Development of a Generalized Flaw Distribution as Input to the Re-evaluation of the Technical Basis for U.S. Pressurized Thermal Shock Regulation of Pressurized Water Reactor Vessels

Deborah A. Jackson, Lee R. Abramson

U.S. Nuclear Regulatory Commission

ABSTRACT

The U.S. Nuclear Regulatory Commission (NRC) is re-evaluating the guidance and criteria in the code of federal regulations (CFR) as it relates to reactor vessel integrity, specifically, pressurized thermal shock (PTS) which challenges the integrity of the reactor vessel's inner wall. The current regulations in 10 CFR 50.61 for PTS were derived from computational models and technologies that were developed in the early-to-mid 1980's. Since that time there have been several advancements and refinements to the various models and technologies. Preliminary studies to date indicate that technical bases can be established to support a relaxation of the current federal regulation for PTS. A potential revision of the PTS regulation could have significant implications for plants reaching the end-of-license periods and future plant license-extension considerations.

Pressurized thermal shock (PTS) transients can lead to reactor vessel failure. These transients have occurred at operating reactors but to date they have not resulted in vessel failure. To properly determine the probability of vessel failure from a PTS event, an accurate estimate of fabrication flaws is necessary. The characteristics of fabrication flaws are inputs to fracture mechanics structural calculations that will determine the probability of vessel failure during a PTS event.

This paper provides an overview and status of the development of a generalized flaw distribution. It discusses the background of PTS, the fabrication process and the introduction of flaws, the non-destructive (NDE) and destructive examinations (DE) of reactor vessel weld and base metal at Pacific Northwest National Laboratory, and an expert judgment process and proposed methodology that be used in developing the flaw distribution.

INTRODUCTION

The PTS rule sets forth fracture toughness requirements for protection against PTS events for pressurized water reactors (PWRs). A PTS event or transient, in which severe overcooling concurrent with or followed by an increase in pressure in the reactor pressure vessel (RPV), challenges the integrity of the reactor vessel's inner wall. Recent ultrasonic examinations of considerable RPV material at Pacific Northwest National Laboratory (PNNL) [1, 2] and industry experience with Yankee Rowe have provided the NRC with a better understanding of PTS issues. PTS is a significant concern as plants reach the mid-cycle of their operating license when the vessels may become more brittle. PTS re-evaluation is also a concern for licensees considering license renewal. The re-evaluation of PTS will consider a risk-informed approach to the PTS rule. One element of this re-evaluation requires development of a flaw distribution for flaws created during RPV fabrication.

In order to obtain an accurate estimate of fabrication flaws to address PTS events for all classes of domestic reactor pressure vessels, a generalized flaw distribution must be developed. The NRC's Office of Nuclear Regulatory Research is revising the PTS acceptance criteria and has determined that an expert judgment process in conjunction with recent data from PNNL, experience from Yankee Rowe, and flaw simulation models provided by RR-PRODIGAL [3] is the most efficient method for determining the bases for a generalized flaw distribution. The expert judgment process will be used in conjunction with empirical data from PNNL RPV studies and modeling with RR-PRODIGAL in developing the generalized distribution.

Previous work on the development of flaw distributions for RPVs is documented in a report by Dr. Walter Marshall [4] of the United Kingdom. The Marshall Distribution, developed in the late 1970's and revised in the 1980s, was based on ultrasonic (UT) examination of 44 RPVs, augmented by data from non-nuclear vessels. Detection efficiency of UT exams during that time period were not designed to detect many of the flaws that have been detected by PNNL. The current work completed by PNNL combines the effectiveness of the synthetic aperture focusing technique for ultrasonic testing (SAFT-UT) system and the destructive validation process.

BACKGROUND

Although, PTS can lead to RPV failure, to date these transients have not fortunately resulted in RPV failure. To determine the probability of RPV failure from a PTS event, an accurate estimate of fabrication flaws is necessary. The estimate of the number, locations and sizes of fabrication flaws in RPV welds and base metal are important inputs to probabilistic fracture mechanics computer codes such as FAVOR [5] and VISA-II [6] for predicting the failure probabilities of RPVs. To evaluate this level of uncertainty, the NRC is supporting research to establish a better basis for estimating the distributions of flaws in RPVs.

