 mm (0.1 inch). As discussed in Section 4.7, it appears that the smallest of the PDI vessel test block flaws is around 2.54 mm (0.1 inch). Section 4.6 describes the obstacles involved with sizing flaws less than about 3.2 mm (0.125 inch) in TWE.

The following observations were made based on the summary of information in Table 4.7.

- The number of recordable indications detected in the beltline welds of the 13 PWR plants ranged from none to 119.
- The indication with the largest TWE recorded within 25.4 mm (1 inch) of the clad-to-base metal interface was 10.92 mm (0.43 inches). This is important because 10 CFR 50.61a requires a TWCF analysis for any flaws that exceed 0.475 inch (12.1 mm) TWE.
- Four or fewer recordable indications were detected within 25.4 mm (1 inch) of the clad-to-base metal interface in the beltline welds of 11 of the13 plants. Two plants had no recordable indications and seven plants had either one or two recordable indications within 25.4 mm (1 inch) of the clad-to-base

metal interface in the beltline welds. The number of recordable indications detected within 25.4 mm (1 inch) of the clad-to-base metal interface of plants K and M, which had the highest number of recordable indications, were 10 and 7, respectively. With the information provided, it is not possible to definitively determine whether these differences are due to differences in examination procedures, differences in the implementation of the examination procedures, or inherent differences in the number of flaws present in the welds.

- As discussed in Section 4.3, the number of recordable indications detected in the first inch of the beltline welds at Beaver Valley 2 in 1996 was 19. The Beaver Valley 2 reactor vessel with an inside diameter of 395 cm (155.5 inches) is smaller than the reactor vessels of plants K and M, which have inside diameters of approximately 439 cm (173 inches) and 440 cm (173.4 inches), respectively. Had the Beaver Valley 2 reactor vessel been as large as that of plants K and M, it is reasonable to expect that the number recordable indications would be larger than 19. Because the number of recordable indications detected in the first inch of the beltline welds of the two plants out of 13 plants with the highest number of recordable indications, plants K and M, were about half that detected at Beaver Valley 2 in 1996, it appears that the pre-Appendix VIII examination procedures used at Beaver Valley 2 may have been more sensitive than the Appendix VIII procedures used at the 13 plants reported in Palm and Semmler (2011).
- Because Palm and Semmler (2011) does not report data on weld linear dimensions, it was not possible to calculate flaw density to compare with the limits in Tables 2 and 3 of the alternate PTS rule, as was done for Beaver Valley, Unit 2, in Section 4.3 and Browns Ferry, Unit 3, in Section 4.4 of this report.

4.6 Discussions with RPV Inspection Vendors

As part of this study, PNNL contacted RPV inspection vendors to discuss technical aspects for typical examinations performed in the field. These were informal communications aimed at clarifying ultrasonic techniques and protocols that could influence detection or sizing capability in the context of applying §50.61a. Two RPV vendor organizations (WesDyne and IHI Southwest, Inc.) were receptive to these discussions, and senior examiners with many hours of field experience participated in two separate teleconferences. Several UT variables and application methods were discussed, but of primary interest was how these examiners viewed their capability to meet the bin-sizing requirements of §50.61a. Two main items of interest to this study that were communicated were the following:

1. Examination of RPV welds performed prior to the application of Appendix VIII qualifications (in the late 1980s and throughout the 1990s) were fairly sophisticated and, though based on prescriptive ASME Code, Section V, Article 4, UT requirements, it is believed that the examinations employed would have been capable of detecting flaws of interest to §50.61a, even down to a 2–3 mm (0.08–0.12 inch) TWE range. These techniques were based primarily on the signal-to-noise and amplitude of reflectors to meet threshold reporting and evaluation requirements. Several transducers and UT modes of propagation were employed, and in some cases, zone-focused probes helped to provide better sound fields in certain regions of the welds. The applied procedures contained explicit instructions for identifying, measuring, and accepting/rejecting UT responses. The result would be that while many UT signals were detected, a majority would fall below the threshold amplitude required for evaluation by the ASME Code at that time. WesDyne performed the Beaver Valley, Unit 2, reanalysis described above (MRP-207; Spanner 2006) on data collected by prescriptive

examination methods, albeit re-reviewed at higher UT gain settings and without regard to amplitude thresholds.

However, since the inception of qualifications required by ASME Code, Appendix VIII, the prescriptive (and amplitude-based) UT requirements have been supplanted by performance-based criteria. While these procedures are believed to be more robust for detection of service-induced flaws, examiner subjectivity has increased during this process. More importantly, because the emphasis is for examiners to be qualified on simulated components with realistic flaw responses, the types of flaws introduced into these test components dictate how procedure/technique development occurs. Because ASME Section XI targets service-induced, surface-connected reflectors, such as cracks, these (non-fabrication) flaws are the most dominant flaws present in the test specimens; thus, certain UT variables developed to meet Appendix VIII qualifications may not encompass all the UT variables required of earlier ASME Code and other regulatory documents. The result may be that Appendix VIII-based procedures, while effective for detecting simulated service-induced flaws, may not be as sensitive to small fabrication flaws as some of the techniques used prior to the application of Appendix VIII qualifications.

