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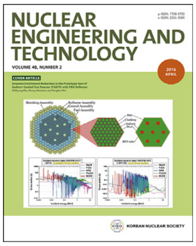

Original Article

Probabilistic Fracture Mechanics Analysis of Boling Water Reactor Vessel for Cool-Down and Low Temperature Over-Pressurization Transients

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ABSTRACT

The failure probabilities of the reactor pressure vessel (RPV) for low temperature overpressurization (LTOP) and cool-down transients are calculated in this study. For the cool-down transient, a pressure–temperature limit curve is generated in accordance with Section XI, Appendix G of the American Society of Mechanical Engineers (ASME) code, from which safety margin factors are deliberately removed for the probabilistic fracture mechanics analysis. Then, sensitivity analyses are conducted to understand the effects of some input parameters. For the LTOP transient, the failure of the RPV mostly occurs during the period of the abrupt pressure rise. For the cool-down transient, the decrease of the fracture toughness with temperature and time plays a main role in RPV failure at the end of the cool-down process. As expected, the failure probability increases with increasing fluence, Cu and Ni contents, and initial reference temperature-nil ductility transition (RT_{NDT}). The effect of warm prestressing on the vessel failure probability for LTOP is not significant because most of the failures happen before the stress intensity factor reaches the peak value while its effect reduces the failure probability by more than one order of magnitude for the cool-down transient.

1. Introduction

The reactor pressure vessel which encloses fuel assemblies under highly pressurized coolant is the most important component in a nuclear power plant. Therefore, it is important to ensure that brittle fracture of the vessel does not occur during any condition to which the vessel may be subjected over its service lifetime.

In order to evaluate the integrity of the reactor pressure vessel, either a deterministic or probabilistic fracture mechanics (PFM) approach can be used. The deterministic fracture mechanics method, which has been more commonly used, employs the concept of a safety factor that envelops all kinds of uncertainties related to operating loadings, material properties, and damage mechanisms. It seeks a conservative evaluation by assuming the worst and bounding case. By

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Table 1 – Thermal properties.

Coefficient of heat transfer ($W/m^2/K$)	1,817
Poisson's ratio	0.3
Density (kg/m^3)	7,600
Thermal conductivity (Wm/K)	54.60 at 20 °C, 45.80 at 300 °C
Specific heat (J/kg/K)	488.722 at 20 °C, 568.520 at 300 °C
Thermal diffusivity (m^2/s)	14.70E–6 at 20 °C, 10.60E–6 at 300 °C
Thermal expansion coefficient (/K)	1.090E–05 at 20 °C, 1.490E–05 at 300 °C

contrast, the PFM method can directly treat the uncertainties of the main parameters and provide a more realistic result with the use of best-estimate data. Furthermore, the probabilistic method is useful to understand the effect of important parameters on the failure probability by conducting various sensitivity analyses. The probabilistic assessment has become more important recently.

For a pressurized thermal shock (PTS) event, one of the possible major challenges to the integrity of a reactor pressure vessel, many probabilistic assessments have been conducted. In the USA, screening criteria for PTS were determined based on the results of the PFM analyses [1,2]. From 2009 to 2011, PFM round robin analyses were performed amongst Asian countries to establish reliable procedures to evaluate the fracture probability of the reactor pressure vessel during PTS events [3,4]. Qian and Niffenegger [5] reviewed several PFM computer codes and discussed the effects of warm prestressing (WPS) and fracture toughness on the integrity of the reactor pressure vessel subjected to PTS. In addition, Qian et al [6] and Qian and Niffenegger [7] evaluated failure probabilities of the reactor pressure vessel by considering real crack distribution data, two different PTS transients, and different toughness curves.

For operating conditions other than PTS, however, fewer PFM assessments have been done to evaluate the failure probability of the reactor pressure vessel. Huang et al [8] performed PFM analyses for boiling water reactor (BWR) pressure vessels subjected to a low temperature over-pressurization (LTOP) event. Chou and Huang [9] evaluated the failure probabilities of a BWR pressure vessel under normal cool-down transients by considering the revision of the American Society of Mechanical Engineers (ASME) Section XI, Appendix G, which allows the use of the K_{Ic} curve instead of the K_{Ia} curve for generating pressure–temperature limit curves. However, further sensitivity studies are required to understand the effects of different input parameters on the vessel failure probabilities under the LTOP or cool-down transients.

Table 2 – Mechanical material properties.

Average of initial RT_{NDT} (°C)	−30 for weld, 0 for base
Standard deviation of initial RT_{NDT} (°C)	10
Formula of ΔRT_{NDT}	Reg. Guide 1.99
Standard deviation of ΔRT_{NDT} (°C)	0.0
Average of Cu content (wt%)	0.2
Standard deviation of Cu content (wt%)	0.01
Average of Ni content (wt%)	1.0
Standard deviation of Ni content (wt%)	0.02
K_{Ic} (ORNL average curve)	Standard deviation is 15% of average
K_{Ia} (ORNL average curve)	Standard deviation is 10% of average
Flow stress (MPa)	551.6
Young's modulus (MPa)	2.04E5 at 20 °C, 1.85E5 at 300 °C
Yield strength (MPa)	489 at 20 °C, 423 at 300 °C

ORNL, Oak Ridge National Laboratory.

