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# STRUCTURAL INTEGRITY EVALUATION OF A PWR OUTLET NOZZLE BY AN ADVANCED PFM CODE

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## ABSTRACT

A pressurized water reactor pressure vessel outlet nozzle section is composed of dissimilar welding. This section is usually the most critical failure part susceptible to various degradtion mechanisms, e.g. fatigue and/or stress corrsion cracking. An advanced probabilistic fracture mechanics computer code capable of considering combined aging mechanisms has been developed for an accurate failure analysis of such section. Crack morphology based probabilistic leak flow rate module has also been introduced for more accurate analysis of loss of coolant accident. A benchmarking USNRC analysis based on single failure mechanism has been reinvesitagted by this code. The results show that, contribution of pre-existing cracks in addition to initiating cracks can significantly increase the overall failure probability. Inconel weld location of nozzle section shows the weakest point in terms of relative through-wall leak failure probability in the order of about $10^{-2}$ at the 40-year plant life. Considering whole nozzle section, circumferential direction is prone to cracking rather than axial direction.

**Keywords:** Fatigue, Stress Corrosion Cracking, Combined Aging Failure Mechanism.

## 1. INTRODUCTION

Mechanical structural integrity analysis of a reactor pressure vessel (RPV) hot leg outlet nozzle (ON) section of a pressurized water reactor (PWR) is performed in this study. This hot leg RPV-ON section is usually composed of three dissimilar weld material locations, e.g. low alloy steel, Inconel and stainless steel. In the previous United States Nuclear Regulatory Commission's (USNRC) benchmark study, failure analysis of such a typical weld location was performed using single failure mechanism, i.e. thermal fatigue, based probabilistic fracture mechanics (PFM) code, PRAISE [1]. Only low alloy steel location was considered in that study. But in October 2000, an axial through-wall crack along with a small circumferential crack was discovered on the hot leg nozzle weld section of V. C. Summer Nuclear Station [2]. The objective of this paper is to assess the structural integrity of such a typical weld section considering combined ageing mechanism, i.e. fatigue and/or stress corrosion cracking (SCC) by an advanced PFM code, PINTIN-CAM [3,4].

## 2. DEVELOPMENT OF THE PINTIN-CAM PFM CODE

Probabilistic Fracture Mechanics (PFM) computer code is being used as a tool for determining the leak and break failure probabilities of important structural components, for analyzing the relative risk ranking of particular sections, to investigate the effectivness of different levels and intervals of non-destructive examination methods and for asseing the plant life extension management (PLiM) as a part of the risk-informed regulation (RIR) concept. Several analysis codes such as pc-PRAISE [1], SRRA [5] have been developed to calculate the component failure probability considering the aged condition allowing for factors such as fatigue or stress corrosion growth of either pre-existing or initiating crack in welds under different plant's transients. For example, in the first report, ten numerical examples were presented. All these examples were evaluated by considering single failure mechanism i.e. crack may be grown by fatigue or stress corrosion cracking (SCC) mechanism starting from either pre-existing weld fabrication defect or SCC initiated cracks. In the SRRA approach, the SCC crack initiation was assumed simply as pre-existing fabrication flaw, i.e. one flaw per weld at the start of plant operation.

At KAIST (Korea Advanced Institute of Science and Technology), an advanced PFM analysis computer code named PINTIN-CAM (Piping INTegrity Inner flaws-Combined Aging Mechanisms) has been developed as a continuation of some past works [3, 4].

The code has been designed to assess the integrity of the piping system of a light water reactor (LWR) by considering fatigue and stress corrosion (SCC) cracking phenomenon. The potential failure modes are through wall crack, small or big leak, and break or loss of coolant accidents (LOCA), which may lead to severe accidents. Usually the RCL of a PWR is made of either austenitic stainless steel or cast version of austenitic stainless steel or low alloy steel (LAS) and the surge, spray and branch lines are made of austenitic stainless steels. Usually the nozzle weld areas of connected branch lines to the RCL experiences high fatigue, so these sites must be considered for thermal fatigue degradation mechanism. In case of use of Ni-alloy in the dissimilar metal weld locations (Inconel 82/182 welding wire: similar to Alloy 600; Inconel 52/152 welding wire: similar to Alloy 690) or Alloy 600 instrument penetrations in the reactor coolant piping, primary or pure water stress corrosion cracking (PWSCC) is a major issue.

