Sensitivity Analysis of Failure Probability on PTS Benchmark Problems of Pressure Vessel Using a Probabilistic Fracture Mechanics Analysis Code*

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In this paper, the results of the sensitivity analyses of failure probability are presented for pressure vessel under PTS (Pressurized Thermal Shock) transient, by using our new probabilistic fracture mechanics analysis code. The pressure, the fluid temperature at the inner surface of pressure vessel and other analysis conditions are based on an international benchmark study on PTS. The temperature and stress distributions through wall thickness during transient are obtained by a heat transfer and an elasto-plastic stress analysis with FEM. The new models and methodologies introduced in our code are summarized and the effect of overlay clad and behavior of semi-elliptical crack on the failure probability are investigated especially.

Key Words: Probabilistic Method, Numerical Analysis, Fracture Mechanics, Thermal Shock, Nuclear Engineering, Sensitivity Analysis, Failure Probability, Pressure vessel, R6 Method

1. Introduction

Probabilistic Fracture Mechanics (PFM) has been used in the field of reliability analysis and life extension assessment for important structural components as a rational evaluation methodology. Several analysis codes such as VISA⁽¹⁾, OCA-P⁽²⁾ have been developed. In order to provide a utility analysis tool, however, it is still necessary to improve the accuracy and reliability by introducing new fracture mechanics models and evaluation methodologies. The PFM analysis code named PASCAL (PFM Analysis of Structural Components in Aging LWR) has been developed in this point of view at Japan Atomic Energy Research Institute.

In this paper, the new models and methodologies introduced in this code are summarized and results of the sensitivity analyses by using PASCAL are present-

ed, considering the influence of initial crack size distributions, the direction and the shape of the initial crack, the difference of aspect ratio of semi-elliptical crack, the existence of overlay clad and the non-destructive inspection. The investigations are especially concentrated on the effect of overlay clad and the behavior of semi-elliptical surface crack on the failure probability of pressure vessel, because these problems have been emphasized to be resolved by improving the fracture mechanical model of clad and the short crack model in PTS (Pressurized Thermal Shock) evaluations^{(3),(4)}.

The pressure and fluid temperature transients at the inner surface of the vessel and the other analysis conditions are based on the international PTS benchmark study RPV-PTS-ICAS (Reactor Pressure Vessel Pressurized Thermal Shock International Comparative Assessment Study)⁽⁵⁾ organized by PWG3 of OECD/NEA/CSNI. The temperature and stress distributions through wall thickness during transient were obtained by FEM analysis.

2. Outline of the PASCAL Code

PASCAL has been developed to evaluate the

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Table 1 Main features of PASCAL

Item		Specifications
Analysis objects		Probability of crack initiation and failure of PV under PTS transients
Stress and temperature analysis		Finite element method
Initial crack type and distribution	Crack type	Infinite length surface crack. Semi-elliptical surface crack (fixed initial length, or aspect ratio). Semi-elliptical surface crack (with distribution of both depth and Aspect ratio).
	Depth distribution	Marshall(exponential), OCTAVIA and user's defined distribution
	Aspect ratio distribution	Log-normal, exponential and user's defined distribution
Probabilistic simulation	Probabilistic variable	Initial crack size and distribution, chemical compositions, neutron fluence, fracture toughness, RT_{NDT} , crack detect capability in inspection
	Simulation method	Monte Carlo simulation method
	Re-simulation of deviations	Three procedures are available that are used in VISA-II , OCA-P and FAVOR
Fracture mechanics analysis	Stress intensity factors introduced	Infinite surface crack: the same equations as VISA-II. Semi-elliptical surface crack: equations of Newman-Raju or SHIRATORI. PV including clad: a convenient method.
	Fracture criterion	Fracture toughness K_{Ic} , K_{Ia} and net-section collapse criterion R6 method (FAC: Option 1,2, Category 1,3)
Simulation model	Initiation and extension model for semi-elliptical surface crack	Model A: Semi-elliptical crack is replaced by an infinite surface crack subsequent to the initiation to thickness direction (VISA-II original model). Model B: Semi-elliptical crack is replaced by an infinite surface crack subsequent to the initiation to surface direction (PASCAL Model). Model C: Crack initiation and extension both to surface and thickness direction is evaluated independently (PASCAL Model).
	Fracture toughness curves	Mean value functions by USNRC. ASME Sect. XI equations. Mean value functions by ORNL.
	Evaluation of RT_{NDT} shift	Equations shown in Regulatory Guide 1.99, Rev.2. Equations shown in JEAC4206-1991.
	Fluence distribution	Exponential decay function through vessel wall . User's defined function.
	Inspection model	VISA-II near surface examination model VISA-II volumetric examination model. LLNL inspection model.
	Effect of WPS	Time history of K_I is considered.