2. It is uncertain whether UT depth-sizing accuracy for small flaws will be sufficient to adequately support the binning described by §50.61a. UT flaw-sizing depends on basic time-of-flight methods to discriminate between separate specular and diffracted signals from targeted reflectors. When flaws are very small, on the order of the wavelength of the sound beam, the response from both specular and diffracted signals tends to overlap; therefore, one is unable to adequately discern the difference in time. Thus, when the diffracted signals overlap, or become temporally close to the specular reflections, flaws cannot be reliably sized. If amplitude-based sizing methods are used, the tendency is to over-size small flaws. For this reason, most RPV inspection vendors use some type of "screening" criteria when small flaws are detected. For instance, one of the vendors described their criterion as, if diffracted (tip) responses could not be adequately separated from the main reflection, then the flaw is believed to be very small, and placed into a population of flaws reported as less than, or equal to, 0.32 cm (0.125 inch) TWE. It may be important to understand that this default sizing approach is being used in the field, as this approach was successfully used throughout the Appendix VIII performance demonstration qualification process.

4.7 EPRI Report 1007984, Reactor Pressure Vessel Inspection Reliability Based on Performance Demonstrations

NRC contacted the EPRI NDE Center in Charlotte, North Carolina, to determine if any analyses exist for detection/flaw sizing results in RPV welds. PNNL was provided with EPRI Report 1007984, *Reactor Pressure Vessel Inspection Reliability Based on Performance Demonstrations* (Becker 2004). Portions of this study were summarized in two published papers (Becker 2001, 2002).

The data for this study were obtained while qualifying examiners on ASME Section XI, Appendix VIII, Supplements 4 and 6, requirements under the industry's Performance Demonstration Initiative. PDI has been administered by EPRI since performance demonstrations were initiated in 1994. Becker reported in the 2002 paper that PDI had manufactured 20 RPV mockups containing more than 300 flaws. An array of ultrasonic performance data, including detection, depth sizing, and length sizing, was generated as a result of the PDI program. Supplement 4 of the ASME Code, 2004 Edition, applies to the clad-to-base metal interface and the inner 2.54 cm (1 inch) or 10% of the vessel thickness, whichever is larger. Supplement 6 applies to the remainder of the vessel thickness.

4.7.1 Detection of Flaws

The first step in the qualification process is the detection of flaws. The POD is defined as the conditional probability that a flaw will be detected if present. Becker presented POD data as a function of TWE of the flaw. POD curves were estimated by performing a logistic regression on detection measurements.

For Supplement 4 test blocks, at least 70% of the flaws are required to be cracks. The balance can be cracks, fabrication flaws, such as slag and lack of fusion, or machined notches. Implanted flaws and notches are connected to the clad-base metal interface. Supplement 4 specifies that flaw sizes shall be a representative distribution of through-wall depths among five ranges in TWE from 0.2 cm to 1.9 cm (0.075 inch to 0.75 inch). Flaw-sizing test blocks conform to these same requirements.

The POD estimates shown in Figure 4.6 were based on Supplement 4 performance demonstration data defined by the following conditions:

- Examinations were performed from the vessel inside surface using automated procedures.
- Flaws of interest are located at the clad-to-base-metal interface.
- Dual-side access (two directions perpendicular to the flaw) was available.
- Results from passed and passed-plus-failed candidates are included.
- Results from failed candidates with more than two missed detections or false calls are not included in the data.
- POD curves are not applicable for flaws less than 2.54 mm (0.1 inch) TWE. It appears that the test blocks do not contain flaws smaller than about 2.54 mm (0.1 inch) or do not contain a sufficient number of flaws smaller than 2.54 mm (0.1 inch) to construct the POD curves.

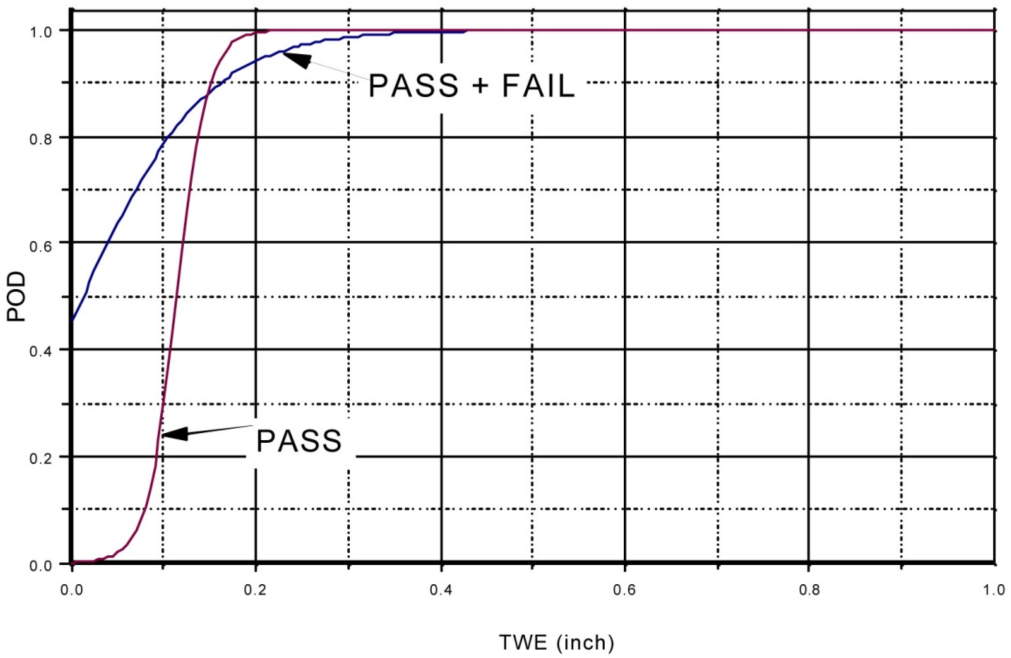

Figure 4.6. POD for Inside Surface Examinations, Passed and Passed-Plus-Failed Candidates for Appendix VIII, Supplement 4, as a Function of the Flaw Through-Wall Extent (Becker 2002)

