U.S. DEPARTMENT OF ENERGY

Technical Letter Report

Development of Flaw Size Distribution Tables Including Effects of Flaw Depth Sizing Errors for Draft 10CFR 50.61a (Alternate PTS Rule)

JCN-N6398, Task 4

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April 2013

Pacific Northwest
NATIONAL LABORATORY

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Abstract

This document describes a new method to determine whether the flaws in a particular reactor pressure vessel are consistent with the assumptions regarding the number and sizes of flaws used in the analyses that formed the technical justification basis for the new voluntary alternative Pressurized Thermal Shock (PTS) rule (Draft 10 CFR 50.61a). The new methodology addresses concerns regarding prior methodology because ASME Code Section XI examinations do not detect all fabrication flaws, they have higher detection performance for some flaw types, and there are flaw sizing errors always present (e.g., significant oversizing of small flaws and systematic under sizing of larger flaws). The new methodology allows direct comparison of ASME Code Section XI examination results with values in the PTS draft rule Tables 2 and 3 in order to determine if the number and sizes of flaws detected by an ASME Code Section XI examination are consistent with those assumed in the probabilistic fracture mechanics calculations performed in support of the development of 10 CFR 50.61a.

Acronyms and Abbreviations

ASME	American Society of Mechanical Engineers
EPRI	Electric Power Research Institute
FAVOR	Factor Analysis of Vessels – Oak Ridge
IGSCC	intergranular stress corrosion cracks
ISI	inservice inspection
NDE	nondestructive examination
NRC	United States Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PDI	Performance Demonstration Initiative
PNNL	Pacific Northwest National Laboratory
POD	probability of detection
PTS	pressurized thermal shock
RMSE	root-mean-square error
RPV	reactor pressure vessel
TWCF	through-wall cracking frequency

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Background

This document describes a method to determine whether the flaws in a particular reactor pressure vessel are consistent with the assumptions regarding the number and sizes of flaws used in the analyses that formed the technical basis for the new voluntary alternative Pressurized Thermal Shock (PTS) rule (Draft 10 CFR 50.61a). Public comments on the draft rule expressed concerns with a methodology presented in a prior document titled *Development of Flaw Size Distribution Tables for Draft 10 CFR 50.61a* (NRC 2007). U.S. Nuclear Regulatory Commission (NRC) staff have directed Pacific Northwest National Laboratory (PNNL) to develop a technical basis for an improved methodology as described in the present document.

The new methodology addresses the following concerns with the prior methodology:

- the assumption that flaws detected by American Society of Mechanical Engineers (ASME) Code Section XI inspections are always reported in terms of a specific set of standardized bins (0.05-inch increments in through-wall flaw depth dimensions)

- the complex approach used to transform flaws sizes from bins used for purposes of probabilistic fracture mechanics calculations with the Factor Analysis of Vessels – Oak Ridge (FAVOR) code (NRC 2007) into the bins that were believed to apply to ASME Code Section XI examinations

- a recognition that ASME Code Section XI examinations suffer from significant limitations in terms of flaw sizing errors. These limitations make it difficult to compare flaw sizes estimated during ASME Code Section XI field examinations with the more precise and optimized laboratory-type measurements made and validated with destructive methods. A valid comparison must, therefore, account for flaw sizing errors present in ASME Code Section XI examinations (e.g., significant over sizing of small flaws of less than 0.25-inch through-wall dimension). Direct comparisons of flaw distributions derived from field measurements with more accurate laboratory measurements would lead to pessimistic conclusions regarding the acceptability of distributions of flaws as estimated from field measurements.

Two new tables for acceptable flaw distributions have been developed (new PTS Tables 2 and 3) for Draft 10 CFR 50.61a that account for effects of expected flaw sizing errors for ASME Code Section XI examinations. The new methodology allows direct comparison of ASME Code Section XI examination results with values in these tables in order to determine if the number and sizes of flaws detected by an ASME Code Section XI examination are consistent with those assumed in the probabilistic fracture mechanics calculations performed in support of the development of 10 CFR 50.61a.

The draft rule provides reference temperature limits for reactor vessel materials that, if not exceeded, will limit the through-wall cracking frequency (TWCF) due to PTS events to less than 1×10^{-6}/reactor year. The FAVOR computer code (EricksonKirk and Dickson 2007; EricksonKirk et al. 2007) developed by the Oak Ridge National Laboratory (ORNL) uses a Monte-Carlo analysis technique to estimate the TWCF as a function of the accumulated neutron fluence at the reactor pressure vessel (RPV), the chemical composition and mechanical properties of the RPV materials, the frequency of various PTS thermal-hydraulic transients and the number, location and sizes of flaws in the reactor RPV. Analyses of three example reactors with relatively high embrittlement were performed with the FAVOR code. These were Palisades, Beaver Valley Unit 1, and Oconee Unit 1. In addition to estimating the TWCF expected

for each of these plants at the end of their original 40-year licenses and the potential 60-year license extensions, various higher neutron fluence levels were used to produce TWCF values near the 1×10^{-6}/reactor year value in order to develop reference temperature limits for the new rule.

