Development of PFM analysis code FERMAT based on Japan electric association guide for PFM analysis of RPVs

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INTRODUCTION

Although the implementation of probabilistic fracture mechanics (PFM) on integrity assessment standards of reactor pressure vessels (RPVs) is not yet actualized in Japan, discussion for standardization and application of PFM is progressed. JEAG 4640-2018 (2018) was established for standardizing methods for assessing failure frequency of RPVs based on PFM. The framework to calculate frequency of crack initiation (FCI) and through wall crack frequency (TWCF) was determined by JEAG 4640-2018. PFM analysis codes tend to be complex to operate, and that can be one of obstacles for application of PFM. Central Research Institute of Electric Power Industry (CRIEPI) is developing a simple PFM analysis code FERMAT (Fracture mechanics Evaluation of RPV MATerials) based on JEAG 4640-2018.

OUTLINE OF FERMAT

FERMAT can assess FCI and TWCF based on JEAG 4640-2018. TWCF is calculated as summation of probability of failure multiplied by frequency of transient occurrence for all considered transients. Probability of failure is evaluated from probability of crack initiation and crack arrest behavior after initiation. All processes, including pre- and post- processes, may be managed using a single graphical user interface (GUI) in FERMAT. Figure 1 shows an example of FERMAT's GUI.

