Development of probabilistic fracture mechanics code for RPVs: FERMAT

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CRIEPI
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Background

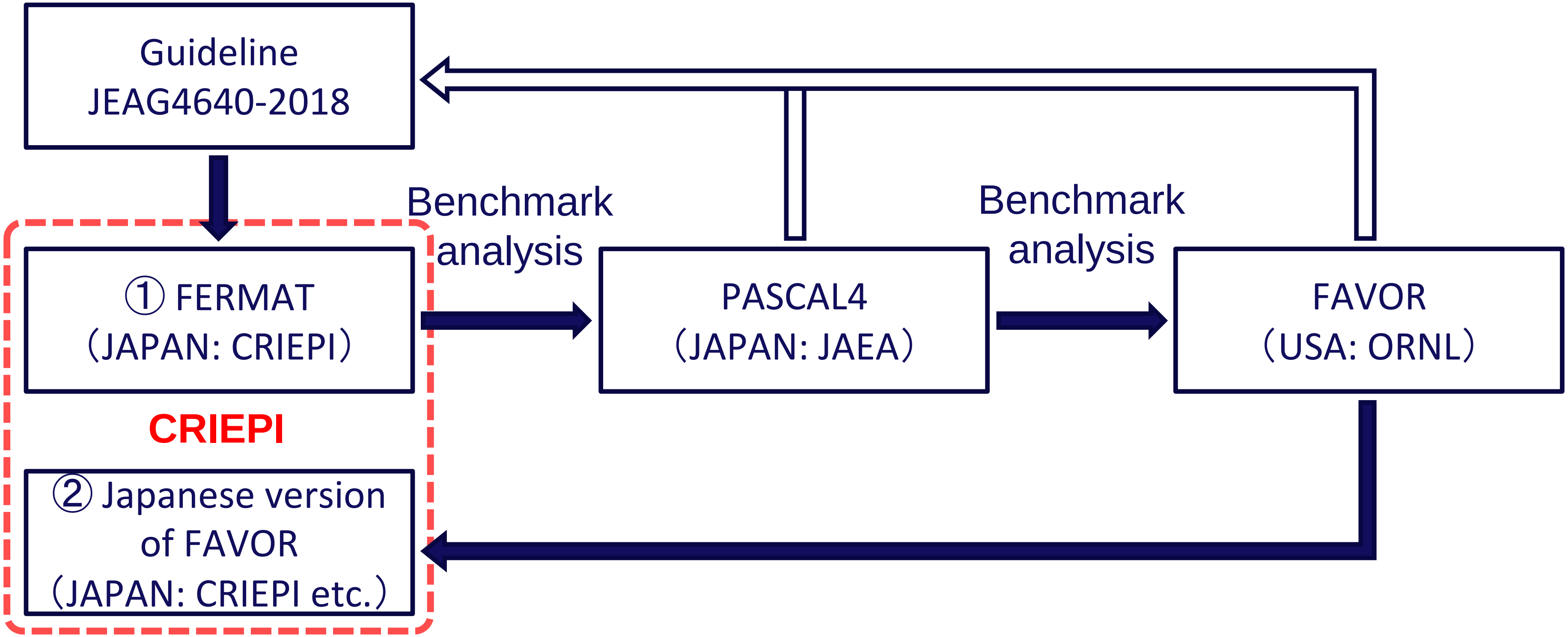
- The actual implementation of PFM on integrity assessment standards of reactor pressure vessels (RPVs) is not yet actualized in Japan. However, The discussions for practical application of PFM is ongoing.

- Guideline JEAG 4640-2018(JEAG4640) was established in 2018.
  - JEAG4640 gives a standard procedure for evaluating failure frequency of RPVs based on PFM.

- There are some differences on models for integrity assessment from other countries (ex. United states).
  - Equations for predicting radiation embrittlement
  - Fracture toughness curve
  - etc.