As part of the NRC's process for developing and implementing a risk-informed rule, it is appropriate to establish that the plants to which the rule will be applied have parameters that are consistent with the parameters in the underlying risk assessments. For the new PTS Rule, part of this process is to compare the number and sizes of the flaws in a plant's RPV to the numbers and sizes of flaws used in the FAVOR analyses that support the new Rule. This comparison focuses on the surface-breaking and embedded flaws within about one-inch of the inner surface of the RPV, because the FAVOR Code indicates that these are the flaws that are responsible for nearly all of the TWCF from PTS events. The through-wall dimensions of the cracks are addressed because that was one of the most risk-sensitive of the crack parameters in the FAVOR analyses. The analyses described herein focus on the Category 2 flaws, which are within one-eighth of the vessel wall thickness (approximately one inch) of the clad-to-base metal interface.

Statement of Problem

The earlier basis for the flaw tables in the draft PTS rule (i.e., Tables 2 and 3 in 10 CFR 50.61a) (NRC 2007) focused on problems that arise from the possible inconsistent reporting conventions between the ASME Code and the flaw model used by the FAVOR code. The revised approach of the present document avoids these problems by allowing direct use of ASME Code data with no restrictions on reporting conventions. In addition, this report focuses on a newly identified concern associated with flaw sizing errors known to occur in ASME Code Section XI field measurements of the through-wall depth dimensions of flaws.

The flaw distributions used for the FAVOR calculations were based on accurate laboratory measurements of the sizes for flaws in weld and base metal specimens removed from reactor pressure vessels that had been manufactured for cancelled nuclear power plants (Simonen et al. 2013). These laboratory measurements were made with a combination of nondestructive and destructive methods conducted under optimized conditions that together provided accurate measurements of flaw dimensions. In contrast, field examinations of vessels by ASME Code Section XI methods are limited to nondestructive methods, which suffer from limitations that significantly degrade the ability to accurately measure flaw sizes. For example, the laboratory measurements were performed on highly machined surfaces in contrast with the field examinations being performed on as-built surfaces. The performance demonstration requirements for Section XI examinations have, therefore, incorporated acceptance criteria for flaw sizing that permit sizing errors consistent with limitations of current NDE capabilities.

Experience at the EPRI NDE Center (Becker 2002) has shown that flaw depth sizing requirements of ASME Code Section XI, Appendix VIII are more difficult to pass than the corresponding flaw detection requirements. The current requirements allow a root-mean-square error (RMSE) in flaw depth sizing as large as 0.15 inch (Becker 2002). In practice, a large fraction of inspection teams have had errors just below this acceptable 0.15-inch value (Becker 2003). The 0.15-inch limit is an average error covering many size measurements rather than a maximum measurement error that can be made for any individual measurement. Another concern is the consistent trend to over size small flaws (including the 0.25-inch flaws that are a significant concern to PTS). In contrast, the depth sizing errors in the optimized laboratory measurements of vessel flaws were about 1 mm (or 0.05 inch). Becker's findings indicate that it will be difficult to compare the flaw distributions that were input to FAVOR with the flaw distributions derived from ASME Code Section XI examinations unless some account is taken of these known flaw sizing errors. For example, flaws with true depths of 0.10 inch would on the average have measured depths of 0.25 inch, and in some cases the measured depth could be even larger than 0.25 inch.

The remaining sections of this report provide additional information on known limitations of ASME Code Section XI examinations. Information on flaw depth sizing errors is presented along with an approach that accounts for flaw sizing errors to develop tables to determine if a measured flaw distribution is consistent with the flaw distributions used for FAVOR code calculations to develop 10 CRF 50.61a.
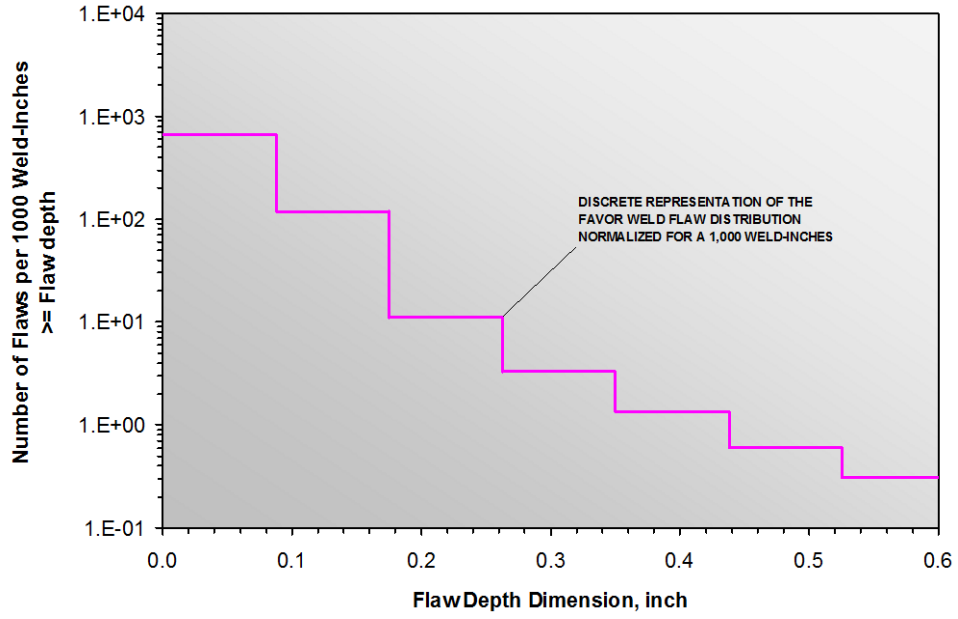
FAVOR-Simulated Weld Flaws

