E-Journal of Advanced Maintenance Vol. 11 No. 4 (2020) 172-178
Japan Society of Maintenology

Verification of Safety Margin of Reactor Pressure Vessel Exposed to Various Thermal Transients Based on Probabilistic Approach

Masahide SUZUKI[1], Kenta MURAKAMI[1], Takashi SUZUKI[1*], Ryuta OKAYAMA[1**], Jinya KATSUYAMA[2] and Yinsheng LI[2]

[1] *Nagaoka University of Technology, Kamitomioka 1603-1, Nagaoka, Niigata, 940-2188, Japan*
[1*] *Formerly graduate student, currently Japan Nuclear Fuel Limited,* [1**] *Formerly graduate student, currently Tokyo Electric Power Company,* [2] *Japan Atomic Energy Agency, Tokai-mura, Nakagun, Ibaraki, 319-1195, Japan*

ABSTRACT

For the reactor pressure vessel (RPV) integrity assessment, deterministic fracture mechanics (DFM) is applied considering factors such as neutron irradiation embrittlement, postulated crack and thermals transients etc. On the other hand, probabilistic fracture mechanics (PFM) can evaluate the failure probability considering the uncertainties of several kinds of factors affecting the RPV integrity. The purpose of present study is to obtain insight concerning the further improvement of RPV structural integrity from the probabilistic approach consideration through careful comparisons with DFM approach. It was found that the transients which give rise to the re-pressurization have a possibility to deteriorate the deterministic – probabilistic correlation.

KEYWORDS

Reactor Pressure Vessel, Probabilistic Fracture Mechanics, Pressurized Thermal Shock, Structural Integrity, Irradiation Embrittlement, Fracture Toughness, Thermal Transients

1. Introduction

More than 15 light water reactors (LWRs) in Japan have been operated for more than 30 years. Regarding the structural integrity of aging reactor pressure vessels (RPVs), pressurized thermal shock (PTS), as shown in Fig.1, is considered the most important event for pressurized water reactor (PWR). In the current Japanese Electric Association Code [7], deterministic fracture mechanics (DFM) is applied considering the safety margins of influencing factors such as the degree of neutron irradiation embrittlement, postulated crack and thermals transient conditions during PTS. The structural integrity of RPVs can be assessed together with the safety margin in terms of temperature margin (ΔT_m) shown in Fig. 2. The influencing factors, however, generally contain the uncertainties. On the other hand, probabilistic fracture mechanics (PFM) has a feature which can take into account such uncertainties pertaining to these factors and can calculate the conditional probability of crack initiation (CPI) and failure (CPF) values.

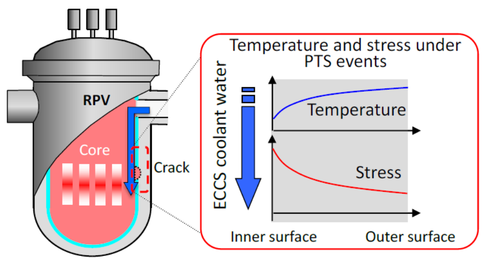

Fig. 1. Schematic view of the PTS events. The inner surface of the vessel wall is cooled as the ECCS coolant water is injected at the LOCA event, and the tensile stress is produced at near surface region.

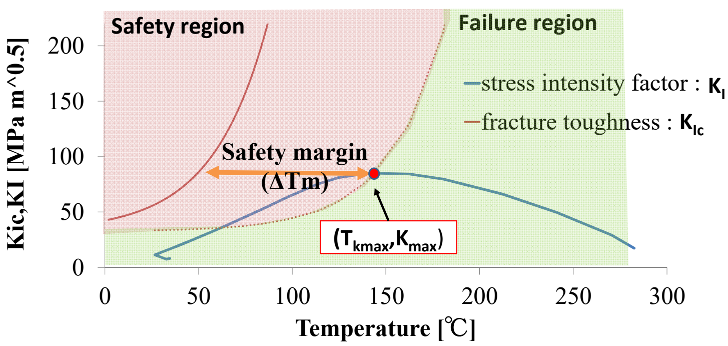

Fig. 2. RPV integrity evaluation scheme. When K_{IC}<K_I , fracture occurs. When the warm pre-stress (WPS) effect is considered, safety margin is expressed as the temperature difference between the safety and failure regions, ΔTm. (T_{kmax},K_{max}) shows the maximum K_I point.

