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AN IMPROVED MODEL FOR POSTULATING FABRICATION FLAWS IN REACTOR PRESSURE VESSELS FOR STRUCTURAL INTEGRITY EVALUATION

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ABSTRACT

This paper presents an improved model for postulating fabrication flaws in reactor pressure vessels (RPVs) and for the treatment of measured flaw data by probabilistic fracture mechanics (PFM) codes that are used for structural integrity evaluations. The model used to develop the current pressurized thermal shock (PTS) regulations conservatively postulated that all fabrication flaws were inner-surface breaking flaws. To reduce conservatisms and uncertainties in flaw-related inputs, the United States Nuclear Regulatory Commission (USNRC) has supported research at Pacific Northwest National Laboratory (PNNL) that has resulted in data on fabrication flaws from non-destructive and destructive examinations of actual RPV material. Statistical distributions have been developed to characterize the number and sizes of flaws in the various material regions of a vessel. The regions include the main seam welds, repair welds, base metal of plates and forgings, and the cladding that is applied to the inner surface of the vessel. Flaws are also characterized as being located within the interior of these regions or along the weld fusion lines that join the regions. Flaws are taken that occur at random locations relative to the embrittled inner region of the vessel. The probabilistic fracture mechanics model associates each of the simulated flaw types with the fracture properties of the region being addressed.

INTRODUCTION

The current U.S. regulations ensure that RPVs maintain their structural integrity when subjected to transients such as pressurized thermal shock events. These regulations were derived from computational models developed in the early-to-mid 1980s. Since that time, there have been significant advancements and refinements in the relevant technologies associated with the physics of PTS events that impact RPV integrity assessment. This has led to an effort by the USNRC to re-evaluate its PTS regulations within the framework established by modern probabilistic risk assessment techniques [1]. Updated computational models (Figure 1) have evolved through interactions between experts in the relevant disciplines of thermal hydraulics, probabilistic risk assessment, statistics, material embrittlement, fracture mechanics, and inspection (flaw detection and characterization). These updated models have been integrated into the FAVOR (**F**racture **A**nalysis of **V**essels: **O**ak **R**idge) computer code [2], which is an applications tool for performing risk-informed structural integrity evaluations of aging reactor pressure vessels.

The model utilized in the prior PFM analyses, from which the current PTS regulations were derived, conservatively postulated that all fabrication flaws were inner-surface breaking flaws. It was also recognized that such flaw-related data had the greatest level of uncertainty of the inputs required for the PTS evaluations. To reduce this uncertainty, the USNRC has supported research at PNNL that has resulted in the postulation of fabrication flaws based on extensive non-destructive and destructive examination of actual RPV materials. Such measurements have been used to characterize the number, size, and location of flaws in various types of welds and the base metal used to fabricate vessels. This has provided a technical basis for critical inputs to FAVOR calculations.

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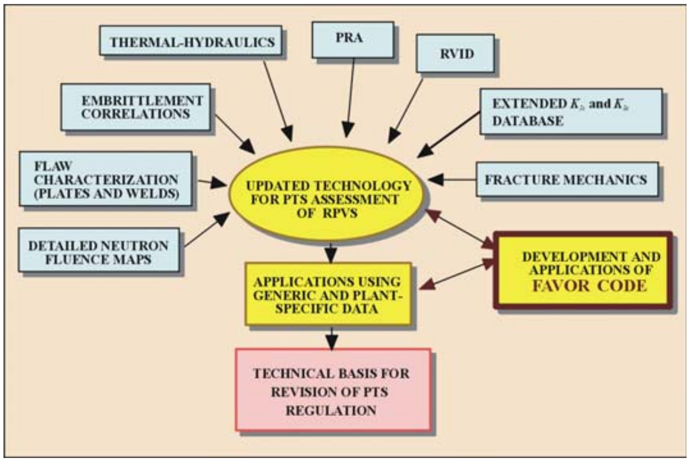

Figure 1. Elements of Computational Model for Predicting Vessel Failure Probabilities and its Application to Regulations for Pressurized Thermal Shock