FAVOR version 06.1 analyses for Palisades were available. The results provided a set of discrete flaw sizes for a range of through-wall flaw dimensions for flaws in weld material. The flaw sizes and the simulated number of flaws for each discrete flaw size are listed in Table 1 and are based on the FAVOR output file "PAL200PFM.OUT". Table 1 as presented here is identical to Table 1 of ML070950392 (NRC 2007). The second column is the average number of Category 2 flaws (i.e., flaws located within one-eighth of the vessel wall thickness from the vessel inner surface but excluding surface-breaking flaws) modeled per the Monte-Carlo vessel simulation in the FAVOR code. A total of 1006 inches of weld length was modeled for the Palisades RPV, and the third column in Table 1 adjusts the number of flaws to an equivalent 1000 inches, which was chosen as the standard unit measure for the table in the rule. The fourth column tabulates the number of flaws that were equal to or greater than the indicated sizes.

Figure 1 presents a plot of the cumulative distribution for weld flaws in the Palisades vessel that is based on the fourth column of Table 1. In FAVOR calculations, continuous flaw distributions are approximated by a set of discrete flaws with their depth dimensions corresponding to one percent increments of the vessel wall thickness. Thus, the stepwise character of the Figure 1 curve comes from the discretization adopted by FAVOR. The flaws within each depth increment are assigned a dimension corresponding to the upper end of the increment.

Table 1. Weld Flaw Sizes and Populations for FAVOR Analyses of Palisades

Flaw Through-Wall Dimension (inches)	Mean Number of Category 2 Flaws	Adjusted to 1000 Inches of Weld Length	Cumulative Number of Flaws ≥ Size
0.088	549.86	546.78	665.62
0.175	108.58	107.94	119.04
0.263	7.86	7.81	11.10
0.350	1.959	1.947	3.29
0.438	0.745	0.741	1.342
0.525	0.295	0.292	0.601
0.613	0.138	0.1370	0.309
0.700	0.0679	0.0675	0.1719
0.787	0.0394	0.0392	0.1044
0.875	0.0230	0.0229	0.0652
0.963	0.0135	0.01346	0.0423
1.050	0.00886	0.00880	0.0289
1.137	0.00509	0.00506	0.0201
1.225	0.00514	0.00511	0.0150
1.313	0.00257	0.00256	0.00988
1.400	0.00200	0.001988	0.00733
1.488	0.00206	0.002045	0.00534
1.575	0.000629	0.000625	0.00330
1.663	0.000743	0.000738	0.00267
1.750	0.000851	0.000852	0.001931
1.873	0.000914	0.000909	0.001079
1.925	0.000171	0.000170	0.000170

DISCRETE REPRESENTATION OF THE
FAVOR WELD FLAW DISTRIBUTION
NORMALIZED FOR A 1,000 WELD-INCHES

Figure 1. Number of Weld Flaws Used in FAVOR Code Calculations for Palisades

FAVOR Simulated Plate Flaws

FAVOR version 06.1 analyses for Beaver Valley were available. The results provided a set of discrete flaw sizes for a range of through-wall flaw dimensions for flaws in plate material. The average number of Category 2 flaws modeled in each flaw size bin are provide in Table 2, based on data from the FAVOR output file "BV200PFM.OUT". Table 2 as presented here is identical to Table 6 of ML070950392 (NRC 2007). The second column is the average number of Category 2 flaws (i.e., flaws located within the one-eighth of the vessel wall thickness from the vessel inner surface but excluding surface-breaking flaws) modeled per the Monte-Carlo vessel simulation in the FAVOR code. Beaver Valley has 79,189 square inches on the inner surface of the plate material for the two shell courses modeled with FAVOR.

It was noted that ASME Code Section XI examinations cover a region of one-half of a vessel wall thickness on each side of the vessel seam welds. For a nominal wall thickness of 10 inches and total beltline weld length of 1000 inches, the examined surface area is estimated to be 10,000 square inches or about ten percent of the total surface area of plate material with the vessel beltline. The third column in Table 2 adjusts the number of flaws to an equivalent 10,000 square inches, which was chosen as the standard measure in the table to represent a vessel beltline region. The fourth column tabulates the number of flaws that were equal to or greater than the indicated size.

