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Probabilistic analysis of PWR Reactor Pressure Vessel under Pressurized Thermal Shock

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Abstract: The beltline region is the most important part of the reactor pressure vessel, become embrittlement due to neutron irradiation at high temperature after long-term operation. Pressurized thermal shock is one of the potential threats to the integrity of beltline region also the reactor pressure vessel structural integrity. Hence, to maintain the integrity of RPV, this paper describes the benchmark study for deterministic and probabilistic fracture mechanics analyzing the beltline region under PTS by using FAVOR code developed by Oak Ridge National Laboratory. The Monte Carlo method was employed in FAVOR code to calculate the conditional probability of crack initiation. Three problems from Probabilistic Structural Integrity of a PWR Reactor Pressure Vessel (PROSIR) round-robin analysis were selected to analyze, the present results showed a good agreement with the Korean participants' results on the conditional probability of crack initiation.

Keywords: *Probabilistic Fracture Mechanics, Beltline Region, Reactor Pressure Vessel, Pressurized Thermal Shock.*

I. INTRODUCTION

The Reactor Pressure Vessel is the most important component of the Pressure Water Reactor (PWR) as it contains the core and control mechanisms. Pressurized Thermal Shock (PTS), one of many potential threats to the structural integrity of Reactor Pressure Vessel (RPV), has been studied for more than 30 years [1]. PTS is caused by several reasons such as break of the main steam pipeline, inadvertent open valve etc., then the emergency core cooling water injects into the RPV, including with the high pressure inside the RPV and flaws in the wall thickness make the appearance of PTS. There are two approaches in analyzing the RPV under the PTS, the first is deterministic analysis, and the second is probabilistic analysis. The deterministic analysis includes thermal, stress and fracture mechanics analysis. Many researchers, for example, Elisabeth K. et al. [2], Myung J.J. et al. [3], IAEA TECDOC [4], Guian Q. et al. [5], performed calculation the distribution of thermal, stress and stress intensity with wall thickness and time. The deterministic results combining with main uncertainty parameters (initial reference

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temperature, crack density, size, aspect ratio, neutron fluence, Cu, Ni content of RPV material) are used as the input of the second approach to work out the probabilistic of crack initiation. There were many studies conducted to perform probabilistic analysis such as probabilistic structural integrity of PWR RPV under PTS, Myung J.J. et al. [3]; comparison of pressure vessel integrity analyses and approaches for VVER 1000 and PWR vessels for PTS conditions Oya O.G. [6]; and probabilistic assessment of VVER RPV under pressurized thermal shock, Vladislav P. et al. [7].

In this study, so as to get more experience in PFM analysis and make a benchmark for sequent studies, a PTS transient of round-robin program named Probabilistic Structural Integrity of a PWR Reactor Pressure Vessel (PROSIR) [9] with a PWR is analyzed using FAVOR 12.1. The deterministic and probabilistic fracture mechanics results are compared with participant results and showed good agreement.

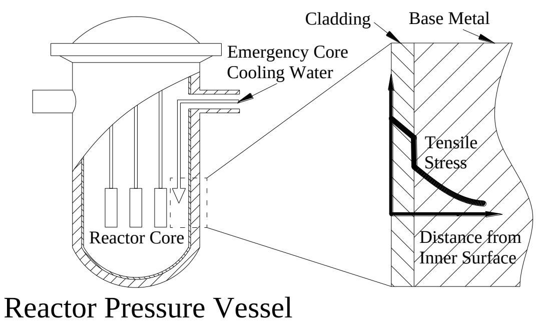


Fig. 1 Beltline region of PWR Reactor Pressure Vessel

A. FAVOR Model

FAVOR code has been developed by ORNL to perform deterministic and probabilistic fracture mechanics analysis of a RPV subjected to PTS events since the 1980s [4]. The beltline region of RPV is the interested object to analysis. **Fig. 1** shows the beltline region with the base metal and cladding thickness. In a deterministic analysis, the history of the coolant temperature, pressure, and heat transfer coefficient is the basic input. Additionally, the geometry, thermo-mechanical of RPV wall thickness is utilized to calculate thermal, stress and stress intensity factor (SIF) distribution with wall thickness during the transient. In FAVOR, the 1-D model with finite element method is used to perform estimation for distribution of temperature and stress through the wall thickness during the transient time. Meanwhile, the influence function method is used to estimate stress intensity factor of the postulated cracks. The fracture toughness K_{IC} of RPV wall thickness is expressed as the Eq. 1.