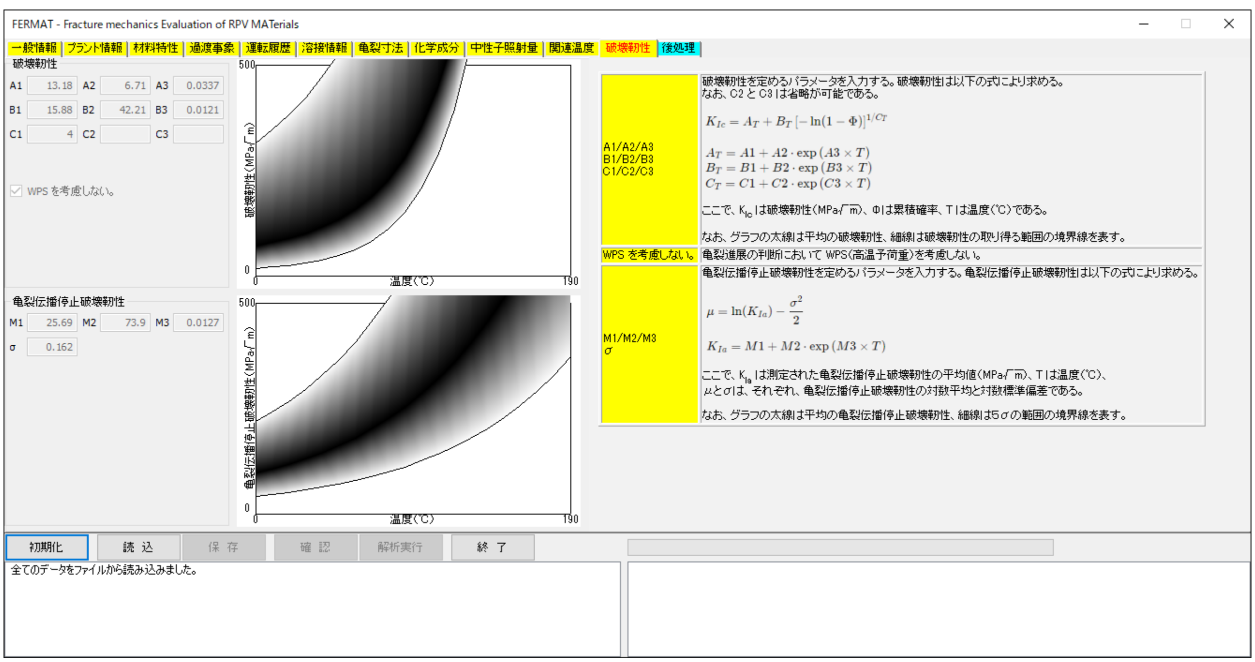

Figure 1. Example of the GUI of FERMAT

Aleatory uncertainty of fracture toughness and crack arrest toughness are considered in FERMAT. FERMAT also considers uncertainty of neutron fluence, chemical compositions, reference temperature, crack distribution, and occurrence frequency of PTS transients as epistemic uncertainty by Monte Carlo method. Through-clad surface cracks and embedded cracks in base metal and weld metal are considered in FERMAT according to JEAG 4640-2018. The stress intensity factor is basically evaluated by using the method specified in the JSME Rules on Fitness-for-Service for Nuclear Power Plants (2012) in FERMAT. The approach is based on the influence function method. Coefficients of fracture toughness curve can be input by users. Fracture toughness curve for Japanese RPV materials is described in commentary section of JEAG 4640-2018, and was used in this study.

ANALYSIS CONDITIONS

Comparison between FERMAT and another Japanese PFM analysis code PASCAL4 (2018) was conducted with two steps: comparison of deterministic analysis results and comparison of PFM analysis results. Analysis conditions of a model case used in PFM analysis in this paper were shown in Table 1. To determine the model case, we referred JEAG 4640-2018, model case developed by JAEA (2018), and chemical compositions of several Japanese RPVs. 20000 was chosen as the number of RPV samples for FERMAT in this study. The number of RPV samples for PASCAL4 was set to be 1000, which was chosen by JAEA in previous study (2018). Analysis conditions for deterministic analysis were shown in Table 2. Deterministic analysis was conducted for one of surface cracks considered in PFM analysis. Time history of coolant temperature, heat transfer coefficient between coolant and internal wall of RPV, and internal pressure were shown in Figure 2, Figure 3, and Figure 4, respectively for stuck open valve (SOV) transient TH129 of Beaver valley nuclear power plant analysed in the US (2004).

Table 1: Main analysis conditions

Category	Item		Value
RPV geometry	Inner radius (to base metal)		2000 mm
	Clad thickness		5.5 mm
	Base metal wall thickness		200 mm
	Height		4000 mm
	Transient		SOV (TH129)
Initial cracks	Surface cracks	Orientation	Circumferential
		Depth (a)	6.5 mm
		Aspect ratio* (2c/a)	2, 6, 10, 100
	Embedded cracks	Orientation	Circumferential and Axial
		Depth (a)	Determined by VFLAW data
		Aspect ratio* (c/a)	1.125, 1.375, 1.75, 2.5, 3.5, 4.5, 5.5, 7, 9, 12.5, 20
		Position	Inner 3/8 of base metal thickness
Radiation condition	Neutron fluence (E>1MeV)	Mean value	7×10^{19} n/cm^2
		Std. deviation	13.1% of mean value
	Neutron flux(E>1MeV)		4.62×10^{10} n/cm^2/s
	Radiation temperature		288 °C

* c is half-length of a crack.

Table 1: Main analysis conditions（Continued）

Cu content	Base metal	Mean value	0.04 wt%
		Std. deviation	0.01 wt%
	Weld metal	Mean value	0.02 wt%
		Std. deviation	0.01 wt%
Ni content	Base metal	Mean value	0.6 wt%
		Std. deviation	0.02 wt%
	Weld metal	Mean value	0.9 wt%
		Std. deviation	0.02 wt%
Initial RT_{NDT}	Base metal	Mean value	-5.0 ℃
		Std. deviation	9.4 ℃
	Weld metal	Mean value	-50.0 ℃
		Std. deviation	9.4 ℃

Table 2: Analysis conditions for deterministic analysis

Category	Item		Value
Initial crack	Surface crack	Location	Base metal
		Direction	Circumferential
		Depth (a)	6.5mm
		Aspect ratio* (2c/a)	6

* c is half-length of a crack.

