

## THE NRC PERSPECTIVE ON FLAW EVALUATIONS FOR VARIOUS NUCLEAR COMPONENTS

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### ABSTRACT

Over the years the Babcock and Wilcox Owners Group, Boiling Water Reactor Vessel and Internals Project (BWRVIP), Combustion Engineering Owners Group, Westinghouse Owners Group, and licensees for individual plants have submitted for Nuclear Regulatory Commission (NRC) review and approval numerous reports regarding the evaluation of postulated and detected flaws in reactor pressure vessels (RPVs), RPV internals, American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME Code) Class 1 piping and tanks, and a variety of other components. The technical areas addressed in these evaluations include flaw sizing; flaw evaluation using linear elastic fracture mechanics (LEFM), elastic-plastic fracture mechanics (EPFM), and limit load analysis; embrittlement due to various environmental conditions; and crack growth rates for fatigue, intergranular stress corrosion cracking (IGSCC), or primary water stress corrosion cracking (PWSCC) under various water chemistry conditions. These flaw evaluations have been used to support license amendments, exemptions, responses to orders, relief requests from ASME Code requirements, responses to generic letters and bulletins, and license renewal applications. This paper summarizes the NRC positions as a result of reviewing these owners group reports and plant-specific submittals. This paper is forward-looking, i.e., flaw evaluations associated with emerging issues such as PWSCC will also be discussed.

**Keywords:** primary water stress corrosion cracking, linear elastic fracture mechanics, elastic-plastic fracture mechanics, flaw sizing.

## 1 INTRODUCTION

Rules and regulations regarding the structural integrity of safety-related structures, systems, and components (SSCs) of a nuclear power unit usually employ flaw evaluations as a tool to obtain information about the adequacy of permitting continued operation of these SSCs with detected or postulated flaws. In accordance with the rules and regulations, the Babcock and Wilcox Owners Group, BWRVIP, Combustion Engineering Owners Group, Westinghouse Owners Group, and licensees for individual plants have submitted for NRC review and approval numerous applications regarding the evaluation of detected and postulated flaws in RPVs, RPV internals, ASME Code Class 1 piping and tanks, and a variety of other components. These flaw evaluations have been used to support license amendments; exemptions; relief requests from ASME Code requirements; responses to orders, generic letters, and bulletins; and license renewal applications.

Flaw evaluation methodologies for various applications can be found in the ASME Code, Section XI and the pertinent regulatory documents as stated below. However, since each of the ASME Code methodologies was developed individually, the organization and emphasis of one methodology is usually different from the others, and they do not always follow the conventional fracture mechanics approach of highlighting flaw sizing, applied stress intensity factors and the associated crack growth evaluation, and identification and characterization of driving force, failure resistance, and flaw stability criteria. This paper attempts to connect these individual methodologies conceptually by applying the conventional fracture mechanics approach to all of them and discussing them in a comprehensive, systematic way, so that the special features of each can stand out. It is the intent of this paper to promote a more thorough understanding of the similarities and differences between these ASME Code methodologies, an understanding which may not be readily achievable based on the ASME Code formulations. This paper groups the methodologies into two categories: (1) those based on postulated flaws and (2) those based on detected flaws. The reason why a methodology based on LEFM, or EPFM, in one category is not applicable to a methodology based on LEFM, or EPFM, in another category will become clear in the discussion of the basic differences between these two categories of flaw evaluations. In addition, this paper summarizes the NRC positions regarding flaw evaluations for various applications. Further, the authors will discuss flaw evaluations associated with emerging issues such as PWSCC. The special features for the flaw evaluation methodologies discussed here will be summarized in Table 1 for future referencing.

## 2 REGULATIONS AND GUIDELINES

The rules and regulations concerning flaw evaluations for various nuclear SSCs can be divided into two categories: those associated with detected flaws and those associated with postulated flaws. Detected flaws in SSCs are normally identified during inservice inspection (ISI) activities performed by licensees, as required by the Code of Federal Regulations, Title 10 (10 CFR), 50.55a, "Codes and Standards." Paragraph 10 CFR 50.55a(g), "Inservice inspection requirements," requires that the ISI of components (including supports) which are classified as ASME Code Class 1, Class 2, and Class 3 meet the Section XI requirements of the ASME Code throughout the service life of a nuclear power facility. Section XI of the ASME Code specifies in IWB-2400, "Inspection Schedule," ISI requirements on the timing and percentage of inspections for each ASME Code examination category of components. IWB-2500, "Examination and Pressure Test Requirements," identifies specific components within each ASME Code examination category and specifies the required inspection method and acceptance standard for each component. IWB-3100, "Evaluation of Examination Results," contains requirements on disposition of indications detected and characterized during the inspection activities: IWB-3110 for preservice volumetric and surface, IWB-3120 for preservice visual, IWB-3130 for inservice volumetric and surface, and IWB-3140 for inservice visual examinations.