## 2.1 Integrated PRA and PFM Approach

Probabilistic risk assessment (PRA) is a technical tool that is based on forecasting the frequency and consequences of actual accident events. In-service inspection (ISI) is one of the most important areas of PRAs. Others are in-service testing, quality assurance, technical specifications, maintenance, etc. The development of a user-friendly computer code based on probabilistic fracture mechanics is a key element for the successful implementation of PRA. A flow chart for a PRA model for piping is shown in Fig.1. The flow program starts for performing in-service inspection (ISI) following the existing regulatory requirement. A typical RCL of a present day standard PWR case can be chosen for explanation. At first for risk-informed ISI program, the cause and results of piping failure have to be defined. Several studies show that these failures are dominated by fatigue mechanisms or stress corrosion cracking. Then the RCL system can be divided into various sections (e.g. hot leg, cold leg and cross over leg) depending on these failures' causes and results analysis. Now each section contains several welds and important base metal portions in case of an elbow joints.

After defining the sections of the RCL system, probabilistic failure analysis (PFA) and probabilistic risk assessment (PRA) are done to define the relative risk ranking of the sections.

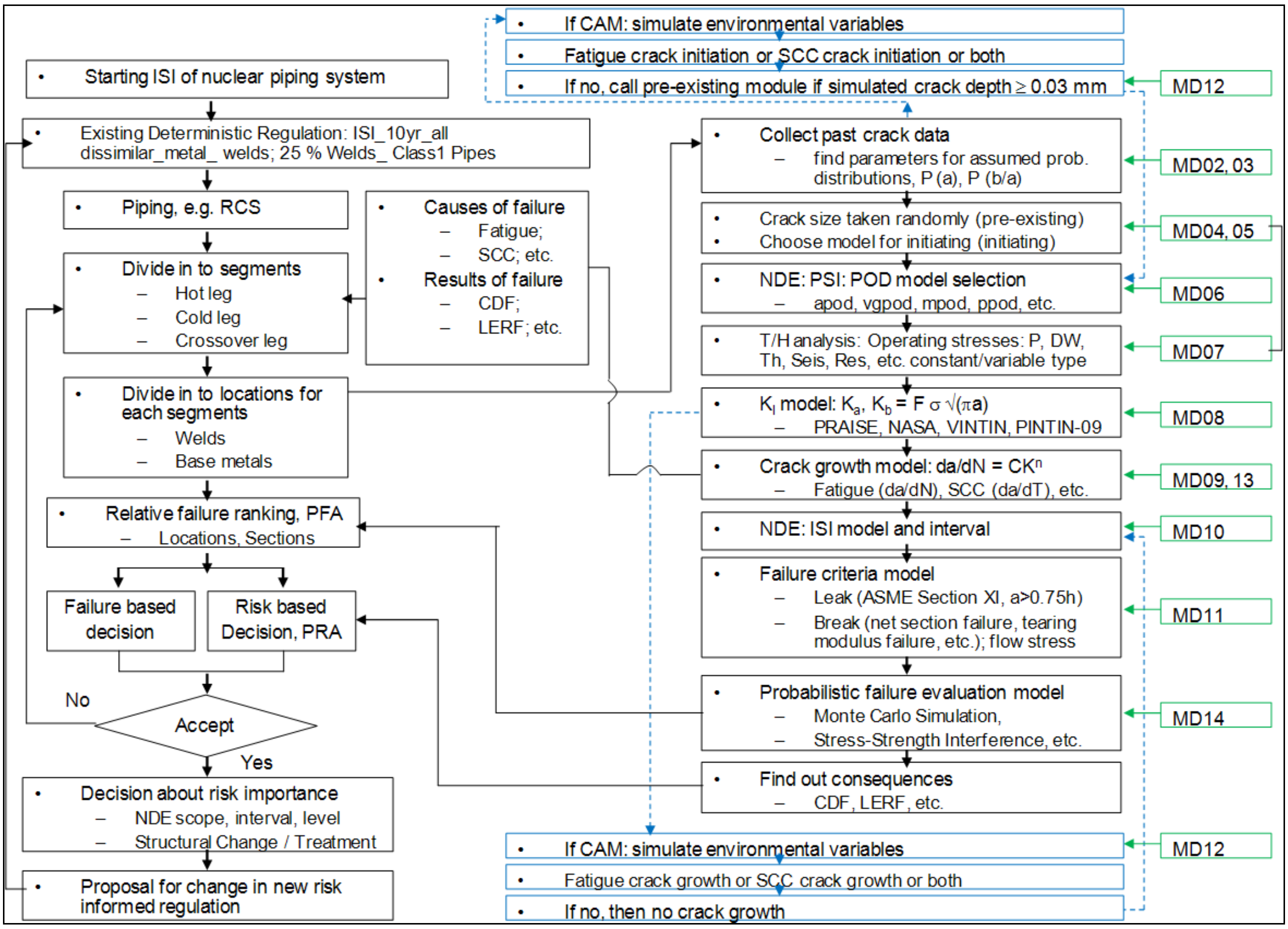

Fig 1. PFM code for the application of PRA

Findings of these analyses can then be used to make new decision about risk importance e.g. inspection methodology, interval or any structural integrity analysis. From this observation, the existing regulation can be revised in to more efficient risk-informed regulation (RIR) concept. The whole process is an iterative procedure. In this point, the PFM code is a helping tool for performing PFA. The right hand side of Fig.1 describes the basic flow chart of this code. Parameters taken in to account as the probability density functions are listed in Table 1. To increase the computational efficiency of Monte Carlo simulations the stratified sampling method has been used in this work.

Table 1: List of probability model used in this PFM code

