G06/5

Sensitivity Analysis of PTS Event by Probabilistic Fracture Mechanics

N. SONEDA, T. ONCHI, T. TAKAO
Central Research Institute of Electric Power Industry, Tokyo, Japan

1 INTRODUCTION

Probabilistic fracture mechanics (PFM) analysis is one of the most promising methods for evaluating the integrity of a reactor pressure vessel (RPV) against a pressurized thermal shock (PTS) event, the most severe accident for a pressurized water reactor RPV. U.S. NRC regulations, 10CFR50.61 (U.S. NRC 1985), recommend the use of the PFM technique for the safety analysis of the RPV, whose RT_{NDT} is projected to exceed the PTS screening criterion. However, since the results of the PFM analyses are given in terms of failure probability of the RPV, the validity of the results can not be assessed by experiment. Therefore, reliability of PFM analysis results must be made clear in some other way.

In the reliability assessment, attentions should be payed on the input data for PFM analyses, some of which are known to have large uncertainties. Since such uncertainties may cause large uncertainties in the analysis results, the relationship between those uncertainties have to be investigated thoroughly.

In this study, we develop a failure probability database of sensitivity to input data, and propose a procedure to estimate the uncertainties in the results of PFM analyses.

2 PFM ANALYSIS CODE, PROFMAC

2.1 Outline of the code

For the integrity analysis of a RPV against a PTS event, we have developed a PFM code, named *PROFMAC*, which is based on the two representative PFM codes, VISA (Stevens et al. 1983) and OCA-P (Cheverton 1984). The *PROFMAC* code consists of two parts: deterministic and probabilistic analysis parts.

In the deterministic analysis part, temperature distribution is calculated through the pressure vessel wall as a function of time, and then, the stress intensity factor K_I as a function of flow size and time is calculated by stress and fracture mechanics analyses utilizing linear elastic fracture mechanics (LEFM).

In the probabilistic analysis part, a failure probability calculation is carried out utilizing the Monte-Carlo simulation technique combined with the stratified sampling method. The flow of the probabilistic part is represented in Fig. 1, showing that, flaw size, neutron fluence, fracture

SMiRT 11 Transactions Vol. G (August 1991) Tokyo, Japan, © 1991

toughness, RT_{NDT} value, copper and nickel contents are simulated according to their probability density functions.

In the present fracture mechanics analyses, considerations are given to crack initiation based on K_{Ic} criterion, crack arrest based on K_{Ia} criterion and the warm prestress (WPS) effect.

2.2 Thermal, stress and stress intensity factor analysis

Thermal transient analysis is performed using 1-dimensional finite element analysis code. The change of coolant temperature, T, is modeled by the following equation developed by NRC staff (U.S. NRC 1982):

$$T = T_0 - (T_0 - T_f)\cdot(1 - e^{-\beta t}) \quad (1)$$

where t is the elapsed time, β the cool down rate, T_0 and T_f the initial and final temperature of the coolant, respectively. Cladding is considered in this analysis.

For each time step of the thermal transient analysis, analysis of thermal as well as pressure stresses is performed using 1-dimensional axisymetric finite element analysis code.

In the fracture mechanics analysis, flaws are assumed to be infinitely long axial surface cracks from the inside surface of the vessel, whose crack tips correspond to the nodal points of the finite elements. Stress intensity factors for all the cracks are calculated by means of the influence function method developed by Heliot et al. (Heliot 1978). The effect of cladding is not taken into account.

2.3 Probabilistic variables

(a) Crack depth: As a crack depth distribution before inspection, PROFMAC employs the distribution by Marshall (Marshall 1982), whose probability density function f(a) for the crack depth a has the form:

$$f(a) = 0.16\, e^{-0.16a}. \quad (2)$$

The probability of crack non-detection by inspection is also reported by Marshall as:

$$B(a) = 0.005 + 0.995\, e^{-0.113a}. \quad (3)$$

The probability density function for flaw depth is given by the product of eqs. (2) and (3). Thus, the crack existing probability $P(\Delta a)$ of a flaw, whose depth is in the range of Δa, can be calculated by the following equation:

$$P(\Delta a) = \int_{\Delta a} f(a)B(a)da\,. \quad (4)$$

(b) Neutron fluence: Normal distribution is used for the neutron fluence. The mean value of the fluence at the inside surface of the vessel wall, F_{surf}, is specified by the user. Standard deviation is defined as 30% of the mean value.