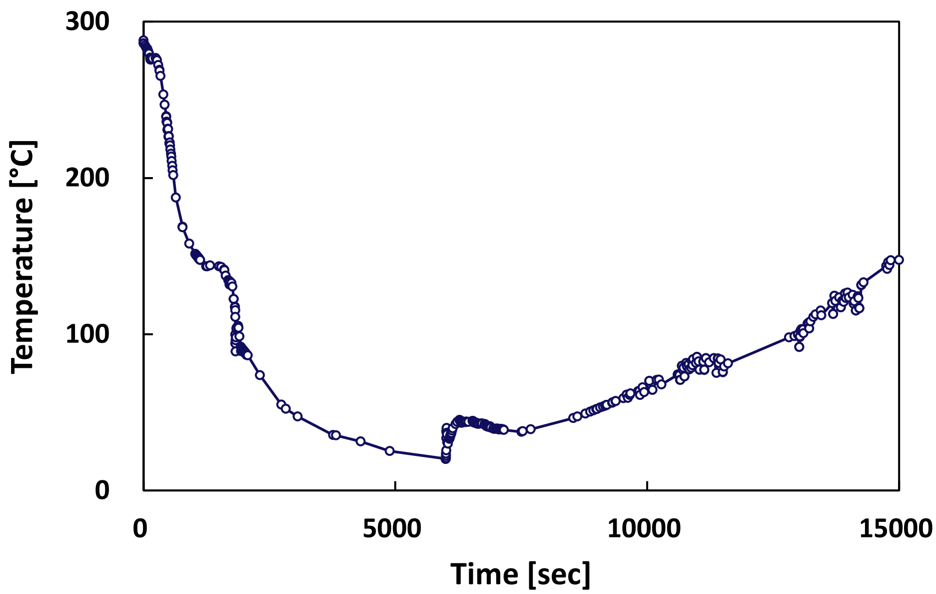

Figure 2. Time history of coolant temperature in SOV

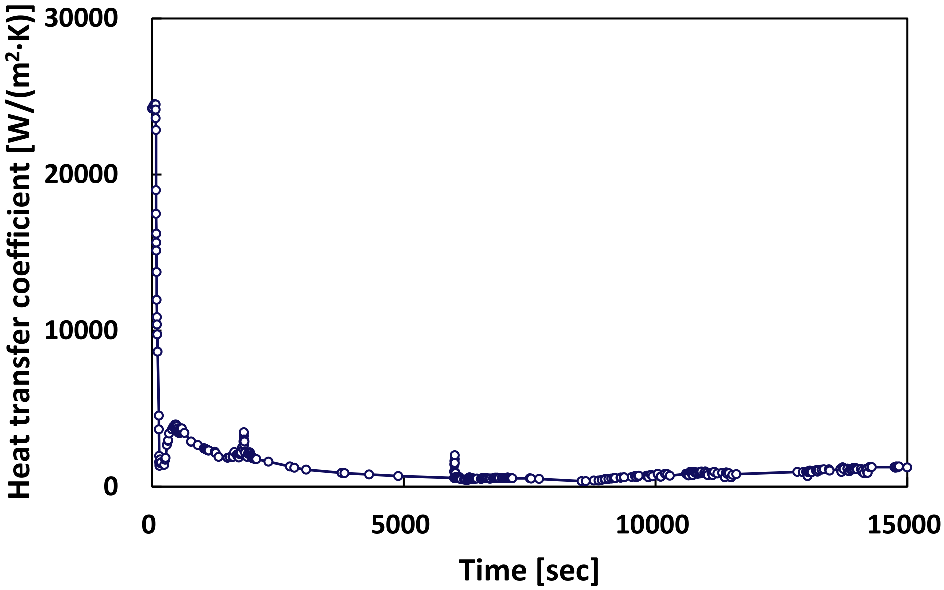

Figure 3. Time history of heat transfer coefficient between coolant and internal wall of RPV in SOV