$$K_{Ic} = 23.65 + 29.56 \exp[(0.02(T - RT_{NDT})] \quad (1)$$

In probabilistic fracture mechanics analysis, the probability of crack initiation and vessel failure is calculated based on Monte Carlo method. The reference temperature RT_{NDT} in FAVOR is estimated based on Regulatory Guide 1.99 ver.2 [10].

$$RT_{NDT} = \text{Initial } RT_{NDT} + \Delta RT_{NDT} + \text{Margin} \quad (2)$$

ΔRT_{NDT}: the mean value of the adjustment in reference temperature caused by irradiation.

$$\Delta RT_{NDT} = (CF) f^{(0.28-0.10 \log f)} \quad (3)$$

CF (°F): the chemistry factor, a function of copper and nickel content.

f(10^{19} n/cm^2, E> 1 MeV): the neutron fluence at any depth in the vessel wall.

$$f = f_{surf}(e^{-0.24x}) \quad (4)$$

f_{surf} (10^{19} n/cm^2, E> 1 MeV): the neutron fluence at the inner surface of the vessel.

x (inches): the depth into the vessel wall measured from the vessel inner surface.

Margin (°F): the quantity

$$Margin = 2\sqrt{\sigma_I^2 + \sigma_\Delta^2} \quad (5)$$

σ_I: the standard deviation for the initial RT_{NDT}.

σ_Δ: the standard deviation for ΔRT_{NDT}.

The conditional probability of crack initiation of certain K_I implemented in FAVOR is expressed as:

$$P(K_{Ic} \le K_I)\begin{cases} 0; & K_I \le aK \\ 1-\exp\left\{-[\frac{K_I-a_K}{b_K}]^4\right\}; & K_I > a_K \end{cases} \quad (6)$$

$$a_K = 19.35 + 8.335\exp[0.02254(T - RT_{NDT})] \quad (7)$$

$$b_K = 15.61 + 50.132\exp[0.008(T - RT_{NDT})] \quad (8)$$

B. PROSIR Model

PROSIR is a round-robin exercise with the objective to issue some recommendation of best practice in probabilistic analysis of RPV and to understand the key parameters of this type of probabilistic analysis methods, such as transient description and frequency, material properties, defect type and distribution [11]. There are 3 round-robin problems (RR) to consider the effect of different parameters on the conditional probability of crack initiation such as reference temperature, transients, crack shape, crack depth distribution etc. There are 16 participants from 9 countries joined the round robin. In this study, the present study is compared with the results from Korean participants.

Shift formula equations are separated to express for base metal and weld. Base metal:

$$\Delta RT_{NDT}=[17.3+1537*(P-0.008)+238*(Cu-0.08)+191*Ni^2Cu]*\varphi^{0.35} \quad (9)$$

Weld:

$$\Delta RT_{NDT}= [18+823*(P-0.008)+148*(Cu-0.08)+157*Ni^2Cu]*\varphi^{0.45} \quad (10)$$

P, Cu, Ni: % of phosphorus, copper and nickel

φ: fluence in n/m^2 divided by 10^{23}

Irradiation decrease through the RPV wall:

$$\varphi = \varphi_0^{e-0.125x} \text{ for } 0<x<0.75t, \text{ and } x \text{ in } 10^{-2}\text{m} \quad (11)$$

The fracture toughness K_{IC} of RPV wall thickness

$$K_{Ic} = 36.5 + 3.1\exp[0.036(T - RTNDT + 55)] \quad (12)$$

II. PROBLEM DEFINITION

A. Reactor Vessel

A typical 3-loop PWR is selected by the round-robin to study the probabilistic risk evaluation, with the inner radius of 1994 mm, a base metal thickness of 200 mm and a cladding thickness of 7.5 mm. Six participants from Korea joined the project, the computer codes and participants are shown in **Table I**. Each participant performed deterministic and probabilistic fracture mechanics analysis with different models, and computer codes. The participant P1 used influence coefficient from VISA to express K_I. The participants P2, P3 both used influence coefficient from PROSIR to assume K_I. The participant P4 also used calculated K_I directly from the finite element analysis. The participant 5 used PROBie-Rx computer code to estimate K_I. The participants P6 used influence coefficient from FAVOR 2.4 to calculate K_I. The thermo-mechanical properties of wall thickness including base metal and weld are shown as in **Table II**. **Table III** shows the chemical compositions and initial RT_{NDT} of the base metal and weld.

