April 3, 2007

MEMORANDUM TO: Matthew A. Mitchell, Chief
Vessels & Internals Integrity Branch
Division of Component Integrity
Office of Nuclear Reactor Regulation

FROM: Barry J. Elliot, Senior Materials Engineer ***/RA/***
Vessels & Internals Integrity Branch
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SUBJECT: DEVELOPMENT OF FLAW SIZE DISTRIBUTION TABLES FOR DRAFT PROPOSED TITLE 10 OF THE CODE OF FEDERAL REGULATIONS (10 CFR) 50.61a

Enclosed is a detailed description of the methodology and basis for the allowable number of flaws in welds, plates and forgings in Tables 2 and 3 of draft proposed to 10 CFR 50.61a, "Alternative Fracture Toughness Requirements for Protection against Pressurized Thermal Shock." The enclosed document was written by Steve Long, Senior Reliability and Risk Analyst, Office of Nuclear Reactor Regulation. Comments from myself and staff from the Office of Nuclear Regulatory Research, Pacific Northwest National Laboratory and Oak Ridge National Laboratory have been incorporated, where applicable.

Enclosure:
Development of Flaw Size Distribution Tables

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Development of Flaw Size Distribution Tables for Draft 10 CFR 50.61a (The Voluntary Alternate PTS Rule)

Background:

This section of the new rule provides a means for determining whether the flaws in a particular reactor pressure vessel is consistent with the assumptions regarding the number and size of flaws used in the analyses that provide the technical basis for the new rule.

The draft rule is intended to provide reference temperature limits for reactor vessel materials that, if not exceeded, will limit the through-wall cracking frequency (TWCF) due to pressurized thermal shock (PTS) events to less than $1x10^{-6}$/reactor-year. The FAVOR computer code developed by the Oak Ridge National Laboratory uses a Monte-Carlo analysis technique to estimate the TWCF as a function of neutron fluence to the reactor pressure vessel (RPV), the chemical composition and mechanical properties of the reactor vessel materials, the frequency of various thermal-hydraulic transients that create PTS, and the number and sizes of flaws in the RPV. Analyses for three example reactors with relatively high embrittlement were performed with the FAVOR code. These were Palisades, Beaver Valley, and Oconee. In addition to estimating the TWCF expected for each of these plants at the end of their original 40-year licenses and potential 60-year license extensions, various higher neutron fluence levels were used to produce TWCF values near the $1x10^{-6}$/reactor-year value in order to develop the associated reference temperature limits for the new rule.

As part of the agency's process for developing and implementing a risk-informed rule, it is necessary to establish that the plants to which the rule will be applied have parameters that are consistent with the parameters in the underlying risk assessment. For the new PTS Rule, part of the 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 surface-breaking flaws 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 dimension of the cracks is addressed because that was one of the most risk-sensitive of the crack parameters in the FAVOR analyses. Surface breaking flaws were assumed to be very rare in the FAVOR calculations, and are thus not acceptable for the new rule application. Therefore, this analysis focuses on the Category 2 flaws, which are within one-eighth of the vessel thickness (approximately one inch) of the clad-to-base metal interface.

Statement of the Problem:

The comparison of flaw sizes in a real RPV, as determined by an in-service inspection (ISI), to the flaw sizes assumed in the FAVOR calculations is complicated by an inconsistency in the reporting conventions established by the ASME Code for RPV examinations and the conventions used to model flaws in the FAVOR Code. The ISI conventions typically report flaws in size increments of 0.05-inch, resulting in flaw populations for "bins" spanning 0.05-inch, each and centered on a multiple of 0.05 inch. The FAVOR calculations were performed with increments of one-hundredth of the RPV wall thickness, which is 0.088-inch for Palisades, 0.086-inch for Oconee, and 0.080-inch for Beaver Valley. A further complication in the FAVOR calculations is that all of the flaws estimated to be in a particular size bin were modeled to be at the upper limit of that bin. While the FAVOR assumptions were "conservative" with respect to

estimating the risk produced by a group of flaws with dimensions distributed across a FAVOR bin, it would not necessarily be conservative to directly compare the number of FAVOR flaws that fall anywhere in an ISI bin to the flaws distributed across the ISI bin in a real plant. The risk-importance of small flaws increases rapidly as their size increases (as will be explained in detail, below), so calculating the risk as if all flaws in an ISI bin are near the lower size limit of that bin can be very non-conservative. In addition, the larger bins sizes in the FAVOR calculations results in modeling no flaws in the size ranges that are spanned by some of the ISI bins. Therefore, it is necessary to either convert the ISI results to the FAVOR bin dimensions or to convert the FAVOR bins to the ISI size conventions before making a comparison. It was decided to convert the FAVOR bin populations to the ISI bins.