Fluence attenuation in a vessel wall is modeled by the following equation:

$$F = F_{surf} e^{-0.0094x}, \quad (5)$$

where x is the distance from the inside surface of the wall in meters.

(c) Copper and nickel contents: Normal distribution is used for copper content. The mean value of copper content is given by the user, while the value of 0.025 wt.-% is assumed here for the standard deviation. Nickel content is treated as a constant value, which is given by the user.

(d) RT_{NDT}: RT_{NDT} is the sum of the initial RT_{NDT}, RT_{NDT0}, and its shift due to neutron irradiation, ΔRT_{NDT}, for both of which normal distribution is used. A standard deviation of 9°C is assumed for the RT_{NDT0}.

ΔRT_{NDT} is calculated as a function of copper and nickel contents and neutron fluence using the equation either of 10CFR50.61 or of Regulatory Guide 1.99 Rev.2 (U.S. NRC 1988).

(e) Fracture toughness, K_{Ic} and K_{Ia}: Normal distributions are defined for both fracture mechanics parameters. The respective standard deviations of 15% and 10% are for the both K_{Ic} and K_{Ia} values of ASME Code, which give the lower bound values of K_{Ic} and K_{Ia}. The mean values are calculated and found from adding twice the above standard deviations to the values of ASME Code.

2.4 WPS effect

In the LEFM, fracture occurs when the applied stress intensity factor of a crack, K_I, exceeds the fracture toughness of the material, K_{Ic}. However, when the material had been subjected to a higher load at a higher temperature beforehand, fracture does not occur even if the value of K_I becomes greater than that of K_{Ic}. This effect is known as warm prestress (WPS) effect.

In the present calculation, WPS effect is taken into account in the way that fracture will not occur when K_I is decreasing.

3 SENSITIVITY ANALYSIS

Sensitivity analyses are performed to lay the sensitivity database. In the calculations, neutron fluence, copper and nickel content, initial RT_{NDT}, final cool down temperature and cool down rate are varied as parameters. The effects of ΔRT_{NDT} calculation method and of the WPS are also examined.

All the calculation cases are summarized in Table 1. The total number of calculations come up to 560 cases. The changes of water temperature for the three types of events are defined is Fig.2, where a final temperature of 107°C is for both events 1 and 3 and 177°C for event 2, while a cool down rate of 6.7×10^{-4} min^{-1} is for event 1, and 1.7×10^{-3} min^{-1} for both events 2 and 3. Figure 2 shows the change of the water temperature under such parameters. An internal pressure of 15.9MPa was kept constant during these events. The material properties used in these calculations are shown in Table 2.

Figure 3 shows changes of the failure probability with neutron fluence for different nickel contents. The sensitivity (i.e. slope of curve) of the failure probability increases with decreasing neutron fluence. The failure probabilities in the region where the neutron fluence is greater than 5×10^{19} n/cm^2 are almost saturated. In other words, the sensitivity is almost zero.

Figure 4 shows changes of the failure probability with initial RT_{NDT} also for nickel contents. The changes of the failure probability is almost linear with initial RT_{NDT} in all cases. The sensitivity becomes, however, larger when the nickel content is small.

Figure 5 and 6 demonstrate the effects of final temperature and cooldown rate on the failure probability for variable nickel contents. In Fig. 5, the final temperature of solid lines is lower than that of broken lines. The effect of final temperature is very large when copper and nickel content are small. However, the sensitivity to the copper content change is very small when the nickel content is large. On the other hand, in Fig. 6, where cool down rate of solid lines is larger than that of broken lines, the effect of cooldown rate is relatively small compared with the results of Fig. 5.

The effect of WPS on the failure probability is shown in Fig. 7. The solid lines trace the results of analyses without WPS effect, while the broken lines those with WPS effect. This figure clearly demonstrates that WPS is very effective for the prevention of failure except for vessels of high copper and high nickel content.