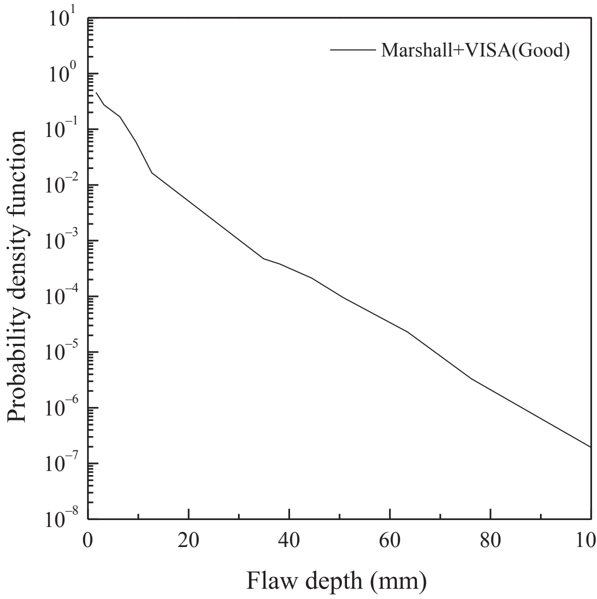

Fig. 1 – Flaw distribution and size for VISA-II model.

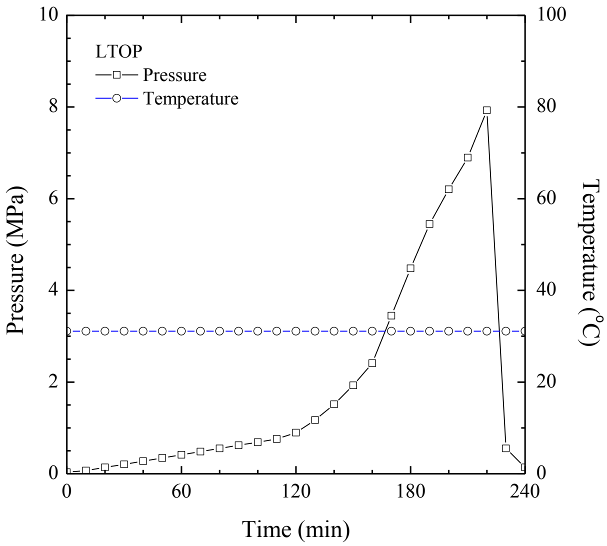

Fig. 2 – Pressure and temperature histories of low temperature over-pressurization.

Table 3 – Transient condition for cool-down.

Initial water temperature (°C)	276
Final water temperature (°C)	20
Cooling rate (°C/hr)	55
Inner pressure	Allowable pressure*

[*] Values determined from the equation $K_{Im} + K_{IT} = K_{Ic}$.

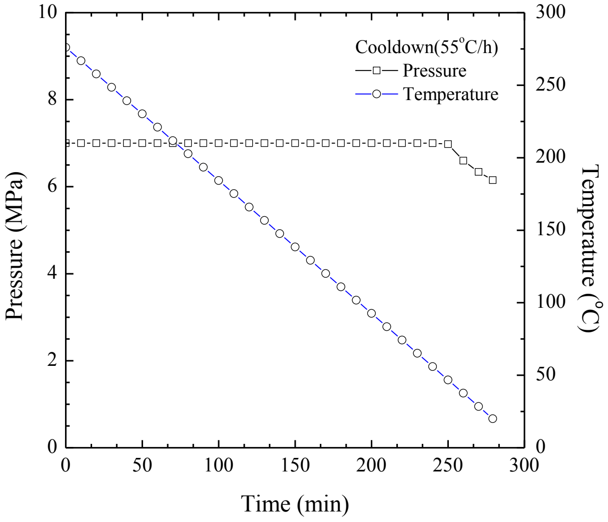

Fig. 3 – Pressure and temperature histories of cool-down.

In this study, LTOP and cool-down transients, which are important in the design but have relatively low probabilities of causing fractures, are considered for PFM evaluations of the reactor pressure vessel. For the cool-down transient, a pressure–temperature limit curve is generated in accordance with the ASME Section XI, Appendix G procedure but without the margin factors that have been applied to the fracture toughness curve and the stress intensity factor due to pressure. The effects of the transients, copper (Cu) and nickel (Ni) contents, initial reference temperature-nil ductility transition (RT_{NDT}), fluence level, and WPS on the vessel failure probability are analyzed using a PFM computer code, Reactor-Probabilistic Integrity Evaluation (R-PIE) [10].

2. Problem definition

2.1. Geometries and material properties

The reactor pressure vessel considered in the analysis has an inner surface radius (*R*) of 3,200 mm and a base metal thickness (*T*) of 160 mm without cladding. Thermal and mechanical properties (ASTM A533B-1) used in this study are shown in Tables 1 and 2. The average values of the properties between 20 °C and 300 °C are considered.