Analysis and Results:

It is important to realize at the beginning that there is no mathematically exact means to transform the FAVOR results to another set of flaw sizes, short of rerunning the FAVOR code with the new bin sizes. Due to administrative time constraints, it was not feasible to rerun the FAVOR Code for this purpose. Therefore, the discussion below will describe the bases for the modifications and also some of the potential inaccuracies that they create. Because the tables that result from this process are intended to be somewhat conservative tests of the applicability of the FAVOR results to a particular plant, the staff believes that the inaccuracies of the methods used are acceptable. However, the staff does not believe that further application of these methods could be used with reasonable assurance to estimate the TWCF for a plant-specific flaw distribution that does not meet the limits of the resulting tables. Such calculations should be performed using FAVOR with flaw inputs consistent with the ISI data for the plant of concern.

Separate tables of flaw sizes are needed for weld material and plate material, which were modeled separately in the FAVOR calculations using different flaw densities and size distributions. FAVOR calculations with sufficient embrittlement levels to result in a TWCF near the intended limit of 1×10^{-6}/reactor-year were used because the contributions of different flaw sizes change as the embrittlement changes, and the intent is to check a plant's flaw distribution against FAVOR assumptions that were used to establish the reference temperature limits at the TWCF limit. Because the Palisades TWCF results are dominated by weld flaws, the analysis for Palisades at 200 effective full power years (EFPY) of operation was used as the basis for the weld flaw table. Because the TWCF results for Beaver Valley are dominated by plate flaws, the Beaver Valley analysis at 200 EFPY was used as the basis for the plate flaw table. At 200 EFPY, the mean TWCF for Palisades is 1.74×10^{-6}/reactor-year and the mean value for Beaver Valley is 5.73×10^{-7}/reactor-year. These values represent the 80.5% and 81.5% values of their respective TWCF probability distributions. However, the new Rule is based on the 95% values of the probability distributions, which are 6.12×10^{-6}/reactor-year and 2.45×10^{-6}/reactor-year, respectively, for Palisades and Beaver Valley.

Weld Flaws:

FAVOR 06.1 analyses for Palisades were performed with a set of discrete flaw sizes for the through-wall dimension of the flaws. Those sizes and the number of flaws at each size are listed in Table 1, based on the FAVOR output file "PAL200PFM.OUT." 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 non-surface breaking) modeled per 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 size for the table in the Rule. The fourth column tabulates the number of flaws that were equal to or greater than the indicated size.

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

Flaw through-wall dimension (inches)	Mean number of Category 2 flaws	Adjusted to 1000" of weld length	Cumulative >/= 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

As can be seen from fourth column of Table 1, on average, FAVOR modeled less than one flaw per vessel in the size ranges above 0.438 inch.