As noted by Becker, the data from the failed candidates only includes the results from candidates with two or fewer missed detections or false calls. These candidates normally passed on a second attempt after a brief retraining and review. Becker noted that inclusion of passed candidates only may be overly optimistic and that inclusion of Pass-plus-Failed candidates provides a lower-bound estimate of expected performance.

The PASS curve in Figure 4.6 is based on the POD for passed candidates being constrained to zero for the zero flaw size, which introduces considerable uncertainty in the POD curve. Becker indicates that the POD for the PASS + FAIL curve was not constrained to zero and that the POD curves for passed-plus-failed candidates are not related to false calls at zero flaw size. Note that contrary to expectation, the POD for PASS + FAIL is higher than the POD for PASS for TWE from 2.54 mm (0.1 inch), the lower limit of applicability, to about 3.56 mm (0.14 inch). It is apparent that the statistical techniques used to construct the POD curves can have a large effect on the curves, particularly for the smallest flaw sizes of interest to §50.61a.

Supplement 6 requires test blocks to include embedded and outside surface-connected flaws. For Supplement 6 test blocks, at least 55% of the flaws shall include cracks and the balance shall be cracks or fabrication flaws, such as slag and lack of fusion. Embedded flaws may be as large as 5.1 cm (2 inches) in depth. Flaws in the outer 10% are in the same range as Supplement 4 flaws. Figure 4.7 provides the POD for Appendix VIII, Supplement 6, for examinations performed from the inside surface.

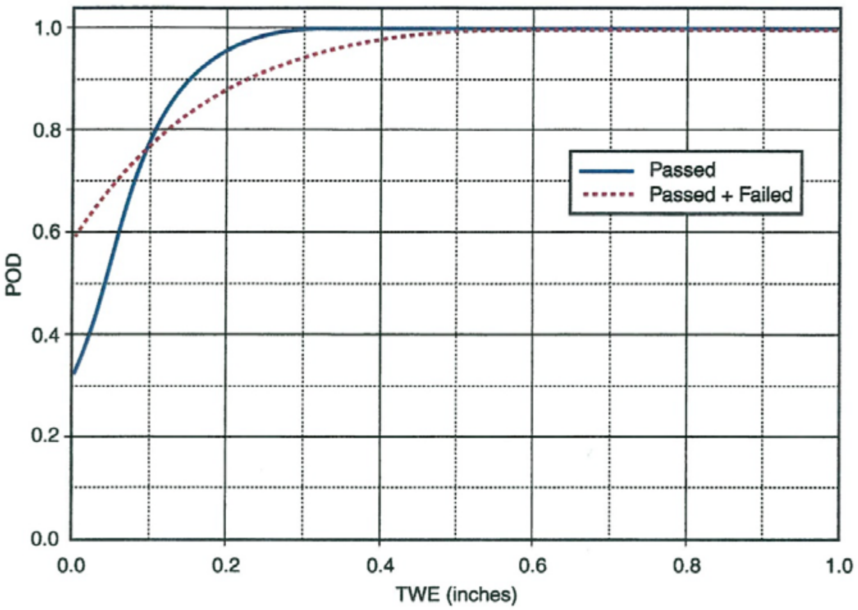

Figure 4.7. POD for Inside Surface Examinations, Passed and Passed-Plus-Failed Candidates for Appendix VIII, Supplement 6, as a Function of the Flaw Through-Wall Extent (Becker 2004)

Although not included here, the EPRI report also provides POD curves with 95% uncertainty bounds.

4.7.2 Sizing Performance

The second step in the qualification process is determination of flaw-sizing capability. NDE sizing error describes the difference between the estimated and the actual through-wall flaw size. This convention yields a positive error for over-sizing and a negative error for under-sizing. Supplement 4 requires depth sizing as compared to true depth to be within 4 mm (0.15 inch) root mean square error (RMSE). Supplement 6 requires depth sizing as compared to true depth to be within 6 mm (0.25 inch) RMSE.

The distribution of sizing errors as a function of true flaw size for Supplement 4 flaws is shown in Figure 4.8. This data shows that the sizing distribution may be characterized by a mean error with a negative slope and that there is a demonstrated tendency to over-size smaller flaws and under-size large flaws. This trend to over-size small flaws and to under-size larger flaws has been observed and documented in round-robin tests conducted on thick-section steel components and piping such as the Programme for the Inspection of Steel Components – Phase II (Nichols and Crutzen 1988). Becker noted that Figure 4.8 was provided for a qualitative understanding of the error distribution.

