Comparison of probabilistic fracture mechanics codes for PTS transient evaluation of PWR

Tae Hyun Kim [a], Yoon-Suk Chang [a*] and Jong-Min Kim [b]
[a]*Dept. of Nuclear Engineering, Kyung Hee University, 1732 Deokyoung-daero, Yongin, Kyunggi, 446-701, Korea*
[b]*Nuclear Materials Research Division, Korea Atomic Energy Research Institute, 1045 Daedeok-daero, Yuseong, Daejeon, 305-353, Korea*
[*]*Corresponding author: yschang@khu.ac.kr*

1. Introduction

During long-term operation, RPV walls are exposed to the radiation embrittlement caused by continuous neutron fluence. If several transients such as PTS were to occur, existing flaw of the RPV could initiate and rapidly propagate along the vessel. For the quantitative evaluation of structural integrity of the RPV, PFM were widely adopted, which basically evaluate the applied stress intensity factor with the fracture toughness. Three representative PFM codes of R-PIE, PASCAL and FAVOR are compared herein under typical PTS transients. Besides, parametric influences in each code are also analyzed with equivalent conditions.

2. PFM codes and problem definition

2.1 R-PIE

A korean PFM (Probabilistic Fracture Mechanics) code, R-PIE (Reactor-Probabilistic Integrity Evaluation), is developed for the quantitative risk assessment of the RPV at the PTS (Pressure Thermal Shock) events, of which the schematic diagram is shown in Fig. 1 [1].

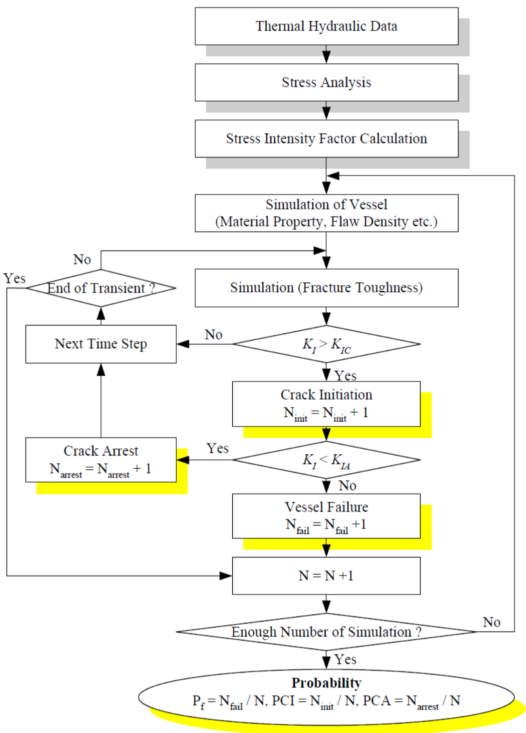


Fig. 1. The schematic diagram of R-PIE

R-PIE consists of two parts of the deterministic analysis and probabilistic analysis. In the deterministic analysis part, the stress intensity factor, K, is calculated from the thermal-hydraulic data and Raju-Newman method. In the probabilistic analysis part, fracture toughness values, K_{IC}, are compared with simulated K_I. Finally, failure probabilities are determined from these iterations until enough number of simulations.

2.2 PASCAL

A JAERI's PFM code, PASCAL (PFM Analysis of Structural Components in Aging LWR) has a purpose of evaluating the failure probability of aged pressure components, of which the schematic diagram is shown in Fig. 2 [2].