Table 2. Plate Flaw Sizes and Populations for FAVOR Analyses of Beaver Valley

Flaw Through-Wall Dimension (inches)	Mean Number of Category 2 Flaws	Adjusted to 10,000 Inches of Plate Surface Area	Cumulative Number of Flaws ≥ Size
0.080	663.33	83.77	140.01
0.161	374.98	47.35	56.24
0.241	64.12	8.097	8.891
0.321	5.599	0.070	0.794
0.402	0.689	0.087	0.087

Figure 2 presents a plot of the cumulative distribution for plate flaws in the Beaver Valley vessel that is based on the fourth column of Table 2. FAVOR calculations for plate and forging materials approximate flaw distributions by a set of discrete flaws in the same manner as for weld materials. Flaw depth dimensions correspond to one percent increments of the vessel wall thickness. The stepwise character of the Figure 2 curve again comes from the discretization adopted by FAVOR. The flaws within each depth increment are assigned a dimension corresponding to the upper end of the increment.
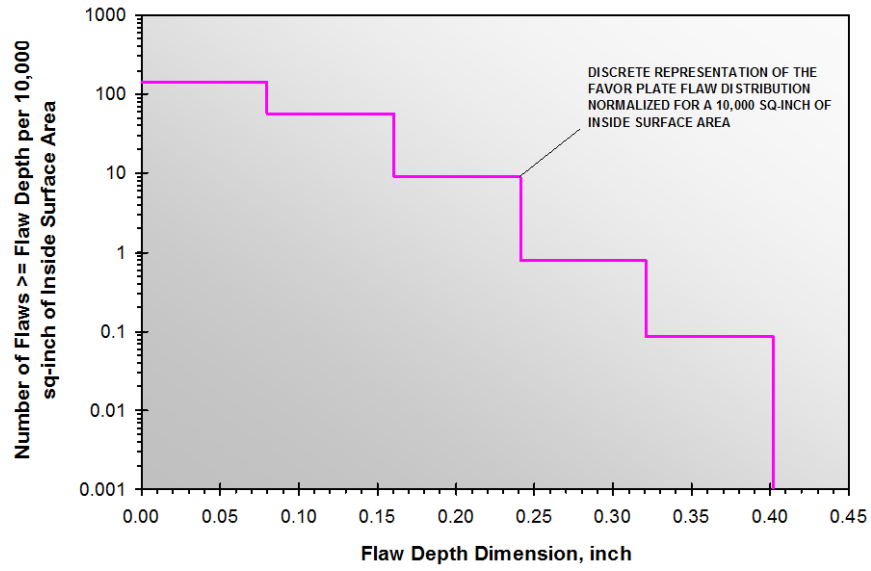
**Figure 2**. Number of Plate Flaws for FAVOR Analyses of Beaver Valley

Through-Wall Depth Sizing Errors for ASME Code Section XI Appendix VIII Supplement 4 Inspections

The depth sizing errors associated with inservice inspection/nondestructive examination (ISI/NDE) measurements can have a significant impact on the estimated distribution of fabrication flaws in a reactor pressure vessel; the purpose of this letter report is to address these errors. 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. The Performance Demonstration Initiative (PDI) efforts administered at the Electric Power Research Institute (EPRI) NDE Center has generated a large body of data on flaw detection and sizing capabilities of the inspection personnel, equipment and procedures that perform ASME Code Section XI examinations of reactor pressure vessels. Unfortunately, little of this data has been published because of the confidential nature of this PDI work. However, Larry Becker of the EPRI NDE Center published two papers (Becker 2002, 2003) that examined the effectiveness of ultrasonic examination techniques currently being used to detect and size flaws located in the near-surface zone containing the clad-to-base metal interface region located in the reactor vessel core belt line area. These papers contain considerable information from the PDI database concerning the performance of Appendix VIII Supplement 4 inspections conducted from both the outside surface as well as from the inside surface. The paragraphs below discuss the significant trends exhibited by the data presented in Becker's papers.

Becker (2002, 2003) examined the sizing performance of the first 41 successful candidates to meet the Appendix VII Supplement 4 requirements. Becker's study included 772 total observations (this includes data on passed and failed attempts) as well as examination sizing data for the inside and outside surfaces, dual-side access and single-side access measurements, and both automated and manual sizing information.

Figure 3 (Becker 2002, 2003) shows the sizing performance of 41 successful Appendix VIII Supplement 4 depth-sizing candidates. The Y-axis of Figure 3 indicates the number of the 41candidate inspectors that demonstrated an RMSE of the range indicated on the X-axis. Notice that there were some very good sizing results (i.e., RMSE values less than 0.07 inch); these were the results produced by the staff that developed the sizing procedures for the ISI companies. It needs to be noted that the number of successful candidates tends to peak near the pass criterion of 0.15 inches RMSE. About half (17 of 41) had RMSE values within 0.01 inch of the pass criteria. Thus, a typical candidate would most likely have sizing errors close to the 0.15-inch RSME criterion specified in Supplement 4 to ASME Code Section XI, Appendix VIII. It is important to note that there were other inspectors who failed to pass because they had sizing errors greater than the limit of 0.15 inches and some inspectors took several attempts to successfully pass the depth sizing test.