Also, the irradiation shift formula is defined as Eq. (1) according to the U.S. Nuclear Regulatory Commission (USNRC) Regulatory Guide 1.99, Rev.2 [11].

$$\varDelta RT_{NDT} = (CF) f^{(0.28-0.10\log f)} \tag{1}$$

where *CF* is the chemistry factor, which is a function of Cu and Ni content, and *f* is the neutron fluence (10^{19} n/cm^2, E > 1 MeV) at any depth in the vessel wall determined as:

$$f = f_{surf}\, exp^{(-0.24x)} \tag{2}$$

where f_{surf} is the calculated value of the neutron fluence at the inner surface of the vessel at the location of the postulated defect, and *x* (in inches) is the depth into the vessel wall measured from the vessel inner surface. The uncertainties of $\varDelta RT_{NDT}$ are described by a normal distribution which is assumed to be truncated between ± 3 standard deviations (SD). The SD of $\varDelta RT_{NDT}$ is assumed to be 0 °C.

The crack postulated is a surface semi-elliptical crack in the axial direction with an aspect ratio of 6. The inspection quality employed for the VISA-II model [12] is used for flaw distribution as shown in Fig. 1 [4].

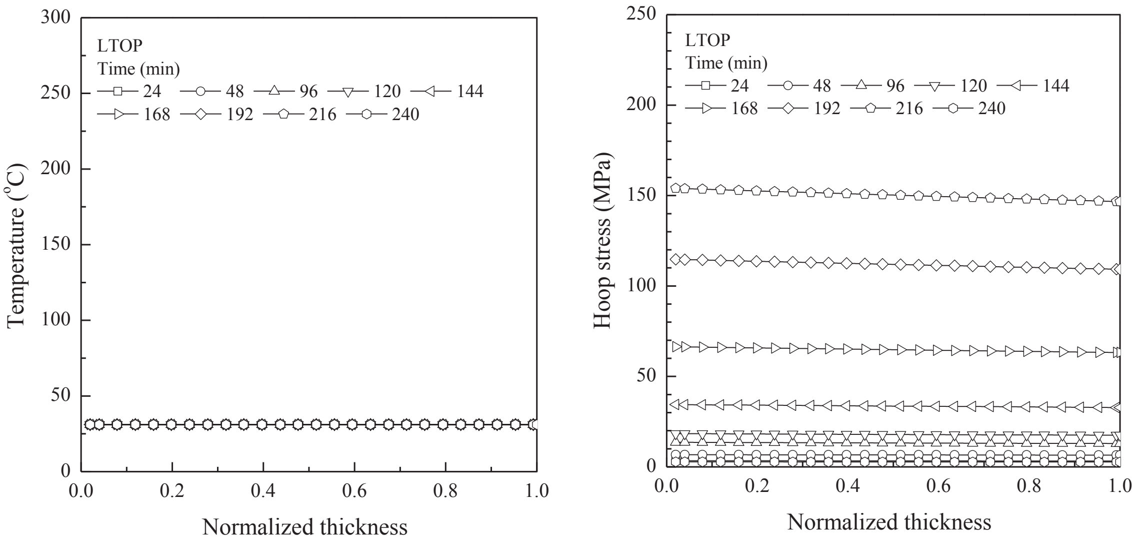

Fig. 4 – Temperature and stress histories along the vessel wall for low temperature over-pressurization.

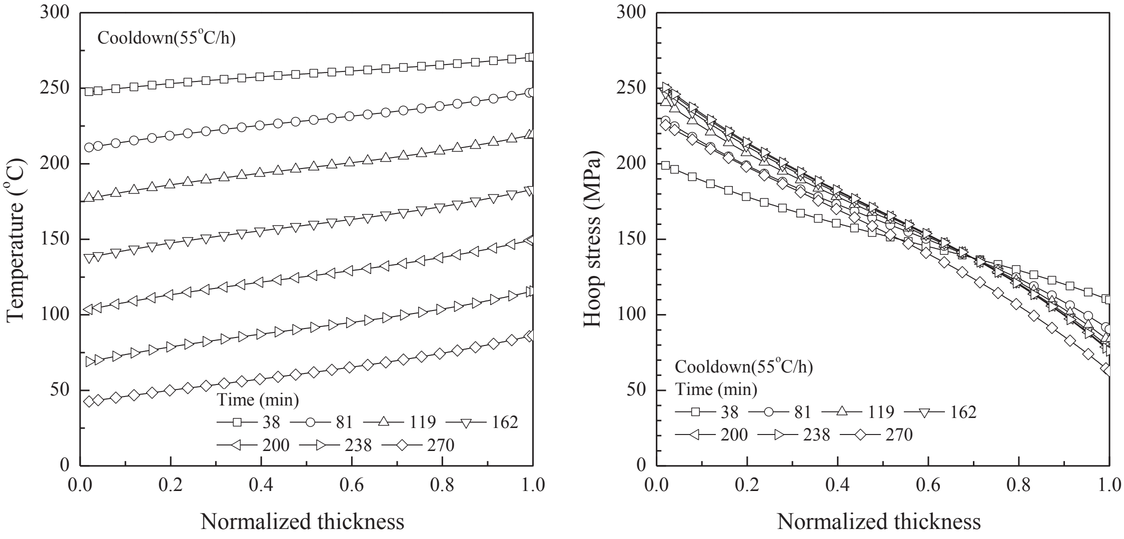

Fig. 5 – Temperature and stress histories along the vessel wall for cool-down.

2.2. *Transients*

In this study, two types of transients are considered. One of them is an LTOP transient, which could cause brittle fracture of the reactor vessel. By referencing an actual recorded LTOP transient happened in a BWR [13], the pressure and temperature histories with time are determined and provided in Fig. 2.