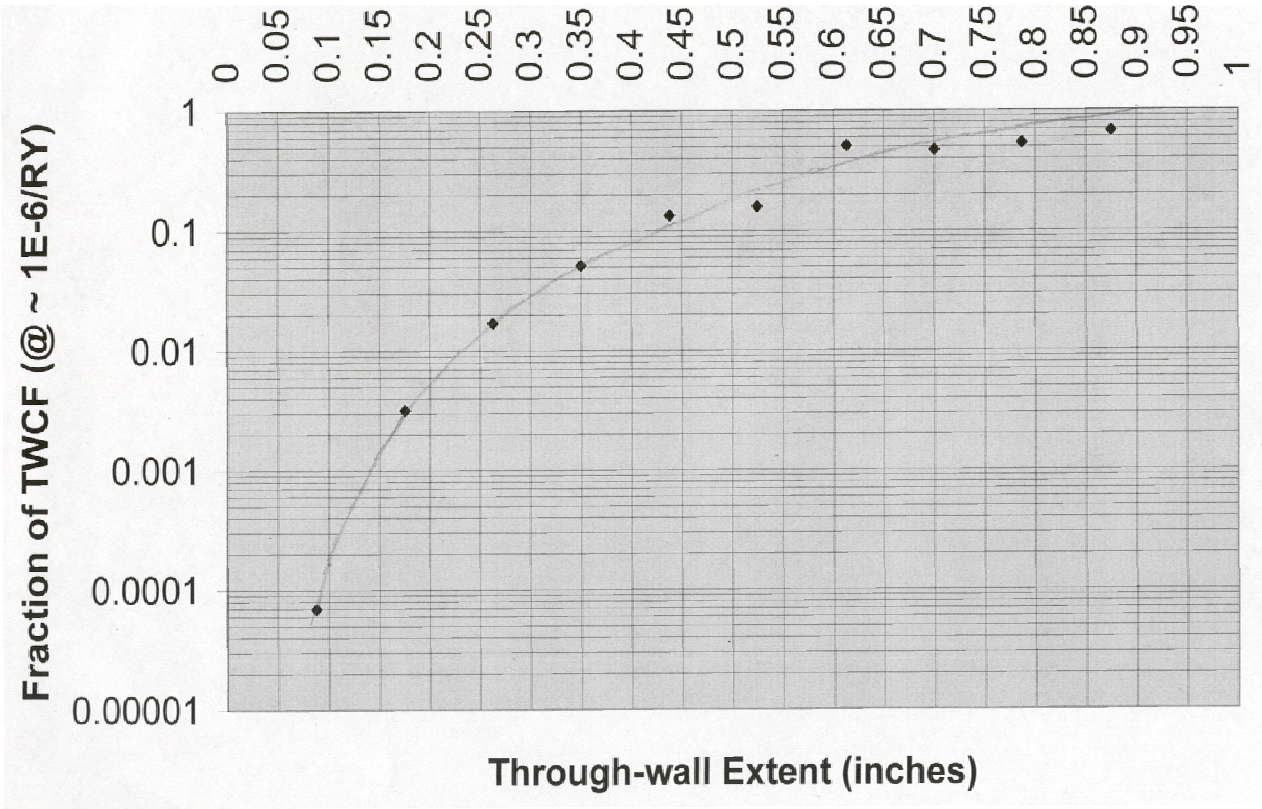
FAVOR also outputs the mean fraction of the TWCF that is contributed by flaws in each size bin. That information is provided in Table 2 for the Palisades analysis at 200 EFPYs, based on the FAVOR output file "PAL200POST.OUT."

Table 2. Contributions of Weld Flaw Size Bins to TWCF and Per-Flaw Importance to TWCF

Flaw through-wall dimension (inches)	Mean % TWCF for Category 2 flaws	Mean per-flaw TWCF importance
0.088	3.82	0.0000695
0.175	34.61	0.00319
0.263	13.38	0.0170
0.350	10.07	0.0514
0.438	9.99	0.134
0.525	4.67	0.159
0.613	7.01	0.509
0.700	3.20	0.471
0.787	2.12	0.537
0.875	1.55	0.674
0.963	3.77	2.78
1.050	1.19	1.35
1.137	0.17	0.334
1.225	1.87	3.64
1.313	0.39	1.52
1.400	0.72	3.60
1.488	0.15	0.729
1.575	0.06	0.955
1.663	0.02	0.269
1.750	0.41	4.78
1.873	0.06	0.656
1.925	0.00	0
	99.23	

As can be seen from the totals in Table 2, the Category 2 weld flaws (embedded less than 1/8th of the RPV wall thickness) accounted for nearly all of the TWCF for Palisades at 200 EFPYs. Category 2 flaws in plates accounted for only 0.15%. Category 3 weld flaws (embedded between 1/8th and 3/8ths of the RPV wall thickness) accounted for 0.62%, and Category 3 plate flaws accounted for 0%. The column on the right of Table 2 represents the mean per-flaw importance of a flaw in each size range to the total TWCF. It is obtained by dividing the second column of Table 2 by the second column of Table 1. A plot of the flaw importance vs flaw size is provided in Figure 1.