Then, the question arises as to whether there exists any certain tendency on the correlation between the deterministic and probabilistic approaches relating to safety assessment (see Fig.3). To expand the use of probabilistic approach in the integrity assessment, detailed comparative analyses on these two approaches are needed. In the present study, the deterministic – probabilistic correlation in the RPV integrity assessment has been investigated from the point of ΔT_m – CPI or ΔT_m – CPF relationships. Although generally good relationship was recognized [1,2], more systematic analysis is needed to clarify the realistic RPV structural or thermal transient conditions, which may deteriorate the deterministic – probabilistic correlation. For this purpose, effects of cladding, crack types (surface crack or under-clad crack) and various transients including ones with re-pressurization are investigated.

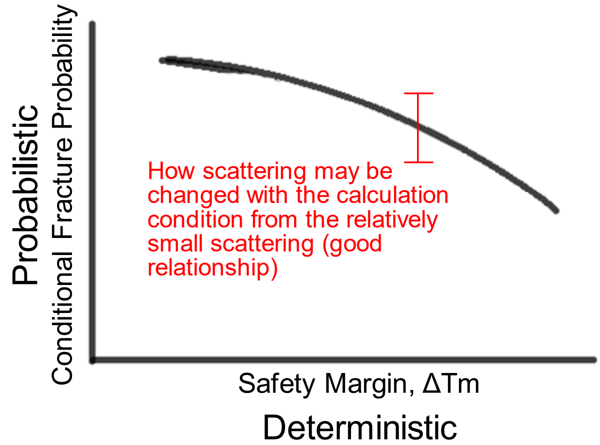

Fig. 3. Schematic illustration of the deterministic – probabilistic correlation. The variation is expected as to the correlation in accordance with the effects of cladding, crack types and transient conditions. If the correlation is with larger scattering, then, the safety margin determined by the deterministic approach does not necessary mean the same safety level.

2. Analytical Method

2.1. Parameters for Calculation

A model plant adopted for the analysis is 2-loop PWR. The inner radius of RPV is 1669mm, with wall thickness of 165mm with cladding of 6mm thickness. The steel contains 0.12wt%Cu and 0.56wt%Ni, and the RT_{NDT} shifts due to neutron irradiation are calculated according to JEAC 4201 -2007 (2013). Assumed defect types are surface and under-clad cracks. On crack data including the distribution formula, we followed the guideline and the code manual [3,4,8,9] .

Table 1. Parameters and assumptions for the probabilistic analysis. (a) Model RPV , (b) Assumed crack

(a)

Inner radius of RPV	1669 [mm]
RPV steel thickness	165 [mm]
Clad thickness	6 or 0 [mm]
Operating temperature	288 [℃]
Chemical composition of steel, Standard deviation	Cu 0.12 [wt.%] Ni 0.56 [wt.%] Cu 0.01 [wt.%] Ni 0.02 [wt.%]
Embrittlement equation	JEAC 4201-2007 (2013 addendum)

(b)

Initial crack (deterministic)	Semi-elliptical 10 (length) × 6(depth) [mm]
Initial crack distribution (probabilistic)	Length: lognormal distribution ＊ Depth: exponential distribution ＊＊
Plasticity correction for under-clad crack	RSE-M (β-correction)

＊ $p(b)=\frac{C}{\sigma b\sqrt{2\pi}}exp\left[-\frac{1}{2}\left(\frac{ln(b/\mu)}{\sigma}\right)^2\right]$, b: aspect ratio

＊＊ $p(a)=\lambda\exp(-\lambda a)$, a: crack depth

Thermal transients used for the calculation were those which correspond to large break loss of coolant accident (LBLOCA), small break LOCA (SBLOCA), main steam line break (MSLB) and stuck open valve events for pressurizer (SO) as shown in Fig.4. In the SBLOCA and MSLB, two different transient conditions (case1 and 2) were used. As for the SO, thermal transient behavior is very complex, and standard pattern has not been established. So, in the present analysis, we used the data described in reference [6]. Five different transients were used for the calculation. It is to be noted that re-pressurization occurs for this type of transients. (The SO numbers in the figures correspond to reference literature [6].)