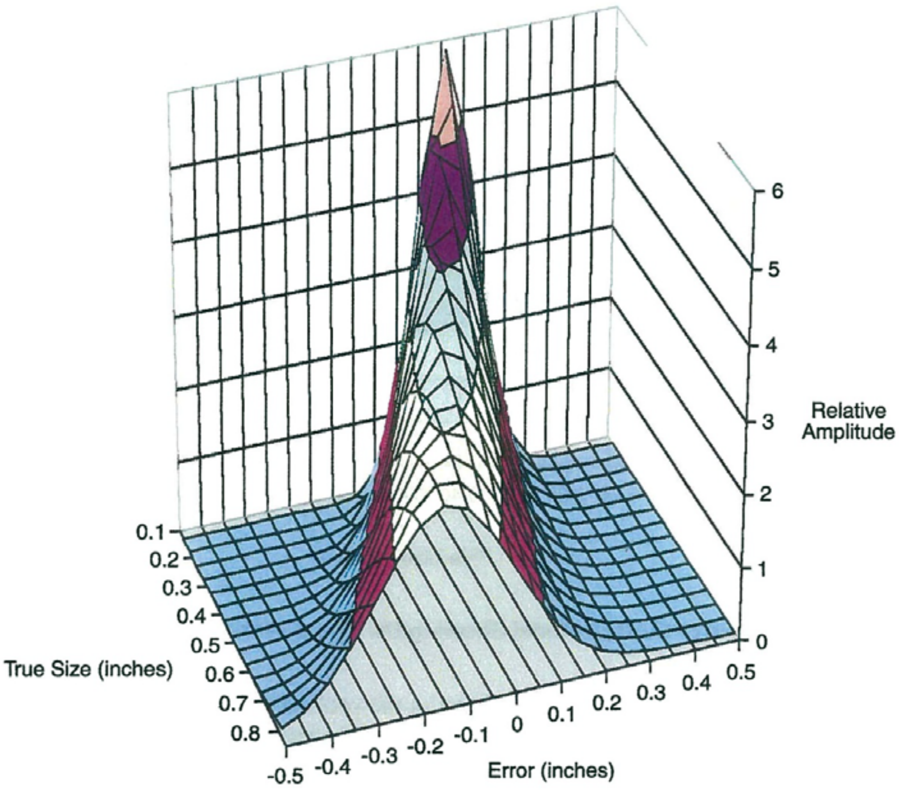

Figure 4.8. Appendix VIII, Supplement 4, Successful Candidate Flaw Sizing Error vs. True Flaw Depth – Surface Model (Becker 2001, 2002, 2004)

Data used in the evaluation of sizing capability are applicable to the following conditions:

- Inside plus outside surface examination.
- Flaws are located at the clad-to-base metal interface.
- Dual-side access and single-side access measurements are included (i.e., access from either side of the weld on a single surface).
- Only passed candidates are included.
- Sizing data from both inside and outside surfaces are included. The data contain both automated and manual sizing information. The total number of observations was 772.

The vessel examinations for pressurized water reactors would be performed from the inside surface, while examinations for boiling water reactors may be performed from both the inside and outside surfaces. The EPRI report (Becker 2004) notes that study of the inside and outside surface access examinations separately, as well as combined, indicates that the differences are not significant. If further analysis of the data in the EPRI report is to be made, it would be of interest to view the data to understand the differences in depth sizing error for inside versus outside surface access examinations.

Figure 4.9 presents data for Supplement 4 depth-sizing error in terms of bias and stochastic error, and Figure 4.10 presents data for Supplement 6 depth-sizing error in terms of bias and stochastic error.

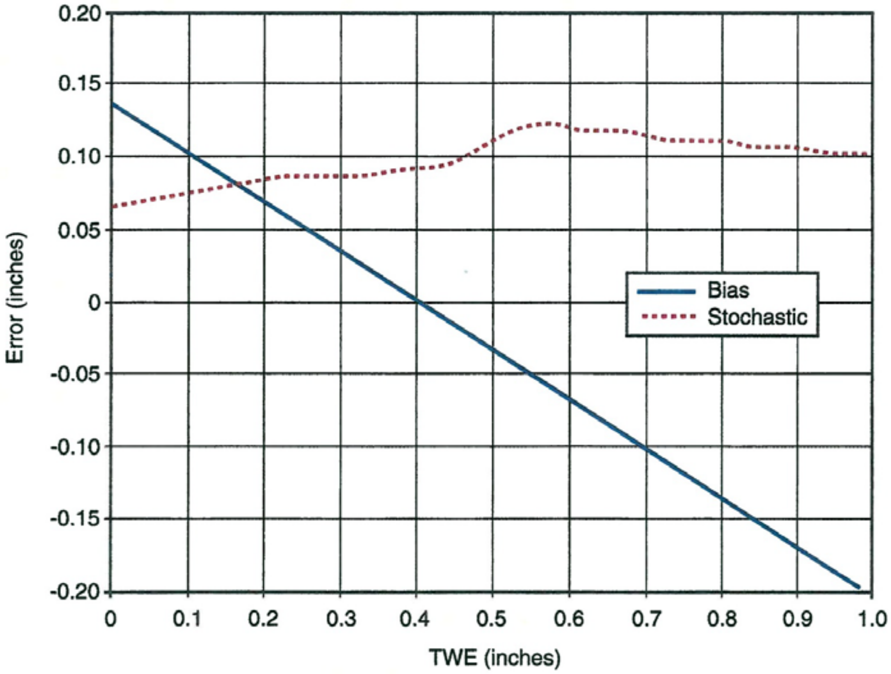

Figure 4.9. Bias and Stochastic Depth Sizing Error for Supplement 4 Flaws; Internal and External Surface Depth-Sizing Measurements; Only Passed Candidates Included (Becker 2004)

