4th International Symposium on Probabilistic Methodologies for Nuclear Applications
November 1-3, 2022, Leicester, UK

PASCAL5 – An Updated Probabilistic Fracture Mechanics Analysis Code for Structural Integrity Assessment of Japanese Reactor Pressure Vessels

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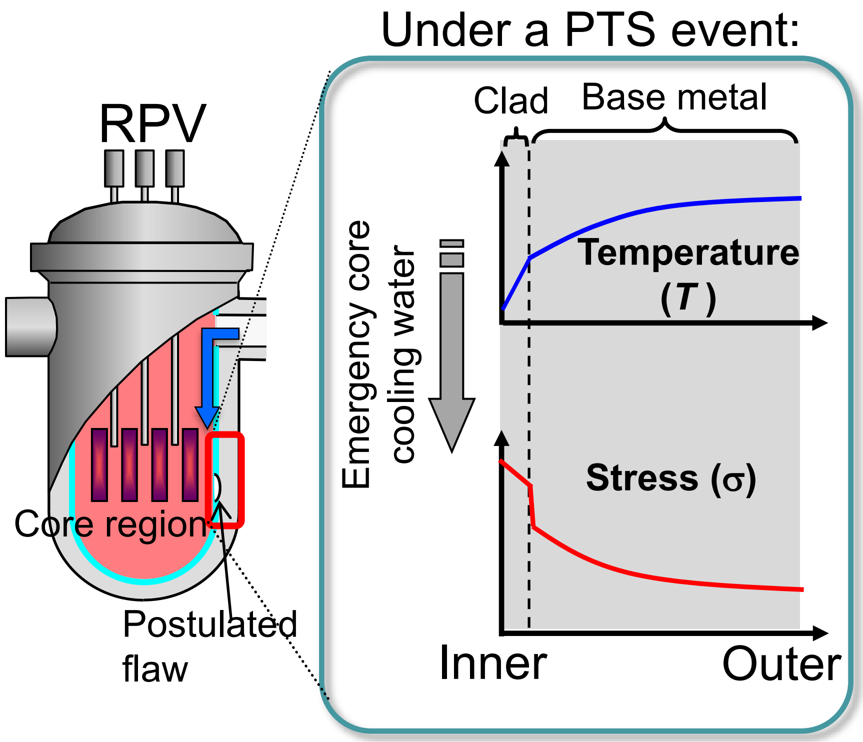
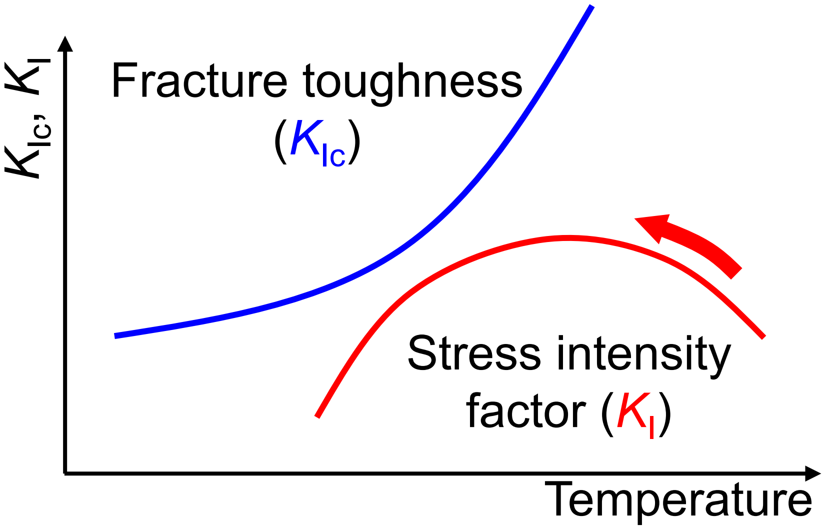
Background

- Reactor pressure vessel (RPV) is one of the most important components in nuclear power plants.
- Structural integrity assessment of RPV is performed by considering neutron irradiation embrittlement and transients including pressurized thermal shock (PTS).
- So far, deterministic approach has been the mainstream in many countries.



Deterministic approach for PTS event

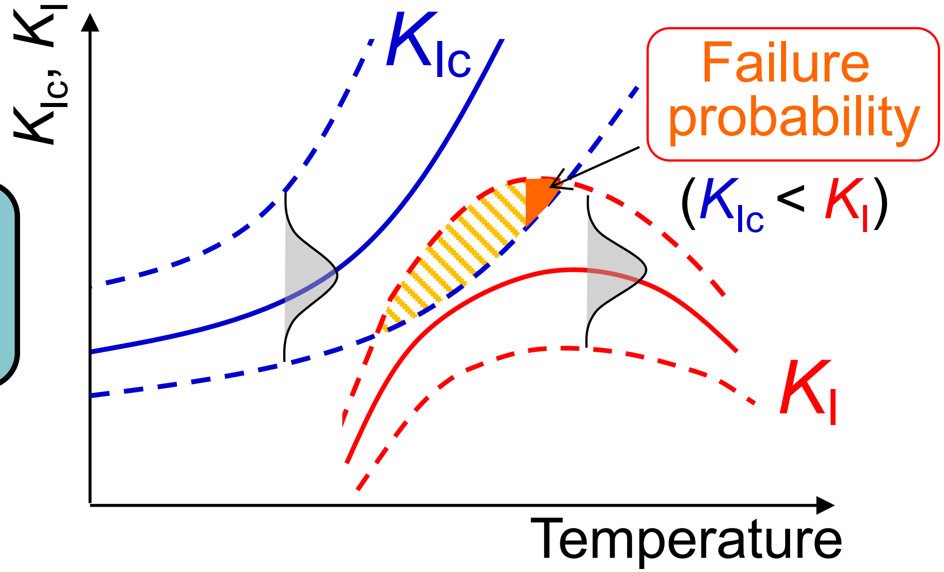
$K_{Ic} > K_I$



PFM Approach

- Probabilistic fracture mechanics (PFM) approach has been recognized as a promising methodology in structural integrity assessment of RPVs.

Integrity assessment by PFM approach for PTS transient

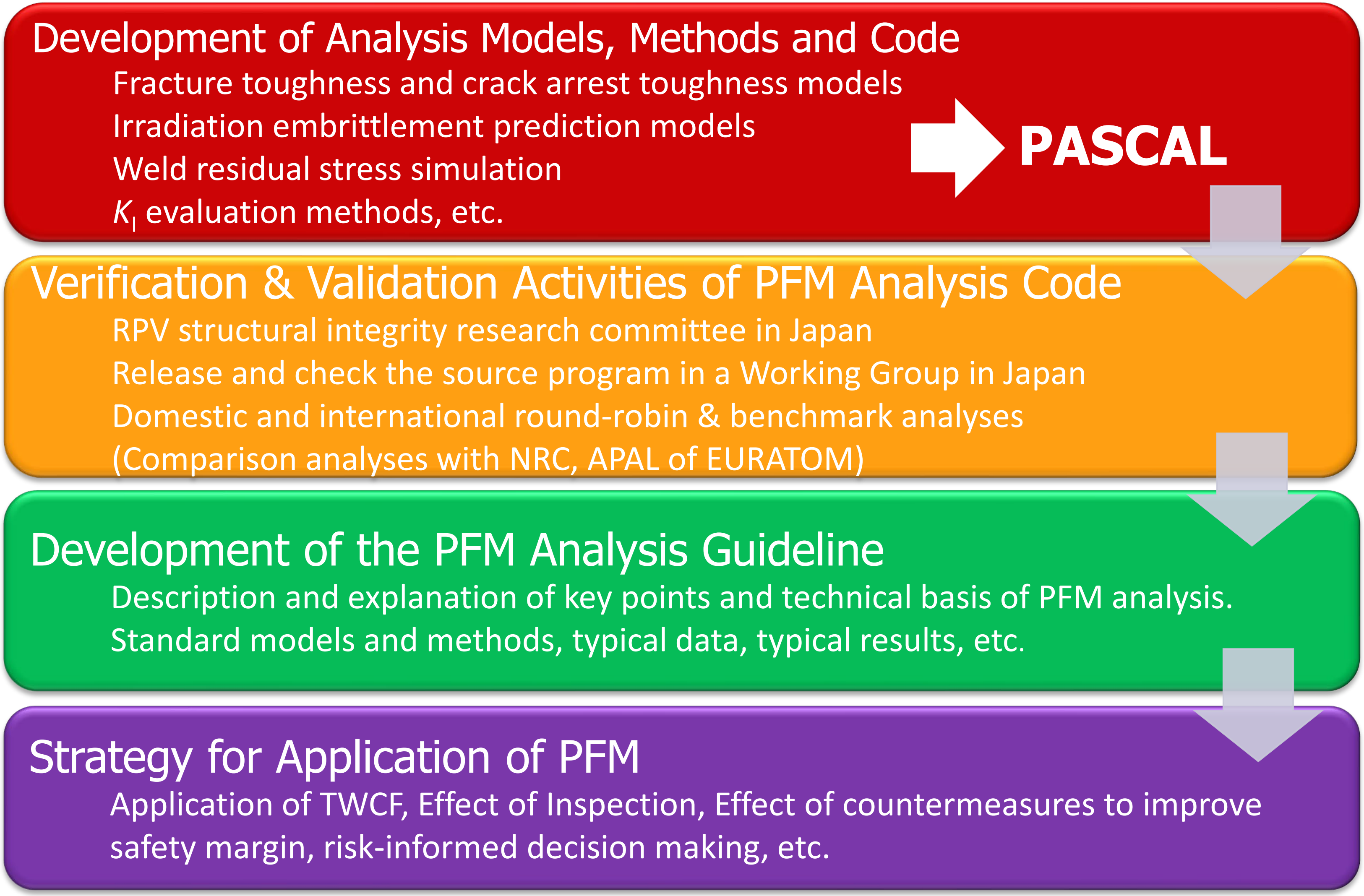


- ✓ **Provides rational evaluation** by considering inherent probabilistic distributions of influence parameters
- ✓ **Gives quantitative evaluation** of numerical indexes such as frequency of crack initiation (FCI), through-wall cracking frequency (TWCF) which are **suitable for Risk-Informed Decision Making**
- ✓ **Enables relative comparisons** for different RPVs & codes…

Overview of Activities in JAEA

- Object: To improve the applicability of PFM to RPVs, especially Japanese RPVs
- Evaluation target: Core region of both PWR and BWR RPVs
- Evaluation Transient: PTS, LTOP*, Start-up, Shut-down, Pressure test, etc.