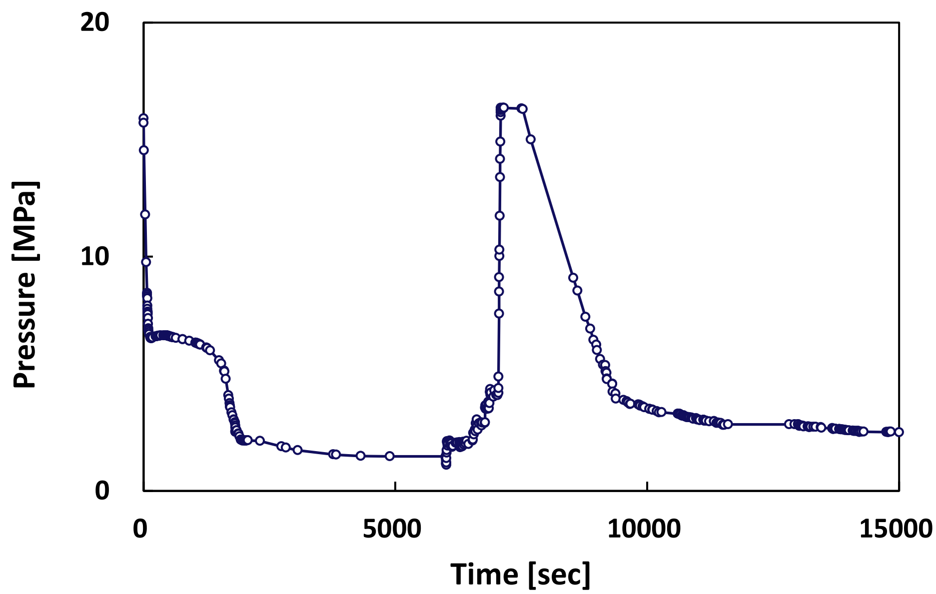

Figure 4. Time history of internal pressure in SOV

RESULTS AND DISCUSSION

As deterministic part of the analysis, stress intensity factor evaluated by FERMAT and PASCAL4 was shown in Figure 5. Significant difference in stress intensity factor for surface crack calculated by those two codes was not observed, though there is some difference in adopted method such as solution of stress intensity factor (2023).

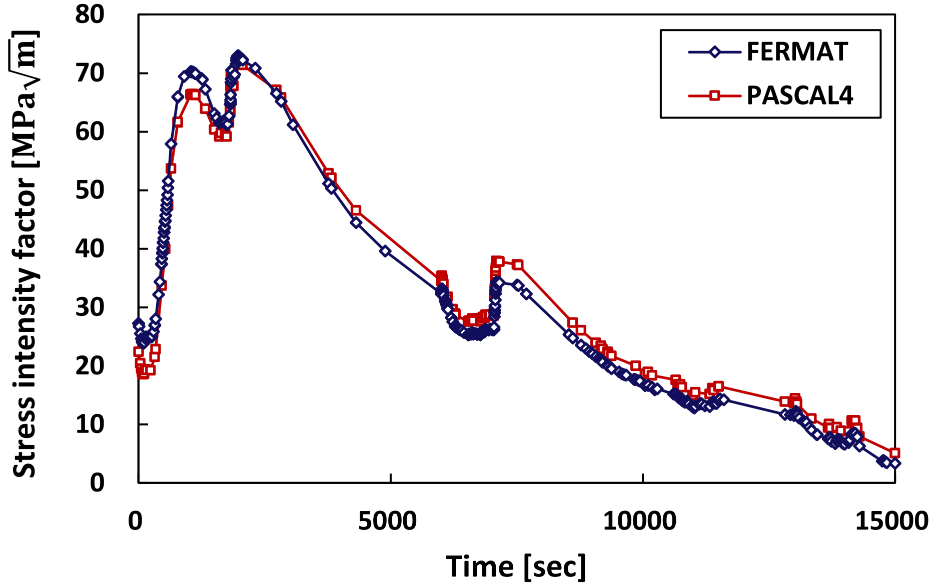

Figure 5. Time dependence of stress intensity factor for a surface crack evaluated by FERMAT and PASCAL4

As probabilistic part of the analysis, the probability of crack initiation and failure assessed by FERMAT and PASCAL4 were shown in Figure 6 and Figure 7, respectively. Outcomes of FERMAT were lower than those of PASCAL4 for both of crack initiation probability and failure probability on 48 EFPY. However, they barely differed from one another. Probability of failure in Figure 7 was nearly equal to probability of crack initiation in Figure 6. Those results indicate that initiated crack is barely arrested in the transient of TH129 in the model case used in this study. Fraction of through wall cracks in all initiated cracks depended on transients.

