Activities of The Committee on Practical Application of PFM - Part 2: Benchmark Analysis on Failure Frequency Assessment for Reactor Pressure Vessel with Analysis Conditions of a Japanese Actual PWR Plant-

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Concept of the benchmark analysis

- In this benchmark analysis, 3 participants (from MHI, JAEA, and CRIEPI) assessed failure frequency of RPVs by same code (PASCAL4) with the same analysis conditions (“Basic analysis condition“ shown in presentation Part 1).

- Each participant freely made input files excepting specified analysis conditions. There are differences in time steps or some internal parameters.
  - Those differences may cause difference in failure frequency calculated by probabilistic fracture mechanics (PFM).

- The difference of the failure frequency calculated by different participants with analysis conditions of a Japanese actual PWR plant were investigated through the benchmark analysis.

Deterministic part of benchmark analysis

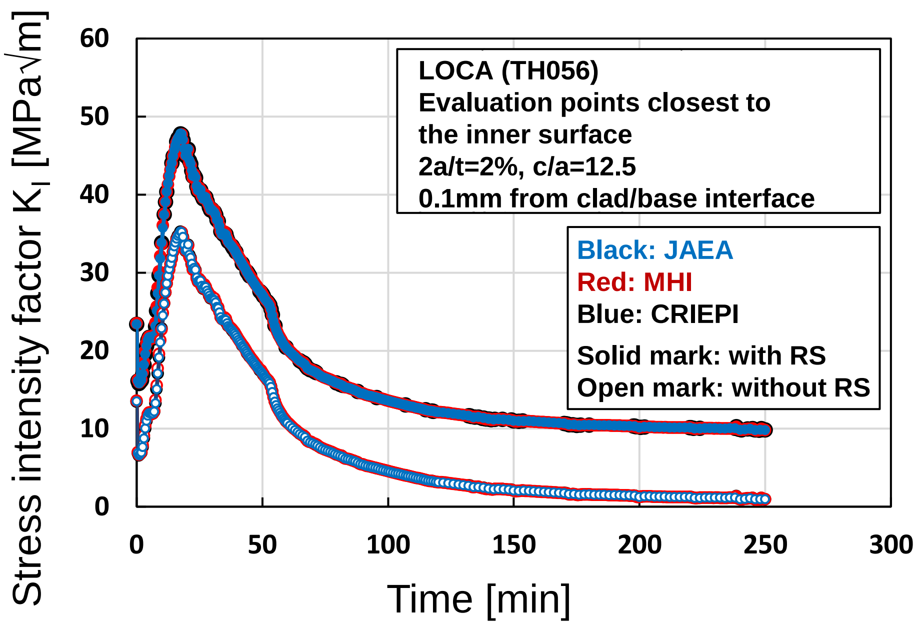
- Analysis codes used for thermal and stress analyses
  - JAEA : Pre-PASCAL
  - CRIEPI : Pre-PASCAL
  - MHI : Abaqus

  * PASCAL4 was used for PFM analysis and stress intensity factor calculation.