Figure 1: Palisades Category 2 Weld Flaw Mean Importance to TWCF vs Flaw Size



As can be seen in Figure 1, the mean per-flaw importance does not vary smoothly with flaw size above a flaw size of approximately 0.35 inch. This is due to the small number of flaws sampled for flaws above this size and the large variations in the importance of a single flaw with respect to its proximity to the inner surface and to localized high fluence areas in the RPV. The lack of convergence effect is even more pronounced for flaws greater than 1 inch.

The plot is used as the basis for adjusting the number of flaws in bins as the size of the bins is changed from the 0.088 inch increments used in FAVOR to 0.05 inch increments used in ISI reports. A convenient mathematical function was not found that fit the importance data very well, so a hand-drawn curve was used to interpolate the data. As can be seen from the plot, a single 0.088 inch flaw contributes on average only about 0.00007 of the TWCF while a flaw at 0.125 inch would contribute 0.0005 of the TWCF, so only (0.00007 ÷ 0.0005 x 546.78 =) 76.52 flaws at 0.125-inch would have a similar importance to 546.58 flaws at 0.088-inch. It is important to mention here that this importance-weighting process for determining the ratio of the

number of flaws of different sizes that are “equivalent” would be expected to leave the *mean* of the TWCF unchanged, but that cannot be said for the 95% value of the TWCF, which is the parameter used in the basis for the draft Rule. Therefore, it is important to minimize the amount of these adjustments and to carefully consider the overall effect before accepting the result as representing a TWCF 95% value of approximately 1 x 10^{-6}/reactor-year.

The first adjustments were made to place the number of flaws equivalent to the populations of the FAVOR bins at the upper or lower limit of the various ISI inch flaw bins, based on flaws at 0.088 inch increments that fell within the various ISI bins. This results in the bin populations shown in Table 3.

Table 3. Populations of ISI Weld Flaw Bins Equivalent to Favor Flaw Bins

Nominal Bin Size	Bin Size Range	Number of Flaws	Adjusted Notes
0.05	0.025 - 0.075		
0.10	0.075 - 0.125	75.9	from 0.088 bin
0.15	0.125 - 0.175	107.94	no adjustment needed
0.20	0.175 - 0.225		
0.25	0.225 - 0.275	6.65	adjusted from 0.263 bin
0.30	0.275 - 0.325		
0.35	0.325 - 0.375	1.52	adjusted from the 0.350 bin
0.40	0.375 - 0.425	0.889	adjusted from the 0.438 bin
0.45	0.425 - 0.475		
0.50	0.475 - 0.525	0.292	no adjustment needed
> 0.50	> 0.525	0.309	no adjustment needed

That leaves four unpopulated bins. However, because any flaws modeled as larger than an actual flaw is a conservative representation of that flaw, it is actually the cumulative flaw distribution that can be used for comparison to assure that the risk is bounded. The 0.05-inch ISI bin does not need to be limited, because flaws in that bin have minuscule significance to the TWCF. The cumulative distribution resulting from the adjusted FAVOR flaw populations is given in the second column of Table 4. The third column provides the cumulative distribution of the flaws as measured in the Shoreham RPV, directly binned into the 0.05-inch bin size. The binning procedure for the third column did not use the conservative representation of the flaw distribution from the FAVOR code nor the approximations used here to go from one bin size range to another.

Table 4. Cumulative Weld Flaw Distribution by ISI Bin and Comparison to Shoreham Data

Nominal Bin Size	Number of Flaws ≥ Bin	Shoreham Flaws	Ratio
0.05	No Limit	228.63	N/A
0.10	193.5	46.66	4.1
0.15	117.6	11.91	9.9
0.20	9.66	5.38	1.8
0.25	9.66	2.67	3.6
0.30	3.01	1.55	1.9
0.35	3.01	0.906	3.3
0.40	1.49	0.541	2.8
0.45	0.601	0.328	1.8
0.50	0.601	0.196	3.1
> 0.50	0.309	1.118	2.6