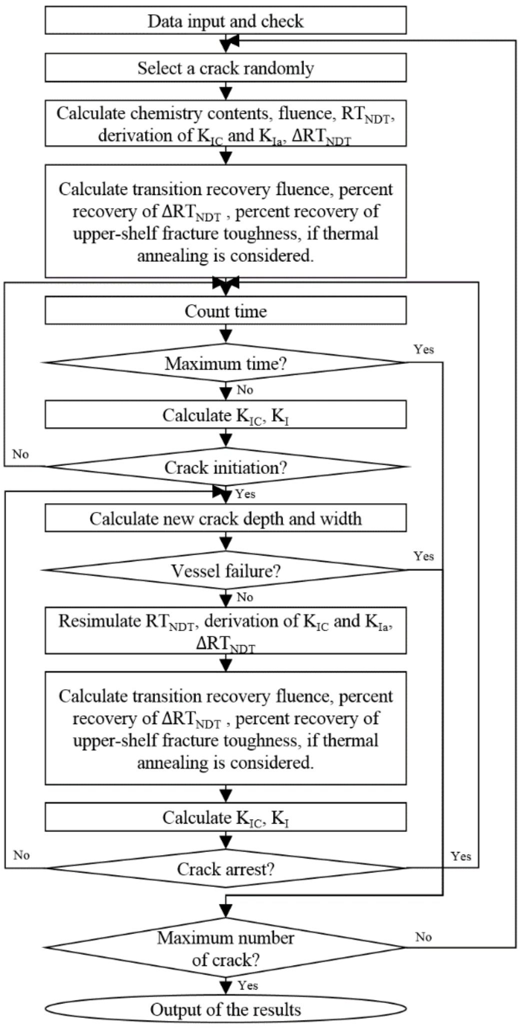


Fig. 2. The schematic diagram of PASCAL

For generating input data of PASCAL, exclusive 3-D FEM (Finite Element Method) processors are necessary such as pre-PASCAL, ABAQUS and ANSYS. In the present study, ABAQUS was adopted to generate the 3-D FEM meshes of RPV and obtain the input transient data for PASCAL.

2.3 FAVOR 12.1

FAVOR (Fracture Analysis of Vessels – Oak Ridge) code has been developed by U.S. NRC and ORNL (Oak Ridge National Laboratory) to perform deterministic and probabilistic risk-informed structural integrity analyses of RPV when subjected to thermal-hydraulic events such as PTS transients.

The latest version of FAVOR 12.1 code is composed of three modules such as FAVLOAD for deterministic analysis, FAVPFM for probabilistic analysis and FAVPOST for post process. Especially, the schematic diagram of FAVPFM module is depicted in Fig. 3 [3].

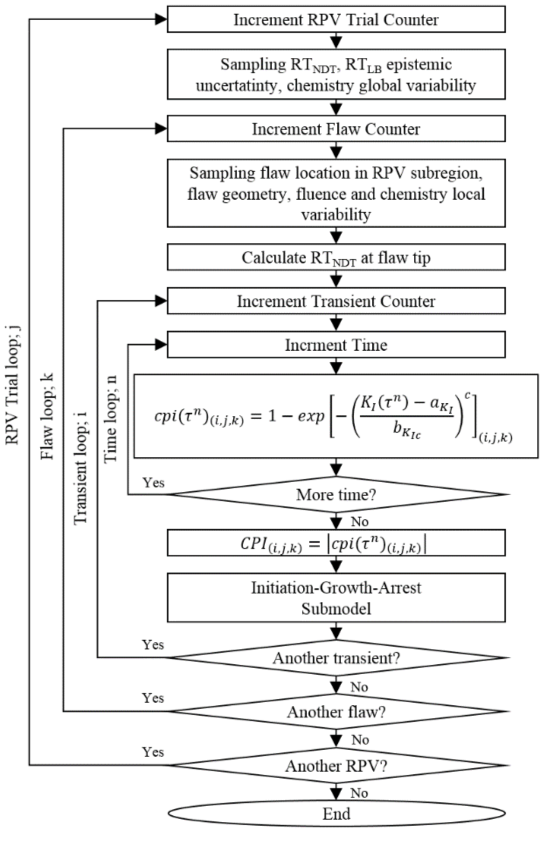


Fig. 3. The schematic diagram of FAVPFM module

2.4 Analysis conditions

For comparison analyses of each code, the same analysis conditions are used as given in Table I. Representative 7 PTS transients of SBLOCA I001, MSLB A001, A014, C014 SGTR E016, F016 and LOHS H001 are also considered [4]. A typical RPV beltline geometry of PWR was adopted, of which axial semi-elliptical surface flaw with aspect ratio of 1/6 was considered. Applied neutron fluences varied from 1 to 8 × 10^{19}n/cm^2.