| **Module No.** | **Module Name** |
|---|---|
| 04, 05 | crack existence probability |
| 02 | depth of a crack |
| 03 | aspect ratio distribution |
| 06,10 | probability of detection |
| 09,13 | fatigue, scc crack growth distribution |
| 11 | probabilistic leak rate detection |
| 14 | weld or base metal location failure |
| 14 | weld or base metal section failure |

## 2.2 Pre-existing Crack Module

The probability of having at least one pre-existing fabrication defect in a circumferential weld volume can be expressed as

$$P(\,) = Vp_v e^{-Vp_v} \sim Vp_v$$
$$V = 2\pi R_i h(2h)\ldots\ldots for\_circumferential\_part$$
$$V = ewl \times h(2h)\ldots\ldots for\_longitudinal\_part$$
$$p_v = cracks\_per\_unit\_volume \qquad (1)$$

where $p_v$ is the cracks per unit weld volume and it was initially suggested as $10^{-4}/in^3$ as a baseline value [6]. The weld volume, V includes the heat-affected zone which is taken to two wall thickness wide. *ewl* is the length of the axial weld or base metal part in case of an elbow which depends on elbow bend radius and bend angle. The probability of having at least one pre-existing fabrication defect in a circumferential weld volume can be expressed as $Vp_v$ where V is the volume of weld metal or base metal parts and $p_v$ is the cracks per unit weld volume and it was used as $10^{-4}/in^3$ for nuclear pipes (diameter: 6~24 in and thickness: 0.28~1.22 in) [7]. It was also found that in a PWR simulated environment within 10% period of life the fatigue crack formation (longer than 20μm) frequency in a Type 316NG stainless steel varies from 8 to 14 number of cracks per 7 mm gauge length [8]. As the MCL of this present study is made of CF8M, (cast version of wrought type 316SS) and the axial crown section of elbow base metal parts are susceptible to fatigue cracking due to combined effect of casting defect and highly stressed (~double of straight pipe stress) [9], so for these elbow base metal locations also, the pre-existing crack density $10^{-4}/in^3$ is assumed as a baseline analysis purpose. The well known Marshall exponential crack depth distribution for primary piping components [10] and the lognormal distribution of half aspect ratio (b/a) [11,12] are used in this analysis.