The distribution of sizing errors as a function of true flaw size is shown in Figure 4. 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 oversize smaller flaws and undersize large flaws. This trend to oversize small flaws and to undersize larger flaws has been observed and documented in every round-robin test conducted on thick-section steel components and piping such as the Programme for the Inspection of Steel Components Phases II and III (Nichols and Crutzen 1988; PISC 1993), the Piping Inspection Round Robin (Heasler and Doctor 1996), and the Mini Round Robin (Heasler et al. 1990), to cite just a few of these studies.
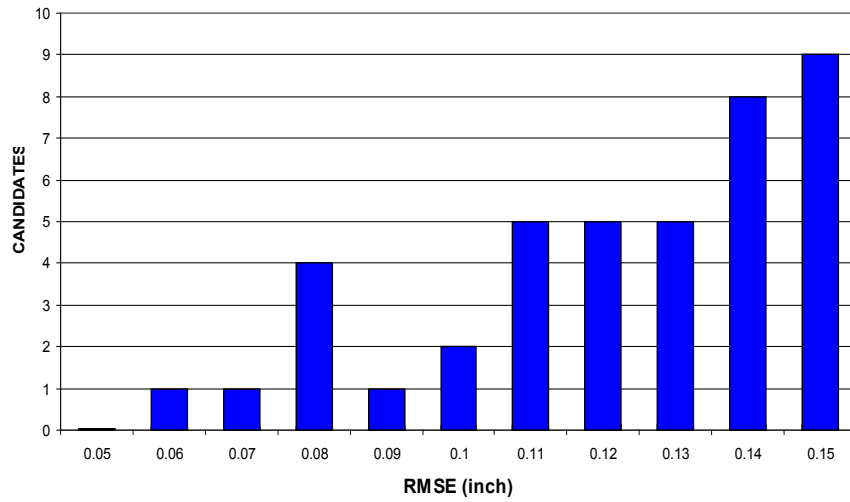
Figure 3.   Appendix VIII Supplement 4 Successful Candidate Depth Sizing Test Scores (Becker 2002, 2003)
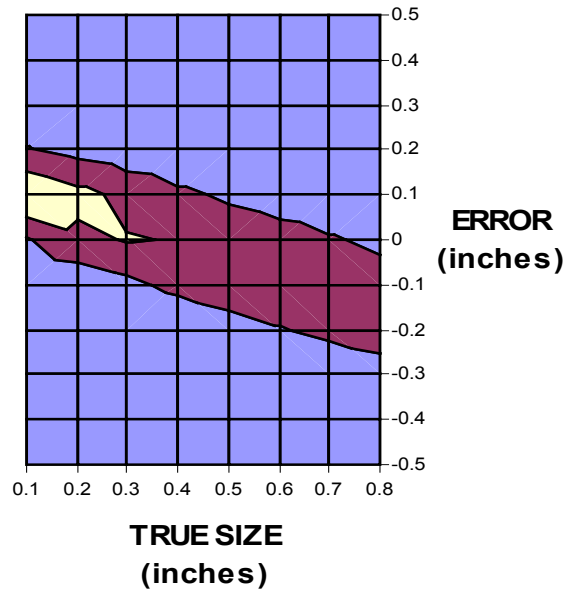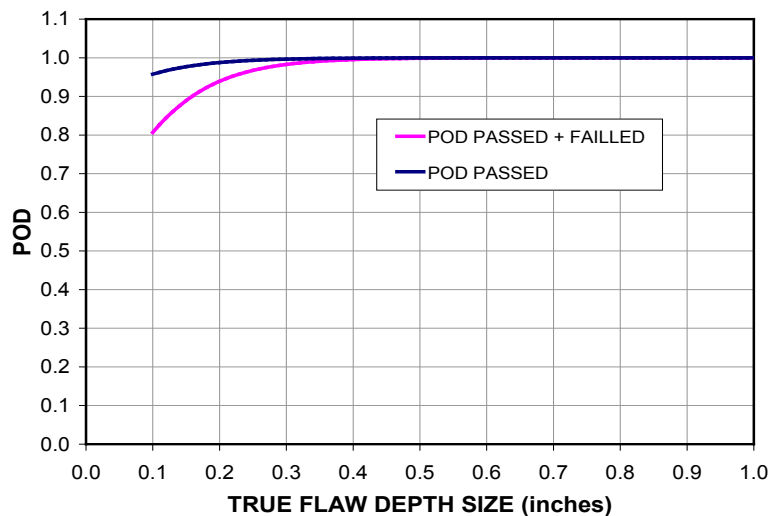

Figure 4.   Appendix VIII Supplement 4 Successful Candidate Flaw Sizing Error vs. True Flaw Depth (Becker 2002, 2003)

Probability of Detection (POD) for ASME Code Section XI Appendix VIII Supplement 4 Inspections

Another issue to be addressed is what is the smallest size of flaw that would be detected only a fraction of the time (say less than 50 percent) during an ISI of an operating nuclear power plant reactor pressure vessel and would be used as the starting point for ISI-based flaw distribution curves. This flaw size covers an undefined number of flaws of this size and smaller for which there are both a small probability of detection and a small expected contribution to through-wall crack frequency. Probability of detection (POD) estimates for Appendix VIII Supplement 4 performance demonstration candidates are presented in Figure 5 (Becker 2003).