Fracture Mechanics Calculations

As previously stated, probabilistic fracture mechanics computer codes require accurate estimates of flaw rates to determine the probability of RPV rupture during a PTS event. Fracture mechanics calculations during the 1980s at Oak Ridge National Laboratory (ORNL) estimated PTS related vessel failure probabilities [7]. These calculations (in support of NRC Regulatory Guide 1.154 [8]) concluded that the inputs for flaw densities and size distributions were the largest source of uncertainty in failure probability calculations. The ORNL inputs were based on results of the Marshall Committee Study [4], and involved a number of approximations and conservative assumptions such as arbitrarily placing all flaws at the inner surface of the vessel.

Given the difficulty of improving on the well-known and extensively used Marshall distribution, little research progress was made until the early 1990s. The literature shows the development of two complementary approaches. One approach involves the statistical analysis of data from nondestructive inservice inspections of welds. Lance et al. [9] and Rosinski et al. [10] describe the use of data from inservice inspections (ISI) along with statistically-based software (the SAVER code) to develop flaw size and density distributions. Another approach, developed by Rolls Royce and Associates in the United Kingdom, simulates the population of flaws in multi-pass welds by application of an expert system model based on input from experts in the areas of welding and vessel fabrication [11, 12]. Both approaches have the objective of using the best available data and knowledge to estimate fabrication flaw occurrence rates.

Domestic Reactor Pressure Vessel Fabrication

The fabrication process involves a number of variables or characteristics that must be considered, some of which have a significant bearing on the introduction of flaws into the RPV. There were three major manufacturers of domestic RPVs: Combustion Engineering, which fabricated approximately 45% of the domestic RPVs, Babcock and Wilcox, which fabricated 35% and Chicago Bridge and Iron, which fabricated the remaining 20%. Although each vessel was inspected to American Society of Mechanical Engineers (ASME) [13] standards prior to operation, the fabrication and inspection process was different for each manufacturer. The fabrication processes for pressurized water reactors (PWRs) and boiling water reactors (BWRs) is very similar but PTS is only a concern for PWRs.

Most RPVs in the U. S. were constructed by welding together plate material and forgings. The shell courses of the RPVs were constructed by either welding three sections of formed plate, resulting in axial weldments or the shell courses were forged rings. The base metal materials used for most plates and forgings were A533B and A508, respectively. The welding process used in the fabrication of the reactor vessels varied with each manufacturer. For the vast majority of PWRs three welding processes were used in assembling the reactor vessels: shielded metal arc welding (SMAW), gas metal arc welding (GMAW) and submerged arc welding (SAW). The GMAW process was rarely used but when it was used it was for cladding repairs. Both SMAW and SAW were used for axial and circumferential welds. A fourth process electroslag, is an automatic process that was mainly used for axial welds in BWR vessels. Before, during and following the welding, both surface and volumetric inspections were performed. A stainless steel cladding was applied to the inside of each shell course. The formed rings were then stacked and welded to form the cylinder. These circumferential weld preparation surfaces were inspected prior to welding and the welds were subjected to inspections during and upon completion of welding. Finally, cladding was applied to the inside of the vessel to cover the newly formed circumferential weld and the clad surface was then inspected

ULTRASONIC DETECTION AND DESTRUCTIVE VALIDATION OF FLAW POPULATIONS IN RPV MATERIALS

As previously stated until the early 1990's, little research progress has been made to update the Marshall flaw distribution and the results of the Marshall Committee Study [4]. Recent publications are available on the development of flaw distributions using the empirical data from PNNL [1,2] and the simulated flaw distribution from RR-PRODIGAL Code [3].

RPV material examined by PNNL

PNNL obtained empirical data from RPV material fabricated by three domestic RPV manufacturers representing four different vessels. NDE inspections were performed on portions of the weldment and base metal of RPV material from Pressure Vessel Research Users Facility (PVRUF), Shoreham, River Bend Unit 2 and Hope Creek Unit 2 vessels. The very sensitive SAFT-UT was used to detect and characterize flaws in the vessel material [1,2]. The welds from the RPV material are SAW and SMAW with different weld geometries. All of the base metal material that PNNL inspected is A533 plate. In the near future the empirical data will include material from the Midland vessel, a RPV fabricated from forged rings thus allowing the flaw distribution data to include both types of base material for domestic RPVs.