## 2.3 Probability of Crack Detection Module

The improved probability of detection (POD) input equations were coded from the recently published NUREG/CR-6934 document [13]. Different risk-based non destructive (NDE) ISI performance levels were used. Equation for different ISI program, e.g. advanced performance (APOD), very good performance (VGPOD), and marginal performance (MPOD) is as follows:

$$POD = 1 - P_{ND} = 1 - \left[\varepsilon + \frac{1}{2}(1-\varepsilon)\,\mathrm{erfc}\left\{\nu.\ln\left(\frac{A}{A^*}\right)\right\}\right] \qquad (2)$$

Where, POD: probability of detection, $P_{ND}$: probability of non-detection, ε: the smallest possible probability of non-detection for very large cracks, ν: slope of non-detection probability function at 50% $P_{ND}$, A : crack area and A*: crack area at 50% $P_{ND}$.

## 2.4 Stress Intensity Factor

The fracture mechanics parameter used in the crack growth analysis is the stress intensity factor (SIF) range (ΔK). For wide ranges of flaw shape and depth, or aspect ratio (2b/a) of 2.0 (semi-circular) to infinite and for normalized depth (a/h) of 0 to 1 the influence coefficients, $G_i$ were taken from [14].

$$K_1 = \left[\sigma_0 G_0 + \sigma_1 G_1\left(\frac{a}{t}\right) + \sigma_2 G_2\left(\frac{a}{t}\right)^2 + \sigma_3 G_3\left(\frac{a}{t}\right)^3\right]\sqrt{\frac{\pi a}{Q}} \qquad (3)$$

For comparison purpose, the pc-PRAISE's rms $K_I$ and NASA/FLAGRO $K_I$ equations are also coded from [6, 15].

## 2.5 Weld Location Failure Module

Monte Carlo Method: *M* : total number of cells, $N_m$ : number of samples from the m-th cell, $N_{F,m}(t)$ : samples taken from the m-th cell, $p_m$ :probability of an initial crack of the m-th cell.

$$P(t_f \le t) = \sum_{m=1}^{M} \frac{N_{F,m}(t)}{N_m} p_m \qquad (4)$$

## 2.6 Weld Section Failure Module

$$P_{f\_section} = 1 - (1 - P_{f\_1})(1 - P_{f\_2})\ldots\ldots\ldots \times (1 - P_{f\_n}) \qquad (5)$$

Where, $P_f$ :the failure probability ($P_f$ <<1.0) of each weld or base metal location.

## 3. A CASE STUDY: RPV ON SECTION

Figure 2 represents a RPV ON section, taken for this paper and input data for structural integrity analysis are presented in Table 2.

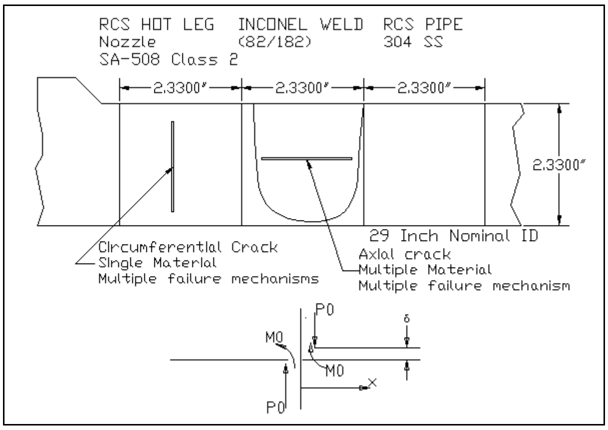

Fig 2. RPV ON section

Table 2: Inputs for RPV ON section analyses [1]