The results in Figure 5 are based on PDI data for automated examinations (performed from the vessel inside surface) of clad-to-base metal interface near surface zone flaws. The POD estimates for candidates that passed and for all candidates (passed + failed) are both presented. While only inspectors that have passed the detection tests are allowed to perform inspections, many of these accepted inspectors have first failed the test before they qualified by a subsequent retest. Experience based on intergranular stress corrosion cracks (IGSCC) for which there is requalification has shown that the passed candidates that come back to re-qualify have a performance that is similar to that of passed + failed. This indicates that their performance deteriorates over time, so inservice performance can be estimated to lie somewhere between passed and passed + failed. Therefore the passed + failed curve was used to estimate POD performance for examinations performed in the field. Because the passed + failed curve suggests that the POD is about 50 percent for flaws having a through-wall extent of 0.05 inches, the upper bound on the threshold for flaw detection was set at 0.05-inch through-wall flaw depth.

Figure 5. Probability of Detection Performance from the Inside Surface for Passed and Passed + Failed Appendix VIII Supplement 4 Candidates (Becker 2003)

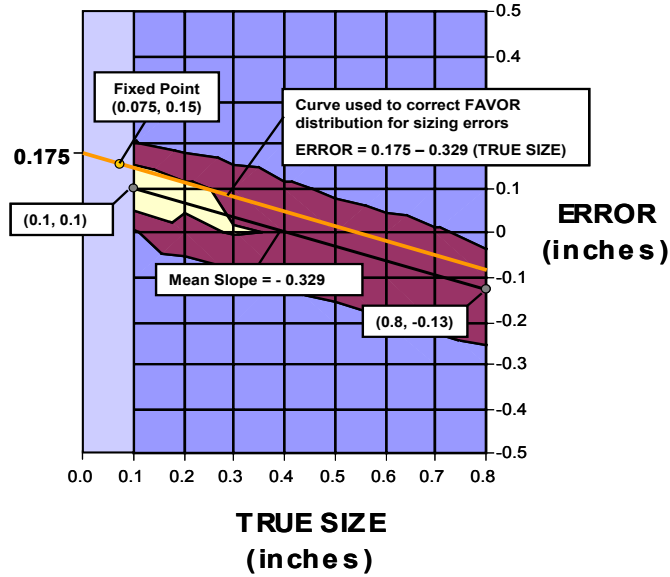# Development of Tables for Allowable Flaws in Weld and Plate Materials

Tables were developed to specify the maximum allowable numbers of flaws that can be present in a volume of examined vessel material without exceeding the corresponding number of flaws assumed in the FAVOR calculations used to establish the alternate PTS rule. The allowable numbers of flaws has been adjusted to account for sizing errors associated with present-day ISI/NDE techniques. Therefore, the tables can be used to identify outlier vessels with flaw frequencies greater than those assumed in the development of 10 CFR 50.16(a) while not improperly rejecting vessels that only ***appear***, by virtue of imperfect flaw sizing capabilities, to have an excessive number of flaws. Because welds and plates were modeled separately in the FAVOR calculations, separate tables have been developed for weld and plate materials. The tables also cover a range of flaw sizes because the smaller the flaw the larger the allowable number of flaws.

The procedure was first to tabulate the number of flaws as a function of through-wall depth dimension by reference to FAVOR code output (Tables 1 and 2) that documented the flaws simulated in the probabilistic fracture mechanics calculations. The output was then normalized to give results on the basis of flaws per unit length of weld (for weld flaws) or flaws per unit area of vessel inner surface (for base metal flaws). The final step was to adjust the flaw sizes in Tables 1 and 2 in order to account for depth sizing errors. These revised tables define 10 CFR 50.61a acceptable weld and plate flaw distributions that can be directly compared with flaw distributions based on ASME Code Section XI examinations.

PNNL chose to use the depth sizing error data in Figures 3 and 4 as a means to compensate for flaw sizing errors associated with field measurements. These data show that the preponderance of examination teams tended to over size small flaws on the order of 0.15 inch and that the over sizing decreases linearly as the flaws get larger. Figure 6 shows that the mean slope of the sizing error data is −0.329. Supplement 4 to ASME Code Appendix VIII requires that examiners demonstrate the ability to detect a 0.075-inch flaw and size it to within an RMSE of 0.15 inch. The following sizing error equation was then defined by passing a straight line having a slope of −0.329 through the point (0.075, 0.15):

$$ERROR = 0.175 - 0.329 \ (TRUE \ SIZE) \tag{1}$$

This relationship uses an over-sizing error of 0.15-inch for the smallest flaw size identified in Supplement 4 to ASME Code Section XI Appendix VIII and decreases the over-sizing error to zero when the through-wall extent flaw size reaches about 0.55 inches.

Figure 6.　Development of Flaw Sizing Error Corrections for Weld and Plate Flaws that form the Basis for the Allowable Flaw Distributions in PTS Tables 2 and 3 of 10 CFR 50.61a

The lower magenta curve of Figure 7, which appeared before in Figure 1, was derived from the data of Table 1 and is a discrete representation of the weld flaw distribution used in FAVOR calculations for the Palisades vessel. Adjustments were made to this curve to account for NDE flaw sizing errors to obtain the upper green curve. Each point on the magenta curve was shifted to the right to account for the over sizing predicted by Eq. (1). In plotting the green curve, the vertical coordinates (number of flaws) were rounded in each case to an integer number of flaws.