In the structural or fracture analysis, WPS (warm pre-stress) effect, welding residual stress, plasticity correction, and so on were considered.

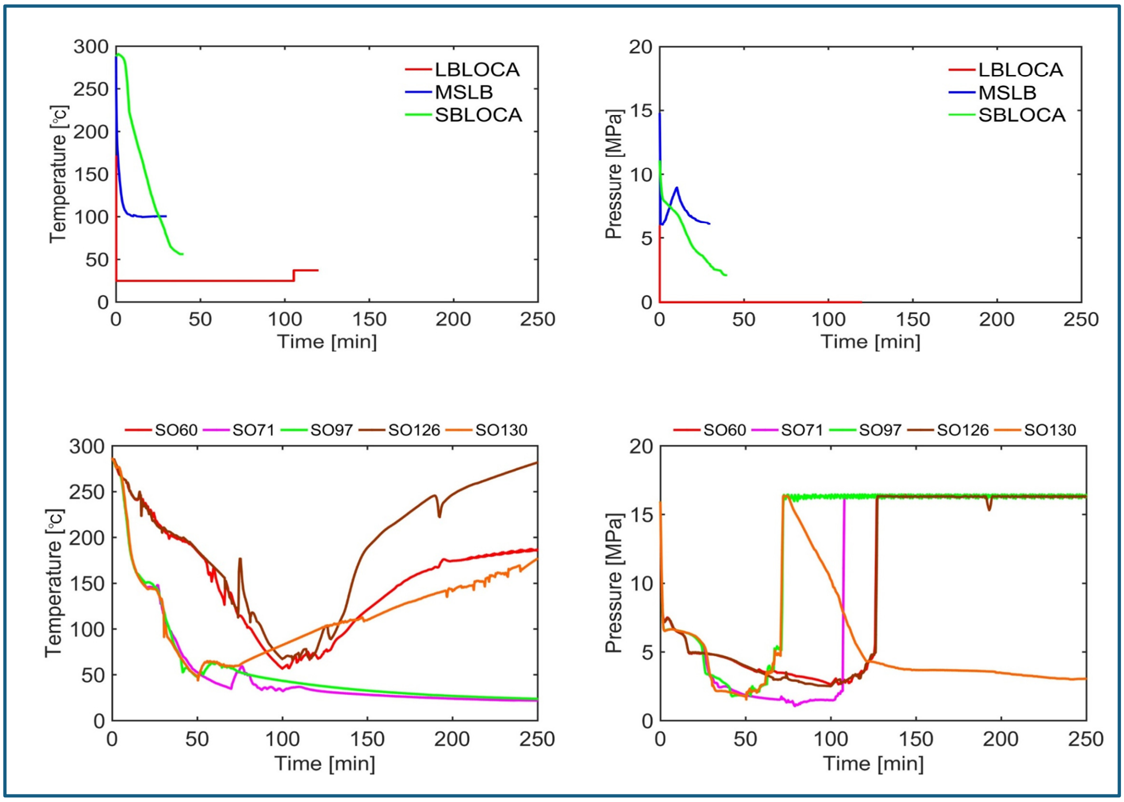

Fig.4. Temperature and pressure change at various transients used in the calculation

2.2 PFM Analysis

The PFM code used to calculate CPI and CPF in this study is mostly PASCAL4.0A, developed by Japan Atomic Energy Agency. The detailed analysis procedure is described in reference [3-5]. As the essential concept of the code is shown in Fig.5, the failure probability which corresponds to the interception of probability curves of fracture toughness and stress intensity factor can be calculated based on the fracture criteria for the aging pressure vessel at the time of the thermal transient. Monte Carlo method is used for the probability calculation.

