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# FAILURE PROBABILITY ASSESSMENT OF A PWR PRIMARY SYSTEM PIPING SUBCOMPONENTS UNDER DIFFERENT LOADING CONDITIONS

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## **Abstract**

The integrity of the primary piping system of pressurized water reactors must be maintained during the plant lifetime. For the integrity analysis, credible structural analyses methodologies including fracture mechanics approach, etc., are required. Conventional deterministic approaches are being widely used for this purpose, but known to have many inherent uncertainties to encumber a coherent assessment. In this respect, probabilistic methodologies are considered as an alternative and appropriate technique for the structural integrity analysis of reactor piping system. In the nuclear reactor piping system, elbows were reported to be among the most highly stressed piping components. This requires an extensive flaw evaluation of these components. The objectives of this paper are to evaluate the fatigue failure probabilities of various subcomponents in a nuclear reactor primary system and to evaluate the relative risk ranking among them. For this purpose, a probabilistic fracture mechanics code using Monte Carlo simulation techniques was developed by incorporating both circumferential and longitudinal crack module. The developed code was used to calculate the fatigue failure probabilities due to small leak, big leak and LOCA situations subjected to all possible loadings. Finally, the effect of reduced inservice inspection interval on the failure probability was evaluated.

## **1. INTRODUCTION**

The structural integrity analysis of nuclear power plant piping system is of great concern as the both primary and secondary piping goes through several ageing mechanisms e.g. thermal fatigue, vibrational fatigue, thermal ageing, primary water stress corrosion cracking, boric acid corrosion, etc. Thermal fatigue is the major ageing mechanism particularly for surge, spray and branch lines and their nozzles that are subjected to thermal transients during plant startup/shutdown, thermal stratification, thermal shock, turbulent penetration, and thermal cycling. The dissimilar metal welds sections of nozzles and base metal section of elbows are susceptible to thermal fatigue. Thirteen leak events (0.004 – 110 gpm) caused by thermal fatigue cracking of nozzle welds and elbow base metal sections of PWR reactor coolant pipes (branch lines) have been reported in various countries [1]. During the whole plant life operation the integrity of piping system specially the primary piping in case of pressurized water reactor must be evaluated with rational accuracy. In order to maintain a high level of safety of reactor primary piping system, usually very complex computational procedure including fracture mechanics procedure, etc. has to be applied widely in the nuclear industry. Conservative deterministic approaches using different large safety factors are being widely used for this purpose though these methods have many inherent uncertainties to encumber a coherent assessment of structural components. These large safety factors were necessary because there are a lot of erroneous data related to actual defect size determination, plant

operating condition, different material failure mechanisms and above all dependable mechanical properties of structural materials. As a result the deterministic approach of structural failure assessment becomes a very conservative approach.

In contrast, probabilistic fracture mechanics (PFM) has been proposed as an efficient tool for failure assessment analysis. This probabilistic approach can consider various uncertainties effectively, especially it can account defect size (the most important variable) of any dimensions. It is a useful methodology for both operators as well as for the regulators to evaluate the life prediction of critical components of nuclear reactor with reasonable accuracy. Various computer codes were developed up to date. However, there are few efficient, user-friendly codes to determine fatigue failure probability due to small leak, big leak and LOCA vs. plant life under individual or combined loading of internal pressure, dead weight stress, thermal stress, residual stress, vibratory stress, etc. Moreover the majority of these computer codes consider only the pipe failure due to circumferential weld cracks only. But in case of elbow the highly stressed longitudinal base metal sections are also susceptible to fatigue failures.

The purposes of this paper are to find out the life time fatigue failure probabilities of primary piping subcomponents of pressurized water reactors (PWR) made of either SS steel or low alloy steel (LAS) and the relative ranking of severity of failure probability of these components. To do so, a probabilistic fracture mechanics (PFM) code has been developed using the Monte Carlo simulation technique. This code can handle both circumferential and/or longitudinal welds and/or base metal section problem. Five components e.g. RPV Inlet Nozzle, Surge Line Elbow, Charging Nozzle Safe End, Safety Injection Nozzle Safe End, Shutdown Cooling Line Elbow were analyzed for circumferential weld cases. Axial base metal parts were also studied for elbow sections considering stress indices for maximum values. All the calculations were done for both stainless and low alloy steels to show relative failure probabilities. Finally attentions were given on small leak failure probabilities with the effects of both preservice and inservice inspection program for ranking the failure probabilities of primary piping sub components for sixty years of plant lifetime.

## **2. DEVELOPMENT OF A PROBABILISTIC COMPUTER CODE**

### ***2.1. Background of probabilistic approach***

The probabilistic fracture mechanics approach is a useful tool for determining failure probabilities ( $P_f$ ) of structural components by varying reactor operating conditions e.g. operating internal pressure, dead weight stress of components, thermal stress; structural geometries e.g. pipe diameter, pipe thickness and material properties e.g. flow stress, fatigue constants, fatigue exponents, etc.