Table I: Problem definition

Vessel dimensions	Thickness	6.5 in (165.1 mm)
	Inner radius	66 in (1676.4 mm)
Thermal material properties	Density	0.282 lb/in^3 (7800 kg/m^3)
	Thermal conductivity	23.63 Btu/ft-hr-°F (40.89 W/m-°C)
	Specific heat	0.1216 Btu/lb-°F (509.11 J/kg-°C)
	Thermal expansion coefficient	7.386 ×10^{-6}/°F (1.329×10^{-5}/°C)
Mechanical material properties	Young's modulus	25620 ksi (176643 MPa)
	Yield strength	50 ksi (345 MPa)
	Average of initial RT_{NDT}	-10 °F (-23.33 °C)
	Std. deviation of initial RT_{NDT}	0 °F (0 °C)
	Average of Cu content	0.29 wt%
	Average of Ni content	0.68 wt%

3. PTS analyses

Fig. 4 shows resulting failure probabilities of each PTS transient according to the different PFM codes. Although there are some differences in input parameters of each code, FAVOR code shows the most conservative failure probability. Meanwhile, R-PIE and PASCAL codes indicated similar results. The most severe PTS transient was SBLOCA I001 and the least one was MSLB A001. The maximum differences among each code were about two orders of magnitude and increased in the low fluence region.

4. Sensitivity analysis

In order to examine the effects of analysis parameters, a series of analyses were performed with different Cu content (0.29, 0.24 and 0.19 wt%), Ni content (0.68, 0.58 and 0.48 wt%) and initial RT_{NDT} (-10, 10 and 30 °F) conditions. RT_{NDT} is nil ductility transition temperature of materials which used to check the chances of cracking. From the calculation procedures of each PFM code, Cu and Ni contents had a significant effect on $\triangle RT_{NDT}$ which makes the probabilistic distribution on RT_{NDT} and initial RT_{NDT} influenced the K_{Ia} and K_{IC} at the crack tip. All the sensitivity analyses were conducted under the same conditions of SBLOCA transient and 8 × 10^{19}n/cm^2 fluence, except for Cu, Ni and initial RT_{NDT}.

Figs. 5 (a) ~ (c) show the sensitivity analysis results of each PFM code. In terms of the failure probability, initial RT_{NDT} had larger effect than Cu and Ni contents. In a view of each PFM code, variation of failure probabilities caused by different parametric conditions was the largest in FAVOR code and the smallest in PASCAL code.

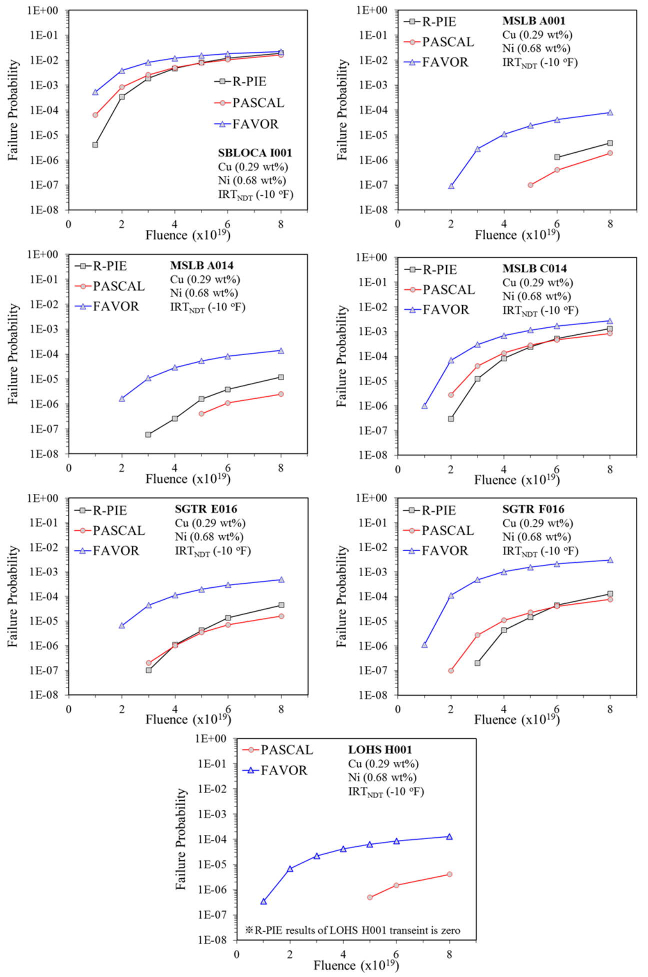
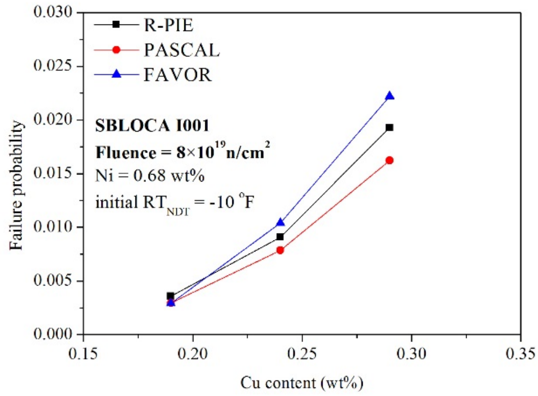