This paper discusses the improved model for postulating fabrication flaws in RPVs, and describes the treatment of that data by the FAVOR code. The discussion presents a methodology that has been developed to estimate the number and sizes of fabrication flaws in RPVs. The methodology has been applied to generate flaw-related inputs for probabilistic fracture mechanics calculations that have been performed as part of an effort to update pressurized thermal shock regulations. USNRC-funded research at PNNL has generated data on fabrication flaws from non-destructive and destructive examinations of RPV material [3-7]. Statistical distributions have been developed to describe the flaws in each material region [8-10]. Results from an expert elicitation [9] helped to fill gaps in the measured data on fabrication flaws. The regions include the main seam welds, repair welds, base metal of plates and forgings, and the cladding at the inner surface of the vessel. This paper summarizes the available data on fabrication flaws in seam welds, repair welds, base metal, and cladding materials and describes the treatment of these data to estimate flaw densities, flaw depth distributions, and flaw aspect ratio distributions. In each case, there has also been statistical treatments of uncertainties in the parameters of the flaw distributions, which have been included as part of the inputs to the PFM calculations. The paper concludes with a presentation of some example inputs for flaw distributions that have supported evaluations by USNRC of the risk of vessel failures caused by PTS events.

ELEMENTS OF PFM MODEL

Figure 1 diagrams the major elements that enter into a PFM evaluation of a RPV subjected to conditions of pressurized thermal shock. Each of these elements has been reviewed and revised as part of an effort to update the technical bases for revision of current USNRC regulations for PTS. In this methodology the loads due to thermal and pressure transients come from detailed probabilistic risk assessments (PRA) and thermal hydraulic calculations. Material properties (fracture toughness estimates) are based on calculated neutron fluence maps, embrittlement correlations, databases on fracture toughness measurements, and vessel parameters from reactor vessel fabrication records (RVID). This paper addresses the critical element of input data that characterizes the flaws in the various regions of the vessel (welds, plates, forgings, and cladding).

SOURCES OF FABRICATION FLAW DATA

The current rules that govern the generic PTS screening limit and plant-specific vessel evaluations were derived from models that utilized the Marshall distribution for flaws in the welds of RPVs. The documents on the Marshall study [11] indicate that the flaw distribution was based on flaw data from a limited population of nuclear vessels and many non-nuclear vessels. The flaw measurements were part of the customary nondestructive preservice examinations as performed 25 or more years ago at vessel fabrication shops. Due to limitations of the NDE technology, the Marshall flaw distribution provides a reasonable representation of flaws only for a range of depth dimensions of about 1 inch or greater. The Marshall distribution has nevertheless been applied to PTS evaluations by extrapolation of curves to the much smaller flaws of concern to PTS calculations (flaw depths of 0.25 inch and smaller).

The objective of the recent USNRC research on vessel flaws has been to examine RPV materials using more sensitive NDE techniques and to collect data on flaws of all sizes including those with depth dimensions as small as a few millimeters. These efforts have exploited advanced NDE methods with high levels of sensitivity. Another advantage came from the use of material from surplus RPVs from cancelled plants. In this regard, ultrasonic scans were not limited to access from the clad inner surface of the vessels, but exploited the use of smaller samples of material removed from intact vessels, and the use of high-resolution SAFT-UT scans from sectioned surfaces which were optimized to detect flaws with orientations normal to the vessel inner surface. The current database provides dimensions for a large number of relatively small flaws of the sizes identified as the major contributors to potential vessel failures for PTS events. Such flaw sizes were not addressed by the data used to develop the Marshall distribution.

Other papers have described the methods used to examine RPV materials and have documented the actual detection and sizing of the flaws in these materials. The flaw measurements have included through-wall depth dimensions, flaw lengths (aspect ratios), and locations of inner flaw tips relative to the inner surface of the vessel. Where limitations in the measured data were identified, other approaches, including expert elicitation [9] and the application of the PRODIGAL weld simulation model [12], were applied to supplement the measured data or to otherwise guide the development of flaw-related inputs to the fracture mechanics model. The objective of the current paper is to describe how new sources of information on RPV flaws were used to support the improved model for postulating fabrication flaws in RPV. The discussion describes the conceptual framework of the PFM in terms of vessel regions and the types of flaws that are important to each type of region.

In the PTS evaluations, the flaws of concern are present at the time of vessel fabrication and not detected and repaired before the vessel was placed into service. The evaluations assume no credible mechanism to cause service-related cracking of the RPV materials. It is also assumed that crack growth mechanisms of fatigue and stress corrosion cracking can be neglected due to the operating conditions of pressurized water reactors.