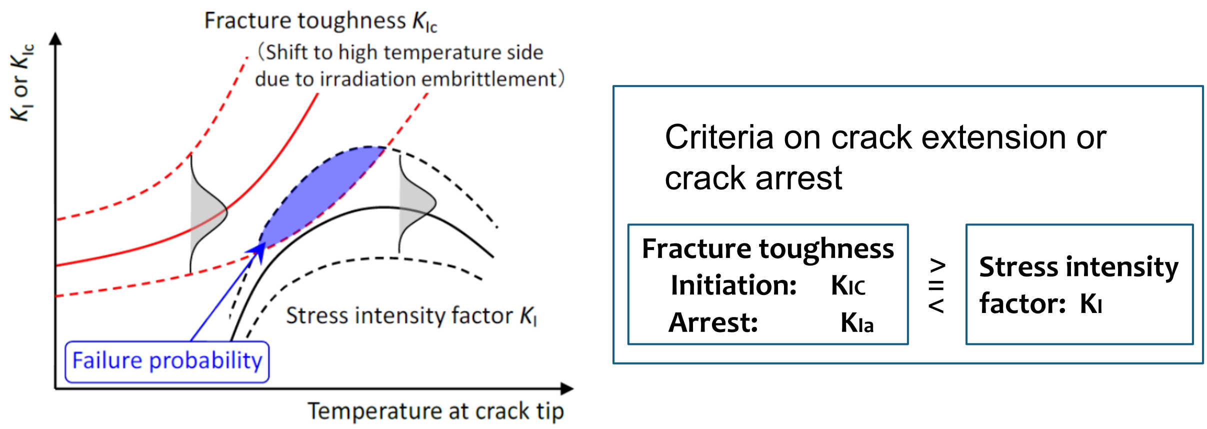

Fig.5. The concept of failure probability and relating fracture criteria in the PASCAL Code.

3. Calculation Results and Discussion

The relationship between failure probability in terms of CPI and ΔT_m or CPF and ΔT_m as a deterministic safety margin is to be discussed with focus on the possible influencing factors in the following sections. Basically, previous study [1,2] as well as this study show a very good relationship between CPI and ΔT_m (see Fig.6 (a)), when the cladding is not considered and when the classical transients like LBLOCA, SBLOCA and MSLB are considered. This correlation would be a starting or reference relation for considering the deterministic–probabilistic correlation.

3.1. The effect of cladding

Fig. 6 compares the calculation results for CPI when the RPV is with and without cladding. While CPI has a very good relationship with ΔT_m for the RPV without cladding (Fig.6 (a)), the same plotting exhibits broader correlation when the RPV is with cladding (Fig.6 (b)). In this case, additional stress is produced during PTS events because thermal expansion coefficients are much different between base metal and stainless overlay cladding. K_I at the crack tip is affected by the thermal stress (i.e. residual stress), which is different depending on the transient types which have different cooling rates. Hence, this broadening is thought to be caused by the cladding effect.