B. Analyzed Transient

One transient analyzed in this study is a typical PTS-transient (TR3), **Fig. 2a** shows the pressure and temperature histories for this transient. Total time of the transient is 15000 seconds. The transient is cold re-pressurization with pressure and temperature decrease simultaneously right after the transient begin. Then the typical PTS shows slowly increase of temperature, quickly increase and maintenance of pressure from the 7000th second after the starting of the transient.

C. Major round-robin problems

1. Round-robin 1 (RR1)

The toughness property distribution versus aging is investigated in this round-robin. The random parameters are initial RT_{NDT}, copper, phosphorus and nickel contents, RT_{NDT} shift. The results are mean values of RT_{NDT} distribution for the different level of the fluence.

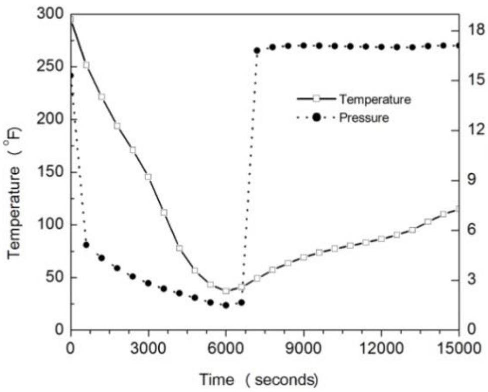
Table I. Participants and Computer Codes

Participant	Organization	Deterministic Analysis	Probabilistic Analysis
P1	Korea Power Engineering Company (KOPEC)	PREVIAS	PREVIAS
P2	Korea Power Engineering Company (KOPEC)	ABAQUS V. 5.8 & Influence Function Method	Fortran
P3	Korea Atomic Energy Research Institute (KAERI)	ABAQUS V. 6.3 Influence Function Method	PFAP Version 1.0
P4	Korea Atomic Energy Research Institute (KAERI)	ABAQUS V. 6.3 FEM 3D Method	Excel
P5	Korea Institute of Nuclear Safety (KINS)	PROBie-Rx	PROBie-Rx
P6	Korea Institute of Nuclear Safety (KINS)	FAVOR V. 02.4	Origin
P7	Present Study	FAVOR V. 12.1	FAVOR V. 12.1

Table II. Thermal and mechanical material properties of base metal, welds and cladding of the RPV

	Initial RT_{NDT}		% Copper (Cu)		% Phosphorus (P)		% Nickel (Ni)	
	Mean	1SD	Mean	2SD	Mean	2SD	Mean	2SD
Base metal	-20°C	9°C	0.086	0.02	0.0137	0.002	0.72	0.1
Weld	-30°C	16°C	0.120	0.02	0.0180	0.002	0.17	0.1

a.



b.

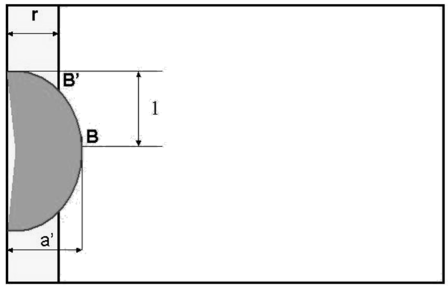


Fig. 2 a. Transient histories of PTS (TR3), **b.** Surface breaking crack, a' = 19.5mm, 2l = 117mm

2. Round-robin 2 (RR2)

This round-robin problem investigates the conditional probability of crack initiation (*CPI*) for PTS transient with surface breaking crack (RR2) in weld and base metal. The postulated surface breaking crack as shown in **Fig. 2b** consist of crack depth a' of 19.5 mm, crack length 2l of 117 mm. The random parameters are toughness distribution from RR1, chemical composition. The non-random parameters are vessel geometry, transient 3, the neutron fluence decreases through the thickness, thermal and mechanical material properties. For the fracture mechanics model, the conditions are elastic K_I computation for a surface with no plasticity correction, crack initiation only at the deepest point B and no residual stress, except the free stress temperature of 300°C.