The other transient is a normal cool-down condition, which is prescribed in the design code, such as the ASME code, Section III. A cooling rate of 55 °C/h is used for the analysis. The allowable pressure for the normal cool-down transient is calculated in accordance with the Appendix G to Section XI of the ASME code [14]. First, an axial surface defect with a depth (a) of one-fourth of the section thickness and a length of 1.5 times the section thickness is postulated. The requirement to be satisfied for determination of the allowable pressure at any temperature during the cool-down transient is:

$$K_{Im} + K_{It} < K_{Ic} \tag{3}$$

where K_{Im} and K_{It} are stress intensity factors (MPa$\sqrt{m}$) due to internal pressure and thermal stress, respectively. K_{Ic} is the time dependent fracture toughness determined by Eq. (4).

$$K_{Ic} = 1.43 \cdot \{36.5 + 3.084\, exp[0.036 \cdot (T - RT_{NDT} + 56)]\} \tag{4}$$

Equation (4) represents the ASME code Section XI lower-bound K_{Ic} curve multiplied by a constant, which was derived by assuming that the ASME lower bound curve represents

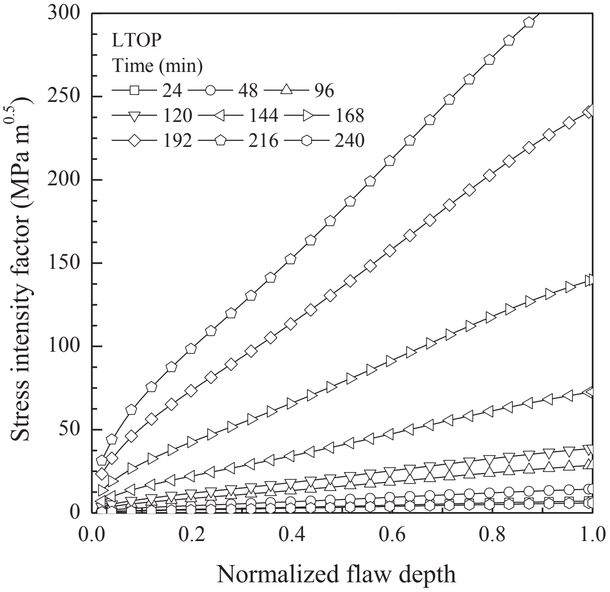

Fig. 6 – History of the stress intensity factor for low temperature over-pressurization.

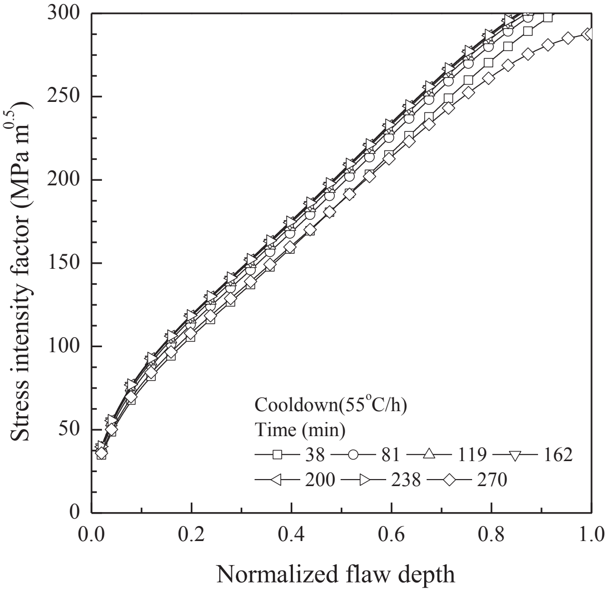

Fig. 7 – History of the stress intensity factor for cool-down.

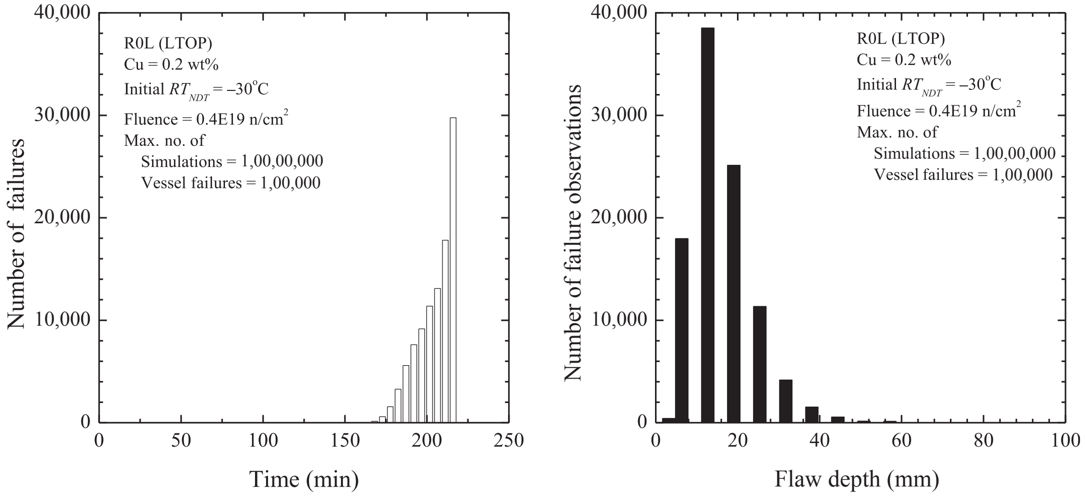

Fig. 8 – Histograms of number of failures and failure observations for low temperature over-pressurization.