VESSEL REGIONS AND FLAW CATEGORIES

Figure 2 depicts the various regions of a RPV and the flaws that are addressed by the PFM model. The conceptual cross sectional view shows axial welds in a vessel. A corresponding cross section to show circumferential welds would show the same categories of flaws but with flaw orientation rotated by 90 degrees.

Figure 3 is a metallographic cross section of a circumferential weld from a RPV. This view shows all the major material regions of concern to vessel integrity, which includes weld metal, base metal, weld fusion lines, and the cladding at the vessel inner surface. In developing inputs for fracture mechanics calculations, the following vessel material regions were addressed.

Seam Welds

Major regions of interest are the axial and circumferential seam welds in the high neutron fluence region of the vessel beltline. These welds have been fabricated by the submerged arc welding (SAW) process or by the manual shielded metal arc welding (SMAW) process. Typically a given seam weld will have some welding from both processes, but with the largest fraction (e.g., >90 percent) of the weld being made by the automatic SAW process. The improved flaw model accounts for separate flaw densities and size distributions for each weld process. However, the identification of local weld regions as being of a particular process is highly vessel specific and requires information not generally available from vessel fabrication records. Therefore, calculations with the FAVOR code have been based on an assumption of a random mixture of SAW and SMAW materials along with a small fraction of repair welding based on trends observed during the detailed examinations of the PVRUF and Shoreham vessels at PNNL.

Flaws associated with seam welds can be located randomly within the volume of deposited weld metal or can be stacked or aligned along the fusion line that separates the weld metal from the adjoining base metal (plate or forging material) as shown in Figure 4. While there can be many flaws associated with the volume of weld passes used to fill the weld joint, measured data has shown very few flaws with significant through–wall dimensions. The majority of larger weld flaws are located along the weld fusion line. Most of these flaws (lack-of-fusion or entrapped slag) are relatively small, but a small fraction of these flaws have through-wall dimensions approaching or exceeding the size of a single weld bead. Based on data on observed flaws, an assumption has been made in the PFM analysis that all weld-related flaws are located along weld fusion lines. Flaws for axial welds are assumed to have axial orientations, and flaws in circumferential welds are assumed to have circumferential orientations.

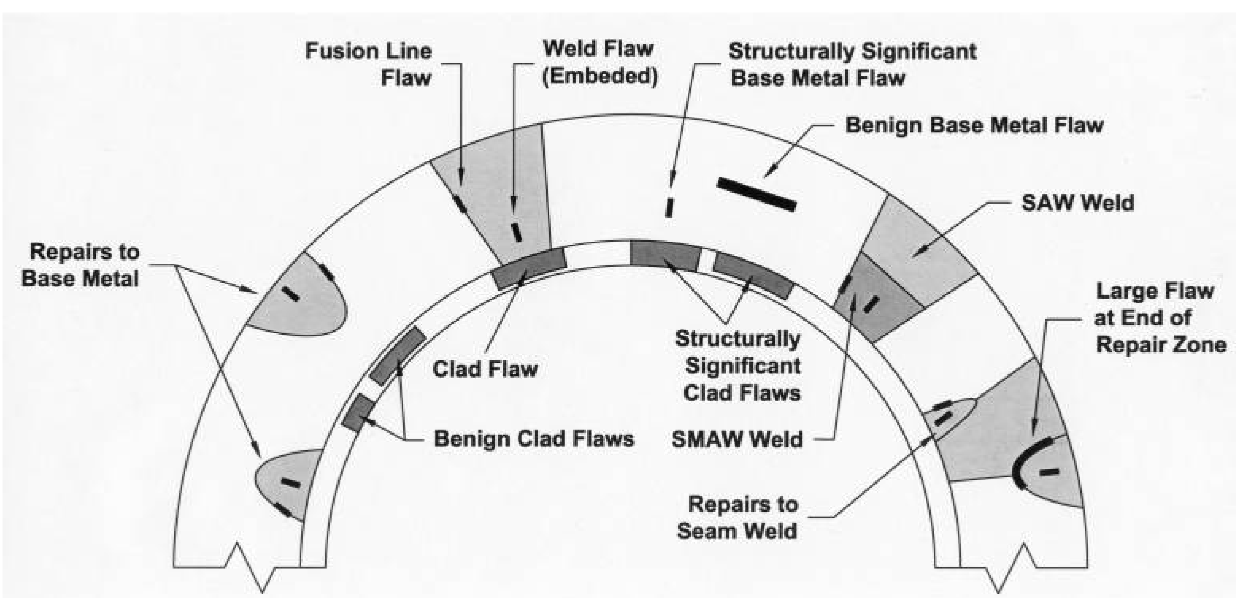

Figure 2. Conceptual View of Material Regions of a Vessel and the Categories of Flaws that can Impact Structural Integrity