| Input Options | |
|---|---|
| Location and material: | RPV ON, (SA508 Cl.2+Alloy 182+304SS) |
| Pipe Geometry: $R_i$, h | 304.8, 76.2 mm (12, 3 inch) |
| Failure Mech. : | Single, combined mode |
| Small, Big Leak Threshold | 113.56, 892.7 liter/minute (30, 500 gpm) |
| Crack profile | Circumferential, axial |
| Operating Temperature | 590°F (310°C) |
| Operating Pressure | 15.51 MPa (2250 psi) |
| Deadweight | 14.34 MPa (2.08 ksi) |
| Load Pairs' data: | Pair No. ksi, num/yr |
| Loss of secondary pres/hydro | 1. 74.460, 0.125 |
| Hydrotest A/Hydrotest B | 2. 38.460, 0.125 |
| Heatup/loss of load | 3. 32.410, 1 |
| Heatup/loss of flow | 4. 31.730, 1 |
| Heatup/cooldown | 5. 31.530, 10.5 |
| Cooldown/plant loading | 6. 29.700, 2 |
| Reactor Trip/plant loading | 7. 25.830, 10 |
| Reactor trip/plant unloading | 8. 23.790, 363 |
| Residual stress | 200 MPa (29ksi) (max. at inner surface) |
| Crack Depth, Aspect Ratio | Exponential, Lognormal |
| Pre-existing crack density | 6.1/$m^3$ (base line value) |
| SCC Initiating crack | 1/circumferential or axial length (base) |
| Fatigue constant (SS) | $9.14x10^{-12}$ [growth rate; in/cycle] |
| Fatigue exponent (SS) | 4 |
| Fatigue constant (LAS) | $1.03x10^{-12}$ [growth rate; in/cycle] |
| Fatigue exponent (LAS) | 5.95 |
| Fatigue constant (Inconel) | $9.00x10^{-10}$ [growth rate; in/cycle] |
| Fatigue exponent (Inconel) | 3.2421 |
| SCC constant (SS) | $1.72x10^{-09}$ [growth rate; in/hr] |
| SCC exponent (SS) | 2 |
| SCC constant (Inconel) | $5.276x10^{-11}$ [growth rate; in/sec] |
| SCC exponent (Inconel) | 1.64 |
| Sample Space | 100x100x100 |

#for PWR case, SCC is treated as PWSCC situation for Alloy182 material.

## 4. RESULTS AND DISCUSSION

The PINTIN-CAM PFM code was run for each location of the RPV ON weld section by considering both single and combined aging failure mechanisms to find out the relative risk ranking of each location. The code was also run for the whole weld section by considering axial and circumferential crack profile to find out the directional failure sensitiveness. The results are discussed in the following sections.

### 4.1 Low Alloy Steel Location: Single Failure Mechanism

Figure 3 shows the cumulative failure probability results of low alloy steel location only by considering the single failure mechanism, i.e. fatigue crack growth of fatigue initiated cracks. No pre-existing weld fabrication defects are considered here. Only circumferential crack profile is considered here. This study is carried out here to find out the similar failure trend as observed in past study [1]. Although fatigue crack initiation starts from the very beginning of the plant life, but the actual through wall crack (TWC) starts at 15 years of plant life and gradually increases up to $10^{-5}$ per weld location at the end of plant life. There is a possibility of small leak (30 gpm) during the last 10 years of plant life. Of course there is no possibility of big leak (500 gpm) or loca (complete break) for this location during the entire lifetime.

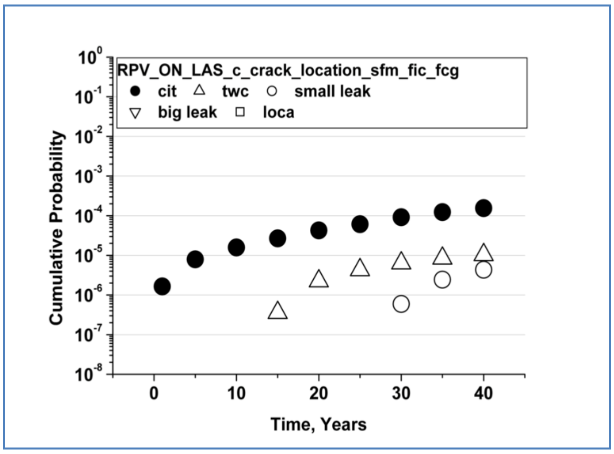

Fig 3. Low alloy steel: Single failure mechanism

### 4.2 Low Alloy Steel Location: Combined Failure Mechanism

To find out the contribution of the pre-existing weld fabrication defects, the same case (section 4.1) is reinvestigated by applying the combined failure mechanism module of this code and results are shown in figure 4.