–2SD values with the normal distribution [15]. Here, we try to reduce any conservatism in the ASME code since best estimate values are recommended for probabilistic assessments. In the same context, a factor of 2, which is recommend to be applied to the K_{Im} values for conservatism, is not used in this study. The value of RT_{NDT} is assumed to be 80.6 °C, which is known as the highest estimated end of life RT_{NDT} for the material of interest. The equations for K_{It} and K_{Im} are:

$$K_{It} = 0.579 \times 10^{-6} \times CR \times t^{2.5} \tag{5}$$

$$K_{Im} = M_m \times \left(\frac{pR}{t}\right) \tag{6}$$

$$M_m = 0.0293\sqrt{t} \tag{7}$$

where CR is the cool-down rate (°C/hour). R and t are the inner radius (mm) and thickness (mm) of the reactor pressure vessel, respectively. After calculating the values of K_I, K_{It}, and M_m, the allowable pressure(p) can be obtained by Eq. (8).

$$p = \frac{(K_{Ic} - K_{It})}{M_m} \times \left(\frac{t}{R}\right) \tag{8}$$

For the cool-down conditions of Table 3, the values of allowable pressure at any temperature were determined using Eqs. (3–8) and are shown in Fig. 3, where the maximum system pressure is defined as 7 MPa.

3. Analysis

A probabilistic fracture mechanics code called R-PIE is used for the quantitative risk assessment of the reactor pressure vessel, which consists of two parts, the deterministic analysis and the probabilistic analysis [10].

For the deterministic analysis, the temperature profile and the resulting thermal stress along the thickness of the reactor pressure vessel are calculated from the given

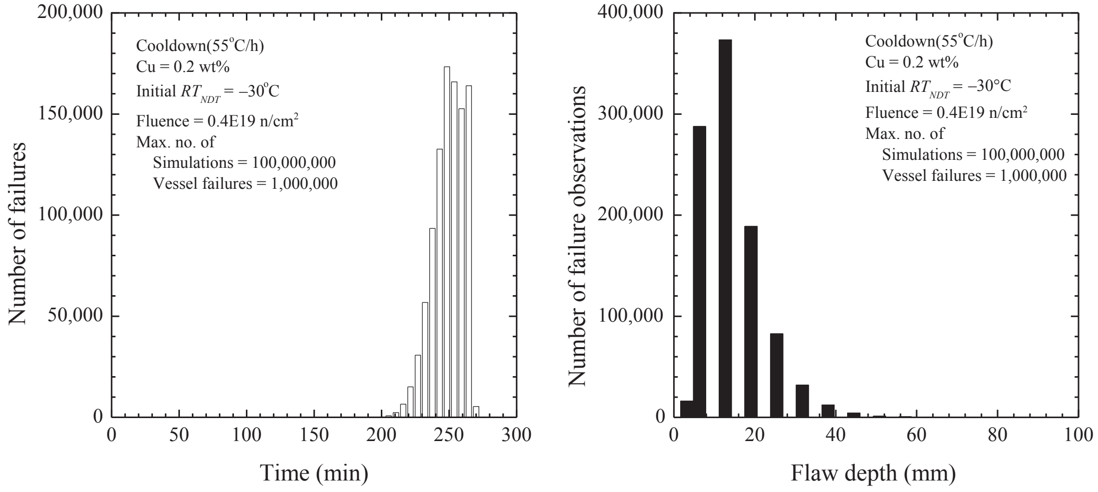

Fig. 9 – Histograms of number of failures and failure observations for cool-down.

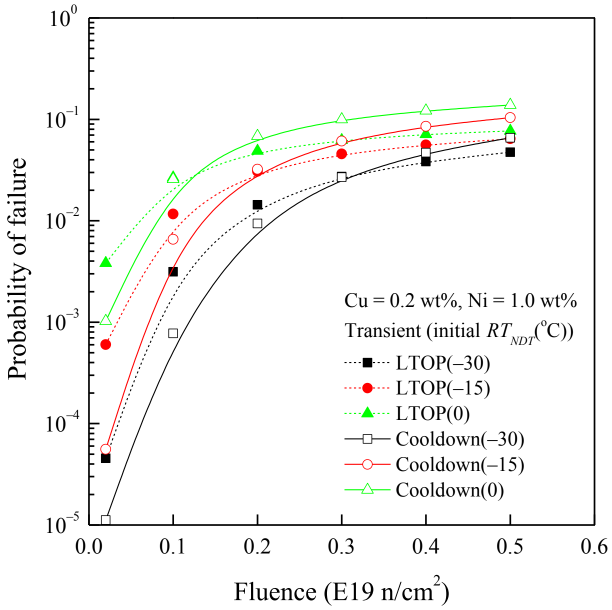

Fig. 10 – Probability of failure due to low temperature over-pressurization and cool-down.