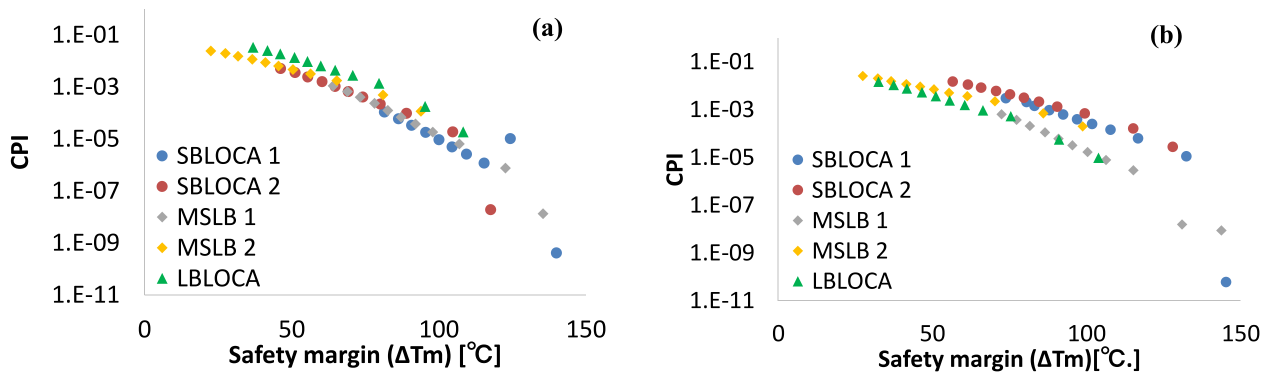

Fig.6. The relationship between CPI and ΔT_m, for RPV (a) without and (b) with stainless overlay cladding .

3.2. On the difference between CPI and CPF

When CPF (conditional probability of failure) is considered, ΔTm – CPF relationship broadened even more than that of CPI (conditional probability of fracture initiation). LBLOCA plotting is, in particular, much deviated (see Fig.7). The difference of CPF and CPI is considered to be related with the increase of crack arrests for LBLOCA. Larger temperature gradients through wall thickness are created during the LBLOCA as shown in Table 2. Hence, in the high probability, crack is arrested in the events for LBLOCA as is clear from Fig. 8 which indicates the crack arrest ratio by CPF/CPI value.

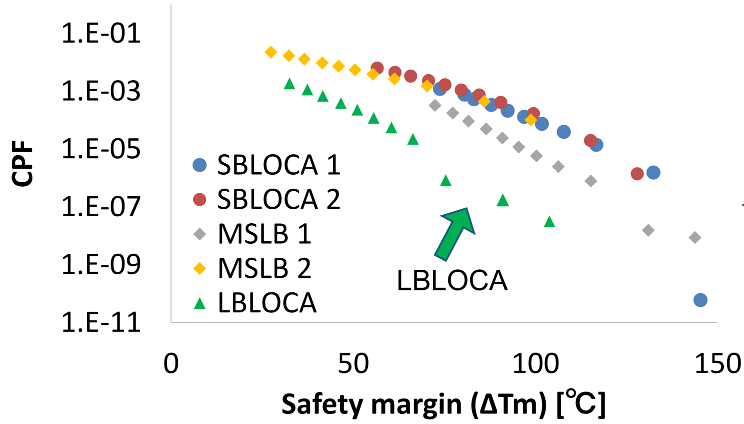

Fig.7. The relationship between CPF and ΔT_m .

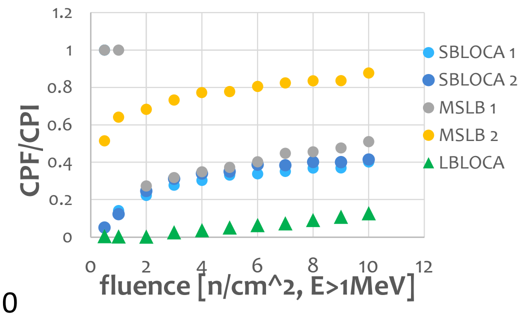

Fig.8. The crack arrest ratio (CPF/CPI).

Table.2. Temperature gap between the inner and outer surface.

	Max gap [℃]	Inner surface [℃]	Outer surface [℃]	Time [min]
SBLCOA1	113.9	98.7	231.2	32
SBLOCA2	147.6	81.5	229.1	25
MSLB1	134.2	147.6	281.8	6
MSLB2	135.4	129.6	265	10
LBLOCA	196.3	83.2	279.4	5

3.3 Effect of transients with re-pressurization

The effect of transients with re-pressurization is considered very important for integrity evaluation. As shown in Fig.9, in the SO events, K_I curves show multiple maximum values caused by not only thermal stress due to rapid cooling, but also the state of the pressurizer including re-closing of safety relief valve (SRV). Therefore, K_I curves become complicated, and it is also true for its relation with K_{IC} curve.