conditional probability of crack initiation and failure of pressure vessel under transient conditions such as PTS events. The verification analyses have shown that the accuracy and reliability of this code are sufficient⁽⁶⁾⁻⁽⁸⁾.

The main features of PASCAL are summarized in Table 1. The probabilistic simulation method used in this code is the importance sampling and the stratified sampling Monte Carlo method. The initial crack size distributions, chemical compositions, neutron fluence, fracture toughness and ductile brittle transition temperature are treated as probabilistic variables.

Four kinds of initial crack shown below can be evaluated in this code.

- Infinite-length surface crack.
- Semi-elliptical surface crack with fixed initial length.
- Semi-elliptical surface crack with fixed initial aspect ratio.

- Semi-elliptical surface crack with distribution of both depth and aspect ratio.

For infinite-length surface crack, the solutions of Simonen⁽¹⁾ are used to calculate the stress intensity factor, and for semi-elliptical surface crack, the solutions of Newman-Raju⁽⁹⁾ and Shiratori⁽¹⁰⁾ are used. When the clad is included in the analysis, a convenient procedure is used based on the superposition of three stress distributions⁽⁶⁾⁻⁽⁸⁾.

For the model of semi-elliptical surface crack extension, three models as shown in Fig.1 are introduced in PASCAL, and they are described as follows :

- Model A : A semi-elliptical crack is replaced by an infinite surface crack once the crack grows deeper.
- Model B : A semi-elliptical crack is replaced by an infinite surface crack once the crack grows longer.
- Model C : Crack growth and arrest in both depth and width directions are evaluated independently by using K_I at the surface or deepest point respectively.

Model A and Model B are approximate models for cutting down the calculating time. Model A has been used in VISA-II, and has been considered conservatively. Comparing with Model A and Model B, Model C is a deliberated model capable of evaluating the configuration of the crack during extension, although it is time-consuming. In this paper, Model C is used because the previous calculations⁽⁶⁾⁻⁽⁸⁾ have shown that the approximate model such as Model A or B does not always give conservative failure probability depending on the transient type and initial aspect ratio.

By using PASCAL, the initiation and arrest of a crack or the fracture of a vessel can be evaluated by K_{Ic} , K_{Ia} and the net-section stress criterion. In this case, the mean value functions developed by NRC⁽¹⁾, the equations shown in ASME Sect. XI⁽¹⁾, the mean value functions developed by ORNL⁽²⁾ or the functions defined by user can be used to calculate K_{Ic} , K_{Ia} . Furthermore, the elastic-plastic fracture analysis model based on R6 method (Option 1, 2; Category 1, 3) is also introduced in this code in order to analyze fracture modes from brittle fracture to ductile tearing.

Besides the features described above, the effects

Fig. 1 The models for semi-elliptical surface crack extension

of warm pre-stress, nondestructive inspection can also be taken into account.

3. Heat Transfer and Thermal Stress Analysis

Before the probabilistic fracture mechanics analyses were carried out, the stress and the temperature had been calculated by using a FEM analysis code for the PTS transients.

3.1 Problem statement for PTS transients

As described above, transients and analysis conditions given by the PFM benchmark study in RPV-PTS-ICAS⁽⁶⁾ are used in this paper. The effect of the overlay clad is included in this problem. The geometry of pressure vessel is shown as follows:

- Inner diameter: 4 394 mm
- Wall thickness of the base metal: 219 mm
- Thickness of the overlay clad: 4.8 mm

The material properties of base metal and clad are shown in Table 2.

Two kinds of transient shown as following are given in PFM study in RPV-PTS-ICAS.

- The simplified stylized transient (transient T0).
- The small break loss of coolant transient (transient T1).