The Monte Carlo simulation method has been used in this paper. This method generates sets of random variables based on the given probabilistic distributions of the basic input variables and throws them in the final limit state functions (LCFs). To increase the computational efficiency of Monte Carlo simulations a variety of well-established methodologies exist; e.g., variance reduction method, stratified sampling, biased sampling, or importance sampling. The stratified sampling method has been used in this work [8]. The basic idea is to divide the sample space into a set of mutually exclusive cells. From each cell a user defined number of samples are then taken. The property, e.g. the crack dimensions (depth,  $a$  and length,  $b$ ) of

each sample is taken randomly. It is assumed that the initial existing probability of all samples is equal within each cell. Then the probability that the weld has failed at or before time  $t$ ,  $P(t_f \leq t)$  can be determined by Eq. (1)

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

where  $M$  is the total number of cells,  $N_m$  is the number of samples from the  $m$ -th cell,  $N_{F,m}(t)$  is the number of samples taken from the  $m$ -th cell which have failed at or before time  $t$ ,  $p_m$  is the probability of an initial crack having dimensions within the region of the  $m$ -th cell. *Fig.1* describes the basic flow chart for running this code.

## 2.2. Conditions for analysis

Initial crack is assumed as a circumferential semi-elliptical crack at the inner surface of the pipe. The depth distribution is expressed by the Marshall exponential distribution [2]:

$p(a) = \lambda \exp(-\lambda a)$ ..... $0 \leq a \leq h$  [a is in inch.] where  $\lambda$  is the intensity or rate parameter for an exponential distribution and corresponds to  $1/\mu$ . Here  $\mu$  is the mean crack depth of 0.246

inch. The distribution was originally suggested for reactor pressure vessel welds, which are quite thick. The aspect ratio,  $b/a$  distribution is expressed by the lognormal distribution [3]:

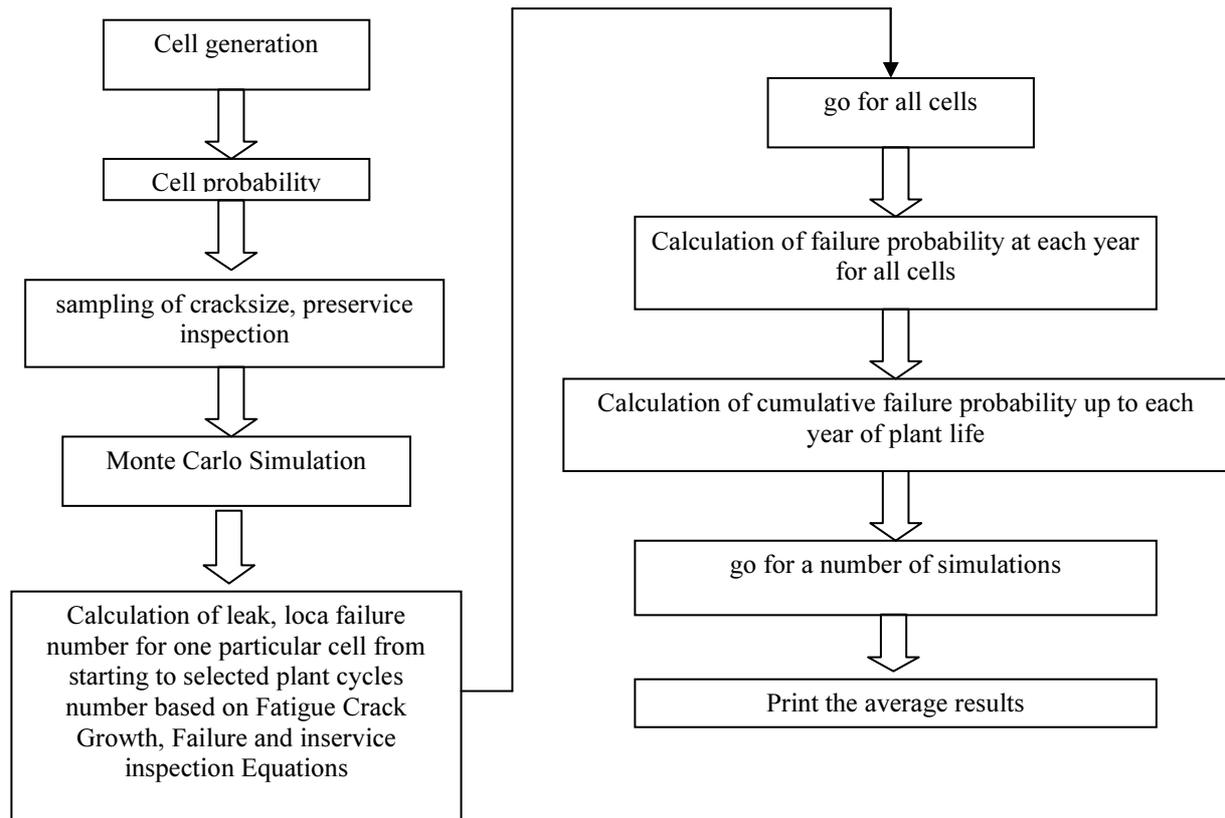


FIG.1. Basic flow chart of the code

$$p(b/a) = \begin{cases} 0 & \dots\dots\dots b/a < 1 \\ \frac{C}{S(b/a)\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\ln(b/a) - \ln M}{S}\right)^2\right] & \dots\dots\dots b/a > 1 \end{cases}$$

where  $a$  and  $b$  are the depth and the length of the initial part-circumferential or part-axial interior surface crack, respectively,  $C$  is the normalization factor,  $S$  is the shape parameter and  $M$  is the median. The use of these distributions for primary piping components is reasonable [4].