PFM analysis approach in CRIEPI

- CRIEPI takes following 2 approaches to develop PFM analysis basis for RPVs.
  - ① FERMAT (Fracture mechanics Evaluation of RPV MATerials)
  - ② Japanese version of FAVOR



Guideline
JEAG4640-2018

Benchmark analysis

Benchmark analysis

① FERMAT
（JAPAN: CRIEPI）

PASCAL4
（JAPAN: JAEA）

FAVOR
（USA: ORNL）

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② Japanese version of FAVOR
（JAPAN: CRIEPI etc.）

Background

- PASCAL4 has already been developed by JAEA to evaluate Japanese RPVs based on PFM.
    - PASCAL4 is excellent code. That has so much flexibility.

- PFM code tends to be complex for newcomers.

- We are developing a new PFM analysis code FERMAT.
    - The concept of FERMAT is minimal design for practical use in structural integrity assessment of RPVs based on JEAG 4640-2018.

- FERMAT code targets at both crack initiation and crack arrest.
    - We are verifying modules for crack arrest model and embedded flaws now.
    - Results for surface crack initiation are reported in this presentation.

Objective

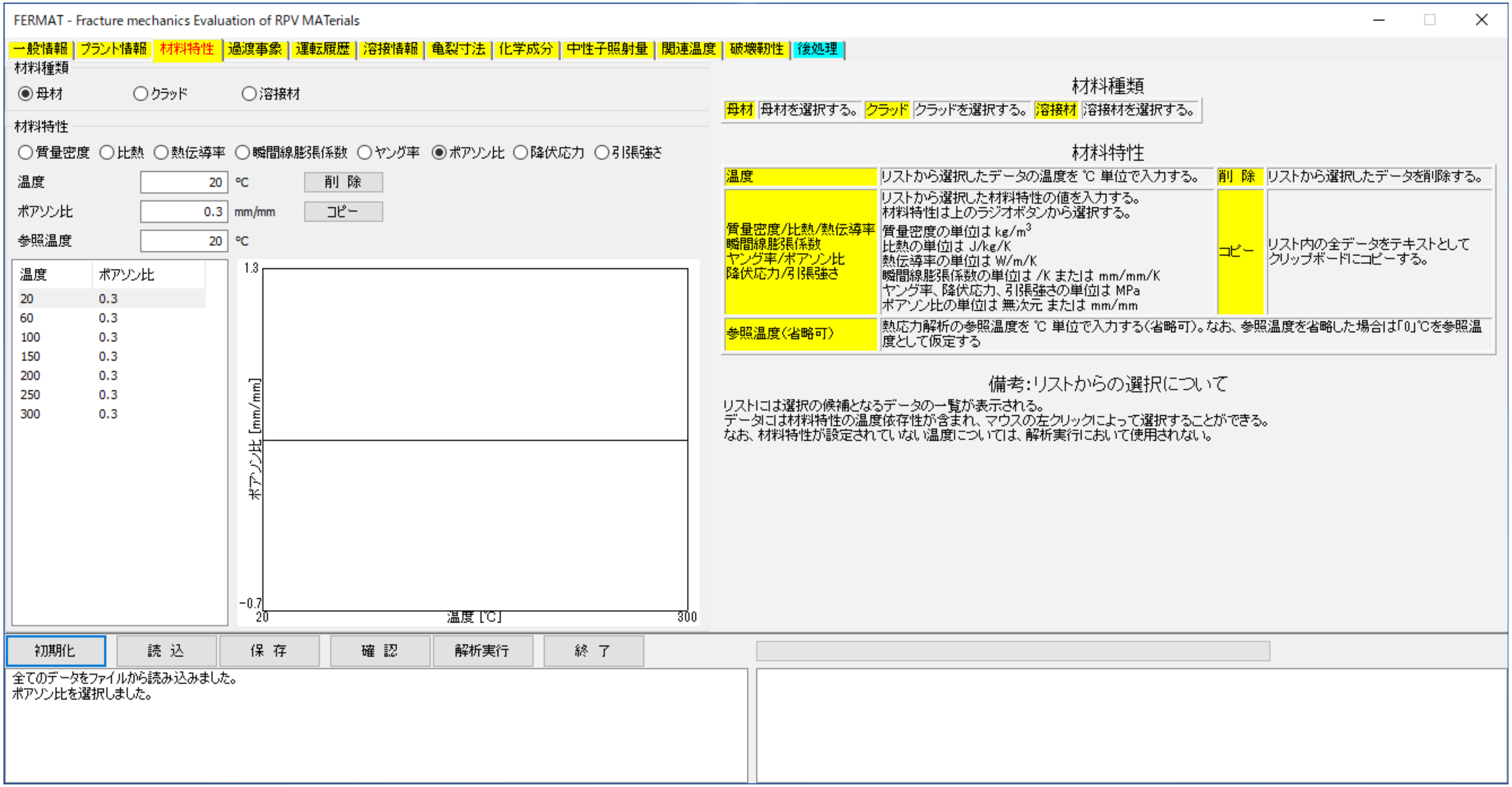
◆ This presentation reports the following.