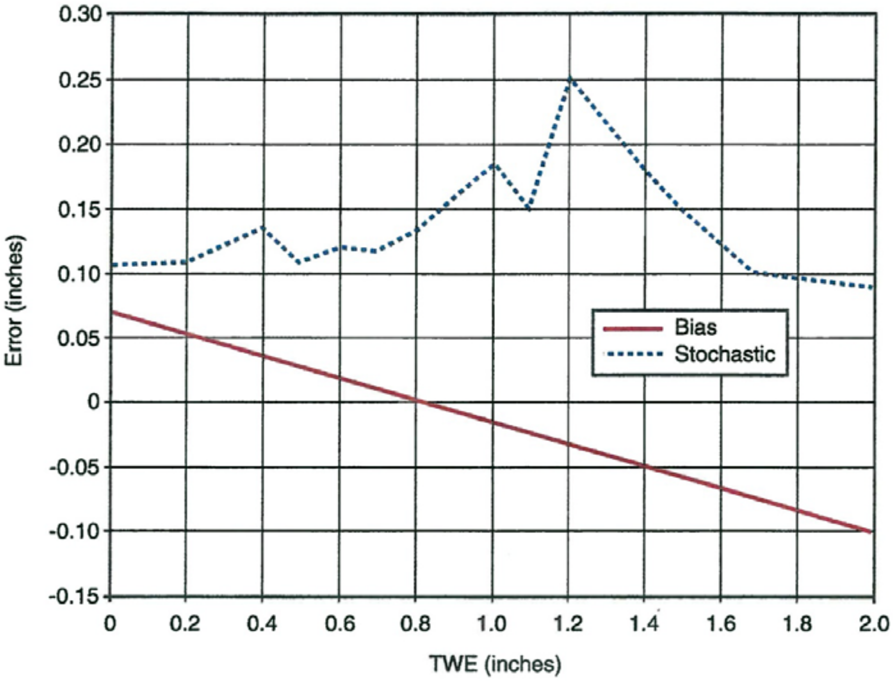

Figure 4.10. Bias and Stochastic Depth Sizing Error for Supplement 6 Flaws; Internal and External Surface Depth-Sizing Measurements; Only Passed Candidates Included (Becker 2004)

Bias sizing error is the mean measurement error as a function of true flaw size. Stochastic error is the stochastic or random error normally distributed with mean of zero and variance of σ^2 (σ = standard deviation). Figures 4.9 and 4.104.104.104.10 exhibit a pronounced tendency to over-size small flaws and under-size larger flaws. The bias error decreases and becomes negative with increasing flaw size. In sizing larger and more complex flaws, there are many opportunities for error; for example, the absolute deepest portion of the flaw might not be found. The increase in stochastic error with flaw size results from the fact that there are more opportunities for errors for large flaws as compared to small flaws (Becker 2004).

The EPRI report also presents data for length-sizing performance. The report notes that length-sizing errors have less impact on RPV integrity than do depth-sizing errors. Length sizing provides insight to the candidate's overall capability. The acceptance criterion for length sizing for Supplements 4 and 6 is 19 mm (0.75 inch) RMSE.

Understanding depth- and length-sizing performance is important for the present study, as the rule requires flaws with large TWE, if detected within the inner three-eighths of the vessel thickness, to be evaluated for contributions to TWCF. The limitation for flaw acceptance, specified in ASME Code, Section XI, Table IWB-3510-1, approximately corresponds to the threshold for flaw sizes that can make a significant contribution to TWCF if present in reactor vessel material at this depth. Flaw length is needed to evaluate allowable flaw size in accordance with ASME Code, Section XI, Table IWB-3510-1. Depth-sizing performance can also have a significant impact on flaw distribution calculations.

4.7.3 Discussion of the EPRI Report and Becker Papers

It should be noted that there are some differences between inspection of the test blocks used by PDI and inspections in the field that would be conducted in connection with the alternate PTS rule.

Although we do not have complete knowledge of the Supplement 4 PDI flaw characteristics, it is our understanding that the Supplement 4 data presented by the Becker papers was developed from test blocks that do not contain full penetration vessel welds, although implanted flaws are welded into excavated volumes and these welds would be expected to contain welding flaws.

Becker indicates that the POD curves are not applicable for flaws less than 2.54 mm (0.1 inch) TWE. It appears that the smallest of the test block flaws is around 2.54 mm (0.1 inch). This flaw depth is contained within the smallest flaw depth bin size of interest to §50.61a. Therefore, it appears that the Supplement 4 procedures may not be qualified to verify the presence of flaws as small as 2 mm (0.08 inch) and the threshold of detection for various flaws types and inspection procedures is not clear from an evaluation of the reports identified by PNNL for this study.

The focus of the performance demonstration tests is on implanted planar flaws that are connected to the clad-to-base metal interface. Candidates at PDI are tested for an ability to detect a minimum number of crack-like flaws in specimens without exceeding the acceptance criteria for false calls of non-crack-like flaws. Candidates are asked to report cracks, and false call acceptance criteria in the testing process discourages reporting of non-crack like indications, such as welding flaws. Therefore, based on the skills needed to pass the performance demonstration, examiners would be expected to focus on detecting, sizing, and reporting crack-like flaws connected to the clad-to-base metal interface. Discrimination of flaw types is not required training for individuals performing UT examinations. By contrast, 50.61a is looking for the licensees' examiners to detect and characterize both fabrication flaws and service-induced flaws.