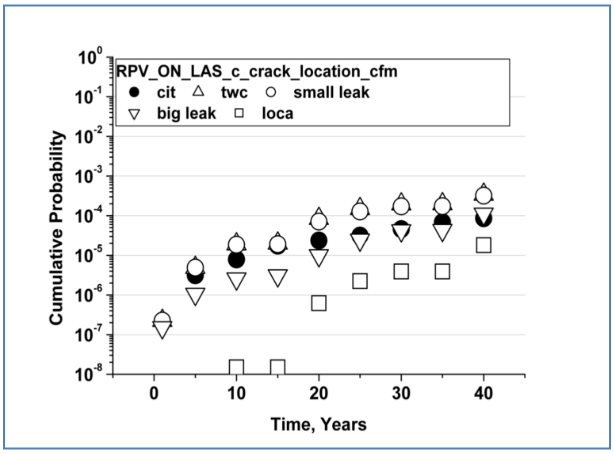

Fig 4. Low alloy steel: Combined failure mechanism

The presence of such defects can significantly increase the through wall crack and hence the small leak failure probability on the order of $10^{-3}$ per weld location at the end of plant life. Pre-existing defects can also contribute to big leak or even loca failure possibilities. So, care must be taken for pre-service inspection as a part of non destructive examination (NDE) to eliminate the pre-existing weld flaws as much as possible.

### 4.3 Inconel Location: Combined Failure Mechanism

Now this combined failure mechanism module has been applied for Inconel weld location of this whole RPV ON section to find out the relative risk sensitiveness. Both fatigue and/or primary water stress corrosion crack (PWSCC) growth of pre-existing cracks, fatigue initiated cracks and SCC initiated cracks are considered. Significant increase of either TWC or small leak is found on the order of $10^{-2}$ at the end of plant life. PWSCC phenomenon might cause significant contribution for both crack initiation and subsequent growth of those initiated cracks.

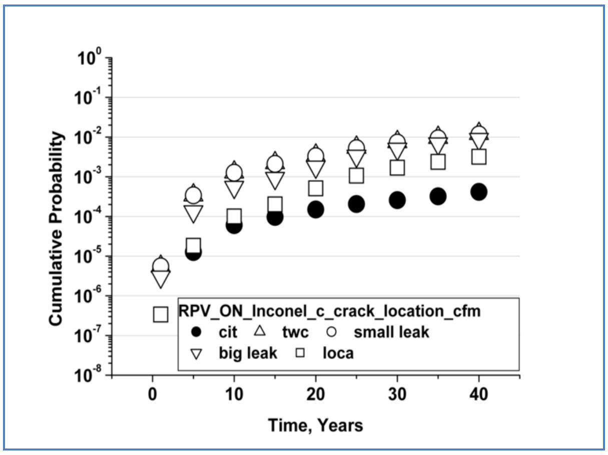

Fig 5. Inconel: Combined failure mechanism

### 4.4 Stainless Steel Location: Combined Failure Mechanism

Figure 6 shows the combined failure probabilities of stainless steel weld location.

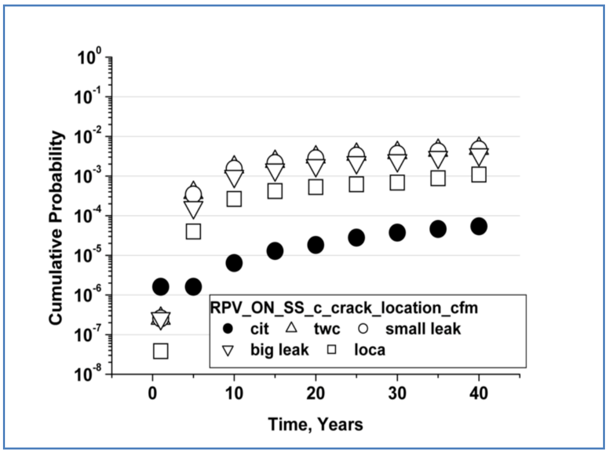

Fig 6. Stainless steel: Combined failure mechanism

The failure probabilities of this location increase for the first 20 years of plant life and remain steady for the last 20 years of plant life. However the final failure probability remains below the $10^{-2}$ per weld line.