The time histories of pressure and fluid temperature of these two transients are shown in Fig. 2 and Fig. 3 respectively.

3.2 Analysis results of temperature and stress distribution

The FEM analysis code MARC was used to calculate the time history of temperature and stress distribution through the vessel wall. 25 quadratic axisymmetric elements and 51 nodes were used in the thickness direction.

The analyses were carried out for the models both with and without overlay clad. As the examples, results of temperature and circumferential stress distribution for the small break loss of coolant

Table 2 Material properties of base metal (SA508 Class3) and cladding 309L-308L

	Base metal and weld metal				Clad			
Temperature (°C)	20	100	200	300	20	100	200	300
Modulus of elasticity (GPa)	204.0	200.0	193.0	185.0	197.0	191.5	184.0	176.5
Poisson's ratio (-)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Thermal conductivity (W/m°C)	37.7	39.9	40.5	39.5	14.0	15.2	16.6	17.9
Density · Specific heat capacity (10 ⁶ J/m ³ °C)	3.488	3.775	4.087	4.423	3.559	3.907	4.160	4.293
Mean thermal expansion coefficient (10 ⁻⁶ /°C)	11.22	11.79	12.47	13.08	15.54	16.00	16.60	17.10
Yield strength (MPa)	350	350	350	350	350	350	350	350
Tangent modulus (MPa)	2000	2000	2000	2000	2000	2000	2000	2000

Fig. 2 Time history of pressure

Fig. 3 Time history of fluid temperature

Fig. 4 Time history of temperature distribution for transient T1

Fig. 5 Time history of circumferential stress distribution for transient T1

transient T1 are shown in Fig. 4 and Fig. 5 respectively.

In Fig. 5, the increase of stress occurs at the overlay clad when the clad exists in the vessel, and the stress at the clad even exceeds yield strength at 50 minute after the transient due to the difference of thermal expansion between clad and base metal. The stress in longitudinal direction shows similar tendency with Fig. 5 although it is omitted in this paper.

4. Probabilistic Fracture Mechanics Analysis

Probabilistic fracture mechanics analyses were carried out by using PASCAL, based upon the FEM analysis results shown above.

4.1 Probabilistic simulation models

The basic analysis conditions, simulation models or methods given in the PFM problems in ICAS benchmark⁽⁵⁾ are shown as follows.

- Flaw depth distribution: Marshall distribution with step-wise cumulative function⁽⁵⁾ specified by this benchmark problem.

- Chemical compositions: Cu: Mean value=0.3%, Standard deviation = 0.025%, $0\% \leq \text{Cu} \leq 0.4\%$, Ni: Mean value=0.75%, Standard deviation=0.1%, $0\% \leq \text{Ni} \leq 1.2\%$

- Fluence attenuation equation⁽⁵⁾: $F(x) = F_{ID} \exp(-0.24x)$, x : depth into vessel wall (inch), F_{ID} : Fluence at inside wall (n/cm^2)

- $RT_{NDT}^{(5)}$: $RT_{NDT} = RT_{NDT0} + \Delta RT_{NDT} + ER_{RTN} \cdot \sqrt{(\sigma_{RTNDT0})^2 + (\sigma_{RTNDT})^2}$, RT_{NDT0} : 20F, σ_{RTNDT0} : 17F, ΔRT_{NDT} : Equation of NRC Regulatory Guide 1.99, Rev. 2⁽¹¹⁾, ER_{RTN} : Gaussian distribution with a mean value of 0 and a standard deviation of 1.0, truncated at 3σ

- Fracture toughness: $K_{Ic} = ER_{K_{Ic}} \cdot (K_{Ic})_{mean}$, $K_{Ia} = ER_{K_{Ia}} \cdot (K_{Ia})_{mean}$, $(K_{Ic})_{mean}$, $(K_{Ia})_{mean}$: Mean value functions developed by ORNL⁽²⁾, $ER_{K_{Ic}}$: Gaussian distribution with a mean value of 0 and a standard deviation of 0.15, truncated at 3σ , $ER_{K_{Ia}}$: Gaussian distribution with a mean value of 0 and a standard deviation of 0.1, truncated at 3σ

- Re-simulating procedure for deviation: The deviations of K_{Ic} and K_{Ia} are simulated at each new crack tip position, and the deviation of RT_{NDT} is simulated once per vessel.