As noted in Section 4.3 on the Beaver Valley, Unit 2, inspection, based on procedure development work at WesDyne, flaw features can be detected and measured using diffraction or satellite features when the flaw is greater than about 3 mm (0.125 inch) in diameter for a round flaw and top to bottom for planar reflectors.

As noted from the validation efforts discussed in Section 4.1, although fabrication flaws may have certain aspects that are crack-like in nature, they are not ideal planar cracks. For instance, in many cases these crack-like fabrication flaws do not have highly sharpened crack tips. In other cases, the flaws had complex morphologies consisting of only partially linked lack of fusion, porosity, slag, and other sources of contamination. All other things being equal, these features may make the fabrication flaws easier to detect than the planar flaws. However, the implanted planar flaws in Supplement 4 test blocks are connected to the clad-to-base metal interface, whereas an RPV would have fabrication flaws throughout the vessel thickness. In an actual vessel inspection, the examiner has to locate the shallowest and deepest part of the flaw. Therefore, the depth-sizing performance reported by Becker from the PDI test blocks may be better than the performance during an actual vessel examination, particularly for small flaws not connected to the clad-to-base metal interface. This point relates to sizing the remaining ligament for embedded flaws. The Becker reports do not provide performance data on this aspect of the examination for either Supplement 4 or 6. Our understanding is (a) Supplement 6 procedures are required to be demonstrated on surface-connected flaws and flaws with unflawed ligaments of more than 5 mm (0.2 inch) but that (b) the ability to size the remaining ligament for embedded flaws is not required to be demonstrated by examiners when they are tested to Appendix VIII Supplement 4 or Supplement 6 requirements. Nevertheless, on a plant-specific basis, sizing by examiners of remaining ligaments would be necessary to implement §50.61a. Also, in other component welds, although examiners are not required to demonstrate the ability to size the unflawed ligament for embedded flaws, it is sometimes necessary for examiners to determine the size of the unflawed ligament to make conclusions regarding fabrication flaws versus those from in-service degradation, and to perform flaw evaluations.

For two-sided access qualification, Appendix VIII, Supplements 4 and 6, require that flaws be oriented either parallel or perpendicular to the clad direction within ±10 degrees. However, it was determined during the PNNL validation efforts that flaws may have complex orientations, particularly flaws introduced as a result of repairs. The inner 2.54 cm (1 inch) of a reactor vessel weld constructed with full thickness welding was approximately the region where back-gouging to sound metal and re-welding occurred to eliminate unacceptable flaws in the root pass. Also, the zones over circumferential shell welds were clad with manual welding rather than strip cladding. We are not aware of whether the PDI test blocks include regions with manual weld cladding. Any flaws that occurred in this back-welded region may have a variety of orientations relative to the direction of cladding. The orientation of flaws and the surface condition of the manually applied clad over the circumferential shell welds may also affect Supplement 4 detectability and sizing performance of vessel flaws as compared to the flaws in the PDI test sets.

The information on sizing performance presented by Becker includes at least one additional difference. The Supplement 4 sizing performance included data based on inspection from the outside surface as well as the inside surface. Some outside surface examinations were performed using manual techniques without encoded data gathering. The inside surface examinations were performed using encoded data gathering techniques. Examinations of PWR vessels are all performed from the inside surface and the data is acquired with equipment that obtains encoded data. For the Supplement 4 inspection volume, Becker does not provide sizing performance data that separates inside and outside surface, or encoded versus non-encoded, sizing performance.

As noted in Section 2.0, Background, of this report, §50.61a does not require the comparison to its Tables 2 and 3 of the density of flaws deeper than 2.54 cm (1 inch) or 10 percent (whichever is greater), of the vessel wall thickness, as measured from the clad-to-base interface. However, it does require that flaws with large TWE, if detected, be evaluated for contributions to TWCF if they are within the inner three-eighths of the vessel thickness. Because of the importance of maintaining confidentiality of the flaw characteristics in the test blocks, PNNL does not have a complete understanding of the flaws in the PDI Supplement 4 and 6 test blocks. Therefore, it is not possible at this time to assess the applicability of the Becker papers to actual RPV fabrication flaws that would need to be evaluated against the allowable standards of Table IWB-3510-1. However, based on Section XI, Table IWB-3510-1, the flaws of interest to the Section XI, Appendix VIII, requirements that apply to this region would be larger than about 4 mm (0.15 inch) in TWE and would be expected to be less challenging to detect and characterize than small flaws (i.e., small flaws in the second bins of §50.61a, Tables 2 and 3) within the inner 2.54 cm (1 inch) or 10% of the wall thickness.

The report and conference papers by Becker provide more quantitative analyses on detection and sizing performance of flaws in RPV weld materials of the size of interest under §50.61a, including small flaws, than any other information found by the PNNL investigators. The information published by Becker is considered to be primarily applicable to service-induced flaws. It is apparent from the information in the Becker reports as well as other reports discussed above that pre- and post-Appendix VIII UT techniques are capable of detecting many of the flaws of interest for §50.61a, including some small flaws. However, based on our current knowledge, for fabrication flaws the differences between the test blocks and actual RPV welds with respect to flaw type, size, location, and orientation would hinder the application of Becker’s POD and sizing performance data to field vessel examinations for PDI-demonstrated procedures. Additional work would be needed to develop similar data for detection and sizing of surface-connected flaws 2 mm (0.08 inch) or less, in TWE and for detection and sizing of fabrication flaws.