### 4.5 RPV ON Section: Directional Sensitivity

Now the combined failure mechanism module is run for the whole RPV ON weld section by considering the circumferential and axial crack profiles to find out the directional failure sensitiveness. From the Fig. 7 and 8, it can be concluded that this section is more susceptible in circumferential direction rather than in longitudinal direction.

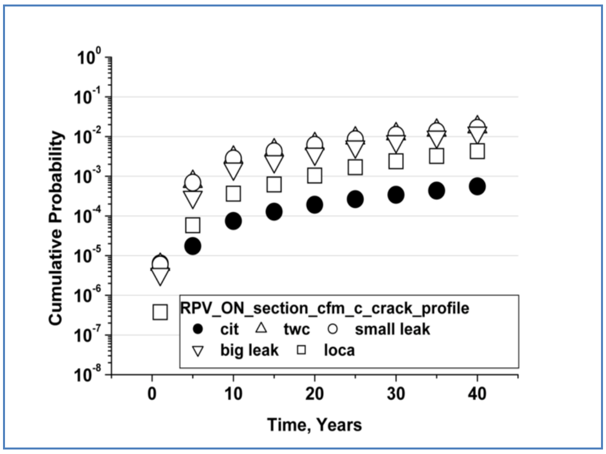

Fig 7. Whole Section: Circumferential direction

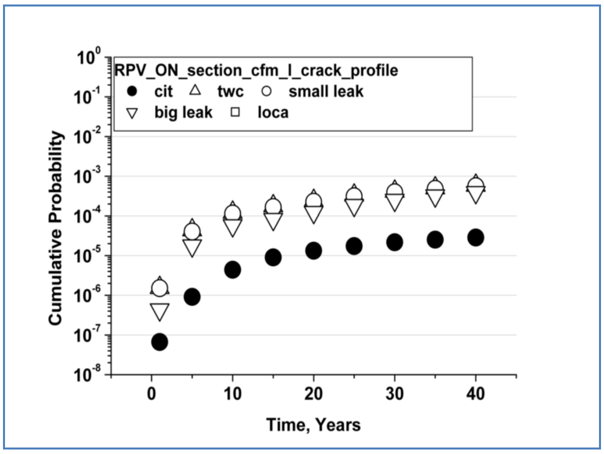

Fig 8. Whole Section: Axial direction

## 5. CONCLUSION

In this paper, a PRA model for a RPV ON weld section was suggested and a PFM code was developed for structural integrity analysis and a relative risk ranking of all the test locations were done. Thereby, the following key findings have been obtained;

(1) The pre-existing weld fabrication flaws have a significant contribution to overall failure probabilities.

(2) Inconel weld location can be considered as the weakest part in RPV outlet nozzle section. Relative failure sensitiveness of locations: Inconel>SS>LAS.

(3) The total section failure probability is in the order of about 2x$10^{-2}$ per weld in circumferential direction. It can be concluded, that in terms of failure probability, the RPV outlet nozzle is relatively more sensitive in the circumferential direction rather than in the axial direction.

## 6. ACKNOWLEDGMENTS

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## 8. NOMENCLATURE

| Symbol | Meaning | Unit |
|---|---|---|
| $a$ | crack depth normalized to the thickness of the pipe | |
| $b$ | crack half length normalized to the thickness of the pipe | |
| $ewl$ | length elbow axial base metal | (mm) |
| $gpm$ | leak flow rate in gallons per minute | (gpm) |
| $h$ | thickness of pipe | (mm) |
| ISI | in-service inspection | |
| $K$ | stress intensity factors | (mpa√m) |
| $K_I$ | mode I applied stress intensity factor at the crack tip | (mpa√m) |
| $P(F/E)$ | conditional pipe failure probability | |
| $P(E)$ | sequence frequency | |
| $p_v$ | number of cracks per unit volume | |
| $POD$ | probability of detection | |
| PSI | pre-service inspection | |
| $V$ | weld or base metal volume of interest | ($m^3$) |

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