The ratio column on the right side of Table 4 indicates that the number of allowed flaws would always be greater than the number found in the Shoreham weld data, but by varying amounts as a result of the uneven rebinning that left unpopulated bins. In order to provide a more even margin to expected ISI results, it was decided to make some adjustments to the flaw populations in the bins with lower ratios, again using the importance-weighted process, this time using ratios of importance between the ISI bins. Specifically, in Table 3, 40 flaws in the 0.15-inch bin were replaced by 14.2 flaws in the 0.20-inch bin, and 2 flaws in the 0.25-inch bin were replaced by 1 flaw in the 0.3-inch bin.

Finally, it was noted that the 0.45-inch ISI bin population of 0.601 flaw in Table 4 would have no practical application, because no plants are expected to have significantly more than 1000 inches of weld length in the volume of vessel material of interest for PTS. Therefore, flaws greater than 0.45-inch were considered for reweighting to 0.45-inch to provide a population or 1.0 or larger for that bin. It was not possible to reach a population of 1 flaw in the 0.45-inch bin by moving only flaws from slightly larger bins, due to the small populations of the larger bins and the relatively slow increase in per-flaw importance in this size range. However, if all flaw sizes above 0.45-inch are considered, it is possible to increase the 0.45-inch ISI bin population to 1 flaw. By basing a per-large-flaw importance on the 27.36% of the TWCF that was contributed by the flaws in bins larger than the 0.438 inch bin by the 0.605 (mean) flaw in the larger bins in Table 1, the average importance of those larger flaws was effectively (0.2736 ÷ 0.605 =) 0.45 of the TWCF. The importance of a single flaw at 0.45-inch is about 0.12. So the flaws above 0.438 in the FAVOR calculation are equivalent *on-average* to (0.605 x 0.45 ÷ 0.12 =) 2.27 flaws. On that basis, it seems to be reasonable for the final distribution of Table 5 to allow one flaw in the 0.45-inch ISI bin, rather than the fractional flaw in Table 4. However, it is noted that it

is the *mean* contribution of a 0.45 inch flaw that is estimated at about 0.12 of the TWCF and individual flaws of that size may contribute much greater fractions, depending on their location with respect to the RPV surface and its most embrittled areas. Therefore, when there are multiple flaws greater than 0.45 in an ISI result, it does not seem prudent to try to employ this flaw importance weighting process to provide assurance that the TWCF is below $1x10^{-6}$/reactor-year. In that case, it is prudent to use the FAVOR code to directly evaluate the TWCF for the actual set of flaws found by the ISI. Therefore, the final flaw size distribution is provided in Table 5.

Table 5. Weld Flaw Size Cumulative Distribution for Draft PTS Rule

Nominal Bin Size	Number of Flaws ≥ Bin	Shoreham Flaws	Ratio
0.05	No Limit	228.63	N/A
0.10	166.7	46.66	3.6
0.15	90.8	11.91	7.6
0.20	22.82	5.38	4.3
0.25	8.66	2.67	3.2
0.30	4.01	1.55	2.6
0.35	3.01	0.906	3.3
0.40	1.49	0.541	2.8
0.45	1.00	0.328	3.0
> 0.45	0.00	0.196	N/A

As a check, a similar calculation was performed for the Beaver Valley weld flaw results. A very similar result was obtained for the flaw importance to TWCF as a function of flaw size, and roughly similar results were obtained for ISI flaw bin cumulative populations in 0.05 inch increments. Attempts to make the Palisades and Beaver Valley flaw bin populations more similar by normalizing to the mean or 95 percentile values of the TWCF were not successful.

<u>Plate Flaws</u>:

A similar analysis was performed for the flaws in plate material, based on the FAVOR 06.1 results for Beaver Valley at 200 EFPYs. Those results have a mean TWCF of 5.73 x 10^{-7}/reactor-year with 63.42% contributed by plate flaws. The 95th percentile value of the TWCF is 2.45 x 10^{-6}/reactor-year. Beaver Valley has 79,189 square inches on the inner surface of the plate material in the two courses modeled. The average number of Category 2 flaws modeled in each flaw size bin are provided in Table 6, based on the FAVOR output file "BV200PFM.OUT."