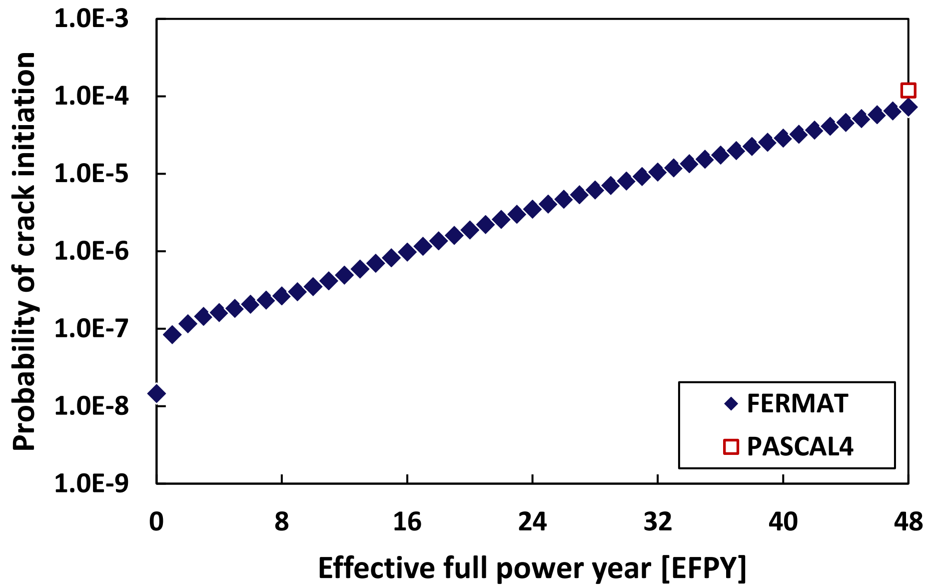

Figure 6. Comparison of the probability of crack initiation between FERMAT and PASCAL4.

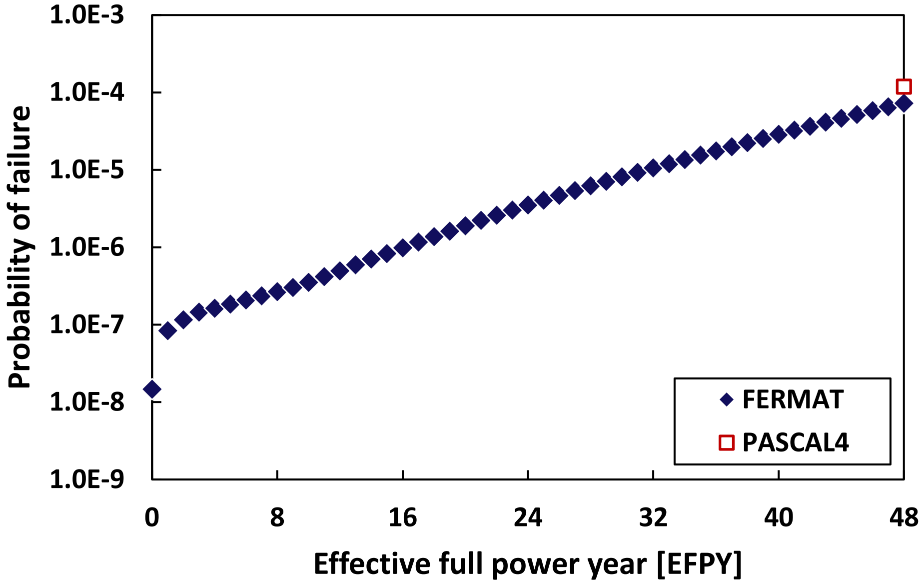

Figure 7. Comparison of the probability of failure between FERMAT and PASCAL4.

CONCLUSION

A new PFM analysis code FERMAT is developed by CRIEPI in Japan. The stress intensity factor evaluated by FERMAT were well corresponding with those evaluated by PASCAL4. Probability of crack initiation and failure were also compared between FERMAT and PASCAL4. The results calculated by those two codes were well corresponding each other.

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