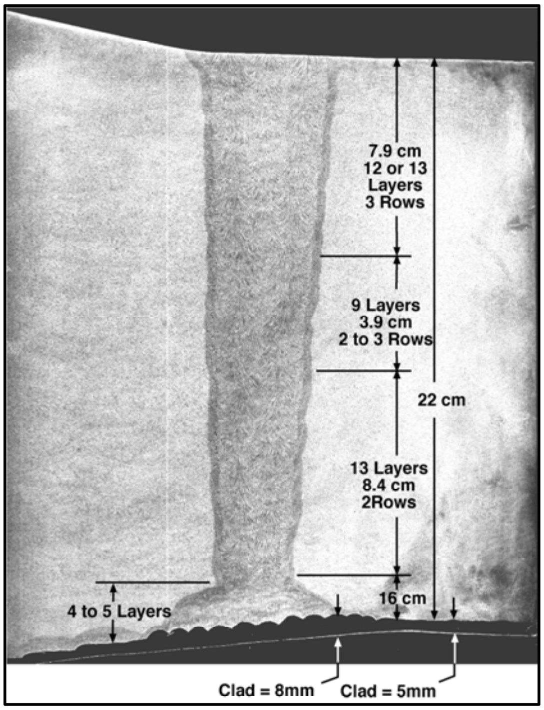

Figure 3. Metallographic Cross Section of a Circumferential Weld Showing Adjacent Regions of Base Metal and Cladding

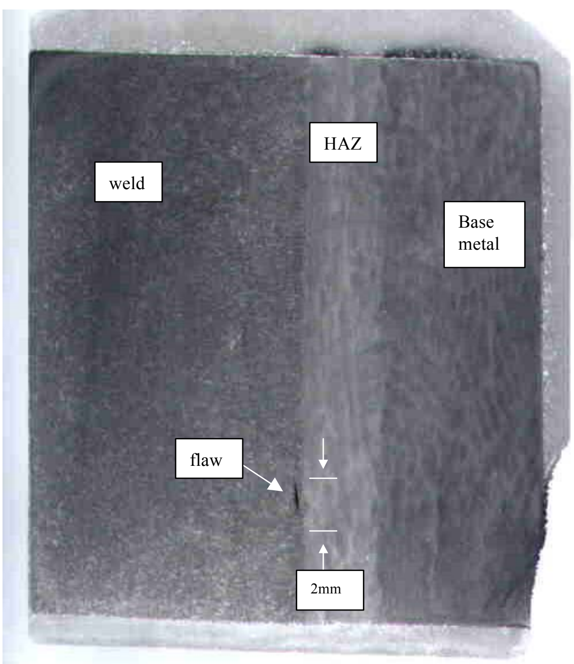

Figure 4. Micrograph of a 25-mm Cube with 2-mm Flaw with the Weld Fusion Line Being a Typical Location for Flaws

Another significant feature of the postulated flaw model relates to the fusion line flaws located in the transition region between the base metal and weld metal. The fracture mechanics model assumes that these fusion line flaws can propagate into either embrittled weld metal or embrittled plate material depending on which material has the lower level of fracture toughness.

Base Metal

Flaws in base metal regions are observed to occur at much lower rates (per unit volume of metal) than in weld regions. Figure 2 shows two flaw categories that were identified for PFM calculations. It is common knowledge that the flaws of largest size in plates and forgings (e.g., laminations) have orientations parallel to the inner surface of the vessels. This orientation results from the rolling and forming operations used to fabricate the vessel plates or forged rings. Although such flaws can be quite large, their orientations are such that they can be assumed to have no significance to vessel failures in the PTS calculations. As indicated in Figure 2, the only flaws of concern are flaws that have some through-wall dimension such as shown by Figure 5. Data from limited examinations of plate materials indicate that such flaws occur at lower rates per unit volume by a factor of ten or greater than in welds.