The probability of having a crack in a circumferential weld volume,  $V = 2\pi R_i h(2h)$  is  $P(t) = V p_v^* e^{-V p_v^* t} \sim V p_v^*$  where  $p_v^*$  is the cracks per unit weld volume  $10^{-4}/in^3$  was suggested.

The weld volume,  $V$ , includes the heat-affected zone which is taken to two wall thickness wide. For base metal sections, weld volume can be replaced by base metal volume. Stress intensity factor for either part-circumferential or part-longitudinal interior surface cracks are chosen as  $\bar{K}_a = F_a\left(\frac{a}{h}, \frac{a}{b}\right)\sigma\sqrt{a}$  and  $\bar{K}_b = F_b\left(\frac{a}{h}, \frac{a}{b}\right)\sigma\sqrt{a}$  [8]. Fatigue crack growth rate for austenitic

stainless steel was calculated as  $\frac{da}{dN} = C \left[ \frac{\Delta K}{(1-R)^{1/2}} \right]^m$ . All the possible stresses e.g. dead weight

stress, axial component of the pressure stress and the thermal stress are considered for circumferential weld section. Residual stresses due to welding process may be ignored as they have only a small influence on fatigue crack growth. But residual stresses are very important in SCC situation. For circumferential weld sections net-section failure criteria  $\sigma_{LC} A_p > \sigma_{fio} (A_p - A_{crack})$  was used for the points in the LOCA region satisfying the double-ended pipe break condition. The net-section failure criterion is considered here because it is generally used for ductile material where the total applied stress exceeds the net section flow stress [5]. In order to determine if a leak is small leak (>30 gpm) or big leak (>500 gpm), it is necessary to estimate the leak rate, which in turn, requires an estimate of the crack opening area, which is estimated by considering the crack to be rectangular in shape with a length  $2b$  and width (opening displacement) of  $\delta$ , where  $\delta = \frac{4\sigma b(1-\nu^2)}{E}$  [inch.]. This equation comes

from the result for a crack in an infinite plate and is conservative. For calculating leak rates,  $\dot{Q}$  in gallon per minute, gpm at 2250 psi and 550°F reactor operating conditions, the following equation is used [8]:

$$\frac{\dot{Q} h^{1/2}}{2b} = \begin{cases} 0.25\delta^2 & \dots\dots\dots \delta \leq 2mils \\ 0.9375\delta - 0.875 & \dots\dots\dots \delta > 2mils \end{cases}$$

The code was further extended by introducing stress indices for elbow sections, carbon and low alloy steels' fatigue growth equations and modified probability of detection curves. In case of axial section of elbows, the hoop stress term  $\sigma_p = \frac{pR_i}{h}$  is included. For elbow axial

section, volume  $V = e_w l \times h(2h)$  is used for analysis where  $e_w l$  is the length of the axial section of elbow which depends on elbow bend radius and bend angle. The pipe inner radius,  $R_i$  and thickness,  $h$  depended stress indices or multiplier is also considered during the circumferential or longitudinal weld / base metal sections of elbows. The equations for stress indices were coded as follows [11]:

For elbow bend angle  $\theta < 90$  deg,  $B_2 = 1.0 + (1.30/h_e^{2/3} - 1.0)\sin\theta$ , but not  $< 1.0$ . For elbow bend angle  $\theta \geq 90$  deg,  $B_2 = 1.30/h_e^{2/3}$ , but not  $< 1.0$ , where  $h_e = hR_{be}/r_m^2$ ,  $h$  = nominal wall thickness of

pipe,  $R_{be}$  = nominal bend radius of elbow and  $r_m$  = mean pipe radius =  $(D_0 - h)/2$ . The slot failure condition of axial crack in case of an elbow was coded as

$$\sigma_{IC} > \sigma_{fio} \left(1 + 1.255\beta_c^2 - 0.0135\beta_c^4\right)^{1/2}$$

where  $\beta_c = \frac{b_c}{\left[h\left(R_r + \frac{1}{2}h\right)\right]}$  [8].