This upper green curve, therefore, presents the apparent flaw distribution that would be observed with imperfect NDE examinations that over size flaws by as much as 0.15 inch. These data suggest that the sizing errors associated with current NDE techniques can increase the apparent number of flaws by a factor of ten or more for a considerable range of flaw depth dimensions; particularly for the smaller flaw sizes that are important in the assessment of vessel performance during postulated PTS events. Table 3 is a tabular version of the green curve of Figure 7.
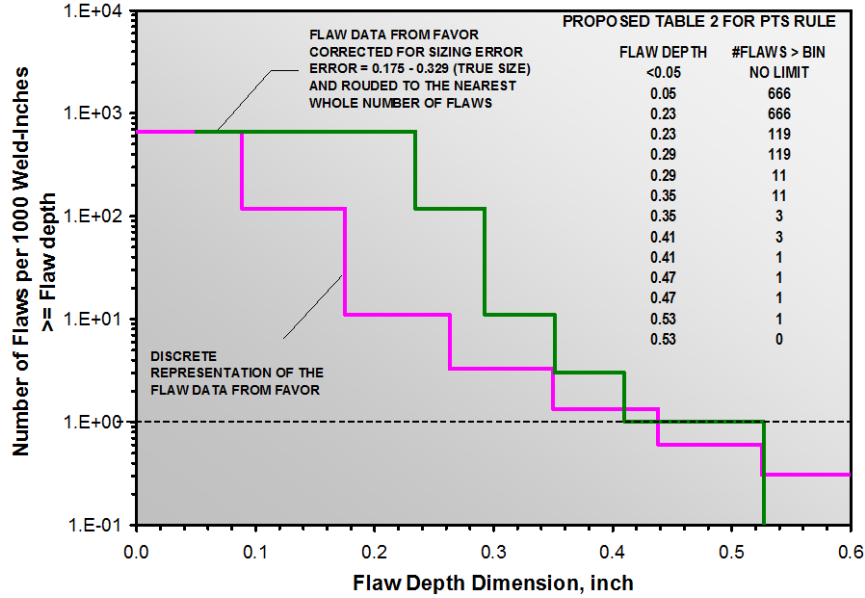
Figure 7. Acceptable Number of Weld Flaws with Allowance for Flaw Sizing Errors

Similarly, the magenta curve of Figure 8, which appeared before in Figure 2, was derived from the Table 2 data for the cumulative number of Category 2 flaws per 10,000 in^2 of inside surface area of plate material. As in the case of weld flaws, Eq. (1) was used to adjust the magenta plate material flaw NDE flaw depth sizing errors to obtain the upper green curve. The tabular version of the green curve in Figure 8 is provided in Table 4.
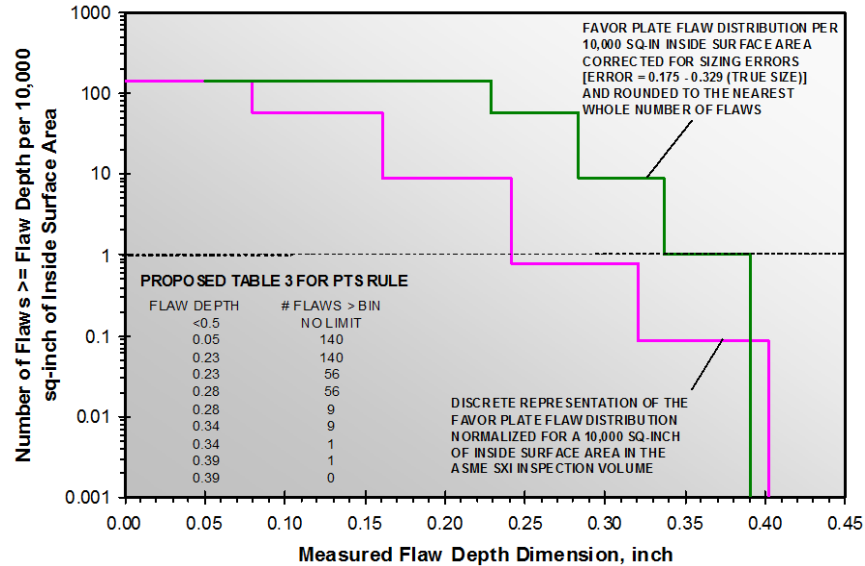

Figure 8. Acceptable Numbers of Plate and Forging Flaws with Allowance for Flaw Sizing Errors

Tables 3 and 4 are being proposed as the new PTS Tables 2 and 3 (respectively) in 10 CFR 50.61a.