Using the above simulation models, analyses for infinite surface crack with longitudinal or circumferential direction under transients T0 and T1, and longitudinal semi-elliptical crack under T0 were performed. Besides, some sensitivity analyses were also carried out with respect to the influence of initial crack size distributions, the direction and the shape of

the initial crack, the model of the non-destructive inspection and difference between the models with and without overlay clad.

4.2 Sensitivity analyses for the infinite length surface crack

As mentioned above, PASCAL has many original functions such as the crack growth model, the initial crack distribution, the calculating procedure of the stress intensity factor for the vessel including overlay clad, and R6 method for evaluating initiation or arrest of the crack. In addition, PASCAL possesses the same functions as the existing code such as VISA-II, and the accuracy and reliability of this code have been verified in some early analyses⁽⁶⁾⁻⁽⁸⁾. In this section, the sensitivity analyses are carried out for the infinite length crack.

The failure probabilities of vessel with longitudinal infinite cracks under the small break loss of coolant transient are shown in Fig. 6 for five models. In this simulation, the effect of overlay clad is not included in the model except for the final case (Marshall distribution with clad).

In PASCAL, if the inspection is considered, the initial crack distribution will be modified by the probability function of non-detection of crack. In this analysis, the inspection model proposed by Harris⁽¹²⁾ is used for the case that pre-service nondestructive inspection is considered. The probability function of non-detection of crack is expressed as follows:

$$P_{ND} = \varepsilon + \frac{1}{2}(1 - \varepsilon)\text{erfc}(\nu \ln A/A^*)$$

$$A = \begin{cases} \frac{1}{2}\pi ab, & 2b < D_B \\ \frac{1}{4}\pi a D_B, & 2b \geq D_B \end{cases}$$

$$A^* = \frac{1}{4}\pi a^* D_B$$

$$\nu : 1.60$$

$$a^* : 1.25 \text{ inch}$$

$$D_B : 1.0 \text{ inch}$$

Fig. 6 Failure probabilities for longitudinal infinite length surface crack

$$\varepsilon : 0.0$$

As shown in Fig. 6, the crack depth distribution of Marshall gives higher failure probability than the distribution of OCTAVIA⁽¹⁾, and the difference between them is about one order of magnitude. Thus it can be said that the initial crack distribution may give large influence on the results. It can also be seen that the inspection and warm pre-stress are effective measures to improve the integrity of the vessel, as they can decrease the failure probability over one order of magnitude. In PASCAL the effect of warm pre-stress is evaluated by comparing the stress intensity factor at current time step to that in the previous time step, the crack initiation is allowed only if the stress intensity factor is increasing with time step.

In the case the clad is included in the analysis, the results of failure probability show higher value than the case without clad due to the difference of the stress distributions between these two cases as shown in Fig. 5.

The effect of overlay clad was investigated in detail for infinite length surface crack, and the results of the crack initiation probabilities are shown in Fig. 7. The small break loss of coolant transient is used in this analysis. When the clad is included in the vessel, both of longitudinal infinite surface crack and circumferential crack give higher probability than the models without clad. This tendency is similar with Fig. 6.

As described previously, the stress intensity factor is calculated by the superposition of three simple stress distributions by modeling the discontinuous stress distribution with overlay clad into three continuous distribution and assuming the thickness of clad is sufficiently thin compared with the base metal. As the fact, under the analysis condition given in RPV-PTS-ICAS, the thickness of clad is only 2% of the thickness of the base metal. The basic concept of this convenient method can be illustrated by using Fig. 8 in the case that the stress distribution along the thickness of

Fig. 7 The influence of overlay clad on crack initiation probability

wall is linear. The stress intensity factor can be obtained by using the following equation.

$$K_I = K_{I(1)} + K_{I(2)} - K_{I(3)}$$

In this way, the stress intensity factor including clad can be calculated for both infinite and semi-elliptical surface cracks in both longitudinal and circumferential direction.

Since the stress intensity factor of longitudinal infinite surface crack considering the overlay clad has been given by Simonen⁽¹⁾ and has been used in VISA-II, the values calculated in this convenient approximate procedure are compared with the results obtained by the equation of Simonen in Fig. 9. As shown in this figure, good agreement can be observed.

