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The Effect of Inspection Model on the Probability of Vessel Failure due to Pressurized Thermal Shock

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1. Introduction

For the quantitative evaluation of the vessel failure risk associated with pressurized thermal shock (PTS), the probabilistic fracture mechanics (PFM) analysis technique has been widely used. The PFM technique basically checks whether hypothetical flaws on the wall propagate through the vessel wall by comparing the applied stress intensity factor (crack driving force) with the fracture toughness (materials resistance to fracture) during the PTS events. Therefore a probabilistic fracture mechanics code called R-PIE (Reactor - Probabilistic Integrity Evaluation) is developed implementing the advanced technologies and new capabilities [1].

In this study, failure probabilities during PTS with repressurization are calculated using the R-PIE code with respect to the flaw distribution and its size according to the inspection model and their characteristics are addressed. Also the effects of fluence and warm prestressing (WPS) are investigated.

2. Analysis

Typical PTS with re-pressurization is assumed. The temperature and pressure start to decrease but at a certain time, 120 min after the transient began, the system pressure increases rapidly and it is maintained and slow heating occurs, which shows typical characteristics of the PTS transient. In this case pressure is assumed to be a dominant factor.

The reactor vessel considered in the analysis is a typical PWR with an inner surface radius of 2000 mm and a base metal thickness of 200 mm without cladding. The material properties for ASTM A533B-1 are used.

Flaw distributions for various inspection models were determined. Marshall [2] used Eq. (1) to calculate the probability of crack with depth a.

$$P(a) = 4.06 \exp(4.06\, a) \tag{1}$$

Then the cumulative flaw density function describing the probability of crack existence larger than a is expressed as following equation.

$$f(a) = \int_0^a 4.06 \exp(-4.06a)\, da \tag{2}$$

If integrated to whole flaw depth range, above equation results in exactly 1, indicating that Eq. (2) is associated with a single flaw.

Also, the probability of non-detection for pre-service inspection is defined as;

$$B(a) = \varepsilon + (1-\varepsilon) \exp(-\mu\, a) \tag{3}$$

where $\varepsilon = 0.005$ and $\mu = 2.88$ in^{-1}, and is valid for edge cracks and semi-elliptical cracks with $a/l = 1/6$. Therefore the flaw distribution and size after inspection can be calculated by incorporating Eq. (3) into Eq. (1). As the detected flaws are effectively removed from the population, the net effect is reducing the number of flaws as well as modifying the flaw distribution. After some rearrangement, the cumulative flaw distribution for Marshall with inspection can be expressed by following equation.

$$f(a) = \int_0^a [0.0346 \exp(-4.06a) + 6.88 \exp(-6.94a)]\, da \tag{4}$$

As before, if integrated to whole flaw depth range, Eq. (4) will result in exactly 1, but the associated number of flaw is 0.5863 instead of 1 because of the above mentioned reason.

VISA-II code [3] describes the relation between the probability of detection P_D and the critical crack size a_c as follows:

$$P_D = P_{d,\max} \frac{a}{a_c} \qquad \text{for } a \le a_c \tag{5-1}$$

$$P_D = P_{d,\max} \qquad \text{for } a > a_c \tag{5-2}$$

where $P_{d,max}$ and a_c depend on surface roughness of material. In the case of smooth cladded vessel, $P_{d,max}$ is around 95% and a_c is around 6 mm. For the case of welded part or non-polished surface, $P_{d,max}$ is around 75% and a_c is around 24 mm. The probability of non-detection is shown in Fig. 1 for comparison with Marshall distribution.