- Outline of FERMAT
- Comparison of results between FERMAT and PASCAL4.

  ⇒This comparison has been conducted as part of validation.

Outline of FERMAT

- All processes (including pre-processes and post-processes) can be finished in one code with graphical user interface.



FERMAT - Fracture mechanics Evaluation of RPV MATerials

材料種類

● 母材 ○ クラッド ○ 溶接材

材料特性

○ 質量密度 ○ 比熱 ○ 熱伝導率 ○ 瞬間線膨張係数 ○ ヤング率 ● ポアソン比 ○ 降伏応力 ○ 引張強さ

温度 20 ℃

ポアソン比 0.3 mm/mm

参照温度 20 ℃

温度	ポアソン比
20	0.3
60	0.3
100	0.3
150	0.3
200	0.3
250	0.3
300	0.3

材料種類

母材	母材を選択する。	クラッド	クラッドを選択する。	溶接材	溶接材を選択する。

材料特性

温度	リストから選択したデータの温度を ℃ 単位で入力する。	削 除	リストから選択したデータを削除する。
質量密度/比熱/熱伝導率 瞬間線膨張係数 ヤング率/ポアソン比 降伏応力/引張強さ	リストから選択した材料特性の値を入力する。 材料特性は上のラジオボタンから選択する。 質量密度の単位は kg/m^3 比熱の単位は J/kg/K 熱伝導率の単位は W/m/K 瞬間線膨張係数の単位は /K または mm/mm/K ヤング率、降伏応力、引張強さの単位は MPa ポアソン比の単位は 無次元 または mm/mm	コピー	リスト内の全データをテキストとして クリップボードにコピーする。
参照温度（省略可）	熱応力解析の参照温度を ℃ 単位で入力する（省略可）。なお、参照温度を省略した場合は「0」℃を参照温度として仮定する		

備考：リストからの選択について

リストには選択の候補となるデータの一覧が表示される。
データには材料特性の温度依存性が含まれ、マウスの左クリックによって選択することができる。
なお、材料特性が設定されていない温度については、解析実行において使用されない。

全てのデータをファイルから読み込みました。
ポアソン比を選択しました。

Outline of FERMAT

- The calculation models of FERMAT are based on guideline JEAG4640.
- Sections of JEAG4640 are shown below.
  - PFM-1000: General information
  - PFM-2000: Calculation of stress intensity factors
  - PFM-3000: Calculation of fracture toughness
  - PFM-4000: Modeling of uncertainty
  - PFM-5000: Calculation of failure frequency
- Flow for calculating frequency of crack Initiation is shown below.
  1. Calculation of stress intensity factor (K_I)
  2. Calculation of fracture toughness (K_{Ic}) of materials
  3. Calculation of failure frequency
     (Frequency of crack initiation in this presentation)