Only IWB-3130 and IWB-3140 in Section XI of the ASME Code have options to permit continued operation of the SSCs without repair using analytical evaluation for flaws exceeding the appropriate acceptance standard (IWB-3510 to IWB-3523), as specified in Table IWB-3410-1. IWB-3130 refers to IWB-3600 for the analytical evaluation requirements along with the acceptance criteria. Since IWB-3140 does not specify what evaluation analysis and acceptance criteria are to be used for indications from inservice visual examinations, the NRC has used those specified in IWB-3130 in conducting relevant evaluations.

If the full extent of the flaw cannot be characterized for technical or economic reasons, then the maximum possible initial flaw size has to be assumed at the appropriate location when indications (e.g., leakage) are detected. In some cases, the repair of SCCs may not be in accordance with the repair option of IWB-3130 or IWB-3140 requirements due to practical reasons. In this situation, a flaw evaluation may be needed in addition to the repair. Several recent relief requests related to RPV control rod drive mechanism (CRDM) and pressurizer penetration repairs fall into this category. These repairs relocated the pressure boundary from the old J-groove weld, which connected the penetration and the interior vessel wall, to a new weldment along the penetration while leaving the flaw in the old J-groove weld intact.

The regulations regarding disposition of detected flaws in SCCs are remedial in nature because the existence of flaws has been confirmed by inservice volumetric, surface, or visual examinations. Structural integrity of the SCCs containing a detected flaw of a known size can be demonstrated through a flaw evaluation using the ASME Code specified acceptance criteria detailed in IWB-3600, "Analytical Evaluation of Flaws." IWB-3600 refers to the methodology in Section XI to the ASME Code, Appendix A, "Analysis of Flaws," for evaluating flaws detected in ferritic materials 10.16 centimeters [4 inches] and greater in thickness, such as RPVs; and Appendix C, "Evaluation of Flaws in Piping," for evaluating flaws in austenitic and ferritic piping. As indicated in the 2004 Edition of Section XI of the ASME Code, Section XI now includes IWB-3660, "Evaluation Procedure and Acceptance Criteria for PWR Reactor Vessel Head Penetration Nozzles," which refers to Appendix O, "Evaluation of Flaws in PWR Reactor Vessel Upper Head Penetration Nozzles," for analytical procedures. In addition, the ASME has adopted (not published yet) a modification to IWB-3612, "Acceptance Criteria Based on Applied Stress Intensity Factor," which changes the relevant fracture toughness for the flaw evaluation acceptance criterion for normal conditions from the crack-arrest fracture toughness,  $K_{Ia}$ , to the plane-strain fracture toughness,  $K_{Ic}$ . Although the 2004 Edition of the ASME Code has not been officially endorsed by the NRC, the Appendix O methodology will still be discussed in this paper because of high occurrences of cracking in RPV CRDM penetrations in recent years. On the other hand, since revision of IWB-3612 has not been published yet, the Appendix A methodology being discussed here will refer to the current IWB-3612 for acceptance criteria. Note that the ASME Code does not mandate the use of Appendices A, C, and O since other methodologies which are capable of demonstrating component structural integrity may be applied.

Regulations on structural integrity of SCCs based on postulated flaws, on the other hand, are associated with demonstrating adequate failure resistance for these SCCs during operation under Level A (normal), B (upset), C (emergency), or D (faulted) loading conditions and any out-of-limit condition. The regulations based on postulated flaws are preventative in nature since certain flaw acceptance criteria are required to be met for the SCCs. Examples are: the requirements on pressure-temperature (P-T) limits, as stipulated in Appendix G to 10 CFR Part 50, "Fracture Toughness Requirements," the requirements on the equivalent margins analysis for low upper-shelf energy (USE) RPV materials in the same Appendix, and the requirements on out-of-limit conditions in Appendix E to Section XI of the ASME Code, "Evaluation of Unanticipated Operating Events." Appendix G to 10 CFR Part 50 explicitly refers to the methodology in Appendix G to Section XI of the ASME Code, "Fracture Toughness Criteria for Protection Against Failure," for the P-T limit evaluation and implicitly refers to Regulatory Guide (RG) 1.161, "Evaluation of Reactor Pressure Vessels with Charpy Upper-Shelf Energy Less Than 50 Ft-Lb," for the equivalent margins analysis for the low USE RPV materials.

### **3 FLAW EVALUATION METHODOLOGIES**

#### **3.1 FLAW EVALUATION METHODOLOGIES BASED ON DETECTED FLAWS**

A typical flaw evaluation for detected flaws includes five elements: (1) flaw sizing; (2) the applied stress intensity factor ( $K_{\text{applied}}$ ) calculation and the associated crack growth evaluation based on fatigue, IGSCC, or PWSCC under various environments; (3) a driving force evaluation for the final flaw size using LEFM, EPFM, or limit load analysis according to the projected failure mode; (4) a failure resistance evaluation considering embrittlement due to various environmental conditions and the projected failure mode; and (5)

a stability evaluation using an ASME Code acceptance criteria with ASME Code-specified structural factors.