*LTOP: Low temperature over-pressure



Development of Analysis Models, Methods and Code

Fracture toughness and crack arrest toughness models
Irradiation embrittlement prediction models
Weld residual stress simulation
K_I evaluation methods, etc.

→ **PASCAL**

Verification & Validation Activities of PFM Analysis Code

RPV structural integrity research committee in Japan
Release and check the source program in a Working Group in Japan
Domestic and international round-robin & benchmark analyses
(Comparison analyses with NRC, APAL of EURATOM)

Development of the PFM Analysis Guideline

Description and explanation of key points and technical basis of PFM analysis.
Standard models and methods, typical data, typical results, etc.

Strategy for Application of PFM

Application of TWCF, Effect of Inspection, Effect of countermeasures to improve safety margin, risk-informed decision making, etc.

Development of PASCAL* Code

[*] PASCAL: PFM Analysis of Structural Components in Aging LWRs

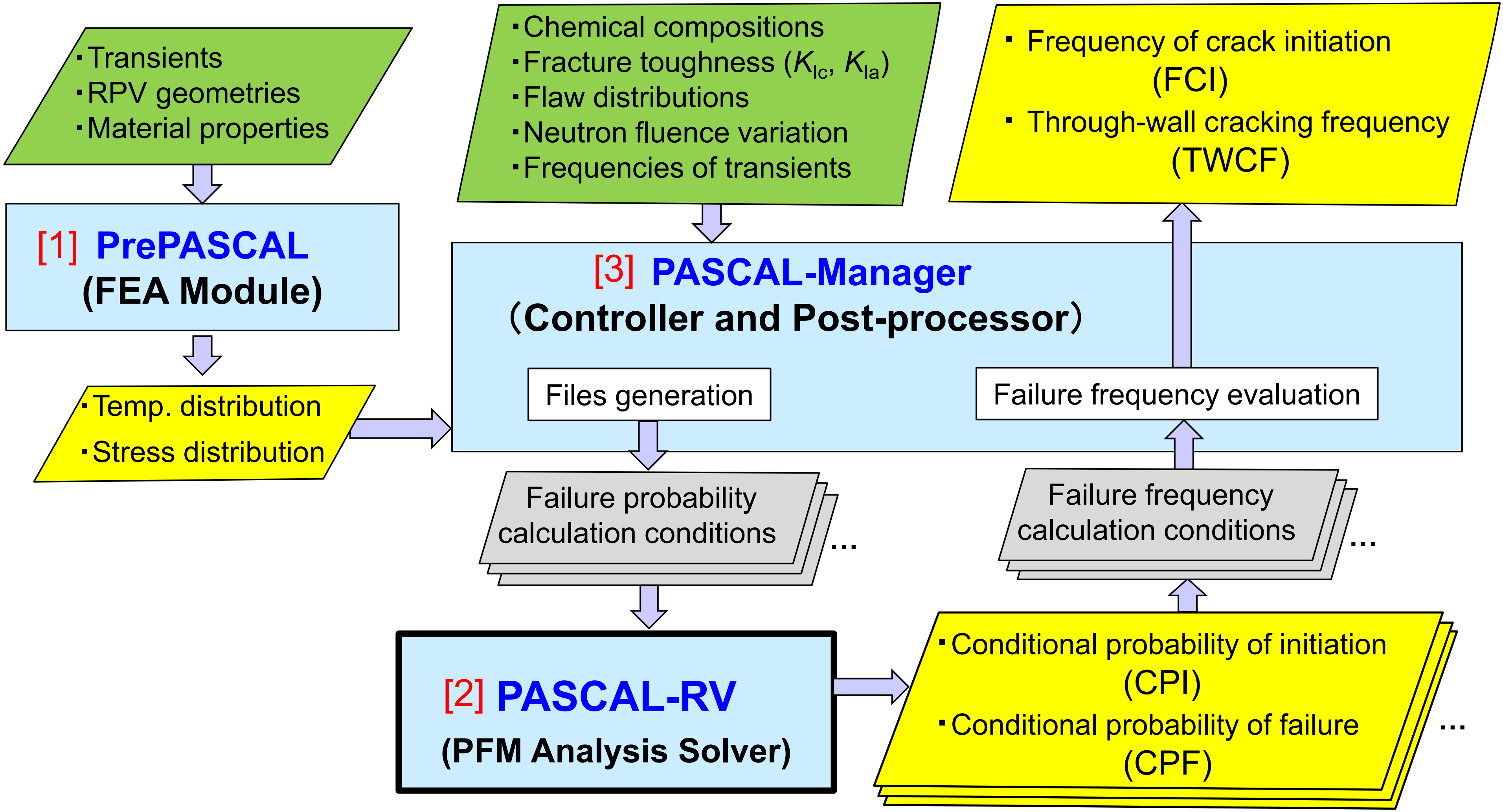
Development of PASCAL Code

- Development of PASCAL was initiated 25 years ago in JAEA.

Time	Historical review of PASCAL development	
1990s		
2000s	PASCAL1	✓ PASCAL1 (2001) could be used to evaluate failure probability of an RPV with a surface flaw under a PTS event.
	PASCAL2	✓ PASCAL2 (2006) added several analysis functions such as the evaluation function for embedded flaw.
2010s	PASCAL3	✓ PASCAL3 (2011) improved some fracture mechanics analysis functions (e.g., considering the effect of weld-overlay cladding).
2018 ▶	PASCAL4	✓ PASCAL4 (2018) improved to enable the failure probability and frequency evaluation for total core region of PWR's RPV considering PTS events.
2022 ▶	PASCAL5	✓ PASCAL5 (2022) improved to enable the failure probability and frequency evaluation of total core region of RPVs for both PWRs and BWRs, considering events such as low temperature over-pressure (LTOP), start-up, shut-down, pressure test, etc. Will be released in this winter.
2020s		

Structure of PASCAL5

- PASCAL5 consisted of 3 modules:



・Transients
・RPV geometries
・Material properties

[1] **PrePASCAL**
(FEA Module)

・Temp. distribution
・Stress distribution

・Chemical compositions
・Fracture toughness (K_{Ic}, K_{Ia})
・Flaw distributions
・Neutron fluence variation
・Frequencies of transients

[3] **PASCAL-Manager**
（Controller and Post-processor）

Files generation

Failure frequency evaluation

▪ Frequency of crack initiation (FCI)
▪ Through-wall cracking frequency (TWCF)

Failure probability calculation conditions …

Failure frequency calculation conditions …

[2] **PASCAL-RV**
(PFM Analysis Solver)

・Conditional probability of initiation (CPI)
・Conditional probability of failure (CPF)
…

Module configuration of PASCAL5

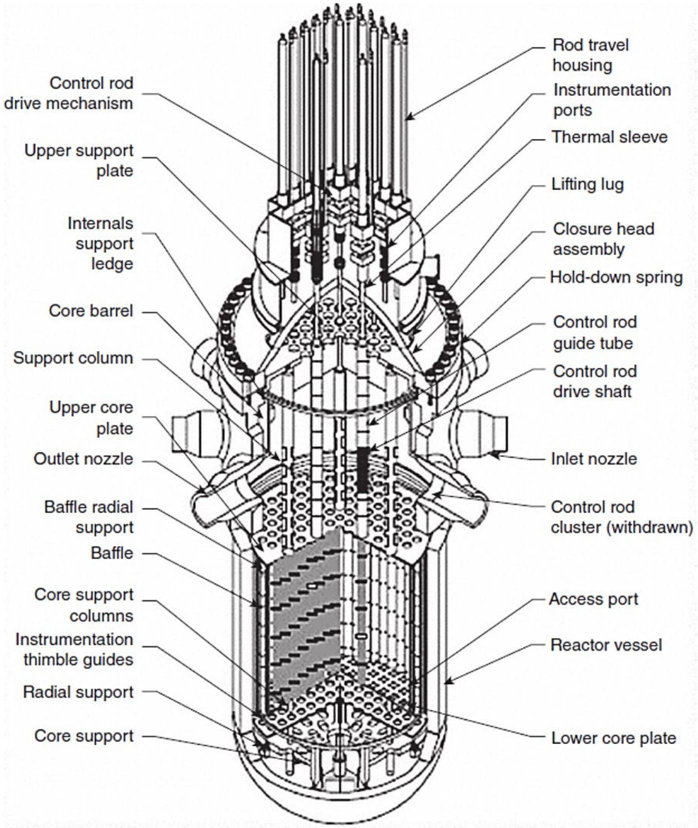
Outline of PASCAL5

- **Green contents: Developed in PASCAL4**
- **Red contents: Developed in PASCAL5**

Item	**Content**	
Evaluation target	Core region of PWR and BWR RPVs	
Ageing mechanism	Neutron irradiation embrittlement	
Transient	PTS, LTOP, Start-up, Shut-down, Pressure test, etc.	
Initial Flaw	Surface flaw, embedded flaw, infinite-length flaw, etc.	
Fracture mechanics analysis	Fracture toughness (K_{Ic}, K_{Ia})	Probabilistic distribution models based on Japanese data, Master Curve model
	Embrittlement prediction method	Probabilistic models based on JEAC4201-2007(sup.2013), new JEAC model
	K_I calculation	Recent K_I solutions & improved methods for complicated stress distribution
	Welding residual stress (WRS)	WRS due to weld-overlay cladding and butt-welding based on detailed 3D FEAs and experimental data, for both PWR and BWR
	Warm pre-stressing (WPS)	Recent evaluation model validated by JAEA's experiments
Probability of detection (POD)	POD model based on UT data of Japanese project	
Probabilistic calculation	･Latin hypercube sampling method, Numerical integration method ･Confidence level evaluation function	