Preliminary Findings

An extensive data base on fabrication flaws is being developed from the UT examinations of weld and base metal material. NDE of four vessels and DE of the PVRUF material has been completed. Additional work is being planned. In addition to the empirical data, PNNL has used the flaw simulation model of RR-PRODIGAL to estimate the number and sizes of flaws in the welds of the PVRUF and Shoreham vessels. Preliminary analysis of the data of the densities of flaw indications in base metal appear to be much less than that in weld metal. However, because there is so much more base metal in a RPV, it is therefore important to know the real flaw density and size distribution functions for base metal in order to conduct meaningful fracture mechanics structural integrity assessments.

Preliminary results for the four vessels show that year(s) of construction may be important. The validation research of PVRUF shows that all flaws greater than 7mm in size were associated with repaired areas. The repair flaws were complex in composition and orientation in both PVRUF and Shoreham. Complex in this work is defined as groups of more than three indications bound by proximity. The density of flaws in the PVRUF and Shoreham vessels is significantly greater than predicted by a Marshall Distribution. The cumulative flaw rate of the Shoreham (unvalidated) vessel material is approximately three times greater than the PVRUF (validated) vessel material.

The amount of empirical fabrication flaw data obtained by PNNL is much greater than the amount of data obtained in developing the Marshall Distribution. Additional information and insight was provided from the expert judgment process from people involved with the actual process of fabrication process of domestic RPVs. The empirical data combined with the results of RR-Prodigal and the expert judgment process will provide the most comprehensive data set of fabrication flaws since the Marshall distribution.

EXPERT JUDGMENT PROCESS

The formal use of expert judgment (sometimes referred to as expert opinion) has been extensively applied to a number of major studies in the nuclear probabilistic risk assessment area. Scientific inquiry and decision-making have always relied on expert judgement, but the formal use of expert judgement as a well-documented systematic process has also been used. In the case of the development of a generalized flaw distribution for domestic RPVs, 17 experts participated as the expert panel. The panel was needed to review, interpret and supplement available information on reactor vessel fabrication processes and reactor vessel flaw distributions. The experts also reviewed the comprehensive work to date by PNNL.

The expert judgment process involved eight steps, a) selection of issues and experts, b) presentation of issues to the experts, c) elicitation training, d) preparation of issue analyses by the experts, e) discuss of issue analyses, f) elicitation of the experts, g) recomposition and h) documentation .

Selection of Issues and Experts

The selection of issues and experts was closely related. The initial selection of issues was developed by NRC staff and PNNL staff and was used to guide the selection of experts. The experts reviewed the list of issues and proposed additions, deletions, or modifications to the list. It was essential that the experts be knowledgeable about the state of the art in their respective fields and they were chosen to represent a diversity of backgrounds, with a wide variety of viewpoints (e.g. academic, consulting, vessel fabricators, forging manufacturers, etc.). The specific areas of expertise were: ASME Code for construction; failure analysis; forgings; metallurgy; NDE; reactor vessel fabrication; statistics; and welding. The 17 experts were selected on the basis of their recognized expertise in the issue areas, such as demonstrated by their publications.

Presentation of Issues to the Experts

Presentation of issues to the experts provided a mechanism to discuss the state-of the art for each issue. An essential aspect of issue presentation was issue decomposition, which allowed the experts to make a series of simpler assessments rather than one overall assessment of a complex issue. This step was crucial, as the decomposition of an issue can vary by expert and thereby, significantly affect its assessment. Upon initial review of the issues, extensive feedback was provided by the experts. This feedback was critical to NRC and PNNL staff in making revisions to the format in which the issues were presented to the experts during their individual elicitation sessions.