A typical flaw evaluation for detected flaws starts with Element 1, flaw sizing in accordance with Section XI of the ASME Code, IWA-3000, "Standards for Examination Evaluation." Section XI of the ASME Code does not require adding nondestructive evaluation (NDE) uncertainties to the characterized flaw size. Instead, the quality of flaw size determination by ultrasonic testing (UT) is controlled through implementing the NDE requirements of either Appendix III, "Ultrasonic Examination of Vessels not Greater than 2 Inches (51 mm) in Thickness," or Appendix VIII, "Performance Demonstration for Ultrasonic Examination Systems" of Section XI of the ASME Code. Similarly, the quality of flaw detection and sizing by eddy current testing (ET) and visual examination is controlled through the requirements of Appendix IV, "Eddy Current Examination," and Appendix VI, "Qualification of Personnel for Visual Examination" of Section XI of the ASME Code. The NRC staff will request detailed information to substantiate the initial flaw size determination if it is not in accordance with Section XI of the ASME Code, as modified by 10 CFR 50.55a.

Element 2 concerns the  $K_{\text{applied}}$  calculation and the associated crack growth evaluation. The crack growth evaluation in ASME Code, Section XI, Appendix A for RPV flaws, Appendix C for austenitic and ferritic piping flaws, and Appendix O for RPV upper head penetration nozzle flaws, requires information on  $K_{\text{applied}}$  for flaws at every step of the crack growth. In the most recent version of the ASME Code (the 2001 Edition through the 2003 Addenda) which has been endorsed in 10 CFR 50.55a, Appendices A and C provide complete information to calculate  $K_{\text{applied}}$  values. However, plant-specific applications do not always use them. Therefore, the NRC's review always includes examination of the  $K_{\text{applied}}$  calculations, the associated plant-specific or generic finite element modeling for the SSCs, and the applicability of the proposed published analytical or numerical fracture mechanics solutions to the SSCs. Appendix A provides fatigue crack growth rate curves for carbon and low alloy ferritic steels exposed to air and water environments; Appendix C provides fatigue crack growth rate curves for austenitic stainless steels exposed to an air environment. Appendix O provides a PWSCC crack growth rate for thick-walled Alloy 600 upper head penetration nozzles exposed to a primary water environment. For IGSCC, BWRVIP reports provide a series of proprietary bounding crack growth rates for BWR coolant pressure boundary piping under different water chemistry conditions.

Next, Element 3, the driving force for the final flaw after crack growth and Element 4, the failure resistance for the material are estimated based on the anticipated failure mode: cleavage fracture, ductile tearing, or net section collapse. LEFM is the theory used to evaluate flaws anticipated to fail by cleavage fracture, with  $K_{\text{applied}}$  as the driving force and the plane-strain fracture toughness,  $K_{\text{IC}}$ , and  $K_{\text{Ia}}$  as the fracture resistance. EPFM is the theory used to evaluate flaws anticipated to fail by ductile tearing, with applied J-integral,  $J_{\text{applied}}$ , as the driving force and the J resistance (J-R) curve, or  $J_{\text{material}}$ , as the fracture resistance.

Fracture resistance is a material property concerning fracture toughness which can be obtained from specimens according to American Society for Testing Materials (ASTM) standards [1-3], or generically from Appendix A of the ASME Code, Section XI for  $K_{\text{IC}}$  and  $K_{\text{Ia}}$ , and NUREG/CR-5729 [4] for J-R curves. The limit load analysis is used to evaluate flaws anticipated to fail by net section collapse, with the combination of applied membrane, bending, and expansion stresses as the driving force and the sum of the plastic collapse bending stress based on flow stress,  $\sigma_f$ , and the applied membrane stress as the failure resistance. The driving force, regardless of the failure mode, is dependent on plant-specific loadings, the component geometry and properties such as Young's modulus and Poisson's ratio, and the final flaw geometry. Whether using LEFM, EPFM, or limit load evaluation methodologies, Element 5, the final step, calls for a test of the failure criteria, i.e., a comparison of the driving force to the failure resistance of the material to determine the acceptability of the assumed flaw considering certain specified structural factors. (The "structural factor" is a new terminology in the 2003 Addenda to the ASME Code to replace "safety factor" that appeared throughout earlier editions of the ASME Code.)

### 3.1.1 Appendix C EPFM Analysis for Circumferential Flaws in Piping Welds

A typical flaw evaluation methodology for detected flaws is completely defined by the five technical elements discussed above. For example, the ASME Code, Section XI, Appendix C EPFM analysis for circumferential flaws in piping welds under combined loading is completely defined by the following:

- Element 1: The NDE characterized length and depth is in accordance with IWA-3000, as modified by Appendix C.
- Element 2: The  $K_{\text{applied}}$  calculation and the associated crack growth evaluation is in accordance with Appendix C.
- Element 3: The driving force for the final flaw after crack growth is  $\sigma_m + \sigma_b + \sigma_e/SF_b$ , where  $\sigma_m$  is the applied piping membrane stress,  $\sigma_b$  the applied piping bending stress,  $\sigma_e$  the applied piping expansion stress, and  $SF_b$  the structural factor for bending stress, which is defined in Appendix C as 2.3 for Level A, 2.0 for Level B, 1.6 for Level C, and 1.4 for Level D loading conditions.
- Element 4: The failure resistance for the material is  $(\sigma_b^c / SF_b) + (\sigma_m / SF_m)$ , where  $\sigma_b^c$  is the plastic collapse bending stress based on flow stress,  $\sigma_f$ , and  $SF_m$  is the structural factor for membrane stress, which is defined in Appendix C as 2.7 for Level A, 2.4 for Level B, 1.8 for Level C, and 1.3 for Level D loading conditions.
- Element 5: The crack stability is established by comparing the driving force to the failure resistance through the equation:  $Z(\sigma_m + \sigma_b + \sigma_e/SF_b) \leq (\sigma_b^c / SF_b) + (\sigma_m / SF_m)$ , where  $Z$  is an empirically derived factor to represent the elastic plastic fracture behavior of SMAW and SAW welds for austenitic piping and base metals and welds for ferritic piping using the limit load formulas.