Table 3. Proposed New PTS Rule Table 2 for Weld Flaws Including Adjustments to Account for Flaw Depth Sizing Errors

Range of Through-Wall Extent (TWE) of Flaw (in.)	Allowable Number of Cumulative Flaws per 1000 inches of Weld Length in the ASME Section XI Appendix VIII Supplement 4 Inspection Volume
0.05 ≤ TWE < 0.23	666
0.23 ≤ TWE < 0.29	119
0.29 ≤ TWE < 0.35	11
0.35 ≤ TWE < 0.41	3
0.41 ≤ TWE < 0.53	1
≥ 0.53	0

Table 4. Proposed New PTS Rule Table 3 for Plate and Forging Flaws Including Adjustments to Account for Flaw Depth Sizing Errors

Range of Through-Wall Extent (TWE) of Flaw (in.)	Allowable Number of Cumulative Flaws per 10,000 inches of Inside Surface Area in the ASME Section XI Appendix VIII Supplement 4 Inspection Volume
0.05 ≤ TWE < 0.23	140
0.23 ≤ TWE < 0.28	56
0.28 ≤ TWE < 0.34	9
0.34 ≤ TWE < 0.39	1
TWE ≥ 0.39	0

Probabilistic Fracture Mechanics Calculations

Probabilistic fracture mechanics calculations have been performed by Oak Ridge National Laboratory with the FAVOR code (EricksonKirk and Dickson 2007; EricksonKirk et al. 2007). These calculations address NRC staff concerns with the adjusted tables for acceptable flaw distributions if they are applied in the future to ASME Code Section XI inspection data having advanced techniques with near perfect sizing capabilities. In such a case, the adjustments developed to address current NDE limitations would allow an overly large number of flaws to be judged acceptable. The FAVOR computations estimate the amount by which the TWCF increases if a vessel were to, in fact, contain a flaw distribution as represented by the green curves of Figures 7 and 8. Flaw distributions as adjusted for flaw sizing errors (green curves of Figures 7 and 8) were used as inputs to sensitivity calculations. The objective was to evaluate relative increases in TWCF relative to the baseline values corresponding to the unadjusted flaw distributions (magenta curves of Figures 7 and 8). The "TWCF Ratio" results provide an indication of the practical need for future revisions of Tables 2 and 3 of 10 CFR 50.61a to account for improvements in NDE technology.

References

Becker FL. 2002. "Reactor Pressure Vessel Inspection Reliability." In *Proceedings of EC-IAEA Technical Meeting on Improvements in In-Service Inspection Effectiveness*. November 19-21, 2002, Petten, The Netherlands. Paper P14.

Becker FL. 2003. "Examination Effectiveness Based on Performance Demonstration Results for the Flaws at the RPV Clad-to-Base-Metal Interface." In *Third International Conference on NDE in Relation to Structural Integrity for Nuclear Pressurized Components*. November 14-16, 2001, Seville, Spain. Report EUR 20671 EN, pp. 690-698, European Commission Joint Research Centre, Institute for Energy, Petten, the Netherlands.

EricksonKirk M and TL Dickson. 2007. *Recommended Screening Limits for Pressurized Thermal Shock (PTS)*. NUREG-1874, U.S. Nuclear Regulatory Commission, Washington, D.C. ADAMS Accession Number ML0708601567.

EricksonKirk M, M. Junge, W. Arcieri, B.R. Bass, R. Beaton, D. Bessette, T.H.J. Chang, T. Dickson, C.D. Fletcher, A. Kolaczkowski, S. Malik, T. Mintz, C. Pugh, F. Simonen, N. Siu, D. Whitehead, P. Williams, R. Woods and S Yin. 2007. *Technical Basis for Revision of the Pressurized Thermal Shock (PTS) Screening Limit in the PTS Rule (10 CFR 50.61)*. NUREG-1806, Vol. 1, U.S. Nuclear Regulatory Commission, Washington, D.C.

Heasler PG and SR Doctor. 1996. *Piping Inspection Round Robin*. NUREG/CR-5068, PNL-10475, U.S. Nuclear Regulatory Commission, Washington, D.C.

Heasler PG, TT Taylor, JC Spanner, SR Doctor and JD Deffenbaugh. 1990. *Ultrasonic Inspection Reliability for Intergranular Stress Corrosion Cracks: A Round Robin Study of the Effects of Personnel, Procedures, Equipment and Crack Characteristics*. NUREG/CR-4908, PNL-6179, U.S. Nuclear Regulatory Commission, Washington, D.C.

Nichols RW and S Crutzen, Eds. 1988. *Ultrasonic Inspection of Heavy Section Steel Components: The PISC-II Final Report*. Elsevier Applied Science Publishers, London and New York.

NRC. 2007. *Development of Flaw Size Distribution Tables for Draft 10 CFR 50.61a*. ADAMS Accession Number ML070950392, U.S. Nuclear Regulatory Commission, Washington, D.C.

PISC. 1993. *Evaluation of the Sizing Results of 12 Flaws of the Full Scale Vessel Installation*. PISC III Report No. 26 – Action 2 – Phase 1, EUR 15371 EN, Commission of the European Communities, Joint Research Centre, Ispra Site.

Simonen FA, SR Doctor, GJ Schuster and PG Heasler. 2013. *A Generalized Procedure for Generating Flaw-Related Inputs for the FAVOR Code*. NUREG/CR-6817, Rev. 1; PNNL-14268A, U.S. Nuclear Regulatory Commission, Washington, D.C.