Elicitation Training

Elicitation training assisted the experts with encoding their knowledge and beliefs into a quantitative form. Elicitation training can significantly improve the quality of the experts' assessments by avoiding psychological pitfalls that can lead to biased and/or other overconfident assessments. The training was conducted by a normative expert who is knowledgeable about decision theory and the practice of probability elicitation. In addition to elicitation training, NRC and PNNL staff gave presentations on the background of the PTS work and the empirical NDE data from RPV inspections. The definition of a flaw for use during the expert judgment process was developed. For the purposes of this study, a flaw was defined as an unintentional discontinuity that has the potential to compromise vessel integrity and is present in the vessel after pre-service inspection.

Preparation of Issue Analyses by the Experts

In order to perform a comprehensive issue analysis, the experts were given time and resources to analyze all of the issues before their individual elicitation sessions. If an expert's preparation required additional technical support, it was provided by NRC/PNNL staff. Each expert was given a set of documents to review which supplemented the information presented during the three-day meeting in Atlanta.

Discussion of Issue Analyses

Before the elicitation session, the experts were invited to discuss their issue analyses and present the results of their analyses and research. Some of the experts engaged in discussions of the characteristics prior to their individual elicitation sessions. The ensuing discussions served to ensure a common understanding of the issues and the data.

Elicitation of the Experts

The experts were elicited by an elicitation team consisting of a normative expert, two substantive experts, and a recorder. The elicitation team met separately with each expert, to avoid pressure to conform and other group dynamic interactions that might occur if the expert judgments were elicited in a group setting. The elicitation focused on a number of quantitative and qualitative characteristics, listed below. The experts were asked to rank each characteristic in order from highest to lowest in terms of contributing to or having a flaw after preservice inspection. They were then asked for a quantitative assessment, if appropriate. For example, the experts were asked which product form is most likely to have a flaw remaining after preservice inspection. Suppose the response was that weld metal is the most likely to have a flaw remaining following preservice inspection, followed by cladding, plate and forgings. The expert was then asked to assess the relative likelihood of a flaw in cladding, plate and forgings, each compared with the likelihood of a flaw in weld metal. For each relative likelihood (expressed as a ratio or percent change), the expert was asked to supply low, high and median values. For characteristics where the ranking or quantitative assessment did not apply, the experts were asked what effect the characteristic would have on the introduction of a flaw. They were asked which vessel is more likely to have a large number of flaws after preservice inspection and what elements of fabrication are most affected by field vs. shop fabrication.

As the sessions continued, it became apparent to the members of the elicitation team that the experts were not able to provide quantitative data such as ranking of the characteristics and/or pairwise comparisons for all characteristics. For example, welder skill and inspector skill are dominated by human factors issues and quantitative data was not easily provided. The experts also provided the elicitation team with feedback that some of the characteristics should be further subdivided to accurately classify a particular characteristic. Flaw size and cladding process are examples of two characteristics that needed further division.

Recomposition and Summary of Results

Recomposition and summary of results was performed by the normative and substantive experts who recomposed the results into a form suitable for further analysis. This was completed after each session. Upon completion of the 17 elicitation sessions and a preliminary review of the responses, it was apparent that the characteristics had to be divided into quantitative and qualitative characteristics and there was a need to re-elicit the experts on a number of quantitative characteristics and obtain additional information on flaw size. The experts were re-elicited to obtain responses regarding flaw size, density of large flaws vs. small flaws, flaw density in cladding vs. weldmetal, flaw density in base metal vs. weld metal, repaired vs. non-repaired weld metal and base metal for small and large flaws, underclad cracking, flaw density of SAW and ESW vs. SMAW, flaw density of three cladding processes (strip, multi wire and single wire) vs. SMAW.

Quantitative characteristics are those characteristics for which the experts were able to provide numerical comparisons. In most cases, records and data are available to verify information for quantitative characteristics. The quantitative characteristics are product form, weld process, flaw mechanisms, repairs and flaw size. Qualitative characteristics are those characteristics for which the experts could not provide any meaningful numerical comparisons. Records and corresponding information are not readily available. The qualitative characteristics are field vs. shop fabrication, weld procedure, weld materials, welder skill, inspection procedure, inspection skill, base metal properties, surface parameters and preparation, and flaw location.