For Appendix C limit load analysis, the above five elements remain valid after setting  $Z=1$  and  $\sigma_e = 0$ . For Appendix C LEFM analysis, please refer to Appendix C. Appendix C also provides procedures to determine the mode of failure. Examples using LEFM and conventional EPFM approaches will be discussed below for the evaluation of postulated flaws.

### 3.2 FLAW EVALUATION METHODOLOGIES BASED ON POSTULATED FLAWS

A flaw evaluation for postulated flaws normally starts with an assumed initial flaw size (Element 1), but without a crack growth evaluation (Element 2). Consequently, flaw sizing has been replaced by flaw assumptions, and there is no distinction between initial and final flaw sizes. The remaining flaw evaluation for postulated flaws is, however, exactly the same as that for detected flaws, as described in Elements 3, 4, and 5 above. Examples of this kind of evaluation are the P-T limit analysis, the low USE equivalent margins analysis, and the out-of-limit condition analysis. These analyses are discussed here because they provide assessments of margins of safety required for certain components of the reactor coolant pressure boundary during normal, upset, emergency, or faulted operation. The differences among these methodologies usually occur in three areas: (1) the assumed crack geometry (Element 1) under Level A, B, C, or D loading conditions, (2) the driving force (Element 3) and failure resistance (Element 4) of the failure mode involved, and (3) the failure criteria with the ASME Code-specified structural factors (Element 5) under these loading conditions. The P-T limit analysis and the low USE equivalent margins analysis originated from operational concerns. The out-of-limit condition analysis originated from a concern over unanticipated operating events.

#### 3.2.1 The ASME Code, Section XI, Appendix G Methodology

The ASME Code, Section XI, Appendix G methodology, as modified by Appendix G to 10 CFR Part 50, is the underlying methodology for establishing the P-T limits in an operating plant's technical specifications (TS) or pressure-temperature limits report (PTLR). The 10 CFR, Part 50, Appendix G methodology relies on the embrittlement estimation methodology of RG 1.99, Rev. 2 [5] to determine the reference temperature,  $RT_{\text{NDT}}$ , to account for the effect of neutron radiation. The RPV beltline neutron fluence is determined in accordance with RG 1.190, "Calculational and Dosimetry Methods for Determining Pressure Vessel Neutron Fluence." Once  $RT_{\text{NDT}}$  is determined, the  $K_{\text{IC}}$  can be determined from the  $K_{\text{IC}}$  curve in ASME Code, Section XI, Appendix G for further evaluation.

Since the RPV structural integrity during heatup and cooldown, especially at the low temperature region, is the primary concern of 10 CFR, Part 50, Appendix G, cleavage fracture is the dominant fracture process for the material. Consequently, LEFM with  $K_{\text{applied}}$  as the driving force and  $K_{\text{IC}}$  as the fracture resistance will be used here. Originally,  $K_{\text{Ia}}$  was used as fracture resistance in the Appendix G methodology. In

1999, the NRC approved the first use of ASME Code Case N-640, which proposed the use of  $K_{IC}$ , instead of  $K_{Ia}$ , as fracture resistance in the P-T limit calculations. This ASME Code Case was later combined with two other ASME Code Cases to become ASME Code Case N-641, and finally the use of  $K_{IC}$  was formally incorporated into Appendix G in the 2001 Edition through the 2003 Addenda of the ASME Code.

The unique features of the ASME Code, Section XI, Appendix G methodology under Level A and B conditions can be summarized as follows:

- Element 1: The postulated flaws are assumed to be a semi-elliptical surface flaw with a depth of one-fourth of the RPV wall and a length of six times the depth which are located at the inner and outer surface of the RPV.
- Element 2: (Crack growth evaluation is not required.)
- Element 3: The driving force for the postulated flaw is  $K_{applied}$  in accordance with Appendix G to Section XI of the ASME Code.
- Element 4: The fracture resistance for the material is  $K_{IC}$  in accordance with Appendix G to Section XI of the ASME Code as indexed by  $RT_{NDT}$ .
- Element 5: In LEFM, crack initiation is the only failure criterion concerning structural integrity. Crack initiation is established by comparing the driving force to the fracture resistance through the equation:  $K_{applied} < K_{IC}$ , where a structural factor of 2 is used for the contribution due to pressure loading and a structural factor of 1 is used for the contribution due to thermal loading in the  $K_{applied}$  calculation.

Under Level C and D conditions, the ASME Code provides no guidelines and recommends evaluation on an individual case basis.