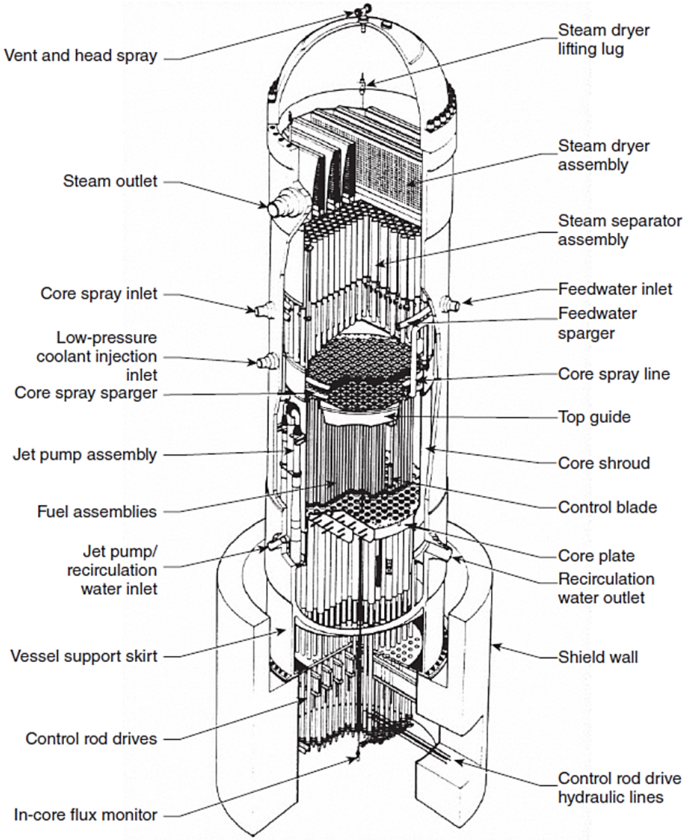
Target RPVs

- In PASCAL4, only RPVs of PWRs were considered.
- In PASCAL5, RPVs in both PWRs and BWRs are taken into account.



Typical Pressure Vessel of PWR

Typical transient: PTS, Start-up, Shut-down, Pressure test



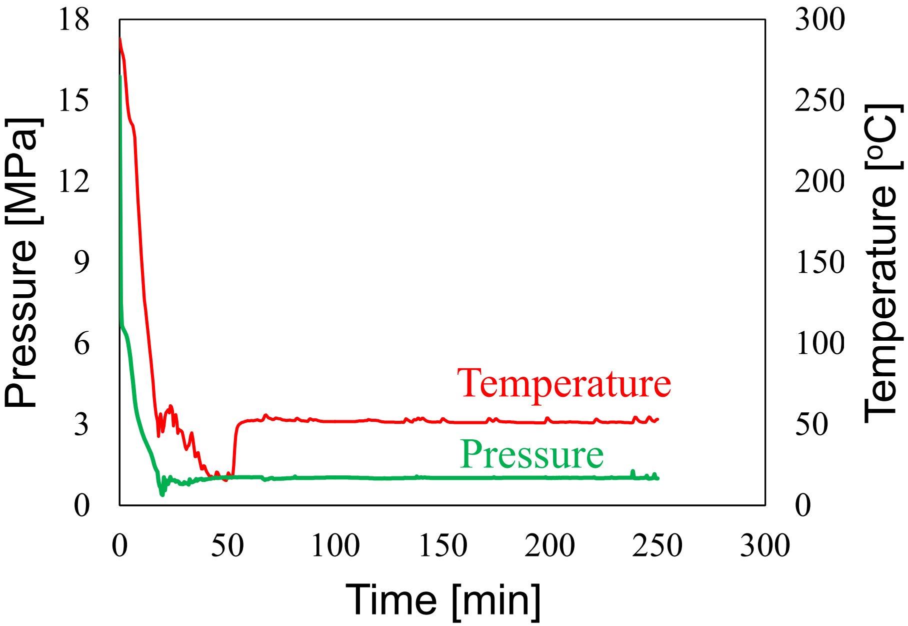
Typical Pressure Vessel of BWR

Typical transient: LTOP, Start-up, Shut-down, Pressure test

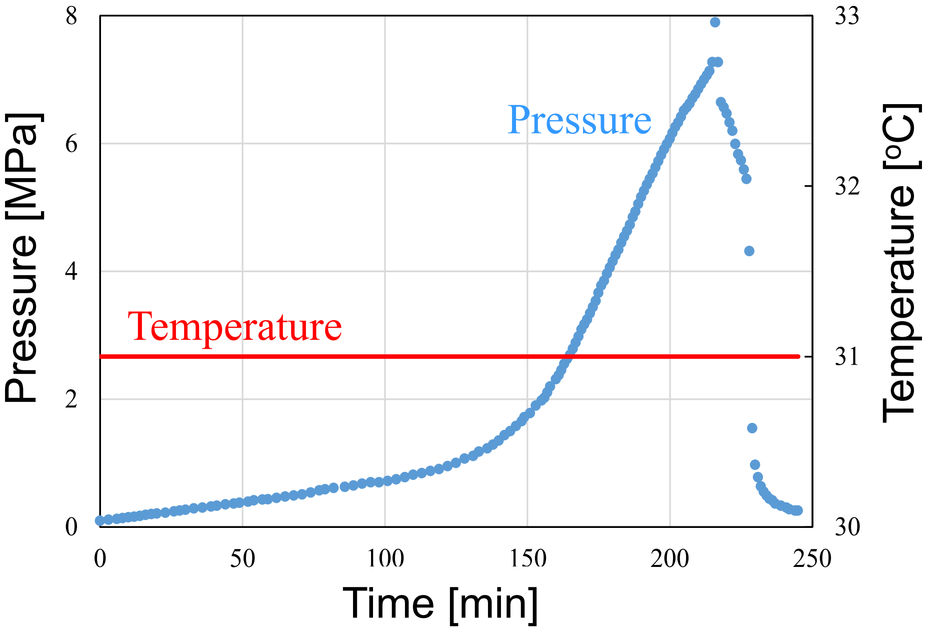
Target Transients

- In PASCAL4, PTS events were considered with their uncertainties.
- In PASCAL5, events such as LTOP* are also taken into account.

*LTOP: Low temperature over-pressure



Typical PTS transient (LBLOCA) for PWR*



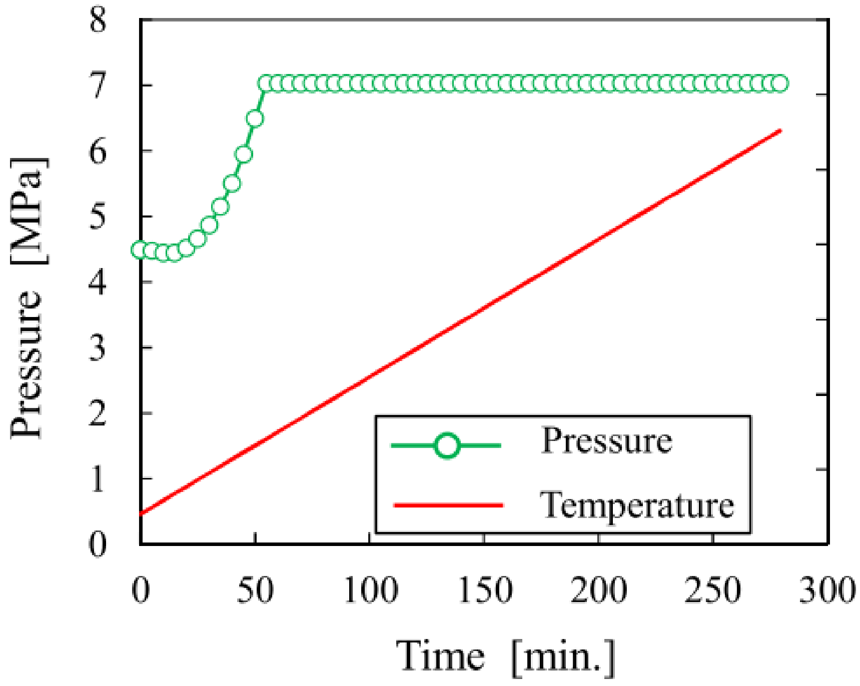
Typical LTOP transient for BWR**

*:W. C. Arcieri, R. M. Beaton, C. D. Fletcher, D. E. Bessette, 2004, NUREG/CR-6858.