4.8 Capability of Surface and Visual Examinations

Paragraph §50.61a(e)(1)(iii) in the alternate PTS rule requires that for each flaw detected in the inspection volume with a through-wall extent equal to or greater than 1.9 mm (0.075 inches), the licensee shall document the dimensions of the flaw, including through-wall extent and length, whether the flaw is axial or circumferential in orientation and its location within the reactor vessel, including its azimuthal and axial positions and its depth embedded from the clad-to-base metal interface.

Ultrasonic testing is the primary examination technique relied upon in §50.61a for detection and sizing of flaws. As discussed in Section 4.7.3, the ability to size the remaining ligament for non-surface-breaking (embedded) flaws is not required to be demonstrated by examiners when they are tested to Appendix VIII, Supplement 4 or Supplement 6 requirements.

Surface techniques, such as eddy current testing (ET), may be capable of determining whether a flaw is surface breaking. However, in accordance with the flaw characterization rules of IWB-3510, any flaw penetrating the clad-to-base metal interface, but not connected to the ID surface, has to be evaluated by proximity rules to determine whether it is to be treated as a surface flaw or a subsurface flaw. This evaluation is based on a relationship between the TWE and the remaining ligament (S) between the flaw and the ID surface of the cladding. While ET, under the right conditions, may be able to determine whether a flaw is surface-breaking, the capability of ET to detect subsurface flaws and measure the size of an unflawed remaining ligament that penetrates the clad-to-base metal interface has not been demonstrated by industry. Further, as-built surface conditions of the cladding would need to be factored into any such demonstration because of the challenges to uniform probe contact that these uneven surfaces may present.

The rule also allows the use of visual examination to verify that clad-to-base metal interface flaws do not open to the inside surface of the vessel. The capability of in-vessel visual examination techniques is currently being assessed in a joint PNNL-EPRI project. The results of this capability demonstration have not been released. Regardless of the status of this project, visual examination is, by its nature, not capable of providing information about the size of a remaining ligament of a flaw that penetrates the clad-to-base metal interface but does not quite reach the clad ID surface. In addition, remote visual methods, which would be necessary in this case, have inherent limitations to “seeing” cracks, depending on the crack opening dimensions; in other words, depending on how tight the crack might be. This limitation has been understood for many years; and is the primary reason that several surface examination methods such as liquid penetrant and magnetic particle testing were initially developed. These methods are essentially enhanced visual techniques.

In summary, the alternate PTS rule requires that for each flaw detected in the inspection volume with a through-wall extent equal to or greater than 1.9 mm (0.075 inches), the licensee shall, among other things, document its depth embedded from the clad-to-base metal interface. The capabilities of NDE to document the remaining ligament of a flaw as required by §50.61a(e)(1)(iii) have not been demonstrated.

5.0 Conclusions

1. From the results of the PVRUF research, the validated flaws were mostly small, 3 mm (0.12 inch) or smaller in TWE extent. The fusion surfaces between the weld and the base metal contained a high concentration of planar discontinuities. The flaws in the PVRUF vessel, although crack-like in nature, were not ideal planar cracks as conservatively assumed in fracture mechanics calculations. In many cases, the crack-like flaws did not have highly sharpened crack tips, and therefore should have lower stress intensities than assumed for ideal planar cracks.
2. For the largest flaws associated with repairs to welds, the flaws had complex morphologies consisting of only partially linked lack of fusions, porosity, slag, and other sources of contamination. These crack-like flaws may be easier to detect than planar cracks. It follows from this finding that significant fabrication flaws can have an ultrasonic straight-beam response. Straight-beam examination was included in the Browns Ferry, Unit 3, “Spirit of Appendix VIII” examination procedures and contributed to the identification of weld indications.

   Based on the information in MRP-207 (Spanner 2006), straight-beam examinations were not included in the 1996 Beaver Valley, Unit 2, examination procedures. Examination with straight-beam probes may not be included in Appendix VIII, Supplement 4 and 6, procedures qualified through PDI as it is possible to pass the PDI examination without using them.
3. The allowable flaw density from Table 2 of §50.61a bounds the flaw density determined from the Beaver Valley, Unit 2, reanalysis. However, it is possible that there were more fabrication flaws in the inspection volume than detected in the 1996 examination, and that pre-Appendix VIII examination techniques may not have been sensitive enough to detect very small flaws (with TWE on the order of the smallest two flaw bins in §50.61a).
4. Based on a review of reactor vessel weld examination results of 13 PWRs, it appears that the pre-Appendix VIII examination procedures used at Beaver Valley, Unit 2, were more sensitive than the more recent Appendix VIII-demonstrated procedures used at the 13 plants reported in Palm and Semmler (2011).
5. For Browns Ferry, the only large differences in density between the examination and analysis results and the allowable limits are in the second and third bins in Tables 2 and 3 from §50.61a, the bins that include the smallest flaws. It is possible that there were more fabrication flaws in the inspection volume than detected in this 1993 examination. Regarding the discussions with inspection vendors, examination of RPV welds performed prior to the application of Appendix VIII qualifications (in the late 1980s and throughout the 1990s) were fairly sophisticated, and it is believed that UT examinations applied were generally capable of detecting some flaws as small as 2–3 mm (0.08–0.12 inch) in TWE. However, Appendix VIII-based procedures, while effective for detecting simulated service-induced flaws, may not necessarily be sensitive to small fabrication flaws. NRC guidance may be needed on detecting and binning flaws that are too small to reliably size.
6. The ability to detect embedded fabrication flaws and size such flaws and the unflawed remaining ligament is not demonstrated by examiners when they are being tested to Appendix VIII, Supplement 4, requirements. In addition, false call acceptance criteria in the performance demonstration testing process discourages the reporting of indications other than surface-connected, crack-like flaws.