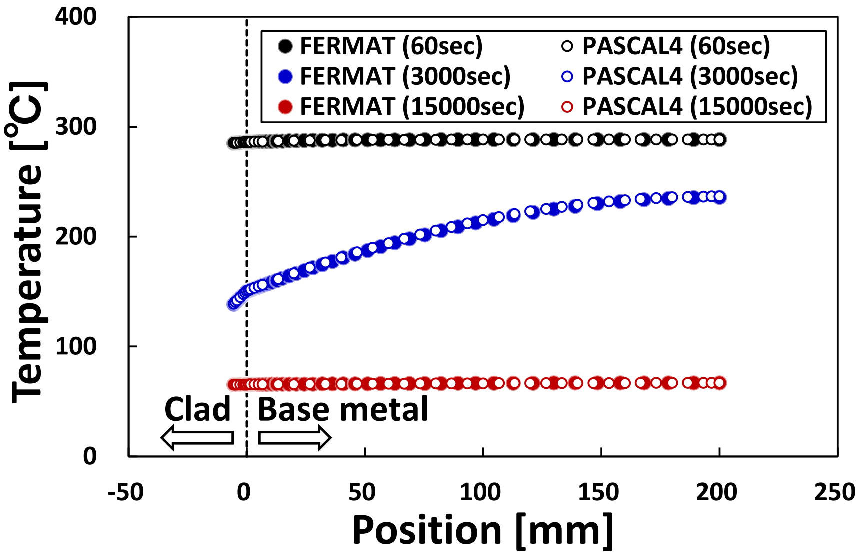
Analysis conditions

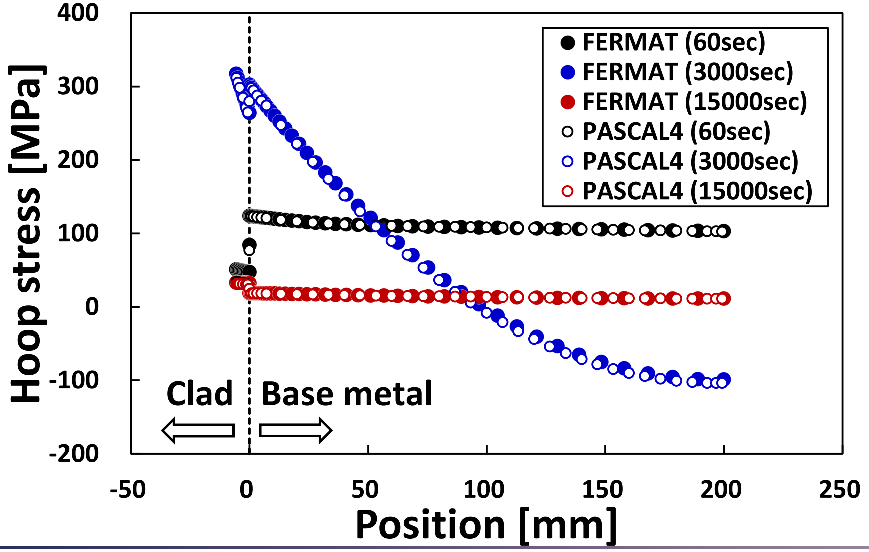
	items		Analysis conditions
Transients	Determine transients		Dominant 13 transients in Japanese RPV conditions selected from transients of Beaver Valley [13]
Flaws	Surface flaw	Crack direction	Only circumference flaws
		Crack depth [mm]	6.5
		Aspect ratio	2, 6, 10, 100
Irradiation conditions	Neutron fluence [n/cm^2] (E>1MeV)	Spatial distribution	Not considered
		Mean value	7×10^{19}
		Standard deviation	13.1%
	Neutron flax [n/cm^2/s](E>1MeV)		4.62×10^{10}
	Irradiation temperature [℃]		288
Chemical composition	Base Cu [wt%]	Mean value	0.16
		Standard deviation	0.01
	Base Ni [wt%]	Mean value	0.61
		Standard deviation	0.02
Initial RT_{NDT}	Base [℃]	Mean value	-3.9※ (-5.0)
		Standard deviation	9.40
	Weld [℃]	Mean value	-48.9※ (-50.0)
		Standard deviation	9.40