The fatigue crack growth equations for carbon and low alloy steel were included as follows [7]:

$$\frac{da}{dN} = Z \begin{cases} 1.03 \times 10^{-12} S(\Delta K)^{5.95} & \dots \Delta K \leq K_{knee} \\ 1.01 \times 10^{-7} S(\Delta K)^{1.95} & \dots \Delta K > K_{knee} \end{cases}$$

$$K_{knee} = \begin{cases} 17.74 & \dots R \leq 0.25 \\ 17.74 \left( \frac{3.75R + 0.06}{26.9R - 5.725} \right) & \dots 0.25 < R < 0.65 \\ 12.04 & \dots R \geq 0.65 \end{cases}$$

$$\text{if } \_K < K_{knee} \_S = \begin{cases} 1.0 & \dots R \leq 0.25 \\ 26.9R - 5.725 & \dots 0.25 < R < 0.65 \\ 11.76 & \dots R \geq 0.65 \end{cases}$$

$$\text{if } \_K > K_{knee} \_S = \begin{cases} 1.0 & \dots R \leq 0.25 \\ 3.75R - 0.06 & \dots 0.25 < R < 0.65 \\ 2.5 & \dots R \geq 0.65 \end{cases}$$

Where,  $Z$  is for all possible uncertainties,  $K_{knee}$  is the threshold value below which no crack growth occurs and  $S$  is the adjustment factor.

The improved probability of detection input equations were coded from the section 5.1.5 of recently published NUREG/CR-6934 document [6].

### 2.3 Probabilistic Fracture Mechanics Code

The piping integrity evaluation program based on PFM was developed using Microsoft Visual Basic 6.0. Fig. 2 shows the program window that consists of input material property part, reactor operating condition part, constants part, the controlling part, i.e. cell size, iteration/simulation number and the output result part. This code can handle circumferential and/or axial weld and/or base metal crack failure probability for austenitic stainless steels and carbon or low alloy steels materials which are commonly used for today's light water reactor. All the relevant parameters for analysis are summarized in Table 1. Crack growth due to seismic load, residual weld stress and vibratory stress is not considered here. The circumferential weld and longitudinal base metal sections in case of elbow parts were also analyzed considering stress indices to get the conservative probability of failure at highest bend angle (90°) conditions. The initial crack size, the depth ( $a/h$ ) and the aspect ratio ( $b/a$ ), are divided into  $10 \times 10$  cells, and the number of samples for each cell is twenty five. The total number of the samples, therefore, is  $10 \times 10 \times 25 = 2500$  in all cases. The code was also run to see the effects of preservice and inservice inspection on failure probabilities.

FIG.2. Input sheet of the code (austenitic stainless steels, carbon and low alloy steels with weld/base metal sections).

### 3. RESULTS AND DISCUSSIONS

#### 3.1. Input variables for calculation

Five components of a typical PWR plant e.g. RPV Inlet Nozzle (3" / 24"), Surge Line Elbow (1" / 10"), Charging Nozzle Safe End (0.5" / 4"), Safety Injection Nozzle Safe End (0.5" / 6"), Shutdown Cooling Line Elbow (0.75" / 12") were chosen for this research work. Table 1 includes all the input parameters for analysis. All these reference input data were taken from today's standard light water reactor primary piping system. For conservative analysis the maximum level of input stresses were considered to find out the relative cumulative failure probabilities for the sixty years of plant's life depending on components geometry, material mechanical properties and material dependent marginal probability of crack detection [6].

Table 1. Input variables of 304 SS and SA508 Cl.1a nuclear pipes [7,8,9,10,11]

- Weld joints in a PWR plant
  - RPV Inlet Nozzle (thickness/diameter; 3" / 24")
  - Surge Line Elbow (1" / 10")
  - Charging Nozzle Safe End (0.5" / 4")
  - Safety Injection Nozzle Safe End (0.5" / 6")
  - Shutdown Cooling Line Elbow (0.75" / 12")
- Growth of a Pre-existing crack by Fatigue only
- Small Leak Threshold = 30 gpm
- Big Leak Threshold = 500 gpm
- Operating Conditions:

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- Deadweight = 2.08 ksi
  - Thermal Expansion = 6.5 ksi
  - Operating Pressure = 2250 psi
  - Operating Temperature = 290~310°C
  - Heat-up Cool-down Frequency = 5 per year
  - Plant Lifetime = 60 years
  - Residual Stresses = not considered
  - Vibratory Stresses = not considered
  - Fatigue Crack Growth Properties for 304SS
    - Fatigue constant =  $9.14 \times 10^{-12}$
    - Fatigue Exponent = 4.0
  - Fatigue Crack Growth Properties for SA508 Cl.1a
    - Fatigue constant =  $1.03 \times 10^{-12}$
    - Fatigue Exponent = 5.95
  - Elastic modulus
    - 304SS = 25,500 ksi
    - SA508 Cl.1a = 26,700 ksi
  - Flow Stress at 290°C
    - 304SS = 43 ksi
    - SA508 = 53 ksi
  - Stress Indices for elbow: ~3
  - Initial Crack Size Distribution:
    - Depth Distribution = Exponential
    - Rate parameter = 4.07
    - Aspect Ratio Distribution = Lognormal
    - Median = 1.34
    - Shape Parameter = 0.538
    - Normalizing Constant = 1.4149
  - Cracks per unit volume:  $10^{-4}/\text{in}^3$
  - The Sample Space: 100 cells and 25 samples per cell
- 