By using this convenient approximate procedure, the failure probability of the vessel with overlay clad were analyzed, and the results are shown in Fig. 10.

Since the fluid temperature of transient T0 has a steep decrease at the inner surface at the early stage of transient as shown in Fig. 3, the failure probabilities with transient T0 show higher value than transient T1 as shown in Fig. 10. The difference of failure probabilities between these two types of transient reaches two orders of magnitude for circumferential crack at low fluence. From these results, it can be

Fig. 8 Concept of the convenient method

Fig. 9 Comparison of stress intensity factor calculated by PASCAL and VISA-II

said that the time history of the fluid temperature and the pressure during transient can give large influence on failure probabilities of the vessel.

4.3 Sensitivity analyses for the semi-elliptical surface crack

Sensitivity analyses were carried out for the semi-elliptical cracks with a/b (a : the crack depth, b : the half length of crack) = 1/5, 1/3 and 1/1 using the small break loss of coolant transients T1. The results are shown in Fig. 11.

As described previously, three growth models for semi-elliptical surface crack are incorporated in PASCAL and Model C is used in this paper, because previous investigations⁽⁶⁾⁻⁽⁸⁾ about growth model of finite length crack have shown that the approximate model such as Model A or B can not give appropriate failure probability depending on the transient and initial crack aspect ratio.

As shown in Fig. 11, the failure probability decreases with the initial aspect ratio $\beta = b/a$. As described in chapter 2, the semi-elliptical surface crack with probabilistic distribution for both depth and aspect ratio can also be evaluated by PASCAL as well as the function to analyze the crack with fixed aspect ratio and fixed initial length. The failure

Fig. 10 Failure probabilities for main problems given by RPV-PTS-ICAS

Fig. 11 Failure probabilities for parametric study problems given by RPV-PTS-ICAS

Fig. 12 Comparison of probabilities of semi-elliptical crack with different aspect ratio

probabilities of the vessel with semi-elliptical surface crack considering probabilistic distribution for both depth and aspect ratio are shown in Fig. 12.

In Fig. 12, the small break loss of coolant transient is used and clad is not included in the vessel. For the semi-elliptical surface crack with independent probabilistic distribution for depth and aspect ratio, Marshall distribution for crack depth and the log-normal distribution by Harris⁽¹³⁾ for aspect ratio are used. The log-normal probability density function of aspect ratio ($\beta = b/a$) can be expressed as follows:

$$P(\beta) = \frac{C}{\sigma\beta\sqrt{2\pi}} \exp\left\{-\frac{1}{2}\left[\frac{\ln(\beta/\mu)}{\sigma}\right]^2\right\}$$

$$\sigma = 0.5382$$

$$\mu = 1.336$$

$$C = 1.142.$$

In Fig. 12, the failure probabilities of semi-elliptical surface crack are also calculated for crack with fixed initial aspect ratio $a/b = 1/6$, $1/3$ and $1/1$. The failure probabilities of crack with $a/b = 1/6$ and $a/b = 1/3$ are greater than the values obtained for crack with distribution of initial aspect ratio. But the failure probabilities of crack with $a/b = 1/1$ give opposite results because a semi-elliptical crack with high value of a/b more likely to extend to the surface direction than to the thickness direction. The cumulative probability for initial crack with aspect ratio (β) greater than 5 is considered to be about 1%⁽¹³⁾. Thus for semi-elliptical crack, it seems that the distribution of aspect ratio should be used in probabilistic analysis in order to get appropriate results.

5. Conclusion

In this paper, the results of sensitivity analyses by PASCAL were presented using the transients and analysis conditions given by RPV-PTS-ICAS.

In the sensitivity analyses, the effects of initial crack depth distribution, the direction and the shape of the initial crack, the non-destructive inspection and

warm pre-stress were investigated with respect to the failure behavior of the vessel under PTS events. Furthermore, sensitivity analyses focused on the effect of overlay clad and the behavior of semi-elliptical surface crack were carried out using the simplified stylized transient (transient T0) and the small break loss of coolant transient (transient T1). The conclusions are summarized as follows:

(1) The initial crack distribution may give large influence on the failure probability. The difference of the failure probabilities between the distribution of Marshall and that of OCTAVIA is about one order of magnitude for the infinite length surface crack under the transient T1.