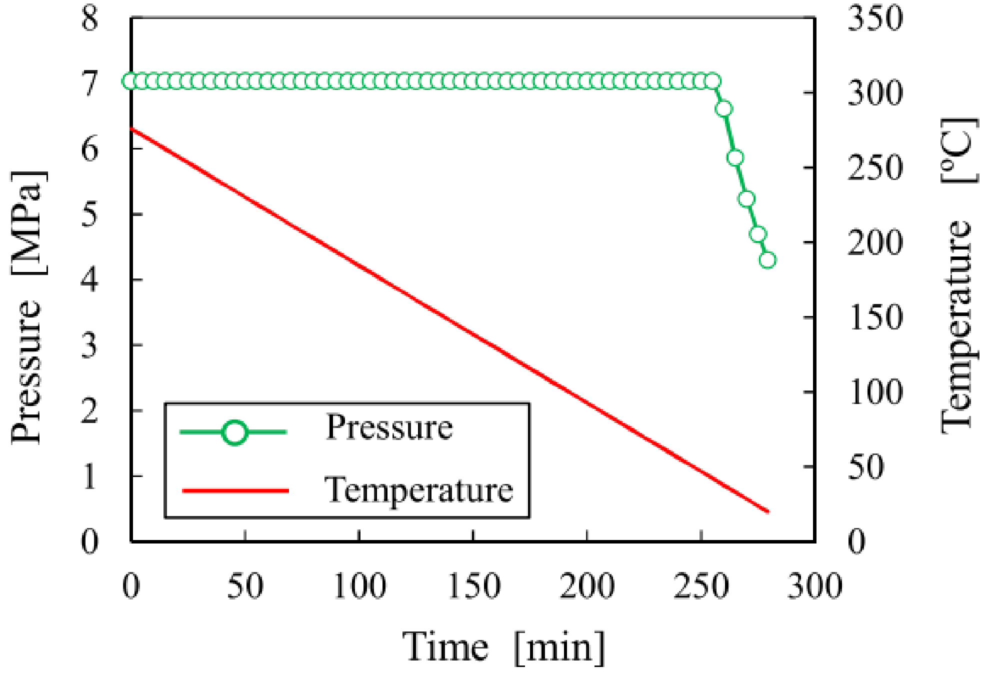
**:Chou & Huang, International Journal of Nuclear Energy, Vol.2015, 785041-1~9, 2015.

Target Transients

- In PASCAL5, events such as start-up, shut-down, pressure test are also taken into account.



An example heat-up transient
based on JEAC4206-2016*



An example cool-down transient
based on JEAC4206-2016*

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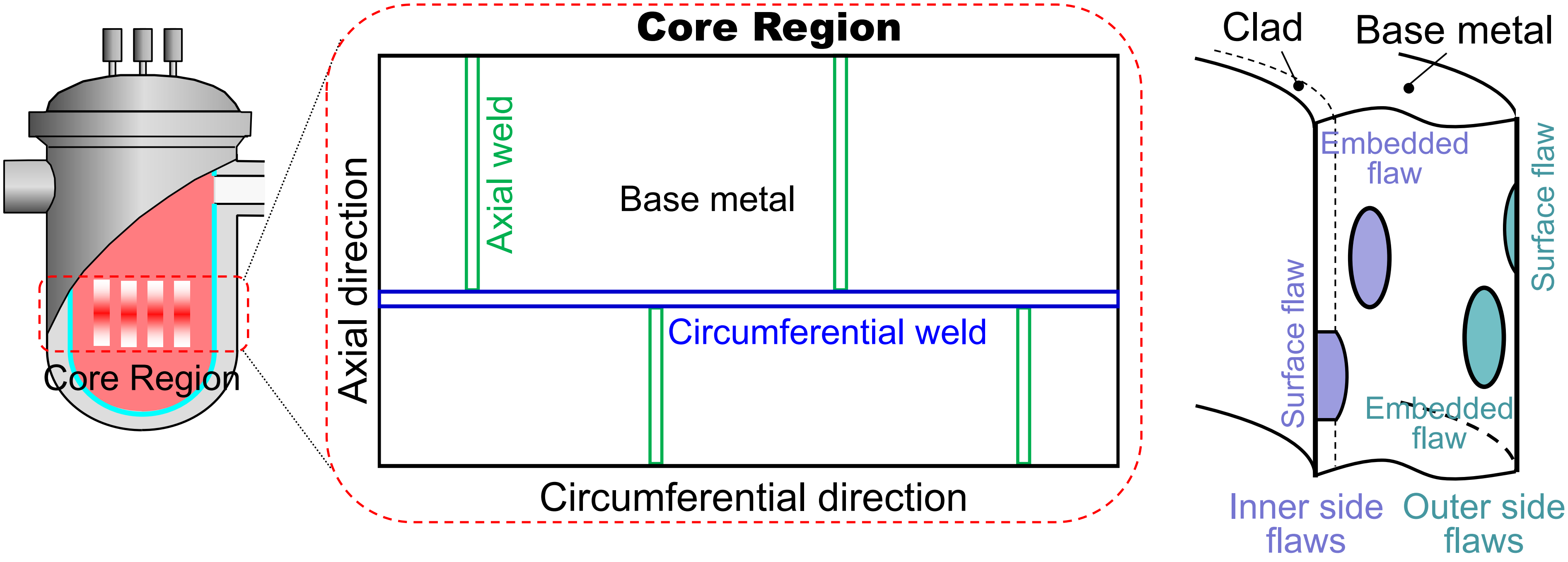
*Japan Electric Association: Method of Verification Tests of the Fracture Toughness for Nuclear Power Plant Components, 2016 (in Japanese). JEAC4206-2016.

Initial Flaws

- In PASCAL4, only surface flaws and embedded flaws on the inner side of RPV, which are effective for PTS transients, were considered.
- In PASCAL5, flaws on both inner and outer sides of RPV are considered, because they can contribute to failure probability for LTOP and other transients.



Evaluation flaw

- ✓ Inner side flaws
- ✓ Outer side flaws

Flaw location

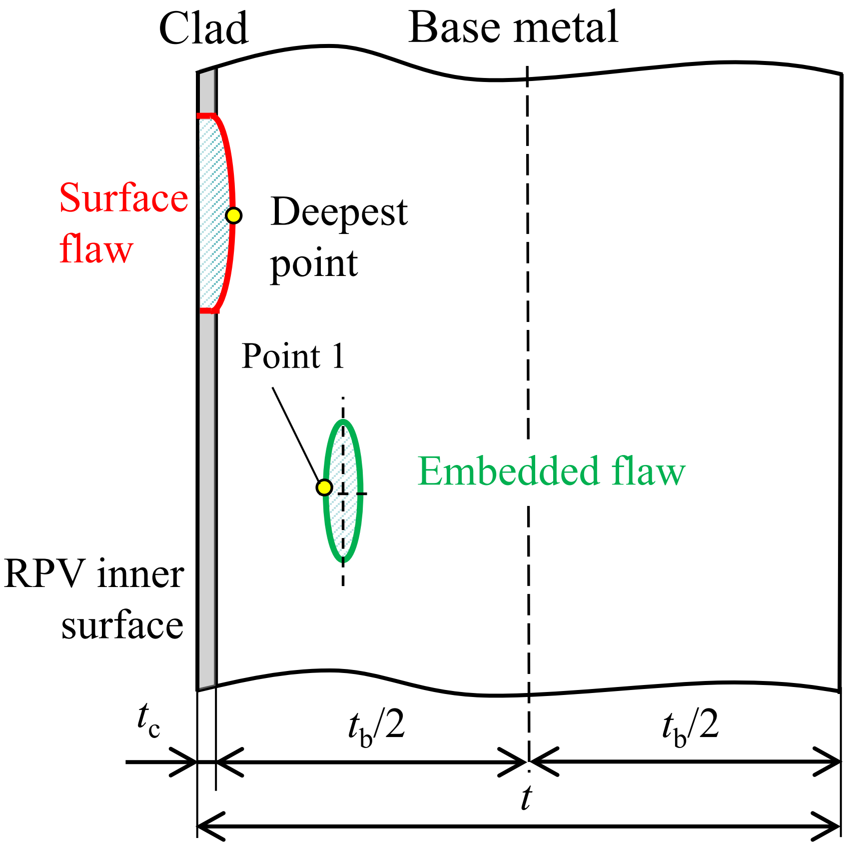
- ✓ Flaws in overlay-welded clad and in butt weld.
- ✓ Flaws in base metal

Direction of flaw

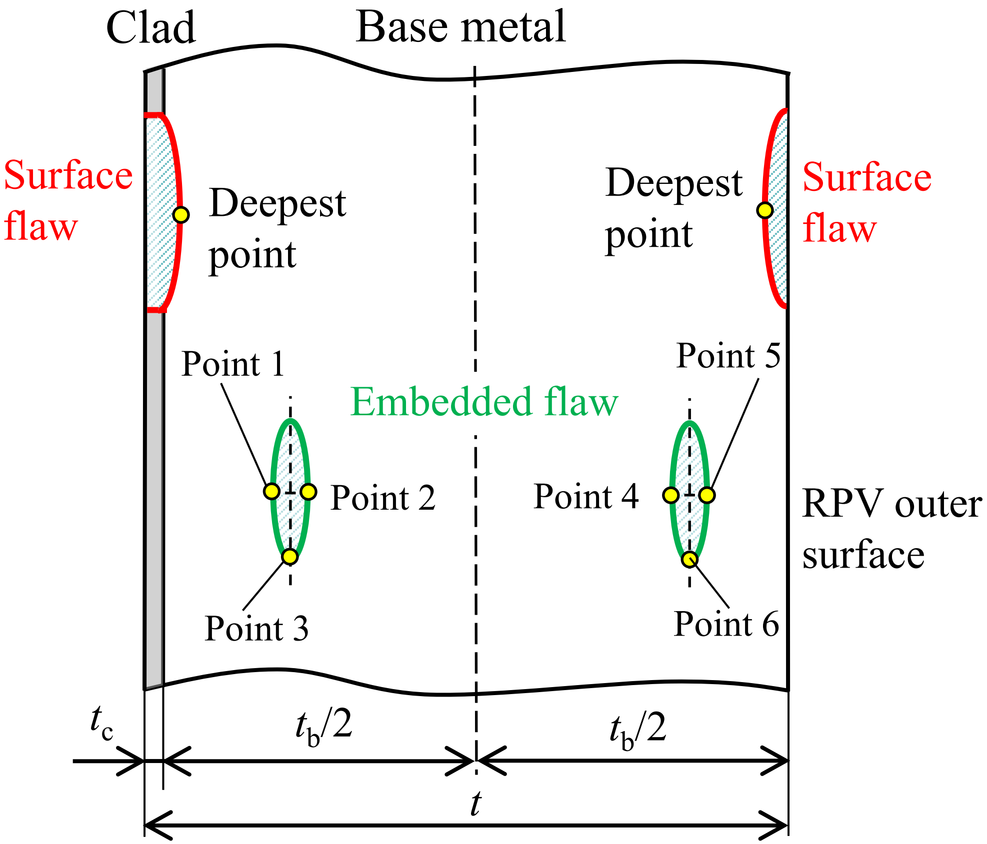
- ✓ Flaws in weld: Weld direction
- ✓ Flaws in base metal: Axial and circumferential flaws

Evaluation Point of Embedded Flaw

- For PTS transients, the embedded flaws near the inner surface are evaluated. The nearest point of embedded flaw to the inner surface is selected as the evaluation point.
- For LTOP transient, the embedded flaws through wall-thickness are evaluated. The deepest points in both thickness and length directions are selected as the evaluation points.