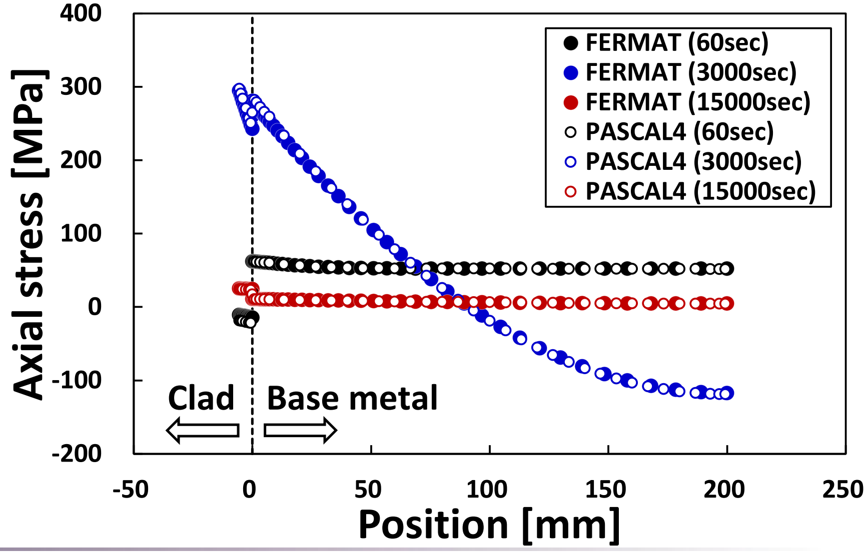
[1]JEAG4640-2018, [2] Katsuyama et.al.,JAEA-Data-Code-2017-015

Deterministic analysis (Temperature and stress distribution)

- Analysis of temperature and stress distribution has been conducted for small breaking loss of coolant accident (SBLOCA).
- Results of analysis by FERMAT and PASCAL4 were well corresponding each other.

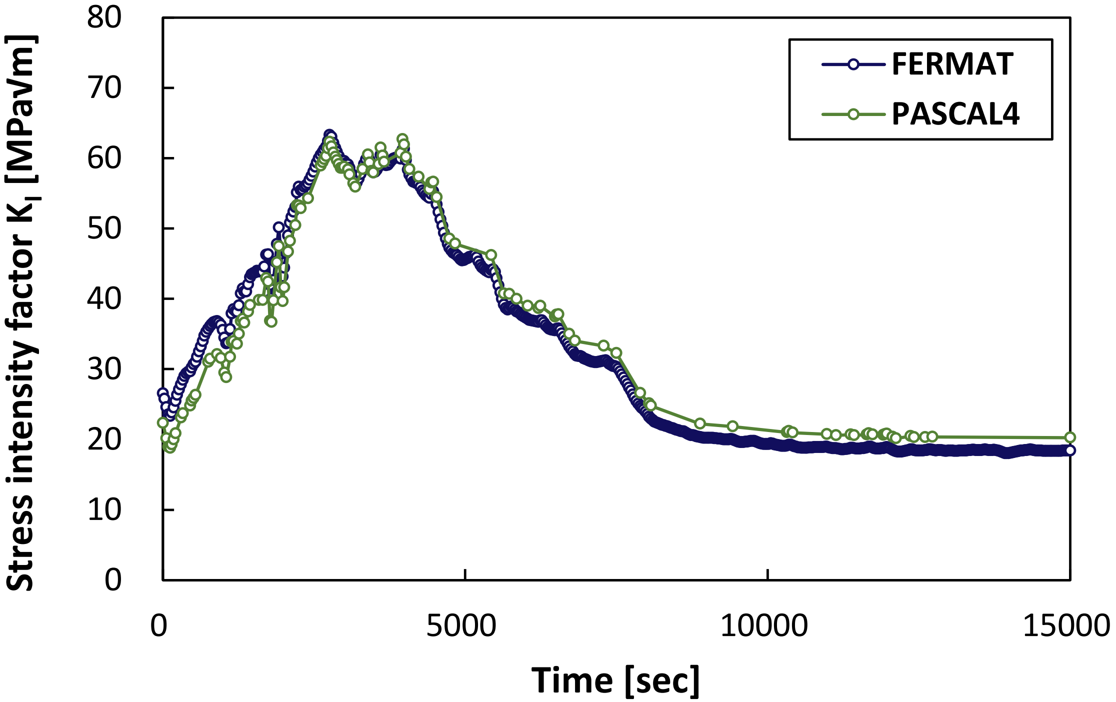






Deterministic analysis (Stress intensity factor)

- Stress intensity factor for SBLOCA is shown below.
- Difference in stress intensity factor calculated by those two codes was not so significant, even though different models were adopted.