(2) The inspection and warm pre-stress are effective measures to improve the integrity of the vessel. They can decrease the failure probability over one order of magnitude under the current analysis condition.

(3) The convenient method for SIF considering the overlay clad is sufficiently accurate, and it can be used for both infinite and semi-elliptical surface cracks in both longitudinal and circumferential direction. For the case the overlay clad is included, the result of failure probability is greater than the case without clad, due to the difference of the stress distributions.

(4) For semi-elliptical surface crack, the deliberated model (Model C) for evaluating the extension of crack has been used. From the analysis results for semi-elliptical surface cracks with different initial aspect ratios and for semi-elliptical surface cracks with independent probabilistic distribution for depth and aspect ratio, it was found that the distribution of aspect ratio should be used in probabilistic analysis in order to get appropriate results.

The probabilistic analysis will be carried out further for semi-elliptical surface crack, especially for the case with the existence of overlay clad.

References

- (1) Simonen, F.A., Jonshon, K.I., Liebetrau, A.M., Engel, D.W. and Simonen, E.P., VISA-II-A Computer Code for Predicting the Probability of Reactor Pressure Vessel Failure, NUREG/CR-4486, (1986).
- (2) Cheverton, R.D. and Ball, D.G., OCA-P, A Deterministic and Probabilistic Fracture-Mechanics Code for Application to Pressure Vessels, NUREG/CR-3618, (1984).
- (3) Soneda, N., Hirano, M., Ohtani, Y., Urabe, Y., Yoshimura, S. and Yagawa, G., Japanese PTS Benchmarking Study using Probabilistic Fracture Mechanics, Proc. 3rd Int Conf. on Nuclear Engineering, ICONE-3, (1995), pp. 411-416.

- (4) Soneda, N., Verification of Probabilistic Fracture Mechanics Analysis Code by PTS Benchmarking Study, Report of Central Research Institute of Electric Industry, (in Japanese), T93053, (1994).
 - (5) Sievers, J., Problem Statement for Reactor Pressure Vessel Pressurized Thermal Shock International Comparative Assessment Study (RPV PTS ICAS), GRS Technical Note, (1996).
 - (6) Shibata, K., Kato, D. and Li, Y.S., Development of a Reliability Analysis Code Based on Probabilistic Fracture Mechanics Methodology (1), Outline of the Code, Proceedings of 1998 Fall Meeting of the Atomic Energy Society of Japan, (in Japanese), Vol. II(1998), p. 519.
 - (7) Kato, D., Li, Y.S. and Shibata, K., Development of a Reliability Analysis Code Based on Probabilistic Fracture Mechanics Methodology (2), Analysis Methodology, Verification and Sensitivity Analysis, Proceedings of 1998 Fall Meeting of the Atomic Energy Society of Japan, (in Japanese), Vol. II(1998), p. 520.
 - (8) Shibata, K., Kato, D. and Li, Y.S., Development of PFM Code for Evaluation Reliability of Pressure Components Subjected to Transients Loading, Transaction of the 15th International Conference on Structural Mechanics in Reactor Technology (SMiRT-15), SMiRT-Paper No. M1-A2-JP, Seoul, Korea, (1999).
 - (9) Newman, J.C. and Raju, I.S., Analysis of Surface Cracks in Finite Plate under Tension or Bending Loads, NASA Technical Paper 1575, (1979).
 - (10) Shiratori, M., Analysis of Stress Intensity Factor for Surface Cracks Subjected to Arbitrarily Distributed Stresses, Bulletin of Faculty Engineering, Yokohama National Univ., Vol. 35(1986), pp. 1-25.
 - (11) US NRC Regulatory Guide 1.99: Radiation Embrittlement of Reactor Vessel Materials, Revision 2, (1989).
 - (12) Harris, D.O., Dedhia, D.D. and Lu, S.C., Theoretical and User's Manual for pc-PRAISE, NUREG/CR-5864, (1992).
 - (13) Harris, D.O., Lim, E.Y. and Dedhia, D.D., Probability of Pipe Fracture in the Primary Coolant Loop of a PWR Plant, NUREG/CR-2189, (1981).
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