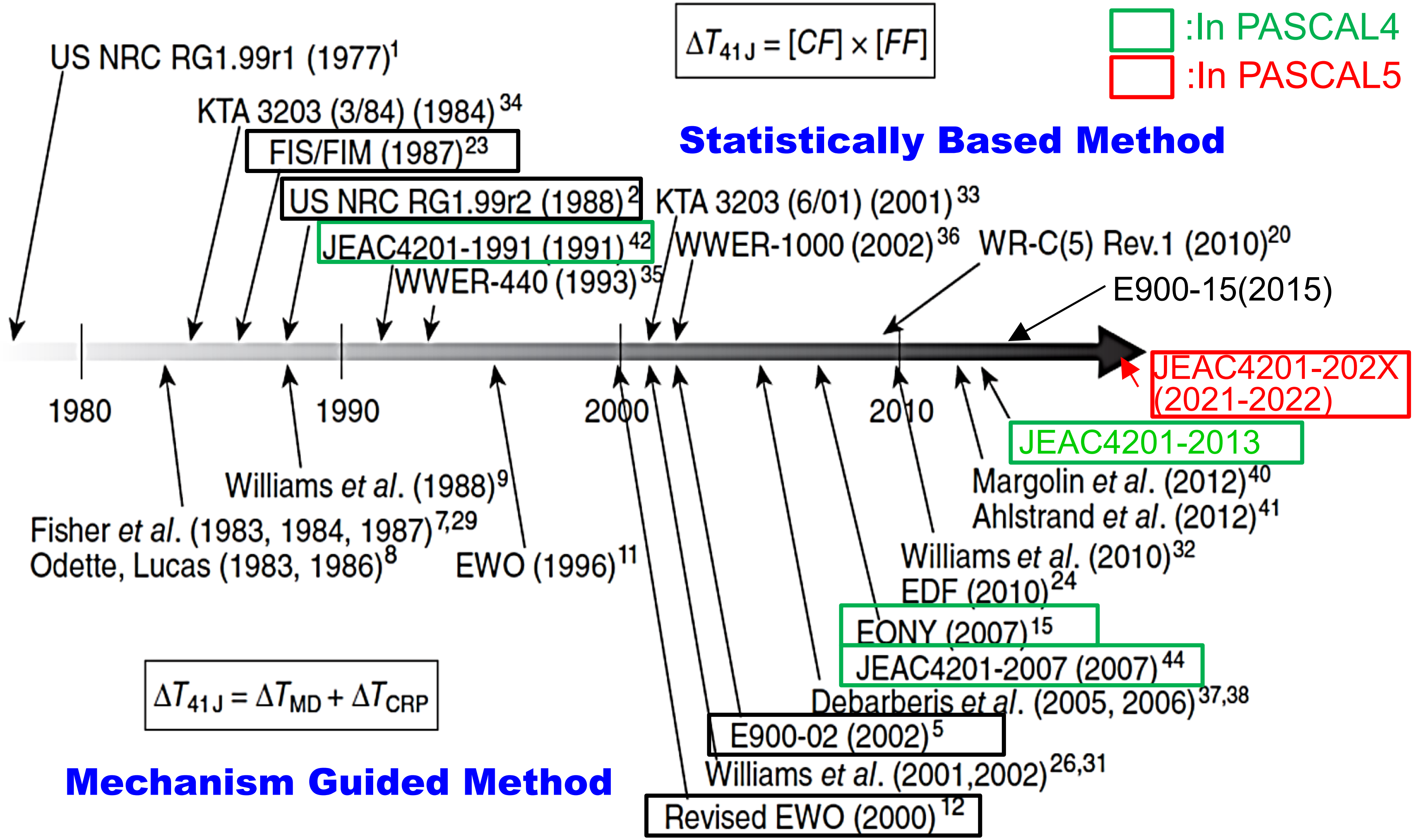


Evaluation point for PTS transients



Evaluation points for LTOP transient

Irradiation Embrittlement Prediction



🟩 :In PASCAL4

🟥 :In PASCAL5

$\Delta T_{41\,J} = [CF] \times [FF]$

Statistically Based Method

US NRC RG1.99r1 (1977)[1]

KTA 3203 (3/84) (1984)[34]

FIS/FIM (1987)[23]

US NRC RG1.99r2 (1988)[2]

JEAC4201-1991 (1991)[42]

WWER-440 (1993)[35]

KTA 3203 (6/01) (2001)[33]

WWER-1000 (2002)[36]

WR-C(5) Rev.1 (2010)[20]

E900-15(2015)

JEAC4201-202X (2021-2022)

1980

1990

2000

2010

JEAC4201-2013

Margolin *et al*. (2012)[40]

Ahlstrand *et al*. (2012)[41]

Williams *et al*. (2010)[32]

EDF (2010)[24]

EONY (2007)[15]

JEAC4201-2007 (2007)[44]

Debarberis *et al*. (2005, 2006)[37,38]

E900-02 (2002)[5]

Williams *et al*. (2001,2002)[26,31]

Revised EWO (2000)[12]

Williams *et al*. (1988)[9]

Fisher *et al*. (1983, 1984, 1987)[7,29]

Odette, Lucas (1983, 1986)[8]

EWO (1996)[11]

$\Delta T_{41\,J} = \Delta T_{MD} + \Delta T_{CRP}$

Mechanism Guided Method

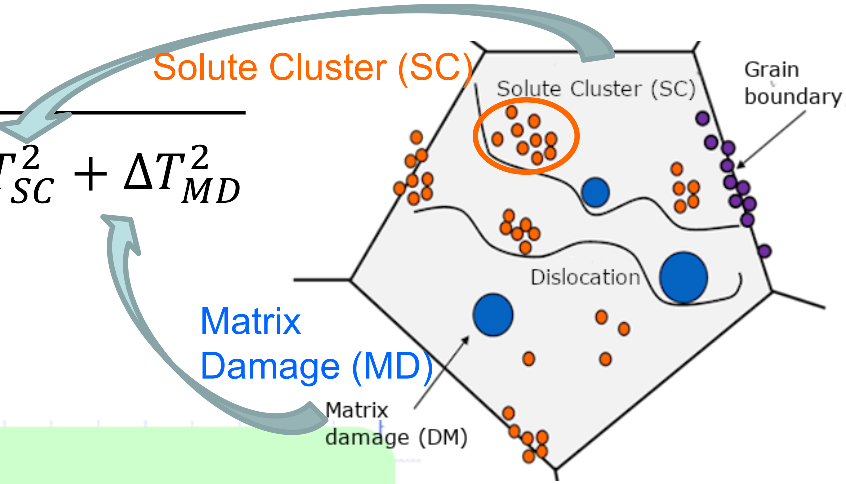
Progress of embrittlement prediction method

*Base on N. Soneda, “Irradiation embrittlement of reactor pressure vessels (RPVs) in nuclear power plants” Woodhead publishing series in energy: number 26, Cambridge, Elsevier UK, 2014.

Irradiation Embrittlement Prediction

- Probabilistic embrittlement prediction method based on JEAC4201-2007 (sup. 2013)

$$\Delta RT_{NDT} = \sqrt{\Delta T_{SC}^2 + \Delta T_{MD}^2}$$



✓Mechanism guided prediction method
  - Chemical composition: Cu, Ni
  - 19 correlation coefficients are used

✓Microstructure formulation

$$\frac{\partial C_{SC}}{\partial t} = \xi_3 \cdot \left(\left(C_{Cu}^{mat} + \varepsilon_1\right) \cdot D_{Cu} + \varepsilon_2\right) \cdot C_{MD} + \xi_8 \cdot \left(C_{Cu}^{avail} \cdot D_{Cu} \cdot \left(1 + \xi_7 \cdot C_{Ni}^0\right)\right)^2$$

$$\frac{\partial C_{MD}}{\partial t} = \xi_4 \cdot F_T^2 \cdot \left(\xi_5 + \xi_6 \cdot C_{Ni}\right)^2 \cdot \phi - \frac{\partial C_{SC}}{\partial t}$$

$$D_{Cu} = D_{Cu}^{thermal} + D_{Cu}^{irrad} = D_{Cu}^{thermal} + \omega \cdot \phi^{\eta} \qquad \frac{\partial C_{Cu}^{mat}}{\partial t} = -v_{SC} \cdot \frac{\partial C_{Sc}^{enh}}{\partial t} - v'_{SC} \cdot C_{SC}$$