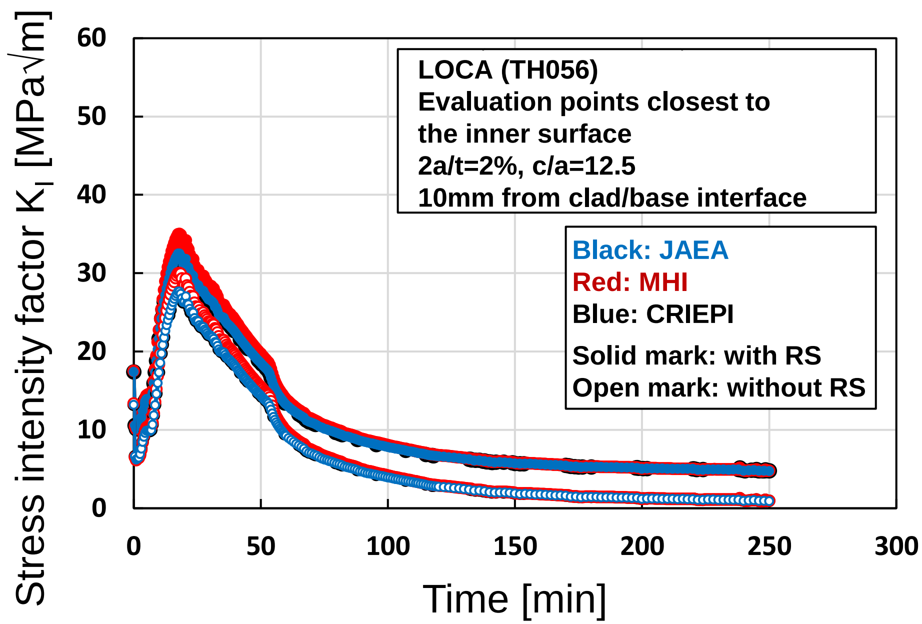
- Stress intensity factor of representative flaws were compared.
  - Embedded flaw
    - Large break loss of coolant accident transient (TH056)
    - Depth: 2a/t=2%, Aspect ratio c/a = 12.5
    - Position: 0.1mm, 10mm (from clad/base interface)
  - Inner surface flaw
    - Stuck open valve transient (TH126)
    - Depth: 6.5mm, Aspect ratio 2c/a = 6, 100

Stress intensity factor of embedded flaws (LOCA-056)

- Stress intensity factor were mostly in good agreement, but had some variation due to differences in analysis codes and/or time step setting.
  - Difference in stress intensity factor at peak (=18 min) was approximately 8% for the case of 10 mm from clad/base interface.
  - Stress intensity factor were agreed well for other cases.



(0.1mm from base/clad interface)

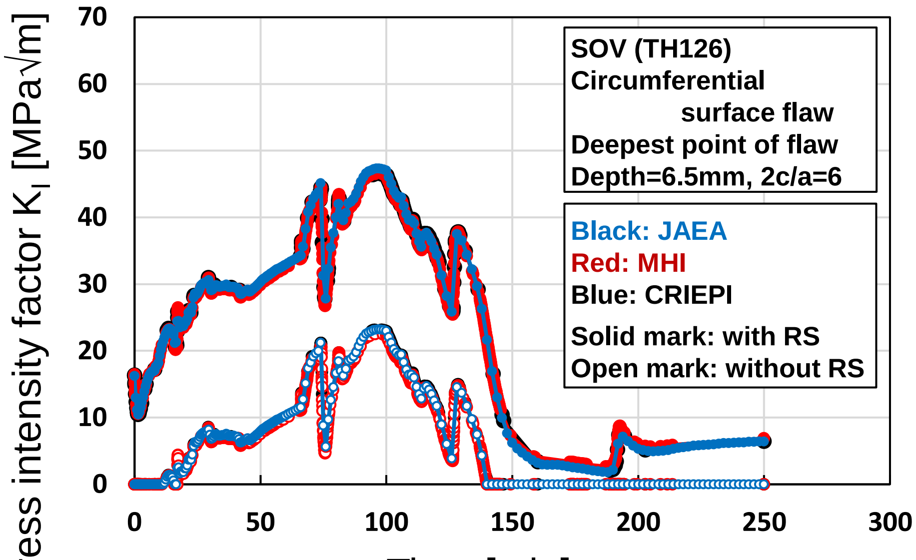


(10mm from base/clad interface)