### 3.2. Evaluation of failure probability

Fig. 3 shows the cumulative small leak, big leak and loss of coolant accident (LOCA) failure probability of per circumferential weld in safety injection nozzle safe end part made of either 304SS or SA508 Cl.1a for the sixty years plant life of interest. The part was analyzed first without any inspection program to determine the maximum failure probability for conservative analysis. Then it was analyzed with preservice inspection program which is a common practice and assuming no inservice inspection. The part was further examined with various inservice inspection interval to show the effect of reduced inservice interval program on failure probability of per circumferential weld in 60 years of plant life. Without any inspection program circumferential weld of safety injection nozzle safe end shows about  $10^{-5}$  small leak failure probability for 304SS and about  $10^{-7}$  for SA508 Cl.1a (Fig. 3a) and introducing preservice inspection these were expected to be around  $10^{-7}$  and  $10^{-9}$  respectively (Fig. 3b). In all cases, the big leak and loca showed much smaller failure probabilities. Although 10 years interval inservice inspection program is a common practice in today's plant life management program for research interest it was also examined with 5 years and 2 years interval inservice program. The effect of reduced interval inservice inspection program was observed for all other components of this work and the trend was almost similar. Such a

result was shown in *Fig. 5* for circumferential weld of charging nozzle safe end. The results showed that applying 10 years interval inservice inspection program would reduce the failure probability from preservice inspected parts at the end of sixty years of plant life about 4% for 304SS and about 8% for SA508 Cl.1a steel. For five years interval inservice program it was further reduced by 6% and 10% respectively. Two years conservative inservice inspection may reduce these figures up to 20% for both materials. Similar trends were observed in recently published NUREG publication [6].

It was reported earlier that the crown of the base metal section of elbow containing longitudinal surface crack was the most highly stressed region and thus need special attention for failure probability analysis [12]. This study also showed that for surge line elbow made of either 304SS or SA508 Cl.1a poses the highest risk of failure probability about  $10^{-2}$  (*Fig. 4a*) considering no inspection for conservative predictions which can be reduced to  $10^{-3}$  for 304SS and  $10^{-4}$  for SA508 Cl.1a (*Fig. 4c*) by introducing 10 years interval material dependent marginal inservice inspection program. For conservative purpose the max bend angle 90deg was assumed for all elbow sections and max stress intensity factor about 3 was taken into consideration. Moreover for axial surface crack problem, the hoop stress was also considered. So, combining this all parameters, the applied total stress becomes the flow stress of the material. In case of circumferential welds in straight pipes and nozzles the total stresses were below 15 ksi and the large leak was found to be 3-6 orders of magnitude less than the small leak probability. But as the applied stresses become increases to flow stress particularly for longitudinal section of elbow, all the leak and break probabilities have almost same result. This very high level of primary stress approaching the flow stress is very serious because even a very small crack might cause net section failures of the components. Components will fail in this condition as leak and break occur at the same moment due to unstable crack growth. In case of circumferential weld of surge line elbow the leak and break failure probabilities are a little bit lower due to the absence of hoop stress. Applying both preservice and inservice inspection for every 10 years interval these could be reduced to below  $10^{-4}$  for 304SS for both leaks and breaks and about  $10^{-7}$  (small leak),  $10^{-8}$  (big leak) and  $10^{-9}$  (loca) for SA508 Cl.1a steels.

Reactor pressure vessel (RPV) inlet nozzle made of either stainless steel or low alloy steel show almost similar trends in small leak failure probabilities. For most conservative analysis the small leak failure probability per circumferential weld at the end of 60 years is about  $10^{-5}$  which could be possible to reduce around  $10^{-7}$  by applying preservice inspection and assuming no inservice inspection. Similar data was reported early [8]. Although RPV shows moderate small leak failure probability it could be further reduced by 10%, 12% and 18% by introducing 10 years, 5 years and 2 years interval inservice inspection program.

Shutdown cooling line elbow shows almost similar behaviour like surge line elbow considering same level of primary stresses for conservative analysis. Although the leak and break trend are same but due to comparatively small (h/d, thickness/diameter) ratio shutdown cooling elbow experienced a little bit higher failure probabilities. So, considering same stress input, axial crown elbow section of shutdown cooling line elbow is the highest susceptible part for leak and break failure but in reality as surge line elbow just below the pressurizer was reported to be the highest thermal stressed zone [1] so surge line elbow might be the most susceptible to leak and break failure probability in practical plant life environment. Detailed finite element stress analysis is required to determine the magnitude and location of actual

stress experienced in surge line elbow sections for correct determination of leak and break failure probability analysis.

Charging nozzle safe end also showed similar trends in leak and break failure probabilities like safety injection nozzle safe end although charging nozzle safe end showed a little bit lower leak and break failure probabilities due to higher (h/d) ratio. So, considering same stress input charging nozzle safe end might be the lowest leak and break probability part. Detail plant life cycle history is then required to accurately find out the leak and break probabilities in these cases.