### 3.2.2 The Equivalent Margins Analysis for Low USE RPV Materials

Although 10 CFR Part 50, Appendix G permits using analysis to demonstrate that "lower values of Charpy upper-shelf energy will provide margins of safety against fracture equivalent to those required by Appendix G of Section XI of the ASME Code," the specifics of this analysis had never been completely defined until the issuance of Draft Guide (DG)-1023 [6] in August 1993. The final form of DG-1023 was published in June 1995 as RG 1.161 [7]. In the same time frame, the NRC staff asked the ASME to develop criteria for the equivalent margins analysis. This action led to the issuance of Appendix K, "Assessment of Reactor Vessels with Low Upper Shelf Charpy Impact Energy Levels," to Section XI in the 1995 Edition of the ASME Code. The staff reviewed the Appendix K methodology and found it technically acceptable but not complete. As a result, RG 1.161 adopted the Appendix K methodology but supplemented it by providing guidance on the selection of transients and material properties. Currently, the NRC staff relies on RG 1.161 to conduct its review of equivalent margins analysis for low USE RPV materials.

In this evaluation, ductile tearing is the dominant fracture process for the material, and EPFM and its specific analysis parameters are used. The unique features of the RG 1.161 methodology are summarized below for different loading conditions because RG 1.161 specifies different crack geometries and structural factors according to the loading conditions.

Under Level A and B Conditions:

- Element 1: The postulated flaw is assumed to be a semi-elliptical surface flaw with a depth of one-fourth of the component section thickness and a length of six times the depth which is located at the inner surface of the RPV.
- Element 2: (Crack growth evaluation is not required.)
- Element 3: The driving forces for the postulated flaw are  $J_{applied}$  and  $\partial J_{applied} / \partial a$  at the intersection of  $J_{applied}$  and  $J_{material}$  in accordance with RG 1.161.
- Element 4: The fracture resistances for the material is  $J_{0.1}$  (the  $J_{material}$  at a crack extension of 0.254 centimeter [0.1 inch]) and  $\partial J_{material} / \partial a$  at the intersection of  $J_{applied}$  and  $J_{material}$  in accordance with RG 1.161. The RG requires a margin factor be applied to the generic

mean J-R curve to reflect the mean minus 2 times the standard deviation curve for these loading conditions.

- Element 5: In EPFM, in addition to crack initiation, crack stability is also a structural integrity concern. Crack initiation is addressed by comparing the driving force to the fracture resistance through the equation:  $J_{\text{applied}} < J_{0.1}$ , where a structural factor of 1.15 is applied to pressure and 1 to thermal loading in the calculation of  $J_{\text{applied}}$ . Crack stability is established by requiring  $\partial J_{\text{applied}} / \partial a < \partial J_{\text{material}} / \partial a$  at  $J_{\text{applied}} = J_{\text{material}}$ , where a structural factor of 1.25 is applied to pressure and 1 to thermal loading in the calculation of  $J_{\text{applied}}$ .

#### Under the Level C Condition:

- Element 1: The postulated flaw is assumed to be a semi-elliptical surface flaw with a depth up to one-tenth of the component section plus cladding thickness and a length of six times the depth which is located at the inner surface of the RPV.
- Element 5: Same crack initiation criterion  $J_{\text{applied}} < J_{0.1}$ , but with a structural factor of 1 applied to both pressure and thermal loading in the calculation of  $J_{\text{applied}}$ . Likewise, same crack stability criterion  $\partial J_{\text{applied}} / \partial a < \partial J_{\text{material}} / \partial a$  at  $J_{\text{applied}} = J_{\text{material}}$ , but with a structural factor of 1 applied to both pressure and thermal loading in the calculation of  $J_{\text{applied}}$ .

Elements 2, 3 and 4 under the Level C condition are the same as those under Level A and B conditions.

#### Under the Level D Condition:

The postulated flaw geometry is the same as for the Level C loading condition. However, since crack initiation is assumed to have occurred, only the crack stability criterion is required to be met. RG 1.161 uses  $\partial J_{\text{applied}} / \partial a$  based on the same  $J_{\text{applied}}$  calculation as for the Level C loading condition. However, no margin factor is required to be applied to the mean J-R curve.

In a typical review of an equivalent margins analysis, the staff will determine whether the submitted analysis is in accordance with RG 1.161 by focusing on how the licensee's evaluation (1) addresses the special features discussed above for Levels A, B, C, and D loading conditions, (2) determines the limiting loading conditions so that a detailed analysis need not be performed for other loading conditions, (3) determines the J-R curve using a generic approach, and (4) projects USE energy so that the applicability of the equivalent margins analysis can be assessed.