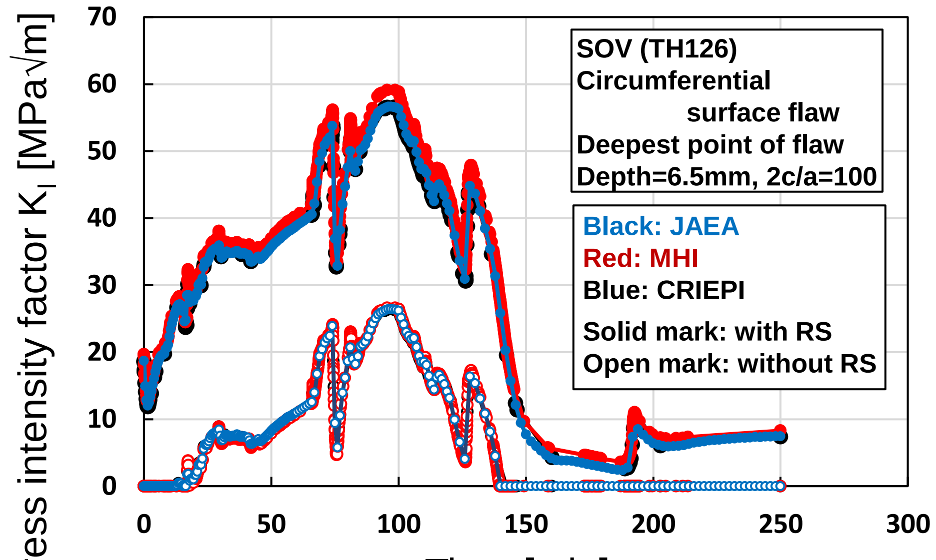
Time dependence of stress intensity factor K_I

Stress intensity factor of surface flaws（SOV-126）

- Stress intensity factor were mostly in good agreement, but had some variation due to differences in analysis codes and/or time step setting.
  - Difference in stress intensity factor around highest peak (≒95 min) was approximately 6% in Maximum for one case (in right figure) when weld residual stress (RS) was considered.
  - Stress intensity factor were agreed well for other cases.



(Aspect ratio = 6)



(Aspect ratio = 100)

Time dependence of stress intensity factor K_I

Results of probabilistic part of benchmark analysis

- Frequency of crack initiation (FCI) and Through wall crack frequency (TWCF) calculated by three participants (MHI, JAEA, CRIEPI) were compared.
  - Mean value of FCI was on the order of 10^{-6} regardless of who analyzed. The maximum value (JAEA) was less than twice the minimum value (MHI).
  - Mean value of TWCF was on the order of 10^{-8} regardless of who analyzed. The maximum value (JAEA) was less than 1.2 times the minimum value (MHI).

	MHI	CRIEPI	JAEA
Frequency of crack initiation (FCI)	1.67E-06	2.19E-06	2.94E-06
Through wall crack frequency (TWCF)	2.33E-08	2.55E-08	2.75E-08

- Do the differences shown above affect judgement of integrity of RPV?
  - No. the difference are not considered to affect the judgement, because TWCF is approximately 2 digits lower than the acceptance criteria in the US (1.0×10^{-6} /ry).

Further investigation

- Even if the difference in failure frequency (TWCF) is not significant, knowledge about detailed situation of those differences is useful.

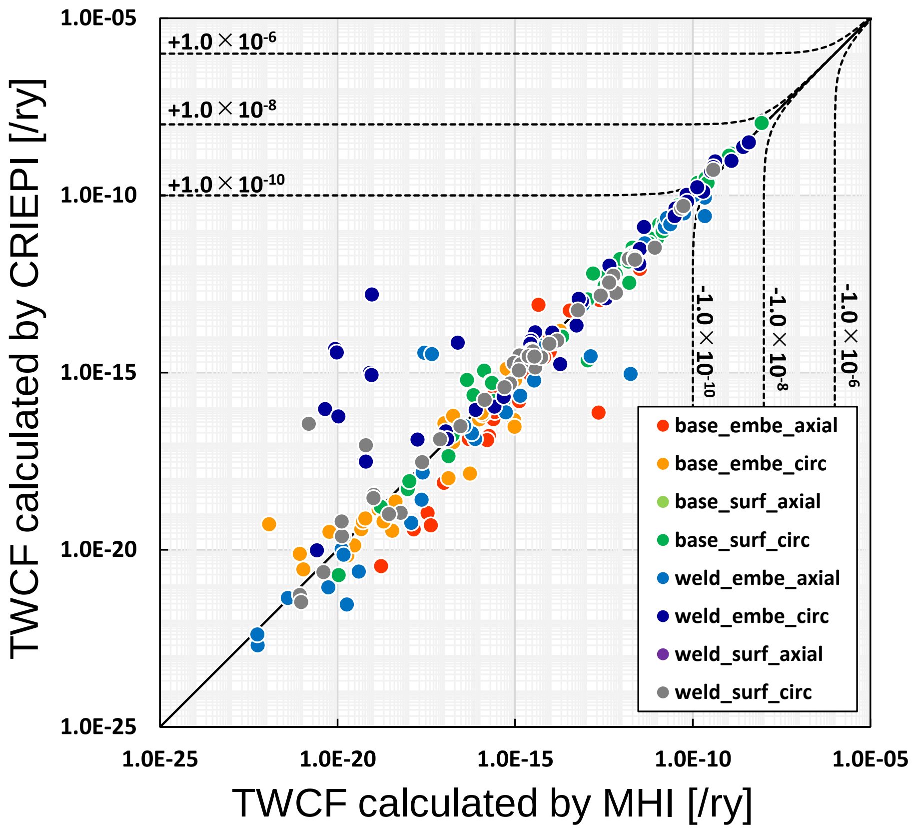
- Further detailed investigation were conducted.
  - Mean value of TWCF was divided with events and flaw types
  - There are 488 event/flaw type combinations
    - 61 PTS events (including LOCA, MSLB and SOV)