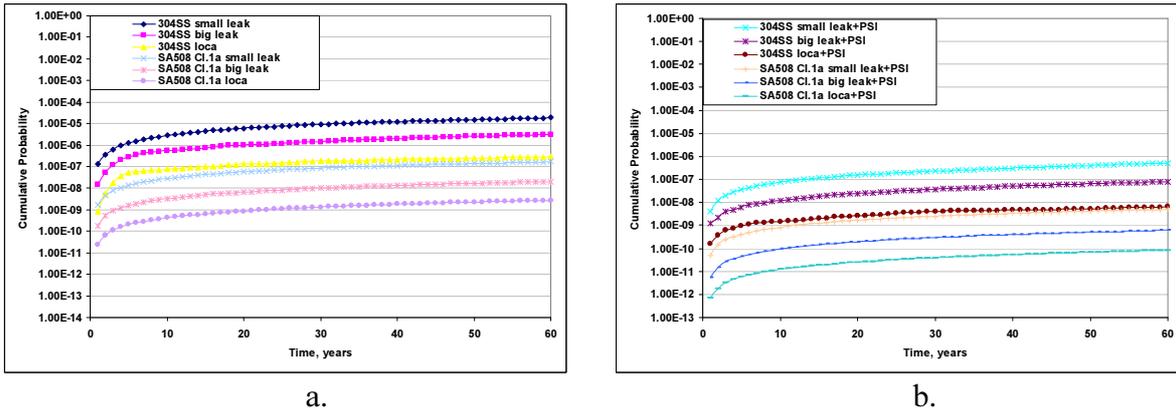


FIG. 3. Cumulative probabilities per circumferential weld in Safety Injection Nozzle Safe End for the failure mode of interest.

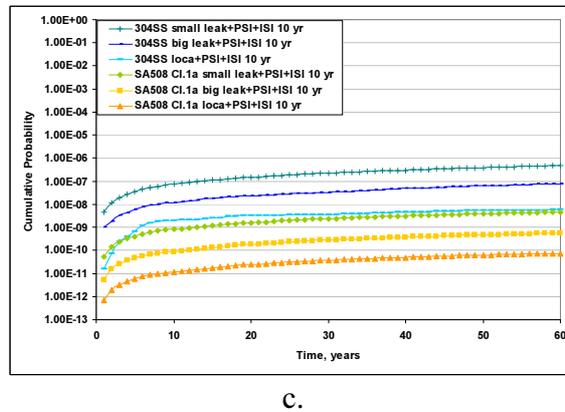
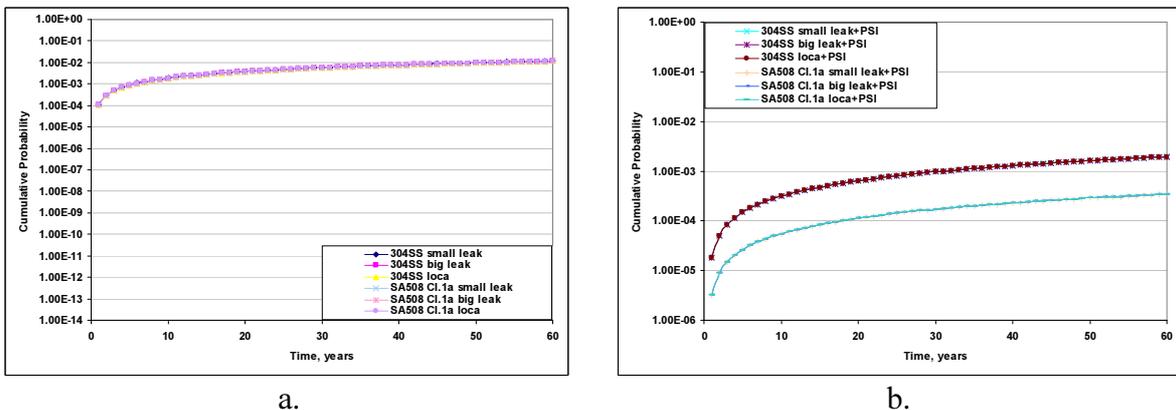
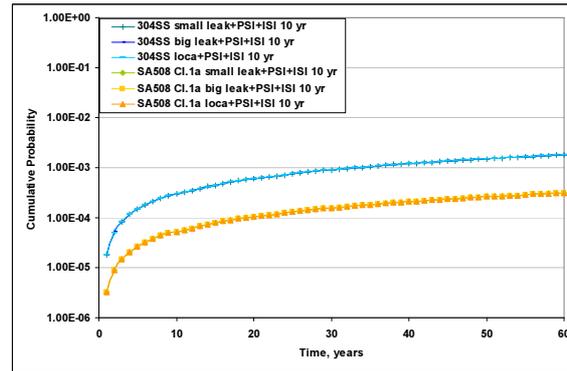


FIG. 3. Cont.