Time dependence of stress intensity factor
(Aspect ratio = 6, residual stress is considered)

Evaluation of K_{Ic} and probability of crack initiation

- K_{Ic} curve and cumulative probability Φ_{KIc} are determined by following equations [6] for each evaluation point of K_I (from K_1 to K_6 in bottom right figure).
- Maximum Φ_{KIc} is determined as conditional probability of initiation.

$$\Phi_{K_{Ic}} = 1 - exp\left[-\left(\frac{K_{Ic} - a_{K_{Ic}}}{b_{K_{Ic}}}\right)^{c_{K_{Ic}}}\right]$$

$$a_{K_{Ic}}(\Delta T_{RELATIVE}) = 13.18 + 6.71 \cdot \exp[0.0337(\Delta T_{RELATIVE})]$$

$$b_{K_{Ic}}(\Delta T_{RELATIVE}) = 15.88 + 42.21 \cdot \exp[0.0121(\Delta T_{RELATIVE})]$$

$$c_{K_{Ic}} = 4$$

Temperature of crack tip

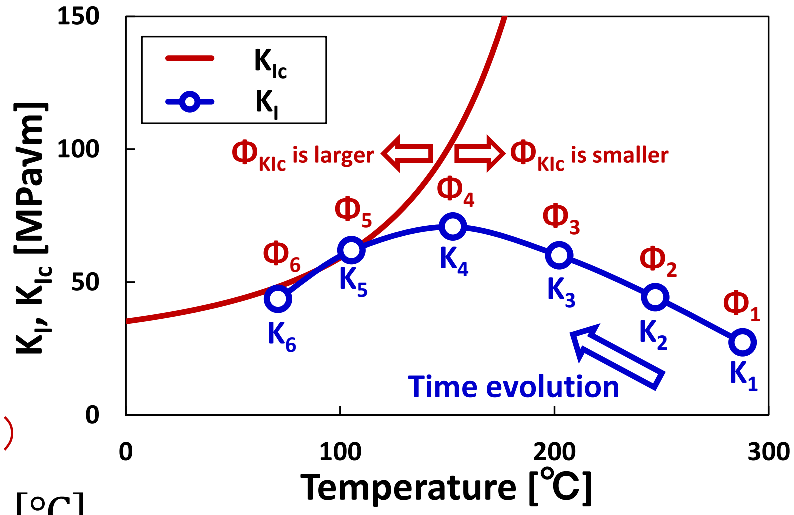
RT_{NDT}

$$\Delta T_{RELATIVE} = T(r,\tau) - RT_{NDT\_C}$$

$$RT_{NDT\_C} = \Delta RT_{NDT} - \Delta RT_{epistemic} + RT_{NDT(0)}$$

⇩ Temperature shift caused by radiation embrittlement

⇩ Initial RT_{NDT}（normal distribution）



$$\Delta RT_{epistemic} = -15.60 + 67.56[-\ln(1-P)]^{1/4.31}\ [°C]$$

$$(0 < P < 1)$$

[3] Report of Nuclear Regulation Authority, 291203, 2018

Conclusion

- New PFM analysis code FERMAT was developed and verified.
- We also conducted validation by comparing results of each module.
  - Results of deterministic analysis by FERMAT and PASCAL4 were well corresponding each other.
    - Results of deterministic analysis by FERMAT were well corresponding to those by PASCAL4 code.
    - There was only a slight difference between stress intensity factor calculated by FERMAT and that calculated by PASCAL4.

Future work

- Crack arrest model and modules for evaluating embedded flaws has already been implemented in FERMAT.
  - We are verifying modules for crack arrest model and embedded flaws now.
    - Crack arrest model is complex, and their specifications influence failure frequency.
    - Specifications for crack arrest are discussed carefully.