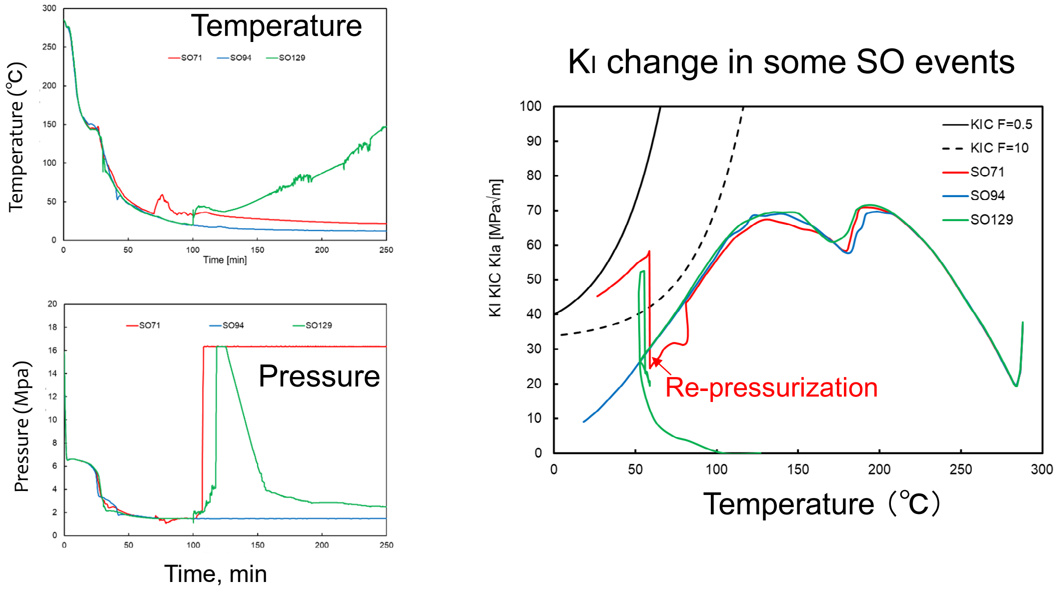

Fig.9. Temperature, pressure and K_I changes in SO events [6] .

Fig.10 shows the ΔT_m – CPF relationship for several transients including the SO events. The correlation curves were roughly diverged to 3 lines. It was found that ΔT_m – CPF relationship varied much for SO transients depending on the characteristic feature of the individual transients, most possibly reflecting the re-pressurization effects. Namely, fracture point on the K_I line is most important. When K_I curve crosses with the K_{IC} curves at the higher temperature region, it resembles the normal PTS events. But when it crosses at lower temperature at the time of re-pressurization, correlation line goes to right (or upper).

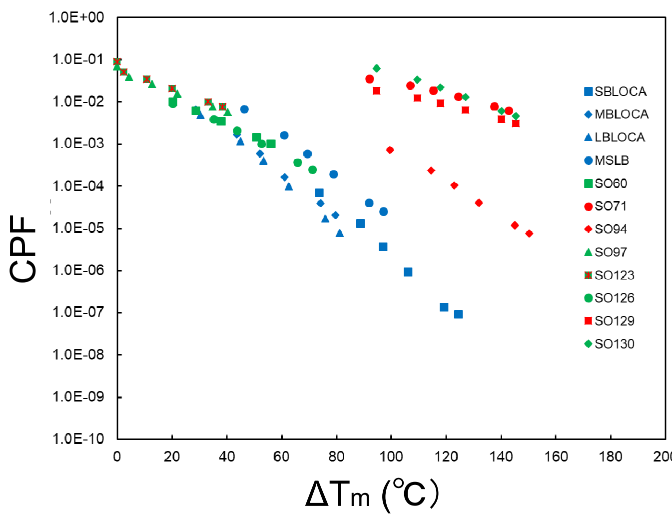

Fig.10. The relationship between CPF and ΔT_m for SO events .