Table 6. Plate Flaw Bins and Populations for FAVOR Analyses of Beaver Valley

Flaw through-wall dimension (inches)	Mean number of Category 2 flaws	Adjusted to 1000" of weld length	Cumulative >/= size
0.080	663.33	8.377	14.001
0.161	374.98	4.735	5.624
0.241	64.12	0.8097	0.8891
0.321	5.599	0.0707	0.0794
0.402	0.689	0.0087	0.0087

The mean contributions to the TWCF from each of these flaw sizes and the contribution from a single flaw at each size are provided in Table 7, based on the FAVOR output file "BV200POST.OUT."

Table 7. Contributions of Plate Flaw Size Bins to TWCF and Per-Flaw Importance to TWCF

Flaw through-wall dimension (inches)	Mean % TWCF for Category 2 flaws	Mean per-flaw TWCF importance
0.080	1.43	0.0000216
0.161	20.86	0.000556
0.241	23.16	0.00361
0.321	11.16	0.0199
0.402	6.82	0.0990
	63.43	

A graph of the mean individual flaw importance as a function of flaw sizes was plotted and a hand-drawn curve was fitted to the data. That plot is provided as Figure 2. It is used as the basis for interpolating to obtain the per-flaw importance of flaws at the upper edges of the 0.05-inch ISI bins sizes. The same importance-weighting process that was used for weld flaws is used for adjusting the number of FAVOR plate flaws that are placed in the 0.05-inch ISI bins.

The first adjustments were made to place the equivalent number of flaws from the FAVOR bins at the upper or lower limit of the various 0.05-inch ISI flaw bins, based on flaws at 0.080 inch increments that fell within those bins. This results in the bin populations given in Table 8.