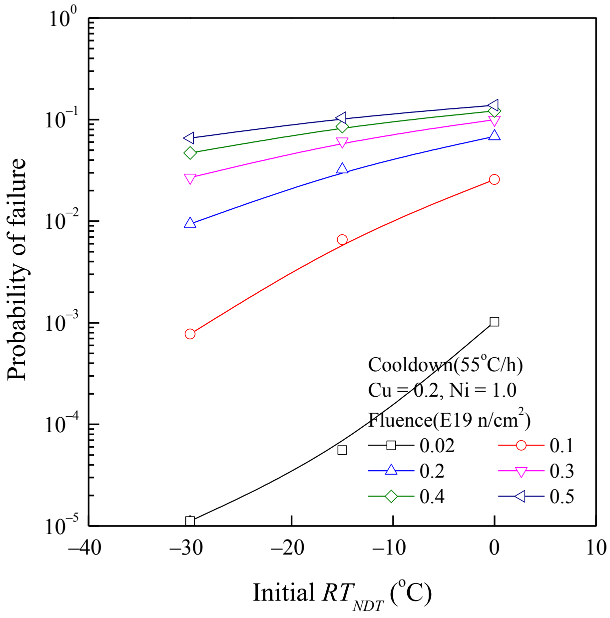

Fig. 12 – Effect of initial RT_{NDT} on the probability of failure for cool-down.

thermal–hydraulic conditions. The distribution of stresses from other sources like pressure and residual stresses are calculated separately. The stress intensity factor from each stress component is calculated by the Raju–Newman method [16] using the appropriate influence coefficients for flaw shapes. Then, the stress intensity factors calculated for the various stress components such as thermal stress, pressure stress, and residual stress are added to obtain the total applied stress intensity factor, K_I. This method can be readily applied to calculate the applied stress intensity factors in the base metal of the reactor pressure vessel.

In the probabilistic analysis part, a variety of statistical parameters such as flaw size, neutron fluence, and Cu and Ni contents, and the RT_{NDT} are simulated for each hypothetical reactor pressure vessel. From the temperature profile and the RT_{NDT}, the mean static fracture toughness K_{Ic} and the mean arrest fracture toughness K_{Ia} at the tip of the flaws are

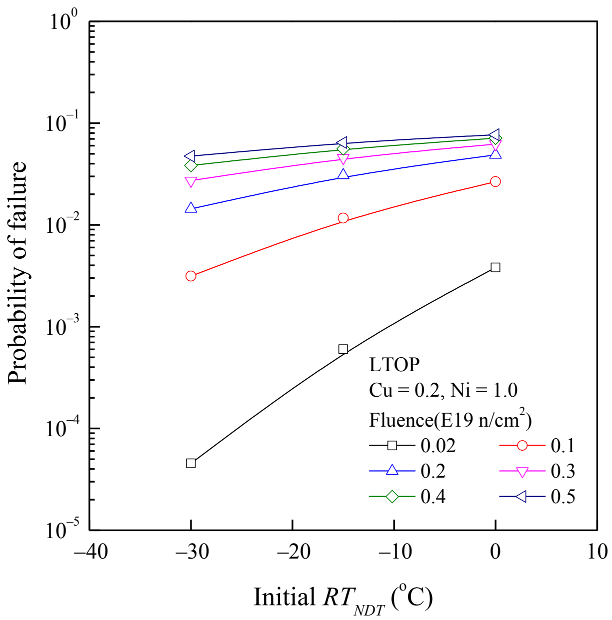

Fig. 11 – Effect of initial RT_{NDT} on the probability of failure for low temperature over-pressurization.

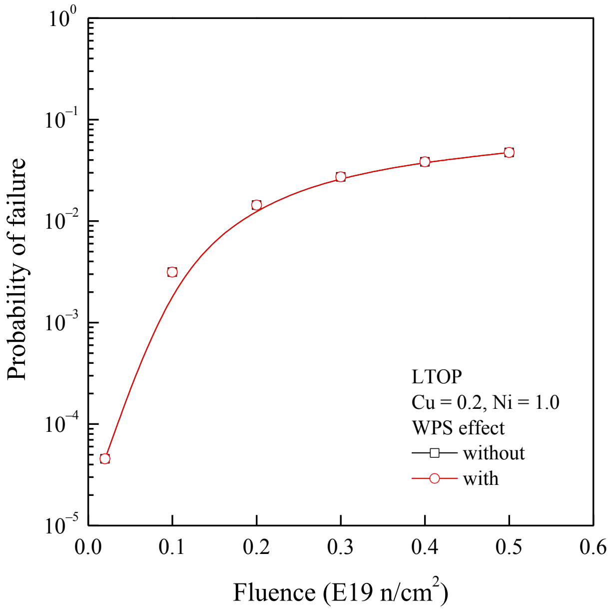

Fig. 13 – Effects of warm prestressing on the probability of failure for low temperature over-pressurization.