Finally, the effect of the ΔRT_{NDT} prediction method is examined as shown in Fig. 8, where the results of R.G. 1.99 Rev.2 and 10CFR50.60 are plotted in solid lines and broken lines, respectively. The results from both procedures differ not so much, except for the results for the vessels of low cupper content.

4 RELIABILITY EVALUATION PROCEDURE

To quantify the reliability of the failure probability, we estimate the uncertainty of failure probability by using the following general approximation equation:

$$dP = \sum_{i=1}^{n} \frac{\partial P}{\partial x_i} dx_i \ , \qquad (6)$$

where, P is the failure probability, X_i the input value, dX_i the uncertainty of x_i, $\frac{\partial P}{\partial x_i}$ the sensitivity of failure probability to x_i.

The effort to quantify the uncertainties in input data, dx_i, had been performed by ASME Section XI Task Group (1991). On the other hand, the sensitivities, $\frac{\partial P}{\partial x_i}$, can be extracted from the results as shown in Figs. 3 to 8. Such work is now under way.

5 CONCLUSIONS

A procedure is proposed to evaluate the reliability of the failure probability of the PFM analysis. Furthermore, a large number of sensitivity analyses are performed to lay the database for such evaluations.

REFERENCES

U.S. Nuclear Regulatory Commission (1885). Fracture Toughness Requirements for Protection Against Pressurized Thermal Shock Events, Code of Federal Regulations 10CFR50.61.

Stevens, D. et al. (1983). VISA: A Computer Code for Predicting the Probability of Reactor Pressure-Vessel Failure, NUREG/CR-3384.

Cheverton, R. and Ball, D. (1984). OCA-P, A Deterministic and Probabilistic Fracture-Mechanics Code for Application to Pressure Vessels, NUREG/CR-3618.

U.S. Nuclear Regulatory Commission (1982). NRC Staff Evaluation of Pressurized Thermal Shock, Enclosure A to Commission Paper, SECY-82-465.

Heliot, J., Labbens, R., and Pellissier-Tanon, A. (1979). Semi-Elliptical Cracks in the mendional Plane of a Cylinder Subjected Stress Gradients, ASTM STP 677, pp.342-64.

Marshall, W. et al., (1976) An Assessment of the Integrity of PWR pressure Vessels, UKAEA Study Group Reports.

U.S. Nuclear Regulatory Commission (1988). Radiation Embrittlement of Reactor Vessel Materials, Revision 2.

ASME Section XI Task Group on Reactor Vessel Integrity Requirements (1991). White Paper on Reactor Vessel Integrity Requirements for Level A and B Conditions.

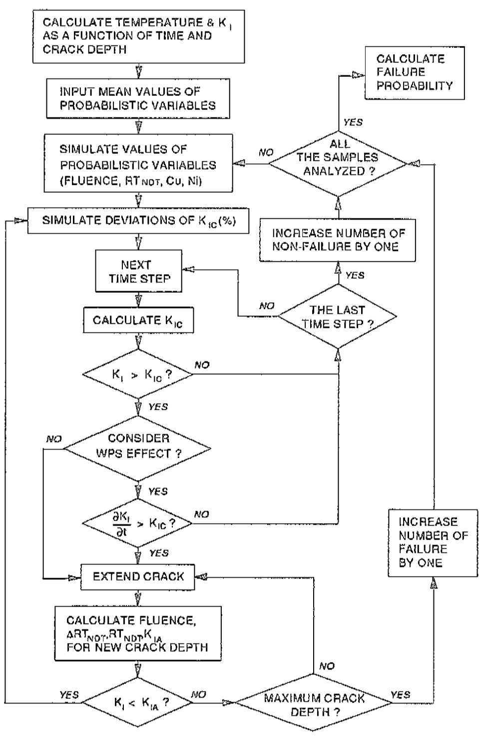

Fig. 1 Flow of Probabilistic Part of PROFMAC

Table 2 Material Properties

	BASE METAL	CLAD
YOUNG'S MODULUS (Pa)	1.931×10^{11}	1.862×10^{11}
POISSON'S RATIO	0.3	0.3
THERMAL EXPANSION COEF. (K^{-1})	1.44×10^{-5}	1.787×10^{-5}
DENCITY (Kg/m^3)	7.836×10^{3}	7.836×10^{3}
HEAT CAPACITY (J/kg·K)	5.02×10^{2}	5.02×10^{2}
HEAT CONDUCTIVITY (W/m·K)	41.5	17.3
HEAT TRANSFER COEF. ($W/m \cdot K^2$)	———	5.678×10^{3}