✓Mechanical properties change due to microstructure change

$$\Delta T_{SC} = \xi_{16} \cdot \sqrt{V_f}, \qquad V_f = \left(\xi_{15} \cdot f\left(C_{Cu}^{mat}, C_{SC}\right) \cdot \left(1 + \xi_{13} \cdot \left(C_{Ni}^0\right)^{\xi_{14}}\right)^2 + \xi_9 \cdot \left(1 + \xi_{10} \cdot D_{Cu}\right) \cdot \phi t\right) \cdot C_{SC}$$

$$\Delta T_{MD} = \xi_{17} \cdot \sqrt{C_{MD}}$$

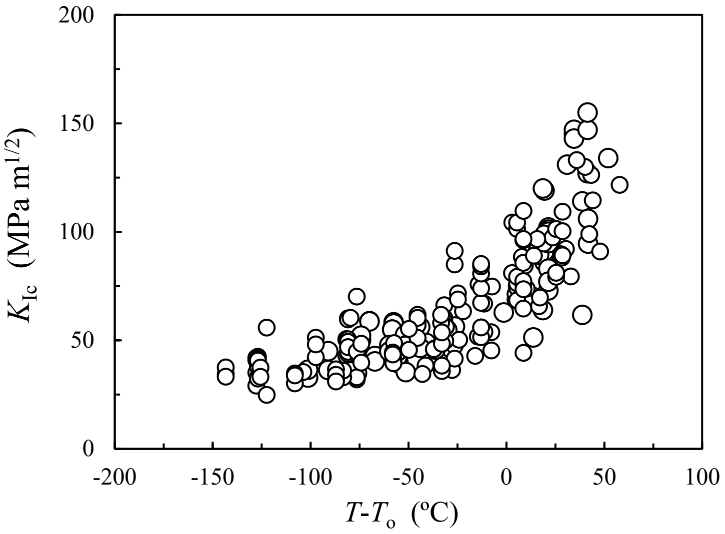
$$\Delta RT_{NDT} = \sqrt{\left(\Delta T_{SC}\right)^2 + \left(\Delta T_{MD}\right)^2}$$

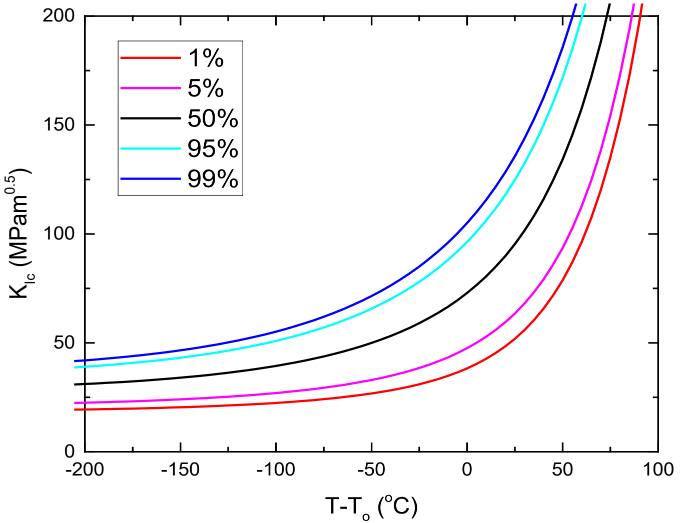
ΔT_{SC} :Shift of temperature due to SC

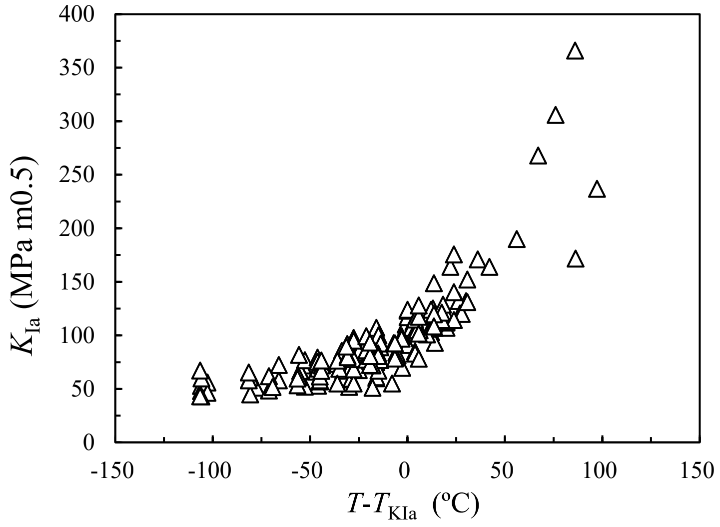
ΔT_{MD} :Shift of temperature due to MD

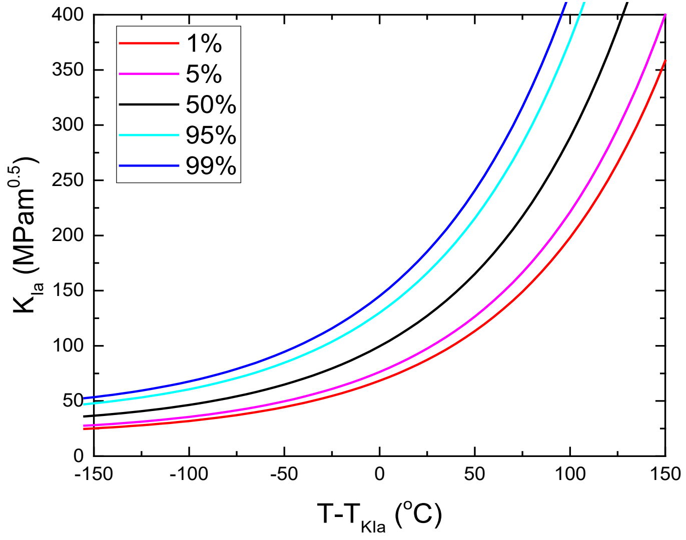
Fracture Toughness

- Fracture toughness (K_{Ic}, K_{Ia}) probabilistic distribution models
  - ✓ Weibull distribution model of K_{Ic} was developed based on Japanese data*
  - ✓ Lognormal distribution model of K_{Ia} was developed based on Japanese data*







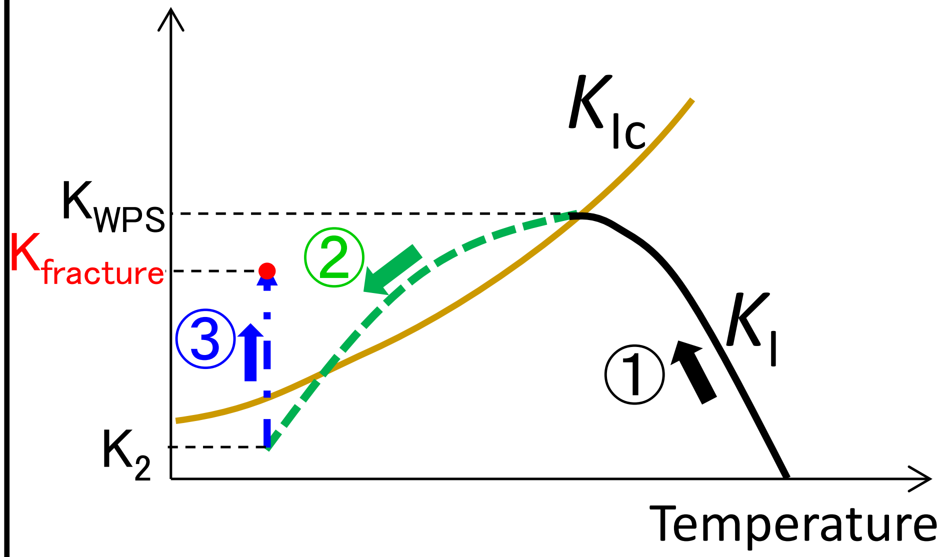


* Katsuyama et al., "Guideline on probabilistic fracture mechanics analysis for Japanese reactor pressure vessels", PVP2017-65921, 2017.

WPS Evaluation Model

- Warm pre-stress (WPS) evaluation model
  - ✓ AREVA-CEA-EDF (ACE) model[*1] is adopted.
  - ✓ Its applicability has been confirmed by JAEA's experiments[*2].

Schematic illustration of ACE model



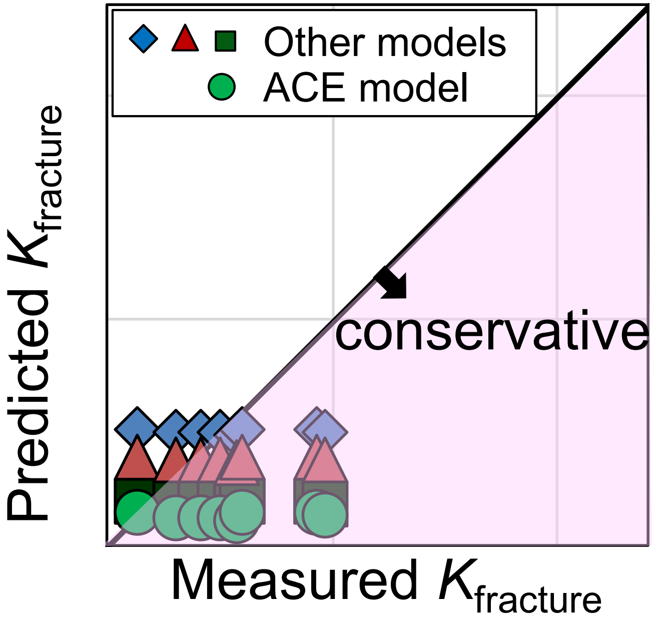
① Loading: failure if $K_I > K_{Ic}$

② Unloading: no failure even if $K_I > K_{Ic}$

③ Reloading: failure if $K_I > K_{fracture}$

$$K_{\text{fracture}} = \text{Max}(K_{\text{Ic}}, \text{Min}(K_{\text{WPS}}, K_2 + K_{\text{WPS}}/2))$$

Experiment validation



Predicted results by ACE model show conservative evaluation.