The application of FAVOR has not yet addressed vessels for which plate material has the limiting toughness. Future calculations will be performed to determine whether the most important flaws for embrittled plate regions are those originated from plate fabrication (embedded within the plates), or the flaws located along the weld fusion lines. The fracture mechanics calculations will address both types of flaws.

Figure 5. Small Base Metal Flaw as Magnified (PVRUF)

Repair Welds

Although it has been observed that repair welds make up only a few percent of the weld metal in a typical vessel, most of the larger flaws (depth dimensions greater than a weld bead) have been associated with repairs. As depicted in Figure 2, repairs consist of a grind out region that has typically been filled by a manual welding process. The repairs can potentially be entirely to seam welds, entirely to base metal, but will most typically span both weld metal and base metal because the repairs are caused by repairs to flaws along weld fusion lines. Repairs have been observed to occur both at the inside and outside of vessels.

Flaws in repair welds have been observed along the fusion line between the metal of the weld repair and the original vessel material. The associated flaws will usually impinge on both seam welds and base metal. The largest flaws found during examinations have been located at the ends of repair cavities, and have been attributed to the difficulties in manual welding within the confined spaces at the ends of the grind out regions. These flaws were located at the triple point of the original weld, repair and base metal.

In modeling of repairs to vessels with the FAVOR code, there have been no attempts to identify specific locations of repairs as may be documented by construction records. Rather the repairs have been assumed to occur at random locations, such that the flaws associated with repairs are blended into the other population of flaws associated with the normal welding processes for the seam welds. The small amount of material from repair welding nevertheless makes a disproportionate contribution to the estimated number of larger flaws.

Cladding

The number and size of surface-breaking flaws at the inner surface of a vessel have been estimated from the flaws that have been detected during examinations of vessel cladding [13]. As indicated in Figure 2, flaws can occur in the cladding applied over both weld and base metal. Due to the much larger area of the vessel inner surface consisting of base metal, all but a small fraction of the clad (or surface-related) flaws will be associated with base metal rather than weld metal.

Figure 2 shows four categories of clad flaws. The FAVOR code assumes that the fracture toughness of the cladding material is sufficiently high so that flaws entirely within the cladding will not propagate. Hence, some configurations of clad flaws are labeled in Figure 2 as benign. Structurally significant flaws are only those flaws, either buried flaws or some larger through-clad flaws, which extend up to the clad-to-base metal interface (as shown by Figure 6). The vessel examinations show that the majority of such structurally significant flaws are of the buried type, both because of the low probability for the larger through-clad flaws and because shop examinations of clad surfaces will detect and repair most surface breaking flaws that may occur from the weld depositing of cladding.

All flaws in cladding, whether the clad is over axial welds, circumferential welds, or base metal, are assumed to have a circumferential orientation. This assumption relates to the fact that all known cladding procedures apply cladding using weld beads that have a circumferential orientation.

Underclad Cracking

A final type of flaw, not yet addressed by the FAVOR code, is underclad cracks resulting from unfavorable conditions during the weld deposition of the cladding material. Underclad cracks have been observed in a few vessels, particularly within the base metal of forged rings. Such flaws have been precluded for most PWR vessels by consideration of the chemical compositions of the base metal of the plates or forgings.