Figure 2: Beaver Valley Category 2 Plate Flaw Importance to TWCF vs Flaw Size

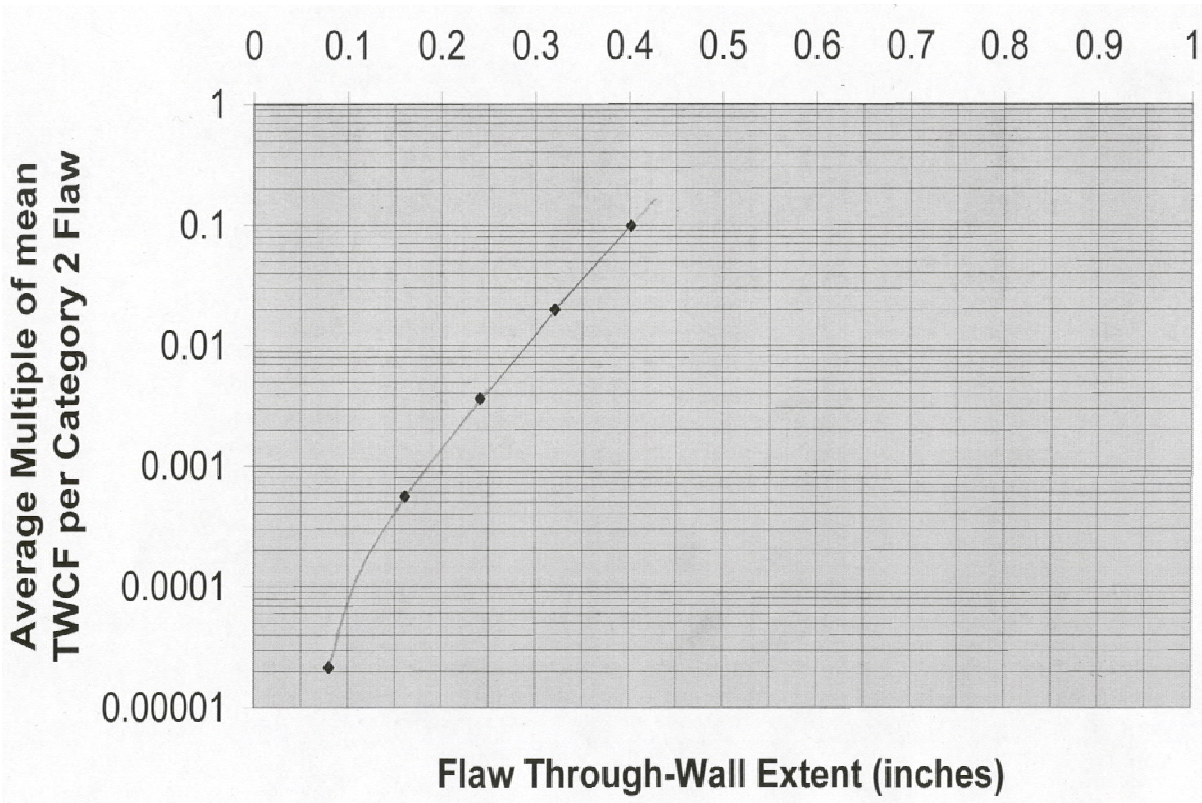


Table 8. Populations of ISI plate Flaw Bins Equivalent to Favor Flaw Bins

Nominal Bin Size	Bin Size Range	Number of Flaws	Adjusted Notes
0.05	0.025 - 0.075		
0.10	0.075 - 0.125	0.9029	adjusted from 0.080 bin
0.15	0.125 - 0.175	3.2928	adjusted from 0.161 bin
0.20	0.175 - 0.225		
0.25	0.225 - 0.275	0.4178	adjusted from 0.241 bin
0.30	0.275 - 0.325	0.0613	adjusted from 0.321 bin
0.35	0.325 - 0.375		
0.40	0.375 - 0.425	0.0054	adjusted from 0.402 bin

That leaves three unpopulated bins. As with the weld flaws, it is actually the cumulative flaw distribution that can best be used for comparison to assure that the risk is bounded, because any flaws modeled as larger than an actual flaw is a conservative representation of that flaw.

The 0.05-inch bin does not need to be limited, because flaws in that bin have minuscule significance to the TWCF. The cumulative distribution resulting from the adjusted flaw populations is given in Table 9, and the cumulative distribution from analysis of the flaws in the plate material of the Shoreham RPV is provided for comparison:

Table 9. Cumulative Plate Flaw Distribution by ISI Bin and Comparison to Shoreham Data

Nominal Bin Size	Number of Flaws ≥ Bin	Shoreham Flaws	Ratio
0.05	No Limit	10.277	N/A
0.10	4.680	5.825	0.80
0.15	3.777	1.964	1.92
0.20	0.4845	0.562	0.86
0.25	0.4845	0.125	3.88
0.30	0.0667	0.0305	2.18
0.35	0.0054	0.0078	0.69
0.40	0.0054	0.0020	2.70

The ratio column on the right side of the table indicates that the number of allowed flaws would sometimes be greater than the number actually found in the Shoreham plate material, but would sometimes be less, as a result of the uneven rebinning that left unpopulated bins. In order to provide a more even ratio to expected ISI results, it was decided to make some adjustments to the flaw populations in the bins with lower ratios, again using the importance-weighted process. Specifically, 1 flaw in the 0.15-inch bin was replaced by 4 flaws in the 0.10-inch bin, and 0.2 flaw in the 0.25- inch bin were replaced by 0.56 flaw in the 0.2-inch bin.

Also, because an RPV is not likely to have more than 100,000 square inches of plate material in the beltline region, a flaw population limit below 0.01 per 1000 square inches is not useful for regulatory purposes. Therefore, the 0.0054 flaw in the 0.40-inch bin was replaced by 0.0143 flaw in the 0.35-inch bin.

The resulting final plate flaw cumulative size distribution is provided in Table 10.

Table 10. Plate Flaw Size Cumulative Distribution for Draft PTS Rule

Nominal Bin Size	Number of Flaws ≥ Bin	Shoreham Flaws	Ratio
0.05	No Limit	10.277	N/A
0.10	8.049	5.825	1.38
0.15	3.146	1.964	1.60
0.20	0.853	0.562	1.52
0.25	0.293	0.125	2.35
0.30	0.0756	0.0305	2.47
0.35	0.0144	0.0078	1.84
> 0.35	0	0.0020	0

For additional explanation, please contact:

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