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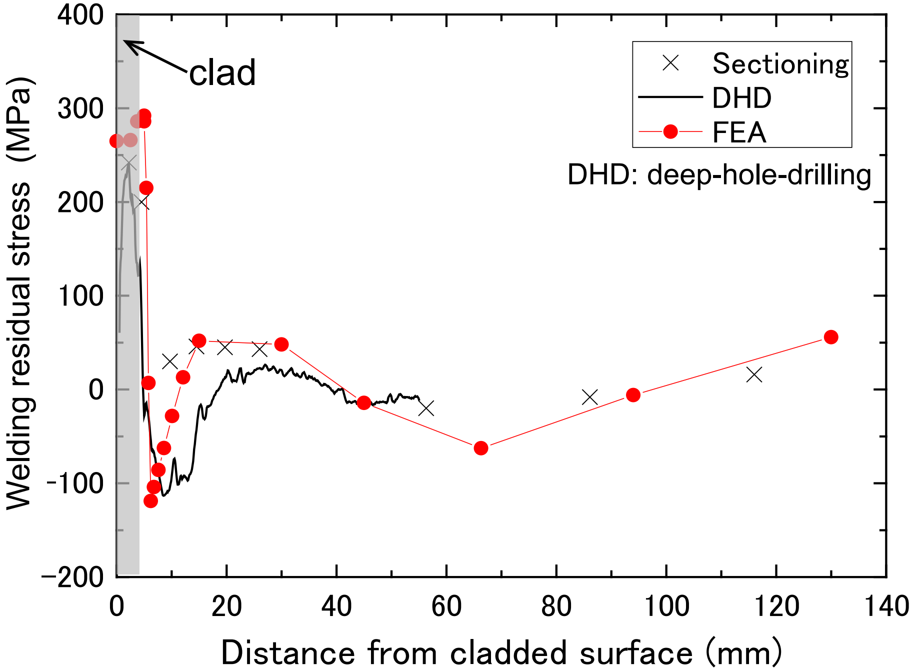
*1: Chapuliot et al., "WPS criterion proposition based on experimental data base interpretation", Fontevraud 7, 2010. *2: Iwata, et al., "Specimen size effect on fracture toughness of reactor pressure vessel steel following warm pre-stressing", PVP2016-63795, 2016.

Weld Residual Stress Distribution

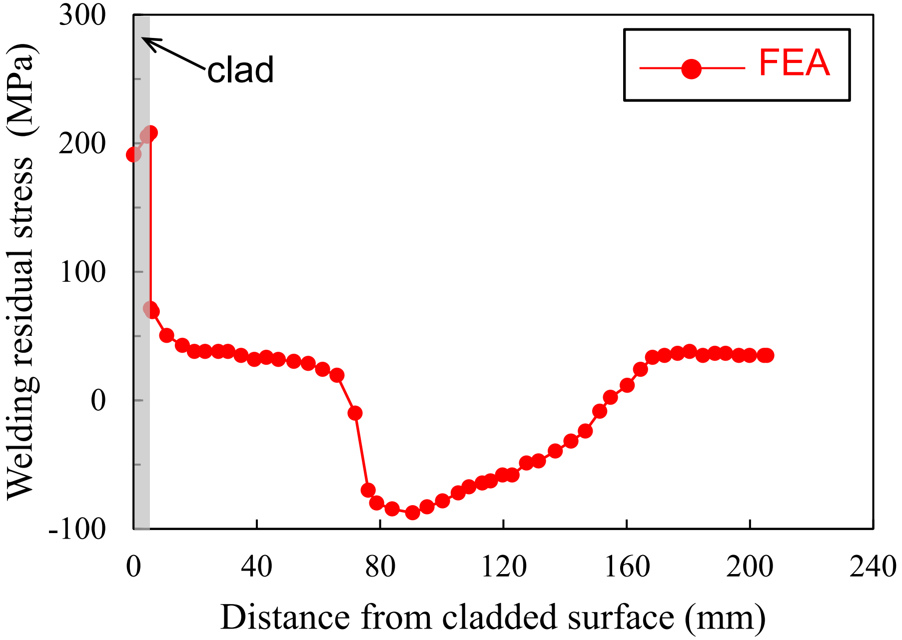
- WRS due to weld-overlay cladding and butt-welding
  - ✓ Detailed 3D FEAs are performed to calculate WRS distributions. The solutions were incorporated in PASCAL5.

WRS due to weld-overlay cladding[*1]



WRS due to wed-overlay welding has been validated by experimental measurements.

WRS due to butt-welding[*2]



Experimental measurements by DHD to validate WRS due to butt-welding is ongoing.

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*1: Katsuyama et al., “Assessment of residual stress due to overlay-welded cladding and structural integrity of a reactor pressure vessel”, Journal of Pressure Vessel Technology, p. 051402, 2013. *2: Hirota, et al., “Proposal for update on evaluation procedure for reactor pressure vessels against pressurized thermal shock events in Japan”, PVP2014-28392, 2014.

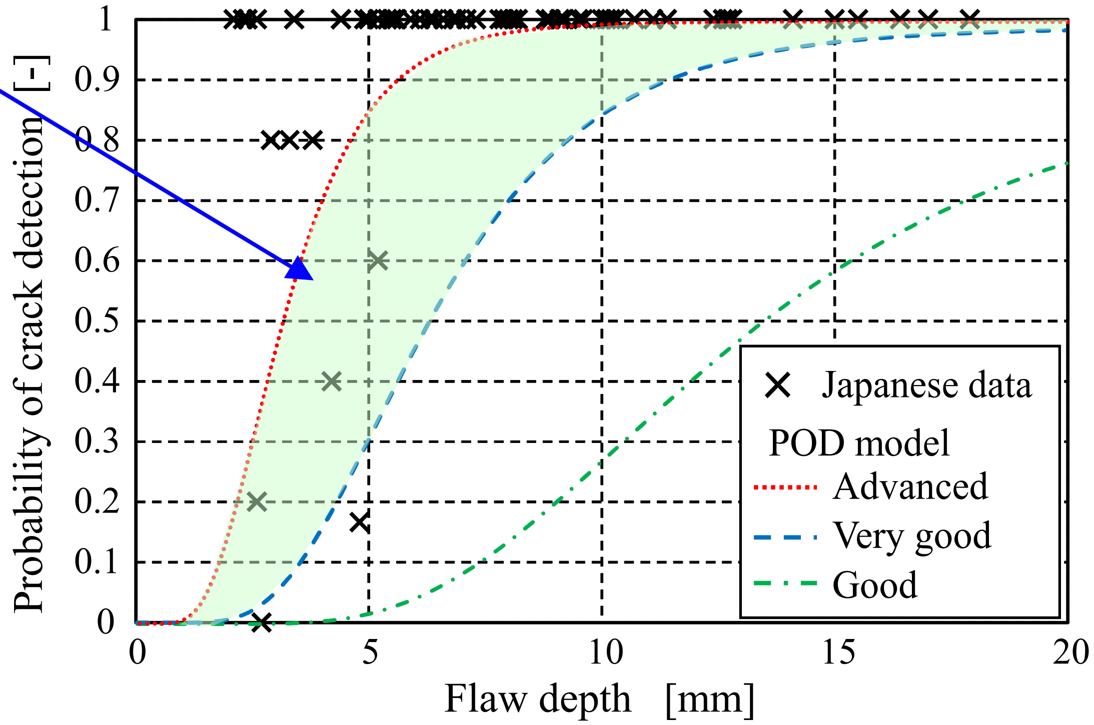
POD Model for Japanese RPVs

- POD (Probability of crack detection) model of ultrasonic testing (UT) for Japanese RPVs
  - ✓ Khaleel model[*1] proposed by Pacific Northwest National Laboratory is adopted.
  - ✓ The parameters are determined based on Japanese UT data[*2] for RPVs.

$$POD = 1 - \varepsilon - \frac{1}{2}(1-\varepsilon)\,\mathrm{erfc}\left(\nu \ln\left(\frac{a}{a^*}\right)\right)$$

a: flaw depth, a^*: flaw depth when POD=50%
ν: slope of POD curve, ε: probability of missed detection

Corresponding to the Japanese data



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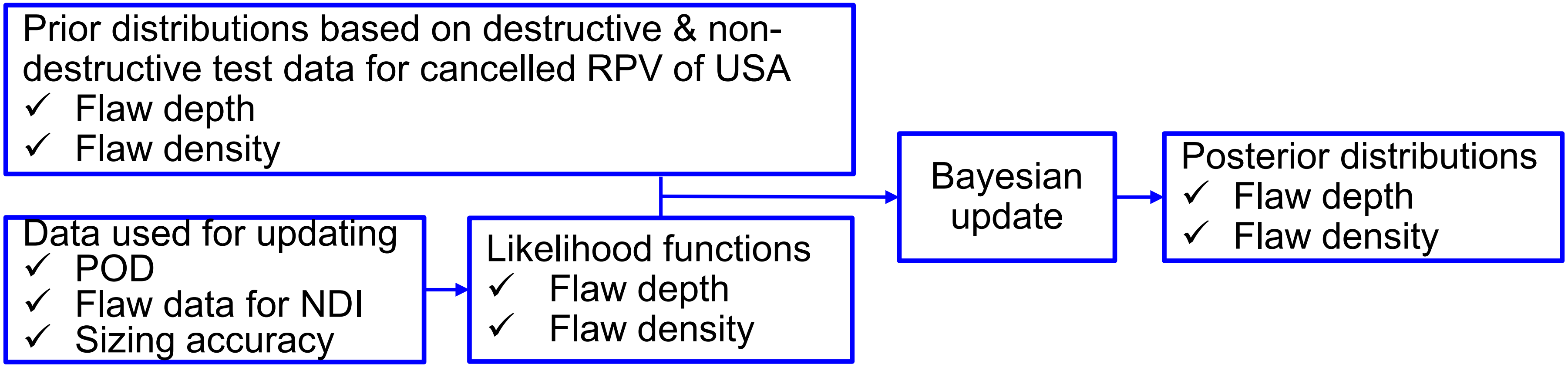
*1: Khaleel and Simonen, “A model for predicting vessel failure probabilities including the effects of service inspection and flaw sizing errors,” Nuclear Engineering and Design, p.353-369, 2000. *2: Japan Nuclear Energy Safety Organization, “Report on the validation project of inspection technologies for nuclear power facilities (confirmation of crack detectability and sizing accuracy in ultrasonic testing),” Document No. 05-0001(2/2), (in Japanese), 2005.