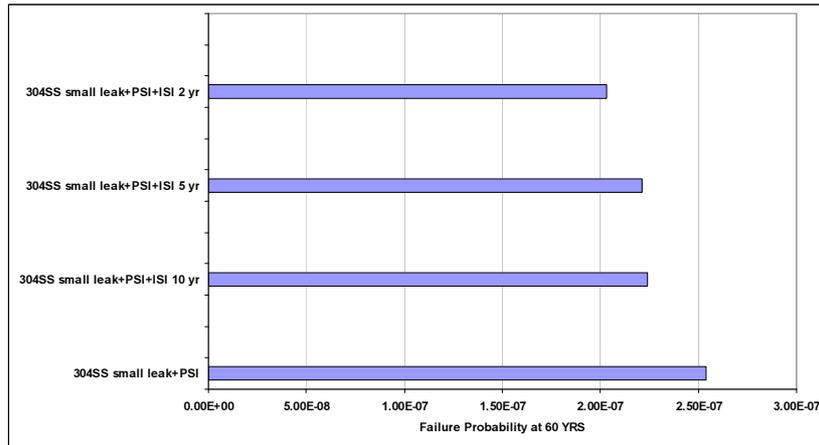


C.

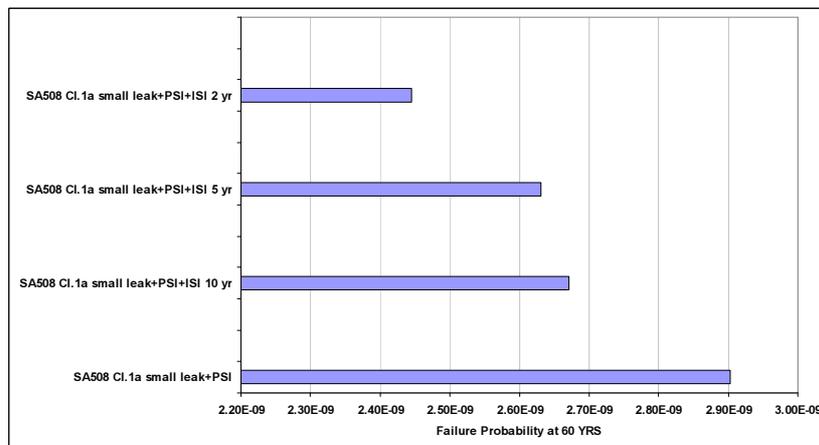
FIG. 4. Cumulative probabilities per longitudinal base metal section in Surge Line Elbow for the failure mode of interest.

### 3.3. Relative ranking of subcomponents

Fig. 6 shows the relative small leak failure probability ranking of all the selected subcomponents of primary system of a LWR considering only preservice inspection. In this study, the relative small leak failure probabilities were found to be shutdown cooling line elbow (304SS~2.66E-03); surge line elbow (304SS~2.00E-03); reactor pressure vessel inlet nozzle (SA508 Cl.1a~2.61E-07); charging nozzle safe end (304SS~2.58E-07, SA508 Cl.1a~2.95E-09); safety injection nozzle safe end (304SS~5.04E-07, SA508 Cl.1a~4.98E-09). Similar trends were noticed for through wall cracks at 60 year's plant life considering only circumferential weld sections of 304/316 and LAS [13]. M.A. Khaleel *et al.* also reported that the leak probability of circumferential surface weld defects of safety injection nozzle safe end was (304SS  $\sim 10^{-7}$ ) [9]. It was reported early that the failure probability of nuclear piping is between  $10^{-4}$  to  $10^{-6}$  per reactor year, and if the diameter of the pipe is smaller, the failure probability will be higher [14]. This study suggests that it actually depends on both thickness and diameter of the components and for parts with identical mechanical properties, if (h/d) ratio is smaller, the failure probability will be higher. Moreover failure probability also depends on material mechanical properties. Assuming similar environmental conditions and its effects on material, low alloy steels show smaller leak and break failure probabilities comparing with stainless steels in almost all cases due to higher flow strength, higher elastic modulus and lower (da/dn) ratio. At same (h/d) ratio, and considering same plant operating conditions, safety injection nozzle safe end and charging nozzle safe end made of low alloy steel have up to 100 times lower failure probability than those made of stainless steels due to 24% higher flow strength of low alloy steel. Similar data was also reported in NUREG/CR-6674 [7]. On the other hand, for same material, due to 50% higher (h/d) ratio charging nozzle safe end showed only 2 times lower failure probability than safety injection nozzle safe end. So, material mechanical properties have the greater effect comparing with geometrical property for reducing failure property of components.



a.



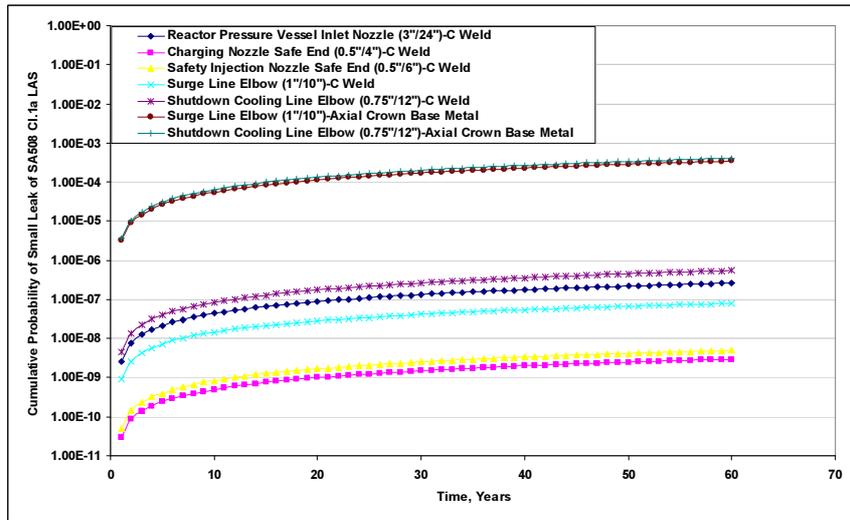
b.