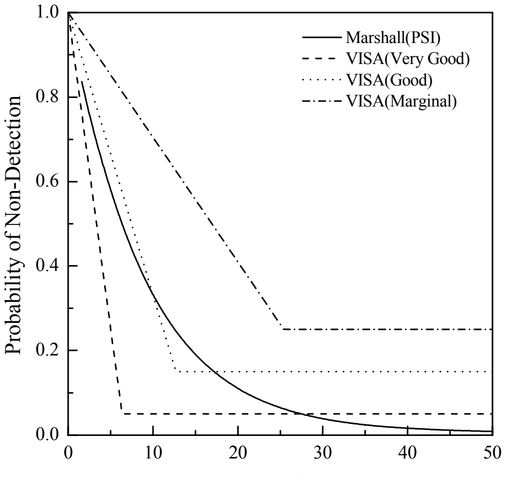

Fig. 1. Probability of non-detection for Marshall and VISA-II models

3. Results and Discussion

The temperature distributions are calculated and the stress analyses due to these temperature distributions and internal pressure are performed using the R-PIE code. These stress variations along the vessel wall are used to get the stress intensity factors. Also temperature distributions along the vessel wall are used to get the fracture toughness. The stress intensity factor and fracture toughness are compared to determine the propagation of the crack generating the failure of the vessel, which is used to calculate the probability of the vessel failure.

The probabilities of vessel failure due to PTS with repressurization are calculated for various flaw distributions and they are shown in Fig. 2. As compared with PTS with constant pressure, the probabilities are lower as expected. The effect of fluence on the failure probability is almost negligible for fluence level of higher than 3×10^{19} n/cm^2.

The effect of inspection quality on the probability of vessel failure is investigated for several different inspection qualities. Probability of failures due to five different flaw distributions such as no inspection, PSI, inspection A, B and C considered in VISA-II code is considered. By comparing the probabilities of failure with respect to the flaw distribution, Marshall distribution without inspection and with VISA-II A (very good) inspection give the highest and lowest probabilities, respectively. Marshall distribution with PSI and VISA-II B (good) inspection generate about the same probability of failure, which indicates that Marshall distribution with PSI normally used in the probabilistic analysis is almost the same level of inspection quality B of VISA-II code. This kind of result can be obtained irrespective of the fluence level, which indicates that the effect of inspection quality has the same trend irrespective of the fluence level.

In the histograms for the number of failures and the number of observations, the maximum number of failures is obtained at 120 min after the transient began, when the system pressure increases very rapidly. Also the number of failure observations is distributed log-normally with the maximum number at the flaw depth of about 13 mm.

The WPS effect uses the basic premise that a crack will not initiate when the stress intensity factor is dropping with time or constant, whether the temperature is dropping or not [4]. Even though the WPS effect is considered, the probability does not change because most of the failure does not happen after the stress intensity factor reaches the peak values, resulting propagating cracks are not available to be stopped by the WPS effect. Therefore, the WPS has an insignificant effect on the failure probability for the PTS with repressurization. This is a general result for the transient with repressurization which has a peak stress intensity factor which is obtained when a repressurization occurs.

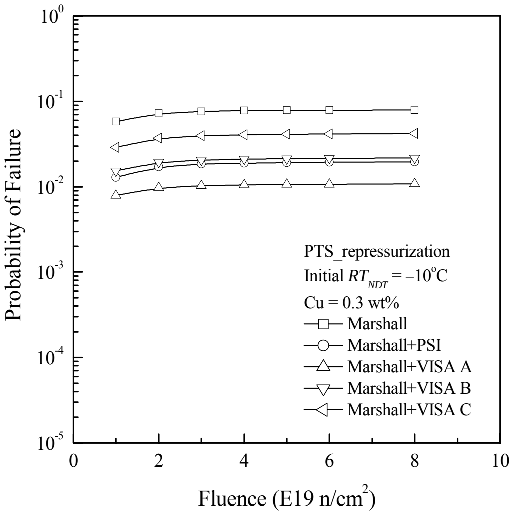

Fig. 2. Probability of failure

4. Conclusions

The probabilistic fracture mechanics analyses of nuclear reactor pressure vessels subjected to pressurized thermal shock with repressurization are performed using the R-PIE code, generating the following conclusions;

- Marshall distribution with PSI normally used in the probabilistic analysis is almost the same level of inspection quality B of VISA-II code.
- The effect of inspection quality on the failure probability has the same characteristics irrespective of the fluence level. And the various inspection qualities considered in this study resulted in about an order of magnitude difference in failure probability.
- The effects of WPS on the failure probability are insignificant for PTS with repressurization.

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