Fig. 4. Failure probabilities under PTS transient conditions

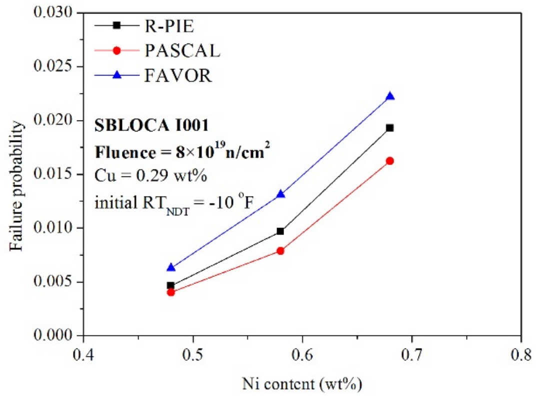
5. Conclusions

This study was carried out to evaluate the structural integrity of RPV under typical PTS transients with three PFM codes, R-PIE, PASCAL and FAVOR. Failure probabilities of PFM codes according to the each transient were compared and results of sensitivity analyses on major parameters were also compared. Thereby, the following conclusions have been derived.

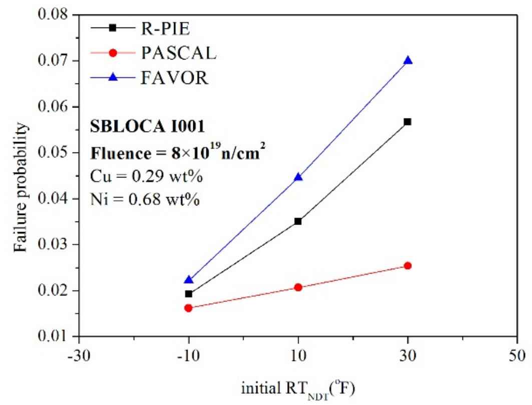
(1) Among the PFM codes, FAVOR code showed the most conservative results. Differences of analysis results between R-PIE and PASCAL were not significant.
(2) The most severe PTS transient was a SBLOCA and the least one was a MSLB. The differences of failure probabilities from each PFM code were larger in low fluence region.
(3) From the sensitivity analysis results, initial RT_{NDT} had a significant effect on failure probability than Cu and Ni contents.
(4) Variation of failure probabilities caused by different parametric conditions was the largest in FAVOR code and smallest in PASCAL code.



(a) Cu content



(b) Ni content



(c) Initial RT_{NDT}

Fig. 5. Effects of analysis parameters on failure probabilities

REFERENCES

[1] M. J. Jhung, Reactor probabilistic integrity evaluation (R-PIE) code, KINS/RR-545, Korea Institute of Nuclear Safety, 2008.
[2] K. Shibata, K. Onizawa, Y. Li and D. Kato, Development of probabilistic fracture mechanics code PASCAL and user's manual, JAERI-Data/Code 2001-011, Japan Atomic Energy Research Institute, 2001.
[3] P. T. Williams, T. L. Dickson and S. Yin, Fracture analysis of vessels-oak ridge FAVOR v12.1 computer code: theory and implementation of alogorithms, methods and correlations, ORNL/TM-2012/567. Oak Ridge National Laboratory, 2012.
[4] Y. H. Choi, Comparison of vessel failure probabilities during PTS for korean nuclear power plants, KINS/RR-692, Korea Institute of Nuclear Safety, 2009.