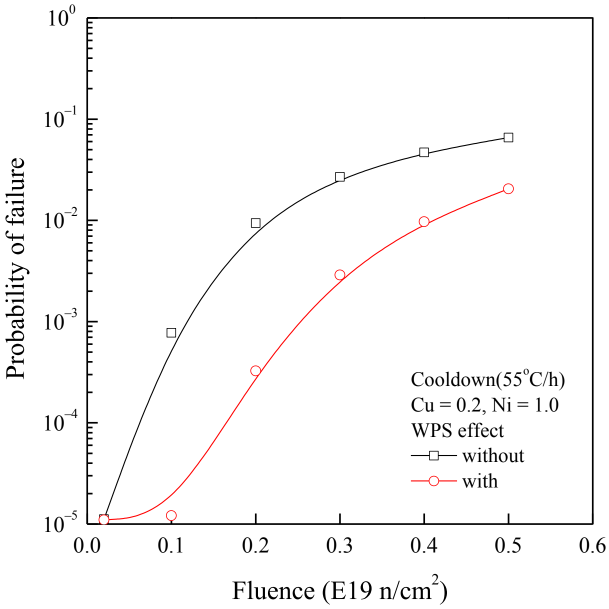

Fig. 14 – Effects of warm prestressing on the probability of failure for cool-down.

calculated using the equation derived from the ASME Section XI lower-bound fracture toughness.

Finally, using the mean values and the associated uncertainties, the fracture toughness values are simulated to compare with the applied stress intensity factors at the tip of the flaw. If K_I is larger than K_{Ic}, the flaw is assumed to initiate and grow a certain distance. Then, at the new flaw size, new values of RT_{NDT}, K_I, and K_{Ia} are determined and compared. If K_I is smaller than K_{Ia}, the flaw is considered to be arrested. Otherwise, the flaw size is increased again and the arrest check is repeated until the end of the transient. By repeating the above analysis millions of times, a statistically significant conditional probability of the vessel failure for the specific thermal hydraulic boundary condition is determined.

Several parametric analyses are performed in this study to investigate the effect of transients, Cu content, Ni content, initial RT_{NDT}, and WPS on the vessel failure probability.

4. Results and discussion

First of all, the temperature distributions are calculated and the stress analysis due to these temperature distributions and internal pressure are performed using the R-PIE code. Temperature and hoop stress distributions along the wall at several times are shown in Figs. 4 and 5 for LTOP and cool-down transients, respectively. The stress variations along the vessel wall are used to get the stress intensity factors and the fracture toughness. The history of the stress intensity factors vs. *a*/*t* are shown in Figs. 6 and 7 for LTOP and cool-down transients, respectively, which shows that stress intensity factors for LTOP increase with increasing time but those for cool-down do not increase with time. These trends can be expected by the stress histories along the vessel wall as shown in Figs. 4 and 5.

The histograms for the number of failures and the number of observations are shown in Figs. 8 and 9 for LTOP and cool-down, respectively. For the LTOP transient, most of failure occurs between 170 minutes and 220 minutes, which corresponds to a period of large stress intensity factors as shown in Fig. 6. For the cool-down transient, most of the failure occurs between 201 minutes and 270 minutes, which corresponds to the period of small values of the fracture toughness due to the lower temperature for cool-down. Alternatively, almost the same stress intensity factor due to temperature difference and pressure is maintained throughout the cool-down transient as shown in Fig. 7, but the value of the fracture toughness becomes lower and lower according to the cool-down process. Therefore, most failures occur at the end of the cool-down process.

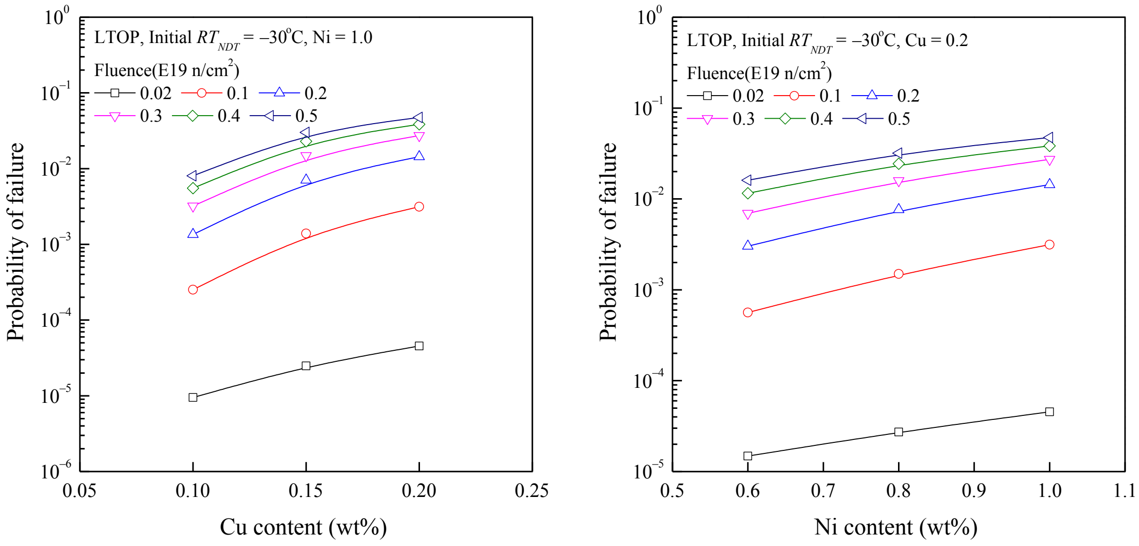

Fig. 15 – Effects of copper and nickel content on the probability of failure for low temperature over-pressurization.