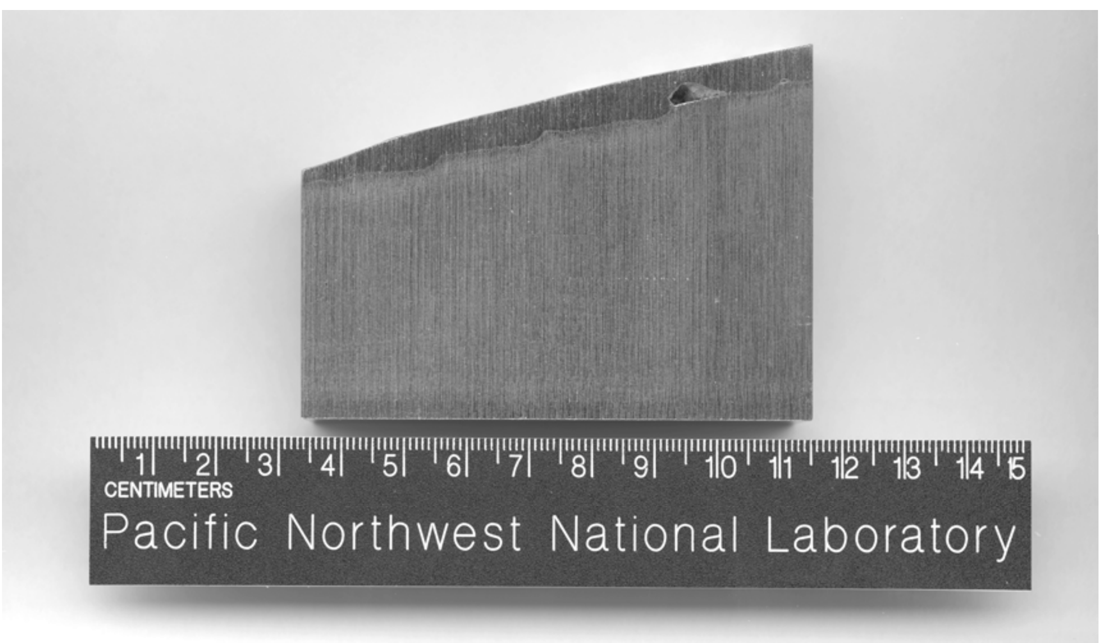

Figure 6. Large Clad Flaw in PVRUF 4-5DBAC-Z5, Lack of Fusion With Slag

TREATMENT OF FLAWS BY FAVOR CODE

The flaw model of the FAVOR code simulates the sizes and locations of flaws and makes use of three input files for 1) flaws in weld regions, 2) flaws in base metal regions, and 3) surface-related flaws in the vessel cladding. In each case the number of flaws per unit volume of material are specified using numerical tables of data. Statistical uncertainties in the estimated flaw-related parameters are treated by generating 1000 possible tables consistent with the estimated uncertainties in the flaw distributions. The elements of the tables correspond to flaws with given depth dimensions as a percentage of the vessel wall thickness and given aspect ratios (flaw length divided by flaw depth). The locations of flaws in weld and base metal regions are assumed to be randomly distributed through the thickness of the vessel wall.

All of the planar-type flaws that have been observed during the vessel examinations are treated by FAVOR as exhibiting ideal crack-like behavior for purposes of the fracture mechanics calculations. For planar flaws, it was not possible to consider the morphology of cracks in detail such as to account for flaws whose tips were somewhat blunted relative to idealized cracks such as sharpened by fatigue crack growth.

User input data to FAVOR PFM analyses includes the volume of metal for each of the RPV subregions. Each of these subregions has its own embrittlement-related properties. From the assigned metal volumes and the inputs for the number of flaws per unit volume of each size category, the total number of flaws in each weld, base metal region, or clad region is calculated. Flaw locations relative to the vessel inner surface are assigned randomly. The FAVOR code also divides the vessel wall thickness into regions with the first region being the inner $1/8^{th}$ of the wall thickness, and the second region being the region from $1/8^{th}$ to $3/8^{th}$ of the vessel wall thickness. It is assumed in FAVOR that flaws located beyond the $3/8^{th}$ of the wall thickness make negligible contributions to the vessel failure probabilities for the PTS evaluations.

EXAMPLE FLAW DISTRIBUTION

Figure 7 is an example plot of estimated flaw frequencies (flaws per cubic foot) as estimated for a representative vessel. The flaw depth distributions of Figure 7 are truncated to preclude extrapolations of curves to flaw depths that are much larger than the depth dimensions of any flaws that were detected in the PNNL examinations of vessel materials. Sensitivity calculations will be performed in the future to establish the effect on calculated vessel failure probabilities of eliminating truncations on flaw depth distributions.

The measured flaw data from examined vessels have shown that weld fabrication flaws occur at random locations relative to the vessel inner surface. In particular, the examinations did not detect any surface-breaking flaws at the vessel inner surface, which is the region that becomes embrittled by irradiation damage during extended service. Flaw aspect ratios have also been characterized by statistical evaluations of measured flaw lengths. Small flaws having flaw depth dimensions that are less than the dimensions of weld beads tend to have relatively large aspect ratios, whereas larger flaws tend to have smaller aspect ratios.