Documentation

The final step in the expert judgment process was to document the entire process. Documentation has several purposes. First, it can be used by the experts involved to assure them that their judgments were correctly reflected. Second, it can be used by potential users of the results of the process to enhance their understanding. Third, it can be used by peer reviewers of the process to provide an informed basis for their review. And finally, documentation can be extremely useful to update the analyses, when future research on other vessel material becomes available. Technical rationales for the responses from each expert were recorded during the elicitation sessions.

Quantitative Characteristics

Information on the quantitative characteristics can also be obtained from construction and QA records for most vessels. Many experts provided similar or identical rationales to justify their assessments. Some of the technical rationales for the quantitative characteristics are as follows:

1. Flaw Size
   a. Large flaws should be detected by NDE and are usually caused by loss of control of the welding process
   b. Small flaws can be missed due to sensitivity and recording levels of NDE equipment
2. Product Form - Base Metal Ring Forgings
   a. The ID and OD of the forgings were machined for weld preparation
   b. Due to the forging process the inside of the forging is more likely to have flaws.
3. Product Form - Base Metal Plate
   a. Laminations and non-metallic inclusions were the most prominent problems
   b. Due to the fabrication process of plates, it is more likely to have flaws in the center of the plate
4. Product Form - Cladding
   a. No volumetric NDE on cladding
   b. Discontinuities in the cladding maybe of no concern to RPV integrity
5. Product Form - Weld metal
   a. Most likely to have flaws as compared to other product forms due to the welding process (starts and stops, flux)
   b. The placement of weld metal is strongly affected by human factors; therefore more likely to have flaws than other product forms
6. Repairs to Weld metal
   a. The flaw state in a repaired weld is the same as repaired base metal
   b. In-process removal of slag, etc. were not considered as a weld repair
7. Repairs to Base Metal
   a. Repair to a weld prep region prior to welding is classified as a repair to the base metal
   b. Most repairs to base metal were to edge prep laminations or other flaws extending to the weld groove and would be detected via MT or PT.
8. Repairs to Cladding
   a. Manual welding process was used to repair cladding
   b. Good access to cladding eliminated difficult repairs geometries
9. Weld Process - SMAW
   a. Strongly affected by human element; more so than SAW and ESW
   b. SMAW is more likely to have a flaw as compared to SAW and ESW due to stop and start during the process to change electrodes
10. Weld Process - SAW
    a. Incorrect equipment setup could result in a large number of flaws
    b. Can have larger flaws than SMAW due to the larger bead size
11. Weld Process - ESW (mainly used in BWRs but information was provided by experts)

a. Most likely to produce very large flaws due to the large pass size of ESW process
b. Large flaws produced by ESW would be detected by NDE

12. Weld Process - Cladding
    a. Multi-wire cladding is superior to single wire because there are fewer interconnections and there are fewer passes to cover a given area with multi wire than with single wire
    b. Strip wire cladding problems are readily visible due to the smooth surface
13. Flaw Location - (Most common areas for flaws)
    a. Weld metal - repairs, start/stop locations, back gouge areas, root pass
    b. Base metal - heat affected zone, forgings at the inside surface, plates at the top and center

Qualitative Characteristics:

For qualitative characteristics it is not possible to quantify the effect the characteristic will have on the introduction of a fabrication flaw and there are no records readily available to document information on these characteristics. However, qualitative knowledge can help guide application of existing data to other vessels. Some of the technical rationales for the qualitative characteristics are as follows:

1. Field vs. Shop Fabrication
    a. Most field fabricated vessels were partially assembled in the shop
    b. All field welds were SMAW in 2G position vs. shop weld being automated and in 1G position
2. Weld Procedure
    a. All weld procedures were qualified to meet ASME requirements
    b. If the weld procedure was properly qualified and demonstrated prior to use, it should not significantly affect the introduction of flaws
3. Weld Materials
    a. In terms of introducing a flaw, weld flux is more important than weld wire
    b. Improvements of weld materials were made over the years of RPV fabrication
4. Welder Skill
    a. Manual processes are strongly affected by human factors
    b. Welding is an art as well as a science
5. Inspection Procedure
    a. NSSS contract inspection requirements varied for each vendor as stated by the client
    b. Fabricators performed independent tests to enhance/improve fabrication process
6. Inspector Skill
    a. Interpretation of NDE information is an important inspector skill
    b. Inspector skills have changed over the years due to experience, equipment improvements and automation of certain NDE techniques
7. Base Metal Properties
    a. Variability of base metal properties should have little or no effect on flaw occurrence
    b. Base metal chemistry can influence under clad cracking
8. Surface Preparation and Parameters
    a. Surface treatment such as sandblasting and grinding can seal a crack or other flaw from dye penetrant
    b. Joints that were prepared by arc/flame cutting may be more susceptible to flaws due to surface contamination