3. Round-robin 3 (RR3)

In this round-robin problem, the random and non-random parameters are almost the same with the RR2 problem, the only difference is the flaw size distribution of Pacific Northwest National Laboratory [9] with defect aspect ratio a/2l=1/6 analyzed to express *CPI* versus time. The PNNL and Marshall flaw size distribution is shown in **Fig. 3**.

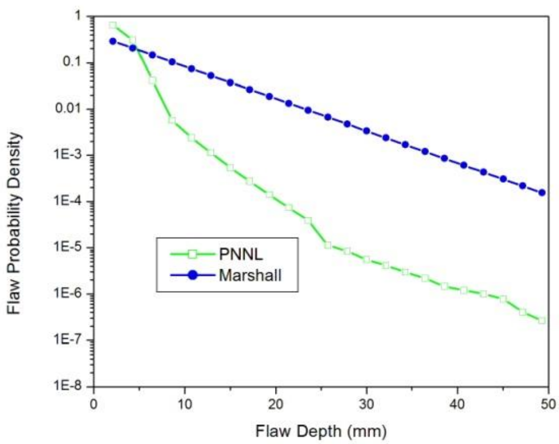


Fig. 3 Flaw distribution and size

III. RESULTS AND DISCUSSION

A. Deterministic Fracture Mechanics Results

In this study, the postulated flaw was given for PWR with a specific size and shape to verify whether it was initiated or not during the PTS transients. To ensure a perfect fitting at pre-requisite for all interesting participants, deterministic analysis including thermal, stress and comparison of temperature and hoop stress with wall thickness at 7200th second are presented in **Fig. 4**. In **Fig. 4a**, a good agreement was reached among temperature distribution results of the participants and the present result, only one participant is an outlier, possibly due to using too simplified analytical method [4]. The outer wall is hotter than the inner because of the inner coolant temperature. As the different thermal conductivity between cladding and base metal, the temperature gradient in the cladding is decliner than the temperature of the base metal. **Fig. 4b** shows the hoop stress distribution results of the participants and this study results. The stress at cladding is much higher than at the base metal, it is due to different thermal expansion coefficient of the base metal and the cladding. This study hoop stress is also equivalent to participant's results.

Besides the temperature and hoop stress distribution with RPV wall thickness, the history of the temperature and stress intensity factor at crack tip (the deepest point) are estimated and shown as in **Fig. 5**. The histories of temperatures at crack tip are very consistent in **Fig. 5a**. However, the stress intensity factors (K_I) histories of participants at crack tip show in **Fig. 5b** are not exactly coincident although those results are acceptable. To estimate K_I, participant P4 used direct FEM 3D to determinate J-integral, participant P1, P2, P3, P6 and this study used influence function method with influence coefficients from different sources, those are VISA, PROSIR, FAVOR 12.1, respectively. Moreover, participant P5 carried out K_I calculation using influence method with independently developed influence coefficient. So the different models and influence coefficients used by the participants are the main reason of the difference among K_I results.

a. **b.**

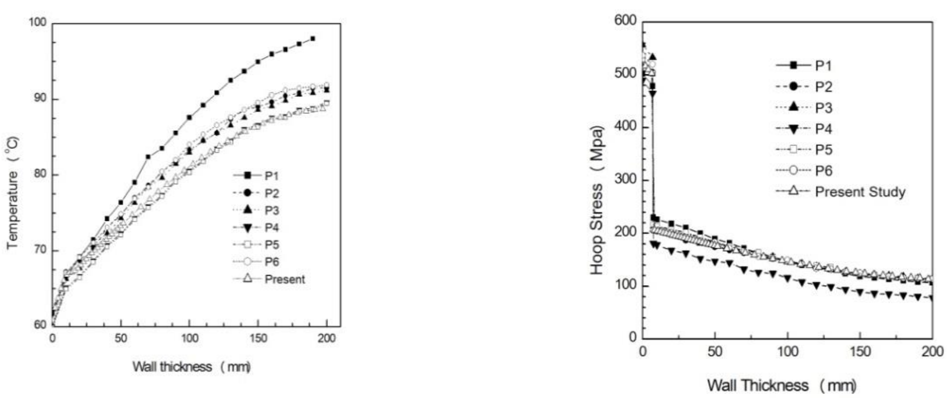


Fig. 4 Variation of **a.** Temperature and **b.** Hoop stress along with wall thickness at 7200th second.