FIG. 5. Effect of reduced inservice inspection on cumulative failure probabilities per circumferential weld in Charging Nozzle Safe End at 60 years of plantlife.

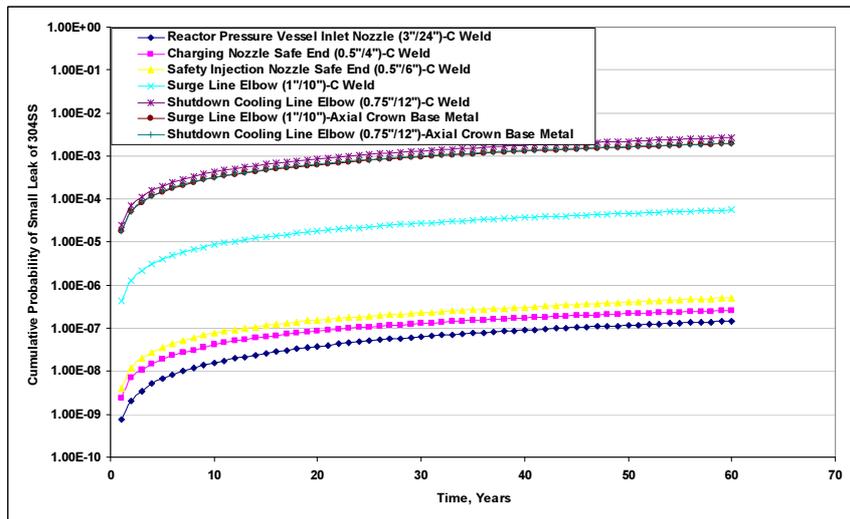
In all cases, for low alloy steel, axial crown base metal section of elbows show the highest small leak failure probability due to high stress concentration. Of course for stainless steel due to low flowstrength and lowest h/d ratio both circumferential weld section and axial crown base metal section of shut down cooling line elbow show almost similar failure probability. The same is not true for surge line elbow made of stainless steel. For surge line elbow made of stainless steel, due to higher (h/d) ratio comparing with shut down cooling line elbow's (h/d), axial crown base metal section has about 10 times more small leak failure probability than that of circumferential weld sections. So, for low strength material, (h/d) has a significant effect on failure probability for elbow sections. In this case, the lower the (h/d) ratio the closer the axial and circumferential direction failure probability thus may give a serious combined failure probability.

Preservice inspection has a significant effect for reducing failure probability when crack depth is greater than 30% of component thickness for both low alloy steel and stainless steel. Of course, now a days it is a common practice to carry out preservice inspection program for every components in nuclear piping system. For conservative analysis purpose, it was assumed no inservice inspection while producing the Fig.6. But as it was found in early section, that marginal probability of detection based inservice inspection program might reduce the failure probability on the order of about 10% for 10 years, about 12% for 5 years

and about 20% for 2 years interval inservice inspection program, so for circumferential weld and base metal section of all elbow sections it might be inspected more frequently.



a.



b.

FIG. 6. Relative Ranking of Cumulative probabilities of small leak of a. SA508 Cl.1a LAS and b. 304SS for all components of interest.

#### 4. CONCLUSIONS

The probabilistic fracture mechanics code with the ability of analyzing failure probability of weld and base metal sections of austenitic stainless steels, carbon and low alloy steels, is developed. Using this analysis code, the failure probability of primary piping system subcomponents of LWR is determined. The conclusions derived based on the analysis are as follows:

O The failure probability of elbows are higher than other pipe subcomponents. Within the elbows the crown section shows higher failure probability than circumferential welds associated with the elbows because of the higher hoop stress in that region.

O The failure probabilities of the subcomponents are estimated as follows:

- On the order of E-03 for the crown section of surge line elbow and shut down cooling line elbow made of 304SS.
- About  $2.61E-07$  for the circumferential weld section of RPV inlet nozzle made of SA508 Cl.1a.
- About E-07 for stainless steel sections of safety injection nozzle safe end and charging nozzle safe end made of 304SS.
- About E-09 for stainless steel sections of safety injection nozzle safe end and charging nozzle safe end made of SA508 Cl.1a.

O The effect of preservice inspection on reducing failure probability is far greater than inservice inspection. Though the inservice inspection reduced the failure probability by 10%, further reducing the inservice inspection interval to 5 years shows almost no reduction in failure probability.

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