GENERALIZED FLAW DISTRIBUTION METHODOLOGY

A generalized flaw distribution (GFD) describes the number of flaws whose depths exceed (x) mm. The present approach is based on two GFDs, one for small through wall dimension (TWD) flaws and one for large TWD flaws. For weld metal, the size for welds separating small and large flaws depends on the bead thickness (b), and for base metal size it is determined by a fixed dimension, with one-quarter inch and less considered a small flaw (also denoted by b). For weld metal, a small flaw is one whose crack depth does not exceed the bead thickness ($x \leq b$) and a large flaw is one whose crack depth exceeds the bead thickness ($x > b$). Because bead thickness can vary from weld to weld, the range of x for small and large flaws may vary from weld to weld or for different welding processes used for a single weld.

Each GFD is composed of three parts: (i) flaw densities; (ii) volumes (for weld metal) or areas (for base metal) of material; and (iii) the distribution of crack depth, given a flaw. The densities and crack depth distributions depend on flaw size, product form, weld process and repair state. The separation of the crack depth distributions from the density of flaws allows crack depth data from different flaws to be combined to estimate the distributions.

The GFDs are given by $N_S(x)$ in Eq. (1) and $N_L(x)$, in Eq. (2) where x = crack depth and $N_S(x)$ = number of small flaws > x, for $x \leq b$ and $N_L(x)$ = number of large flaws > x, for x > b.

$$N_s(x) = [\sum \rho_S(PF, WP, R) \bullet V(PF, WP, R)] \bullet G_S(x;PF, WP, R) \quad (1)$$

$$N_L(x) = [\sum \rho_L(PF, WP, R) \bullet V(PF, WP, R)] \bullet G_L(x; PF, WP, R) \quad (2)$$

where:
PF = Product Form (Weld Metal, Cladding, Plate, Ring Forgings)
WP = Weld Process (SMAW, SAW, ESW; Strip, Single & Multi Wire)
R = Repair State (Unrepaired, Repaired).
$\rho_S(PF, WP, R)$ = density of small flaws per unit volume or area
$\rho_L(PF, WP, R)$ = density of large flaws per unit volume or area
V(PF, WP, R) = volume or area of material.
$G_S(x)$ = ccdf for small flaws = Prob {crack depth > x}, where $x \leq b$
$G_L(x)$ = ccdf for large flaws = Prob {crack depth > x}, where x > b.

CONCLUSIONS

The commitment by the NRC's Office of Nuclear Regulatory Research to develop a generalized flaw size and density distribution for reactor pressure vessels has been positively received by industry and the NRC's Advisory Committee on Reactor Safeguards (ACRS). The development of a generalized flaw distribution will be a step forward in possibly reducing a source of uncertainty in the fracture mechanics calculations for reactor vessel failure and may result in justification for removal of some of the conservative assumptions regarding reactor pressure vessel integrity guidance in the CFR. The recent NDE data on RPV material proves that NDE has played and continues to play a very important role in the assessment of the integrity of RPVs and will be a significant topic during the development of the generalized flaw distribution.

The expert judgment process was not a consensus process. Responses and data were obtained from each expert during individual elicitation sessions. The entire set of data and responses from the process will be published in an upcoming NUREG which will contain the GFD for the entire fleet of domestic reactor vessels along with uncertainty and sensitivity studies. In addition, comments and questions received by NRC related to data acquisition, the process used for the expert judgment process and development of the GFD, flaw depth location, PVRUF flaw sizing and characterization accuracy, flaw distribution development and destructive examination techniques will be addressed in the upcoming NUREG.

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