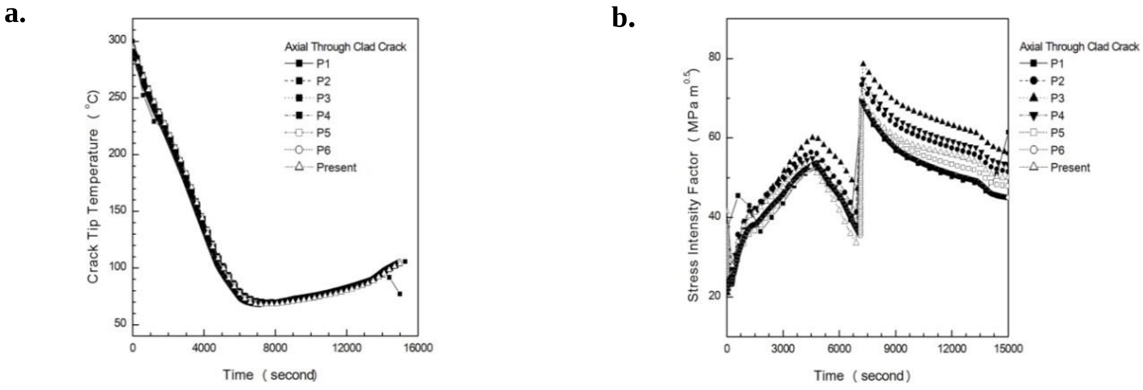


Fig. 5 History of **a.** Temperature and **b.** Stress intensity factor at crack tip

B. Probabilistic Fracture Mechanics Results

The probability of crack is initiation is estimated based on flaw data (flaw density, size, and location), RPV beltline embrittlement (neutron fluence, Cu, Ni, P content), and the results obtained in the deterministic analysis (the distribution of hoop stress, stress factor intensity with wall crack). The mean RT_{NDT} results are shown in **Fig. 6**, all the participants use Reg. 1.99 rev.2 to calculate RT_{NDT}. But there are big differences in the results because of the participant 2 to 6, they also use Eq. 10, 11 to express shift RT_{NDT}, the participant 1 beside equation 1 also used depth as a random variable for RT_{NDT}. This study uses Reg. 1.99 rev.2 to calculate RT_{NDT}.

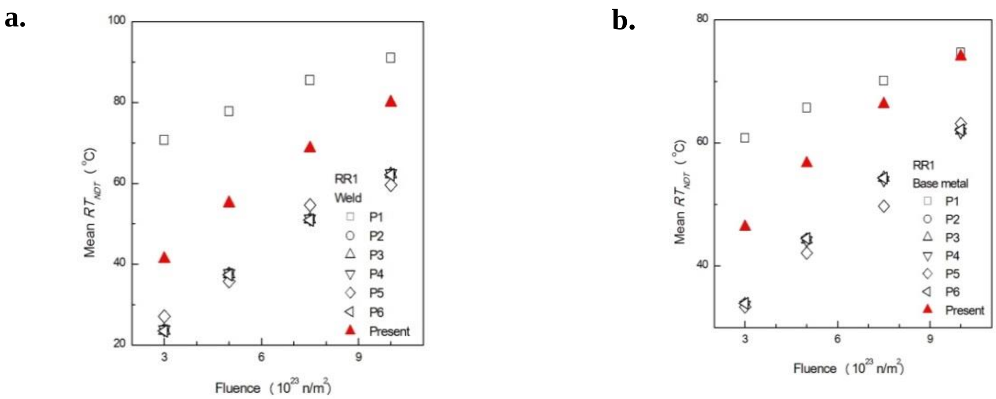


Fig. 6 Variation of mean RT_{NDT} with fluence

As for the RR2, RR3 problems, the conditional probabilities of crack initiation (*CPI*) calculated for the weld and the plate of RPV are shown as in **Fig. 7, 8**. **Fig.7a, 7b** show the CPIs in case of an inner surface breaking crack. The participant P1 results are higher than the results of other participants, it is due to over-estimation of RT_{NDT} [3]. There are slight differences among other participant results because of the different methods used in estimating stress intensity and performing PFM analysis. However, it can be see that this study results almost converge with those of participants P2, P3, P4, P5 at higher neutron fluence. **Fig. 8a, 8b** shows the CPIs in case of PNNL crack distribution, the results are lower than those of **Fig. 7a, 7b** proving that the crack distribution decreases the CPIs. The reasons of the difference among participant results are the same with those in **Fig 7a, 7b**. In summary, although the CPIs are not very coincident but this study results are in the same trend and in the middle of other results, showing a fairly good agreement with the results of participants.