## 4 DISCUSSION ON SOME OBSERVATIONS

In Section 3 of this paper, the authors presented ASME Code flaw evaluation methodologies using LFM, EPFM, and limit load analysis in the format of five technical elements. In Section 4.1 of this paper, ASME Code, Section XI, Appendix A will be discussed at the same level of detail as the methodologies presented in Section 3 when the authors discuss the differences in ASME Code treatment of detected and postulated flaws. Section 4.2 will discuss the differences between two EPFM approaches: the  $J_{\text{applied}}$  and J-R approach, and the J-tearing modulus (J/T) approach. However, to avoid unnecessary repetition, ASME Code, Section XI, Appendix E and Appendix L, "Operating Plant Fatigue Assessment," are listed in Table 1 with limited discussion here. Appendix L uses a flaw tolerance evaluation as an alternative to a fatigue usage factor evaluation. Therefore, by definition, it includes fatigue crack growth analysis. Actually, the flaw tolerance evaluation of Appendix L is the only flaw evaluation based on postulated flaws which considers crack growth. The NRC staff has not endorsed the use of Appendix L because: (1) the assumption of the initial flaw size may not be conservative, and (2) the crack growth rate is not based on the latest environmental crack growth rate data. The ASME is in the process of resolving these two NRC concerns.

### 4.1 Differences in ASME Code Treatment of Detected and Postulated Flaws

So far, flaw evaluation methodologies, applicable to detected flaws and postulated flaws in nuclear plant SSCs, have been presented as separate issues, each having its own characteristics. However, it is worthwhile to examine these differences and the basis for these differences to appreciate the ASME Code philosophy in dealing with detected and postulated flaws in the same nuclear plant SSCs. To highlight the conceptual differences, let us take a closer look at the five elements of the ASME Code, Section XI, Appendix A and Appendix G methodologies (both are applicable to RPVs):

- Element 1: The Appendix A methodology is based on NDE characterized flaw geometry while the Appendix G methodology is based on an assumed flaw geometry.
- Element 2: The Appendix A methodology requires crack growth evaluation based on  $K_{\text{applied}}$  formulas specified in the appendix while the Appendix G methodology requires no crack growth evaluation.
- Element 3: The driving force  $K_{\text{applied}}$  in the Appendix A methodology is based on results derived from a series of finite element RPV models and considers pressure, thermal, cladding-induced, and residual stresses while the driving force  $K_{\text{applied}}$  in the Appendix G methodology is based on much simpler equations and considers only pressure and thermal stresses, though formulas for the thermal  $K_{\text{applied}}$  with an accuracy comparable to Appendix A are provided as an option in Appendix G.
- Element 4: The Appendix A methodology considers  $K_{Ia}$  as the material's fracture resistance for normal conditions and  $K_{IC}$  as the material's fracture resistance for emergency and faulted conditions while the Appendix G methodology considers  $K_{IC}$  as the material's fracture resistance for normal conditions. The Appendix G methodology provides no guidelines for emergency and faulted conditions.
- Element 5: The Appendix A methodology specifies a structural factor of 3.16 for all loading while the Appendix G methodology specifies a structural factor of 2 for pressure and 1 for thermal in examining the initiation criterion equation:  $K_{\text{applied}} < K_{IC}$ .

From this example, it is obvious that the ASME Code imposes a more rigorous LEFM approach and uses a larger structural factor for the Appendix A methodology for a detected flaw than that for a postulated flaw.

Further, the Appendix A methodology for a detected flaw goes beyond the Appendix G methodology for a postulated flaw by considering (1) the time effect through a fatigue crack growth evaluation; (2) the secondary loading such as cladding-induced and residual stresses; and (3) a flaw evaluation for emergency and faulted conditions. This ASME Code philosophy is discernable in other methodologies involving detected flaws and postulated flaws. Since detected flaws are real, confirmed flaws, more rigorous evaluation processes are needed to simulate the situation as close to reality as possible. More stringent requirements such as structural factors are also needed to account for unexpected material degradation and loading.

Attempts have been made to apply selective elements of the methodologies for postulated flaws to detected flaws in SSCs, especially in the area of structural factors. The NRC will consider a proposal of this type only if it is component-specific and includes a comprehensive analysis of extensive, industry-wide operating data regarding the component, because the structural factors are derived largely from engineering experience. The advance of LEFM, EPFM, and limit load methodologies and thermal and structural finite element analyses can provide justification for reducing structural factors. However, these benefits have been somewhat negated by unexpected material degradation mechanisms such as PWSCC.

## 4.2 Differences in the EPFM $J_{\text{applied}}$ and J-R Approach and the J/T Approach

So far, the staff has reviewed and approved applications using either the  $J_{\text{applied}}$  and J-R approach or the J/T approach when EPFM is used. Likewise, the ASME Code accepts both methods for an EPFM analysis. For instance, Appendix K of Section XI lists the former in K-4310, "J-R Curve – Crack Driving Force Diagram Procedure" and the latter in K-4330, "J-Integral/Tearing Modulus Procedure." For the J/T approach, the point of instability is the intersection of the applied J/T curve and the material J/T curve, or  $J_{\text{applied}} = J_{\text{material}}$  and  $T_{\text{applied}} = T_{\text{material}}$ , where  $T_{\text{applied}}$  and  $J_{\text{material}}$  are defined as:

$$T_{\text{applied}} = (dJ_{\text{applied}}/da)(E/\sigma_f^2), \text{ and } T_{\text{material}} = (dJ_{\text{material}}/da)(E/\sigma_f^2).$$