Table 1 Analysis Conditions

#	EVENT #	ΔRT_{NDT}	RT_{NDT} (°F)	WPS	FLUENCE (n/cm^2)	Cu (Wt.-%)	Ni (Wt.-%)
1	1	R.G. 1.99 Rev. 2	-56	NO	1, 2, 4, 6, 8, 10	0.05, 0.15, 0.25, 0.35	0.2, 0.5, 0.8, 1.1
2	1	R.G. 1.99 Rev. 2	-25	NO	2, 6, 10	0.05, 0.15, 0.25, 0.35	0.2, 0.5, 0.8, 1.1
3	1	R.G. 1.99 Rev. 2	-0	NO	2, 6, 10	0.05, 0.15, 0.25, 0.35	0.2, 0.5, 0.8, 1.1
4	1	R.G. 1.99 Rev. 2	25	NO	2, 6, 10	0.05, 0.15, 0.25, 0.35	0.2, 0.5, 0.8, 1.1
5	1	R.G. 1.99 Rev. 2	-75	NO	2, 6, 10	0.05, 0.15, 0.25, 0.35	0.2, 0.5, 0.8, 1.1
6	1	10CFR 50.61	-56	YES	2, 6, 10	0.05, 0.15, 0.25, 0.35	0.2, 0.5, 0.8, 1.1
7	1	R.G. 1.99 Rev. 2	-56	NO	2, 6, 10	0.05, 0.15, 0.25, 0.35	0.2, 0.5, 0.8, 1.1
8	2	R.G. 1.99 Rev. 2	-56	NO	2, 6, 10	0.05, 0.15, 0.25, 0.35	0.2, 0.5, 0.8, 1.1
9	2	R.G. 1.99 Rev. 2	-56	YES	2, 6, 10	0.05, 0.15, 0.25, 0.35	0.2, 0.5, 0.8, 1.1
10	3	R.G. 1.99 Rev. 2	-56	NO	2, 6, 10	0.05, 0.15, 0.25, 0.35	0.2, 0.5, 0.8, 1.1
11	3	R.G. 1.99 Rev. 2	-56	YES	2, 6, 10	0.05, 0.15, 0.25, 0.35	0.2, 0.5, 0.8, 1.1