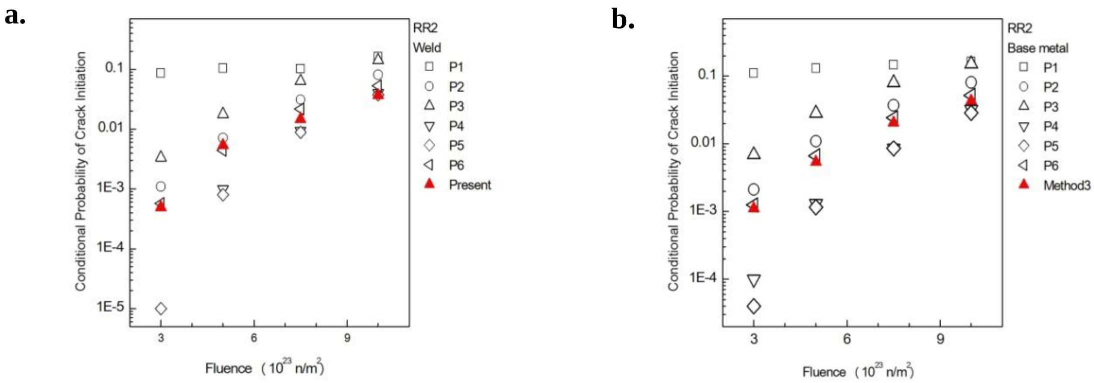


Fig. 7 Surface breaking flaw

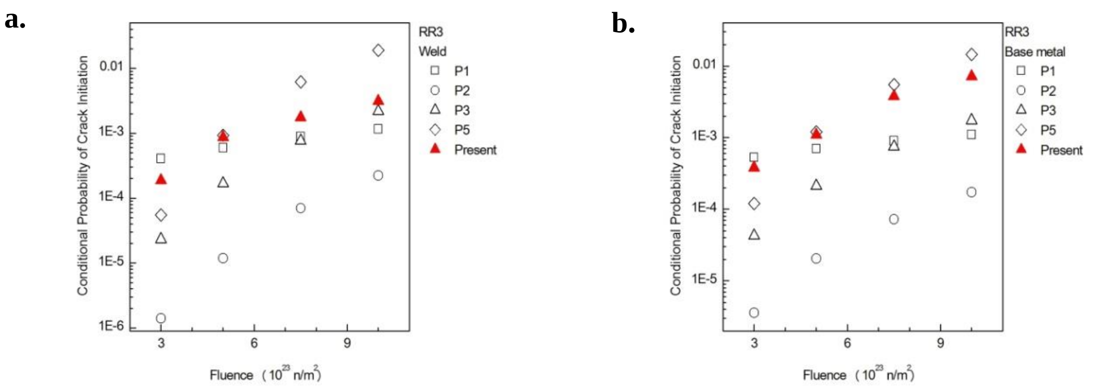


Fig. 8 PNNL flaw size distribution

IV. CONCLUSIONS

The transient in the round-robin proposal of the RPV PROSIR with postulated flaws is performed deterministic and probabilistic analyses using FAVOR 12.1. The results are compared with other results from PROSIR and the conclusions are inferred. The deterministic results are in very good agreement with the other results. As for the probabilistic fracture mechanics, this study results are the same trend and in good agreement with the Korean results. By practicing three cases from PROSIR, the experience and knowledge about probabilistic fracture mechanics analysis significantly improved. Through the benchmark study, it reveals some weakness of the FAVOR 12.1 such as the limited aspect ratio between length and depth of the postulated cracks, it is unable to perform DFM and PFM analysis for semi-elliptical under clad crack. Based on the benchmark test, a succeeding study will be conducted to modify FAVOR 12.1 source code and calculating procedure so as to improve its capabilities to increases the type of crack and the crack aspect ratio FAVOR 12.1 be able to analyze. Additionally, deterministic and probabilistic fracture mechanics of VVER reactor pressure vessel will be analyzed by this computer code.

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