According to the definitions, it is clear that at the point of instability (i.e.,  $J_{\text{applied}} = J_{\text{material}}$  and  $T_{\text{applied}} = T_{\text{material}}$ ),  $dJ_{\text{applied}}/da = dJ_{\text{material}}/da$ , or equivalently that instability will not occur if  $dJ_{\text{applied}}/da < dJ_{\text{material}}/da$ . Hence, as far as the instability criterion is concerned, the  $J_{\text{applied}}$  and J-R approach and the J/T approach are identical. However, this is not true for the other acceptance criterion in the two approaches. Specifically, the  $J_{\text{applied}}$  and J-R approach in RG 1.161 specifies  $J_{0.1}$  as the material parameter for controlling the onset of stable crack extension, which, by definition, occurs after crack initiation. The J/T approach, which is often used in piping applications, uses  $J_{Ic}$  [3] as the material parameter for controlling crack initiation, which defines one end of the material J/T curve.

## 5 AN EMERGING ISSUE: PWSCC

In pressurized water reactors (PWRs), PWSCC of Inconel 600 was first reported in steam generator tubing, but now has occurred in piping welds, RPV vessel head penetration nozzles, RPV upper and lower head instrumentation penetration nozzles, and pressurizer heater penetrations and instrument line penetrations.

Operating experience has demonstrated that Alloy 82/182/600 materials exposed to primary coolant water (or steam) at the normal operating conditions of PWR plants have cracked due to PWSCC. The NRC has previously issued generic communications regarding the emergence of this phenomena, and its consequential effects, in other areas of PWR primary systems.

Information Notice 90-10, dated February 23, 1990, addressed the occurrence of PWSCC in pressurizer heater penetrations and instrument nozzles that occurred at Calvert Cliffs, Unit 2 in 1989. NRC Generic Letter 97-01, dated April 1, 1997, discussed the degradation of the RPV CRDMs as a result of PWSCC. NRC Bulletin 2001-01 required all PWRs to provide past inspection results and plans for future inspections of the RPV head penetration nozzles due to the discovery of axial cracks at Oconee, Unit 1 in 2000 and Arkansas Nuclear One, Unit 1 in 2001. NRC Bulletins 2002-01 and 2002-02 also identified the occurrence of through-wall cracking in a RPV head penetration nozzle at Davis-Besse that resulted in a large cavity in the RPV head due to boric acid corrosion. NRC Bulletin 2003-02 discussed the occurrence of PWSCC in the RPV bottom head instrumentation penetrations at the South Texas Project, Unit 1 which prompted the bare metal visual inspection of all RPV bottom head penetrations. In addition, Bulletin 2004-01 documented the most recent occurrences of PWSCC at Millstone, Unit 2, and Waterford, Unit 3 in 2003, and at Palo Verde, Unit 3 in 2004.

For CRDM penetrations, the NRC issued flaw evaluation guidelines in 2003, which modify an earlier version issued in 2001. As expected, the evaluation guidelines can be characterized by five elements:

- Element 1: The NDE characterized length and depth is in accordance with IWA-3000.
- Element 2: The  $K_{\text{applied}}$  calculation is based on the work of Raju and Newman [8], and the associated PWSCC crack growth evaluation is in accordance with Appendix O to Section XI of the ASME Code, which is the same as that in MRP-55, "Crack Growth Rates for Evaluating Primary Water Stress Corrosion Cracking (PWSCC) of Thick-Wall Alloy 600 Material (MRP-55)."
- Element 3: The driving force for the final flaw after crack growth is the final flaw size, which is a key parameter in determining  $K_{\text{applied}}$  or  $J_{\text{applied}}$  that we discussed in previous Sections.
- Element 4: The failure resistance for the material is the allowable flaw size as defined in the NRC evaluation guidelines, which is almost the same as that in Appendix O to Section XI of the ASME Code.
- Element 5: The time for continued operation is established by setting the calculated final flaw size to the allowable flaw size.

Several licensees have utilized the NRC guidelines to manage axial flaws discovered in the CRDM penetration nozzles, and many licensees have employed some of these elements in justifying relaxation from Order EA-03-009, "Issuance of Order Establishing Interim Inspection Requirements for Reactor Pressure Vessel Heads at Pressurized Water Reactors."

For penetration welds, due to their much higher PWSCC crack growth rate, the staff position is not to determine the acceptability of detected flaws in welds through flaw evaluations, but to fix the problem

through repairs and replacements. Many nuclear power plant facilities have repaired the penetration leakage using methods such as the half-nozzle repair. This repair method relocates a small portion of the pressure boundary from the leaking nozzle's J-groove weld to a new weld buildup along the nozzle, and leaves the through-wall cracks in the J-groove weld intact, necessitating a need to conduct a flaw evaluation for the through-wall cracks left in the J-groove weld. The flaw evaluation which supplements the half-nozzle repair usually bypasses the flaw characterization of Element 1 by assuming that the crack is the maximum that could exist in the penetration weld. Consequently, only fatigue crack growth into the low alloy steel shell needs to be considered in Element 2 of the flaw evaluation.