Update Flaw Distribution Using Inspection Result

- In order to update the flaw distributions based on inspection result and inspection performance, Bayesian updating method has been improved to be applicable for both flaw density and depth simultaneously.



Prior distributions based on destructive & non-destructive test data for cancelled RPV of USA
- ✓ Flaw depth
- ✓ Flaw density

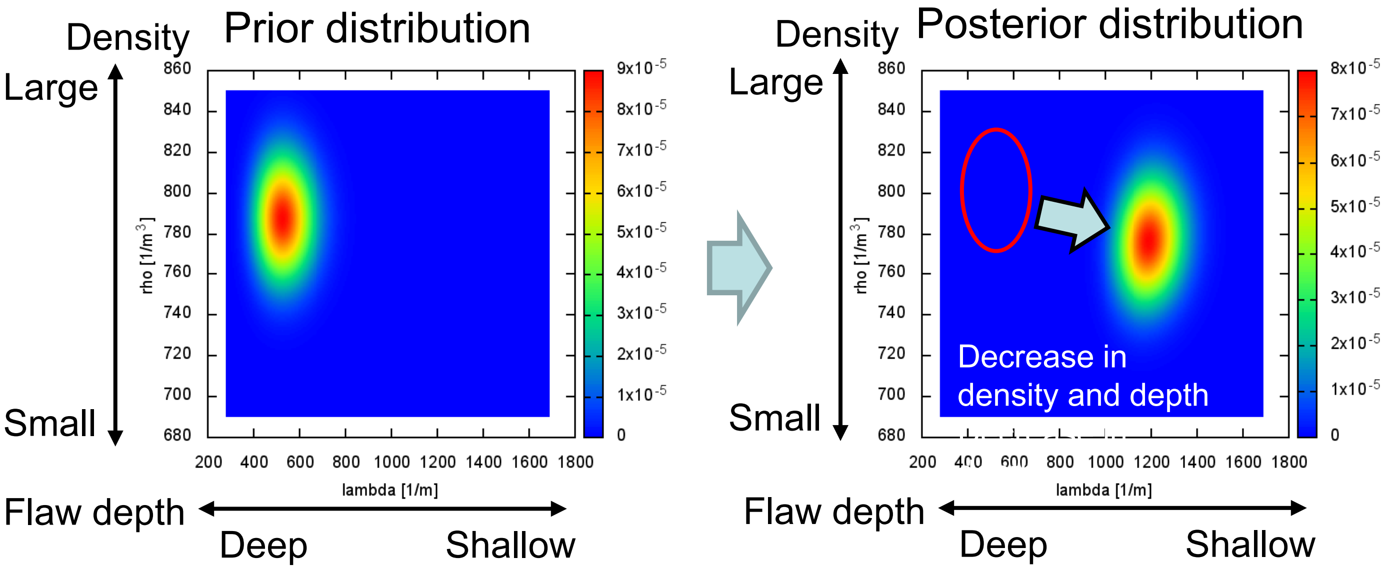
Data used for updating
- ✓ POD
- ✓ Flaw data for NDI
- ✓ Sizing accuracy

Likelihood functions
- ✓ Flaw depth
- ✓ Flaw density

Bayesian update

Posterior distributions
- ✓ Flaw depth
- ✓ Flaw density

Schematic diagram of the Bayesian framework for updating flaw distributions



Decrease in density and depth

An example of flaw distribution updated using Bayesian updating method

Verification & Validation Activities of PASCAL

Verification & Validation Activities

- To strengthen the applicability of PASCAL, a series of verification & validation activities have been performed.
  - ✓ Japanese RPV structural integrity research committee
    - Experts on RPV integrity assessment & PFM approach
    - Consensus on analysis methods, models and functions in PASCAL
  - ✓ Japanese working group
    - Consisted of different members from industries, universities & institutes
    - Cross check on the source program of PASCAL
    - Verifications for analysis method, model and function in PASCAL
    - Comparative analyses by multiple members using PASCAL
  - ✓ Round-robin & benchmark analyses
    - Round-robin analyses by multiple organizations in a Japanese PFM sub-committee
    - Benchmark analyses between PASCAL & FAVOR codes
    - Benchmark analyses in a EURATOM project: APAL

PASCAL5 has been proved to be effective in PFM evaluation for Japanese RPVs

Development of PFM Analysis Guideline

Development of PFM Analysis Guideline

- Analysis procedure, key points of the analysis, the recommendation models and methods are described in the main body. Technical bases are provided in the explanatory section.

The second edition will be published in this winter.

Main body	Explanation
I. General items	I. General items
II. Transients ✓ Flaws types and distributions	II. Transients for PWR and BWR ✓ Supplementations on flaw types, distributions, evaluation points, etc.
III. Fracture toughness ✓ Reference temperature	III. Fracture toughness ✓ Technical basis on definition of reference temperature
IV. Failure frequency evaluation	IV. Failure frequency evaluation Evaluation methods on FCI and TWCF, and their confidence are explained.
V. Analysis code	V. Analysis code
➢ Appendix: Verification of PFM code	➢ Appendix: Examples for PASCAL

Strategy for Application of PFM:
PFM application examples using PASCAL5

Application: PFM analysis

Analysis conditions for a model Japanese RPV of BWR

Item	Parameter/Condition	Note
RPV geometries	Core region of a model Japanese RPV (Type-5 BWR) Inner radius = 3187.5 mm, Base metal thickness: 160 mm Clad thickness: 5.5 mm, Height of core region: 3709 mm	A model Japanese RPV
Transient	LTOP transient recorded in a BWR plant* Frequency: 1.0×10^{-3} /ry**	
Neutron fluence	Maximum value: 5.4×10^{17} n/cm^2 (E > 1MeV, 48EFPY) Distribution in core region: Uniform distribution Standard deviation (S.D.): 13.1% of the mean value	Analysis conditions for the model Japanese RPV
Irradiation temperature	276 ^{o}C	
Initial RT$_{NDT}$ and S.D.	-25^{o}C, S.D.: 9.4^{o}C for base metal -25^{o}C, S.D.: 9.4^{o}C for weld	
Irradiation embrittlement prediction	Method in JEAC4201-2007 (sup. 2013)	
Chemical compositions and S.D.	Cu: 0.08%, S.D.: 0.01% Ni: 0.58%, S.D.: 0.02% for base metal Cu: 0.07%, S.D.: 0.01%, Ni: 0.63%, S.D.: 0.02% for weld	

*Chou & Huang, International Journal of Nuclear Energy, Vol.2015, 785041-1~9, 2015.

**BWRVIP-05, 1995

Initial Flaws

- Surface flaws and embedded flaws are considered.

Initial crack type		Item	Parameter/Condition
Internal	Surface flaw	Orientation	Circumferential crack in base metal and weld (aligned with weld-overlay cladding direction)
		Depth	6.5 mm
		Aspect ratio	Data generated by VFLAW using the welding conditions for a Japanese BWR RPV
		Density	
	Embedded flaw	Orientation	In base metal: axial and circumferential cracks In weld: aligned with the butt-welding directions
		Depth	Data generated by VFLAW using the welding conditions for a Japanese BWR-type RPV
		Aspect ratio	
		Density	
		Location	From clad-base metal interface to inner 1/2 of the base metal thickness
External	Surface flaw	Orientation	In base metal: axial and circumferential cracks In weld: cracks aligned with the welding directions
		Depth	6.5 mm
		Aspect ratio	Data generated by VFLAW using the welding conditions for a Japanese BWR-type RPV
		Density	
	Embedded flaw	Orientation	In base metal: axial and circumferential cracks In weld: cracks aligned with the welding directions
		Depth	Data generated by VFLAW using the welding conditions for a Japanese BWR-type RPV
		Aspect ratio	
		Density	
		Location	From 1/2 of the base metal thickness to RPV outer surface

Analysis Results

- The mean value of TWCF (8.4×10^{-11}/ry) for the model RPV of BWR is about two orders of magnitude lower than the mean value of TWCF for the model RPV of PWR (2.5×10^{-8}/ry) reported in last ISPMNA.
- The contribution of circumferential weld to the total mean value of TWCF is very small, about 0.02%.

Flaw location		Flaw type	Orientation	Mean FCI [/ry]	Mean TWCF [/ry]
Internal	Base metal	Embedded	Axial	6.0×10^{-14}	6.0×10^{-14}
			Circ.	0	0
		Surface	Circ.	9.4×10^{-12}	3.2×10^{-12}
	Weld	Embedded	Axial	1.3×10^{-11}	1.3×10^{-11}
			Circ.	3.5×10^{-15}	3.5×10^{-15}
		Surface	Circ.	5.8×10^{-11}	3.5×10^{-11}
External	Base metal	Embedded	Axial	3.7×10^{-14}	2.7×10^{-15}
			Circ.	0	0
		Surface	Axial	1.9×10^{-15}	2.0×10^{-17}
			Circ.	0	0
	Weld	Embedded	Axial	3.4×10^{-11}	3.2×10^{-11}
			Circ.	1.3×10^{-14}	1.2×10^{-14}
		Surface	Axial	7.6×10^{-13}	2.4×10^{-13}
			Circ.	0	0
Total				1.2×10^{-10}	8.4×10^{-11}

Summary

- In Japan, a PFM analysis code PASCAL5 has been developed for probabilistic structural integrity assessment of both PWR and BWR RPVs.
- Analysis models & methods in PASCAL5 have been improved based on the latest knowledge & findings. It will be released in this winter.
- A PFM guideline has also been updated on how to assess the structural integrity of both PWR and BWR RPVs using PFM approach. It will also be published in this winter.

ACKNOWLEDGMENT

A part of PASCAL4 was developed under the contract research entrusted from Regulatory Standard and Research Department, Secretariat of Nuclear Regulation Authority.

Thank you for your attention.