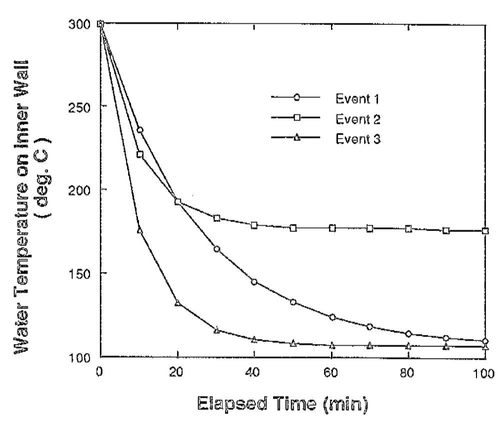

Fig. 2 Definitions of Events

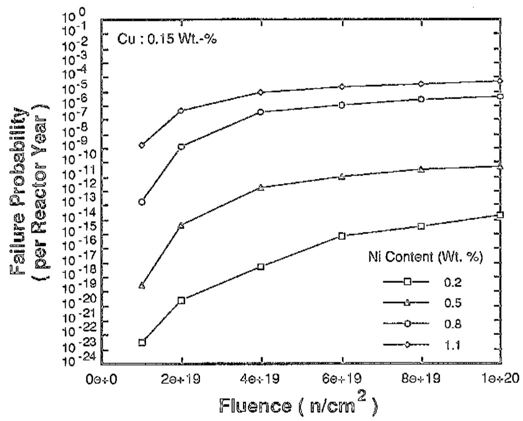

Fig. 3 Effect of Neutron Fluence

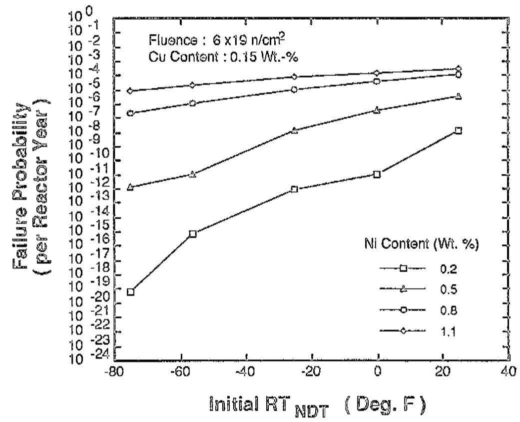

Fig. 4 Effect of Initial RT_{NDT} Values

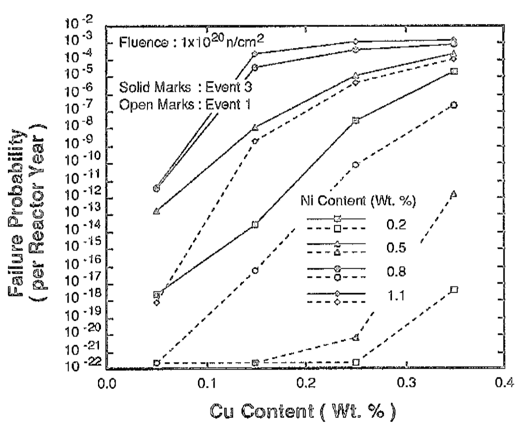

Fig. 5 Effect of Final Temperature

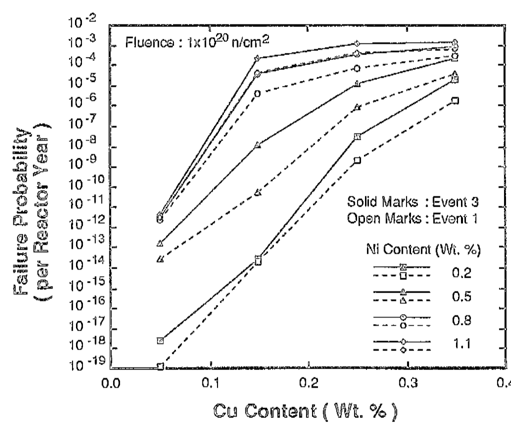

Fig. 6 Effect of Cooldown Rate

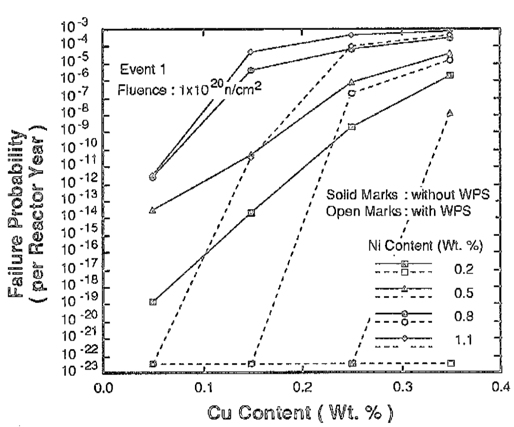

Fig. 7 Effect of WPS

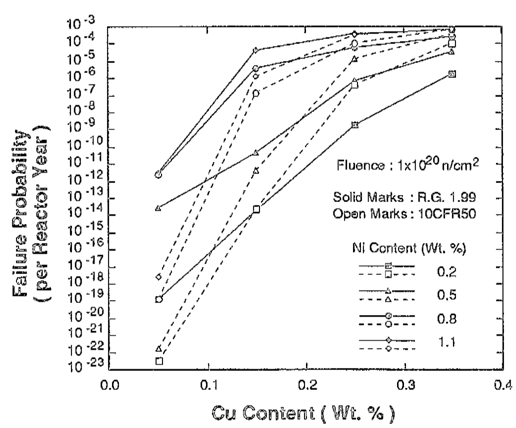

Fig. 8 Effect of ΔRT_{NDT} Prediction Method