## 6 CONCLUSIONS

There are many flaw evaluation methodologies available to use for various applications that are either based on detected flaws or postulated flaws. Typical flaw evaluations based on detected flaws include five elements: (1) flaw sizing, (2) a crack growth evaluation, (3) a driving factor such as  $K_{\text{applied}}$  or  $J_{\text{applied}}$ , (4) a failure resistance evaluation considering embrittlement such as  $K_{\text{IC}}$  and the J-R curve, and (5) failure criteria using an ASME Code specified structural factor. Examples of flaw evaluation methodologies that are based on detected flaws include ASME Code, Section XI, Appendix A for RPV flaws, Appendix C for piping flaws, and Appendix O for RPV upper head penetration nozzles. Flaw evaluation methodologies based on postulated flaws are similar to those based on detected flaws except that the initial flaw size (Element (1)) is assumed instead of being sized by an examination method, and there is no crack growth evaluation as in Element (2). Examples of these methodologies include ASME Code, Section XI, Appendix G for the P-T limits analysis, RG 1.161 for low USE equivalent margins analysis, and ASME Code, Section XI, Appendix E for the out-of-limit condition analysis. These flaw evaluation methodologies were discussed in this paper with respect to the five elements so that the distinctive features of each methodology can stand out. In general, more rigorous evaluation requirements are imposed as well as larger structural factors for detected flaw based evaluation methodologies in order to better simulate each particular situation based on the component geometry, actual crack shape, anticipated or bounding loading, and identified degradation mechanisms. Repairs to components that leave an existing flaw intact are increasingly being used due to emerging degradation mechanisms such as PWSCC. These emerging degradation mechanisms will introduce the need for new analysis parameters that necessitate adapting new methodologies or revising current methodologies. For example, Appendix O is a new addition to the 2004 Edition of the ASME Code for evaluation of PWSCC in RPV upper head penetration nozzles.

## 7 ACKNOWLEDGMENT

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Table 1 Summary of Key Parameters for Flaw Evaluation Methodologies

		Driving Parameter	Resisting Parameter	Assumed Crack Shape			Structural Factors				
				Level A and B Service Loading	Level C and D Service Loading	Out-of-Limit Loading	Level A and B Service Loadings		Level C Service Loading	Level D Service Loading	Out-of-Limit Loading
							Press	Therm	Press & Therm	Press & Therm	Press & Therm
RG. 1.161 Methodology	Criterion 1	Applied J	$J_{0.1}$	Semi-elliptical surface flaw (D:1/4T L:6D)	Semi-elliptical surface flaws up to (D:1/10T + $T_{clad}$ L:6D)	N/A	1.15	1	1	N/A	N/A
	Criterion 2	Applied J slope	J-R curve slope				1.25	1	1	1	
ASME Appendix A Methodology	Criterion 1	Applied K (Include residual and cladding stresses)	$K_{Ia}$	N/A for detected flaws			$\sqrt{10}$	$\sqrt{10}$	N/A	N/A	N/A
			$K_{Ic}$				N/A	N/A	$\sqrt{2}$	$\sqrt{2}$	
ASME Appendix C Methodology for circumferential flaws	Limit Load Criterion	$\sigma_m + \sigma_b$	$\sigma_b^c/SF_b + \sigma_m/SF_m$	N/A for detected flaws			SF <sub>b</sub> for bending stress				
							2.3	2.0	1.6	1.4	N/A
	EPFM Criterion	$Z(\sigma_m + \sigma_b + \sigma_e/SF_b)$	$\sigma_b^c/SF_b + \sigma_m/SF_m$				SF <sub>m</sub> for membrane stress				
				2.7	2.4	1.8	1.3	N/A			
	LEFM Criterion	Applied K (Include residual stresses)	$K_c$ (critical fracture toughness /Appendix C)				SF <sub>b</sub> and SF <sub>m</sub> are the same as above SF of 1.0 is applied to $K_r$ for residual stresses				

Continued on the next page

Table 1 Summary of Key Parameters for Flaw Evaluation Methodologies (Continued)

		Driving Parameter	Resisting Parameter	Assumed Crack Shape			Structural Factors				
				Level A and B Service Loading	Level C and D Service Loading	Out-of-Limit Loading	Level A and B Service Loadings		Level C Service Loading	Level D Service Loading	Out-of-Limit Loading
							Press	Therm	Press & Therm	Press & Therm	Press & Therm
ASME Appendix E Methodology	Criterion 1	Applied K (Include residual stress)	$K_{Ic}$	N/A	N/A	Semi-elliptical surface (D:0 to 2.54cm [1 inch] L:6D)	N/A	N/A	N/A	N/A	1.4 (1.0 for $K_{Ic}$ due to residual stress)
ASME Appendix G Methodology	Criterion	Applied K	$K_{Ic}$	Semi-elliptical surface (D:1/4T L:6D)	N/A	N/A	2	1	N/A	N/A	N/A
ASME Appendix K Methodology	The staff considers the Appendix K methodology as a subset of the RG. 1.161 methodology										
ASME Appendix L Methodology	Criterion	Those of Appendix A	Semi-elliptical surface (D:1/10T to 3/10T depending on T; L:6D)			N/A		Those of Appendix A			N/A
		Those of Appendix C						Those of Appendix C			
		Those of Appendix H						Those of Appendix H			