After conducting a literature search on the capability of RPV UT examinations, PNNL was not able to identify information to assess the performance of Appendix VIII or other UT procedures to accurately size the remaining ligament for embedded flaws. Likewise, PNNL has not identified any data regarding the ability of ASME-qualified UT techniques to distinguish between “crack-like” and “non-crack-like” ultrasonic reflectors.

7. The report and conference papers by Becker provide more quantitative analyses on detection and sizing performance of flaws in RPV weld materials of the size of interest under §50.61a, including small flaws, than other information found by the PNNL investigators. However, the information published by Becker is considered to be primarily applicable to service-induced flaws. It is apparent from the information in the Becker papers, as well as other reports discussed herein, that pre- and post-Appendix VIII UT techniques are capable of detecting many of the flaws of interest for §50.61a, including some small flaws. However, with respect to fabrication flaws, the differences between PDI test blocks and actual RPV welds in the numbers of flaw types, their sizes, locations, and orientations would hinder the application of Becker’s laboratory POD and sizing performance data to field reactor vessel examinations.
8. The alternate PTS rule requires licensees to verify that flaws equal to or greater than 1.9 mm (0.075 inch) in through-wall depth, are axially-oriented, and located at the clad-to-base metal interface do not open to the inside surface of the vessel. Given the need to apply the flaw characterization rules of IWB-3510, the capabilities of NDE to obtain the information needed to perform the verification and evaluation requirements of §50.61a(e)(2) and §50.61a(e)(4) have not been demonstrated.

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Appendix A

An Explanation of Tables 2 and 3 in 10 CFR 50.61a

Appendix A

An Explanation of Tables 2 and 3 in 10 CFR 50.61a

Table 2 of 10 CFR 50.61a contains the allowable number of flaws in welds with respect to flaw through-wall extent (TWE) ranges in inches. The TWE is the maximum dimension, normal to the surface of the component, of the rectangle circumscribing the flaw. The TWE of a flaw is a value measured by either nondestructive or destructive examination and the flaw can be located anywhere in the inspection volume. The TWE value does not infer, for example, that the flaw's inner edge is connected to the clad-to-weld metal interface.

Table 2 – Allowable Number of Flaws in Welds

Through-Wall Extent (inches)		Maximum Number of Flaws per 1000 inches of Weld Length in the Inspection Volume that are Greater Than or Equal to TWE_{MIN} and Less Than TWE_{MAX}
TWE_{MIN}	TWE_{MAX}	
0	0.075	No Limit
0.075	0.475	166.70
0.125	0.475	90.80
0.175	0.475	22.82
0.225	0.475	8.66
0.275	0.475	4.01
0.325	0.475	3.01
0.375	0.475	1.49
0.425	0.475	1.00
0.475	Infinite	0.00

For Table 2, the first bin, flaws with TWE up to 0.075 inch, has no limit on the number of flaws allowed. The second bin, flaws with a TWE between 0.075 and 0.475 inch, has an allowable number of 166.70 flaws per 1000 inches of weld. The third bin, flaws with a TWE of between 0.125 and 0.475 inch, has an allowable number of 90.80 flaws per 1000 inches of weld. The second bin includes the allowable number of flaws in the third bin as well as an allowance for flaws with TWE between 0.075 and 0.125 inch. The same type of cumulative representation applies to the succeeding bins in Table 2 and to Table 3.

In a proposed version of this rule, Tables 2 and 3 specified the allowable number of flaws for each bin using a differential representation; for example, the allowable number of flaws with TWE between 0.125 and 0.175 inch, 0.175 and 0.225 inch, 0.225 and 0.275 inch, and so on. With differential representation of the allowable number of flaws, it may turn out for a particular set of inspection results that there are fewer flaws than allowed for a particular bin, but more than the allowable number of flaws for an adjacent bin. This would be unacceptable with a differential representation of the allowable number of flaws but may be acceptable with a cumulative representation. For example, if the allowable number of flaws in welds were differentially represented, the allowable number of flaws with TWE between 0.425 and 0.475 inch would be 1 flaw and the allowable number of flaws with TWE between 0.375 and 0.425 inch would be

0.49 flaw. Using differential representation, if no flaw were found in the bin for TWE between 0.425 and 0.475 inch and 1.3 flaws were found in the bin for TWE between 0.375 and 0.425 inch, the allowable number would be exceeded for the 0.375- to 0.425-inch bin. However, using the cumulative representation of Table 2, the number of flaws found in the bin for TWE between 0.425 and 0.475 inch would be still be 0 and the number of flaws found in the bin for TWE between 0.375 and 0.475 inch would be 0 + 1.3 = 1.3, which is less than 1.49 and, therefore, acceptable. The cumulative representation provides flexibility in accounting for the number of flaws in the bins while assuring that the probability of vessel failure remains acceptable.

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