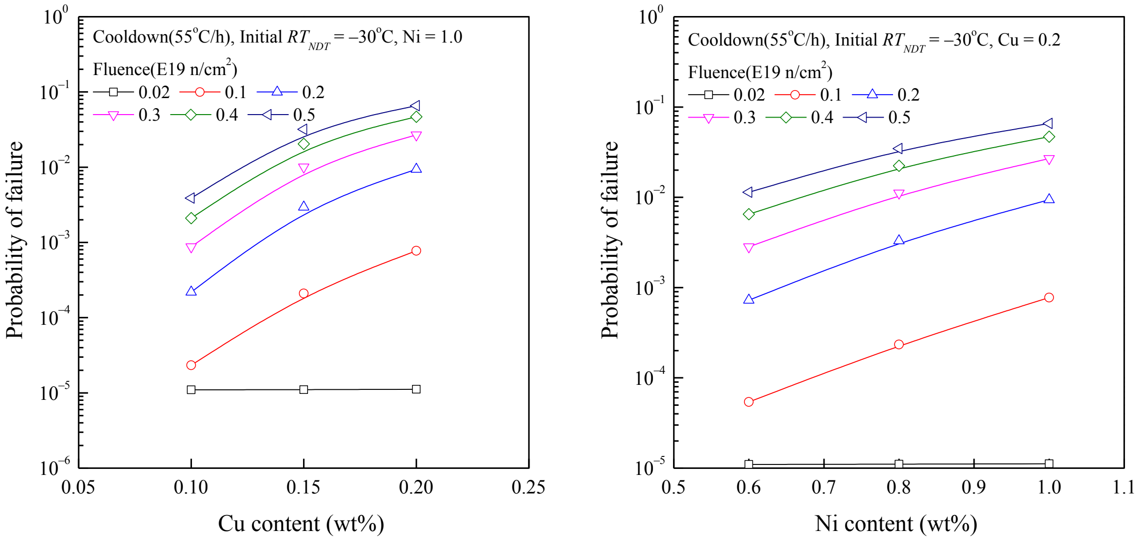

Fig. 16 – Effects of copper and nickel content on the probability of failure for cool-down.

The probability of vessel failure is shown in Fig. 10 with respect to the fluence. As expected, the probability of failure decreases significantly as the fluence decreases. The probability of failure due to LTOP does not vary significantly for fluence larger than 0.2 × 10^{19} n/cm^2. The failure probability of LTOP is lower than that of cool-down for fluence larger than 0.3 × 10^{19} n/cm^2 in initial RT_{NDT} of −30 °C. This trend applies in the same way for 0.2 × 10^{19} n/cm^2 in initial RT_{NDT} of −15 °C and 0.1 × 10^{19} n/cm^2 in initial RT_{NDT} of 0 °C.

The effect of initial RT_{NDT} on the failure probability is shown in Figs. 11 and 12. The effect of initial RT_{NDT} on the failure probability is more significant for the lower fluence region in both transients.

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 [17]. The effect of WPS on the vessel failure for LTOP is shown in Fig. 13. If the WPS effect is considered, the probability of failure decreases a little bit and it is not affected especially for the fluence level of 0.02 × 10^{19} n/cm^2. In the case of the LTOP transient, most of the failures happen before the stress intensity factor reaches the peak value, such that not many propagating cracks are available to be stopped by the WPS effect. The effect of WPS on the vessel failure for cool-down is shown in Fig. 14. If the WPS effect is considered, the probability of failure decreases a lot for all fluence ranges by one or two orders of magnitude. For the very low fluence of 0.02 × 10^{19} n/cm^2, the effect of WPS is negligible.

The effects of Cu and Ni contents on the failure probability are shown in Figs. 15 and 16 for LTOP and cool-down transients, respectively. As the content of Cu and Ni decreases, the failure probabilities decrease linearly. The decreasing rates are almost the same for fluence ranges from 0.1 × 10^{19} n/cm^2 to 0.5 × 10^{19} n/cm^2. For the very low fluence of 0.02×10^{19} n/cm^2, the effect of Cu and Ni contents is negligible especially for cool-down because there is no additional irradiation embrittlement.

5. Conclusions

The probabilistic fracture mechanics analyses of nuclear reactor pressure vessel subjected to LTOP and cool-down transients were performed using the R-PIE computer code. The results were compared, and generated the following conclusions:

- For the LTOP transient, the time when the failure of the RPV mostly occurs corresponds to the period when a sudden rise of pressure occurs. For the cool-down transient, the decrease of the fracture toughness with temperature and time plays a main role in the RPV failure at the end of the cool-down process.
- As the fluence decreases, the probability of failure decreases significantly. But the probability of failure does not vary significantly for fluence higher than 0.2 × 10^{19} n/cm^2 for LTOP and cool-down.
- The effect of the initial RT_{NDT} on the failure probability is more significant for the lower fluence region and lower initial RT_{NDT}.
- The effects of WPS on the vessel failure probability for LTOP are not significant because most of the failures happen before the stress intensity factor reaches the peak value. However, the effects of WPS for cool-down are significant for most ranges of fluence with one or two orders of magnitude
- As the content of copper and nickel decreases, the failure probabilities decrease linearly. The decreasing rates are almost the same for fluence ranging from 0.1 × 10^{19} n/cm^2 to 0.5 × 10^{19} n/cm^2.

Conflicts of interest

All authors have no conflicts of interest to declare.

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