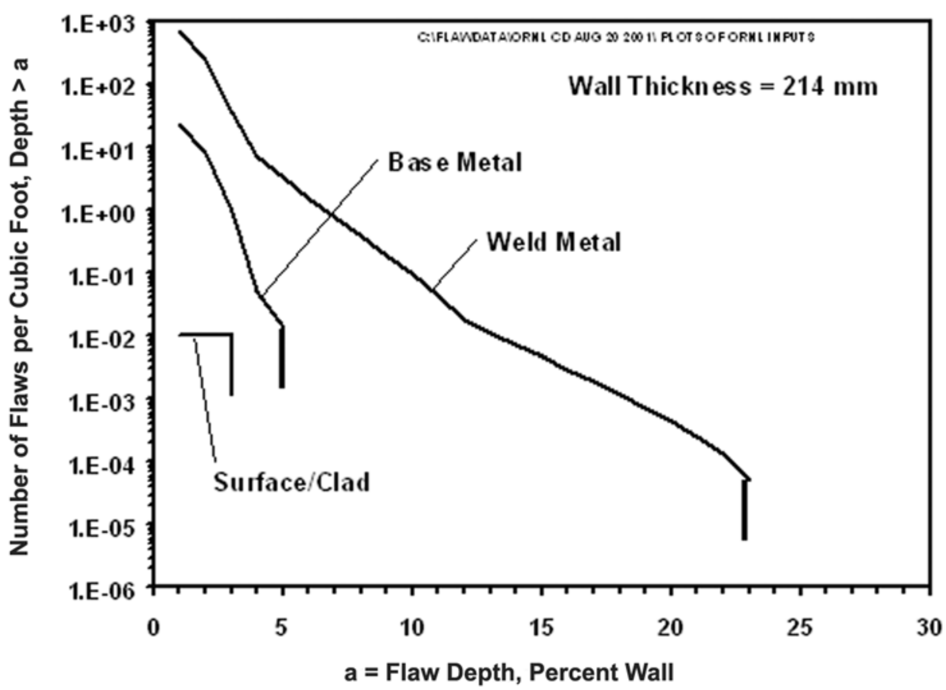

Figure 7. Example Flaw Distribution for Use in Probabilistic Fracture Mechanics Calculations

The number of flaws per unit volume is significantly smaller for the base metal than for the weld metal. However, given the large amount (by a factor of about 50:1) of base metal relative to weld metal, the total number of flaws in base metal exceeds the corresponding total number of flaws for weld metal. Nevertheless, preliminary calculations with FAVOR show negligible contributions of base metal flaws to vessel failure probabilities because the typical level of embrittlement in base metal regions was significantly less than the embrittlement for weld regions.

SUMMARY AND CONCLUSIONS

An improved model for postulating fabrication flaws in reactor pressure vessels has been developed that is based on empirical data representative of fabrication practices in the U.S. from the late 1960s through early 1980s. This model addresses three broad categories of flaws: 1) weld flaws, 2) base metal flaws, and 3) cladding flaws. A separate set of input data corresponding to each flaw category is provided as input to the FAVOR code for PTS calculations. The input files describe the number of flaws per cubic volume, the distribution of flaw depth dimensions, and the distribution of flaw aspect ratios. Other key features of the flaw model are as follows.

1. The flaw model treats the flaw locations as uniformly distributed through the thickness of the vessel wall, and does not assume that the flaws are inner surface breaking.
2. Weld flaws are assumed to lie along the weld fusion line in a manner to allow them to potentially grow into either the weld material or base metal, whichever is more limiting from the standpoint of fracture toughness.
3. Clad materials are assumed to have sufficient fracture toughness to preclude the growth of flaws within the cladding material, which implies that the clad flaws are structurally significant only if they extend up to or penetrate beyond the clad to base metal interface.
4. Underclad cracks in base metal are not addressed, although the present model could be enhanced in the future to evaluate vessels of concern to PTS for which underclad cracking is considered a credible mechanism of cracking.
5. Flaws of most concern to failure of base metal regions include flaws associated with weld fusion line and flaws associated with cladding in addition to flaws within the base metal itself.

Data files have been prepared for use by ORNL for PTS calculations with the FAVOR code. Calculations will be performed for several representative vessels that will consider plants from the major NSSS suppliers. Although most calculations will be for vessels for which the weld material is the most limiting from the standpoint of embrittlement, one vessel will have base metal as the most limiting material.

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