3.4 Summarizing of the analysis

Other factors were also investigated whether they affect the relationship. For example, the effect of crack types was investigated, because in the latest Japanese code, the crack used for the PTS evaluation is changed from the surface crack to under-clad crack [7]. As a result, however, significant influence has not been found from the point of the ΔT_m – CPF relationship. Hence, most distinct results could be summarized as the following three.

(1) For the RPV without cladding, CPI has a very good relationship with ΔT_m. While, in the case of the RPV with cladding, the broader correlation is revealed. The broadening is thought to be caused by the residual stress due to overlay cladding.

(2) For CPF, the relationship even more broadens than that of CPI. LBLOCA plotting is, in particular, much deviated. The deviation is related with the increase of crack arrests for LBLOCA because of larger temperature gradients through wall thickness.

(3) In the SO events, K_I curves show multiple maximum values caused by not only thermal stress due to rapid cooling, but also full water state of the pressurizer or re-closing of safety relief valve (SRV). As a result, the SO events exhibit broader ΔT_m – CPF relationship.

4. Conclusion

From the intensive set of PFM calculations, it was found that the SO transients which give rise to the re-pressurization have a possibility to deteriorate the deterministic – probabilistic correlation. Implication was also obtained that useful safety consideration could be possible by probabilistic safety assessment, which cannot be obtained by deterministic assessment alone. To improve further the reliability or structural integrity of aged RPV, important factors can be extracted. Even if the safety margin is the same from the deterministic evaluation, actual reliability is not the same. This difference is made clear from the present correlation analysis, and hence PFM evaluation could be used for the continuous improvement of the safety of aged plants.

Acknowledgement

Thanks are due to JAEA technical staffs for their supports.

References

[1] K. Onizawa, K. Masaki, J. Katsuyama, “Probabilistic Structural Integrity Analysis of Reactor Pressure Vessels during PTS Events”, Proceedings of the ASME 2012 Pressure Vessels & Piping

[2] R. Okayama, M. Suzuki1, Y. Li, J. Katsuyama, “Structural Integrity Sensitivity Analysis of Reactor Pressure Vessel Based on Probabilistic Fracture Mechanics During Thermal Transient Condition”, AESJ Domestic Meeting, September 2016 (in Japanese).

[3] J.Katsuyama, K.Osakabe, S.Uno, Y.Li, "Guideline on Probabilistic Fracture Mechanics Analysis for Japanese Reactor Pressure vessels", PVP2017, 16-20(2017)

[4] J.Katsuyama, K.Osakabe, S.Uno, Y.Li, " Guideline on a Structural Integrity Assessment for Reactor Pressure Vessel Based on Probabilistic Fracture Mechanics (Contract Research)JAEA-Research 2016-022 (2016),

[5] Y. Li, G. Katsumata, K. Masaki, S.Hayashi, Y.Itabashi, M.Nagai, M. Suzuki, Y. Kanto, "Verification of Probabilistic Fracture Mechanics Code PASCAL", ICONE25-66468, July 2-6, 2017, Shanghai, China

[6] M. EricksonKirk, M. Junge, W. Arcieri, B.R. Bass, R. Beaton, D. Bessette, T.H.J. Chang, T. Dickson, C.D. Fletcher, A. Kolaczkowski, S. Malik, T. Mintz, C. Pugh, F. Simonen, N. Siu, D. Whitehead, P. Williams, R. Woods, S. Yin, “Technical Basis for Revision of the Pressurized Thermal Shock (PTS) Screening Limit in the PTS rule (10CFR50.61)”, NUREG-1806, U.S. Nuclear Regulatory Commission, (2006).

[7] Japanese Electric Association Code, JEAC4206 (2016)

[8] K.Masaki, H.Nishikawa, K. Osakabe, K. Onizawa, "User's Manual and Analysis Methodology of Probabilistic Fracture Mechanics Analysis Code PASCAL3 for Reactr Pressure Vessel" JAEA-Data/Code 2010-033, March 2011

[9] Japanese Electric Association Guide JEAG4640 (2018)