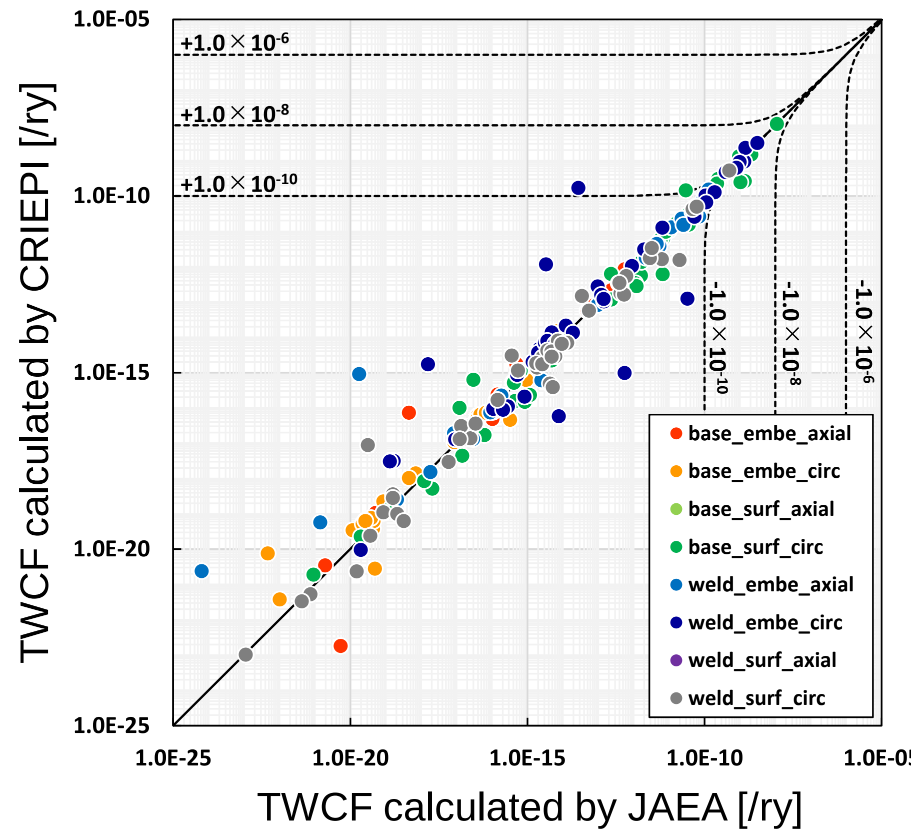
      X
    - 8 flaw types (2 positions X 2 types X 2 directions)
      - 2 positions: base metal (base), weld part (weld)
      - 2 types: surface flaw (surf), embedded flaw (embe)
      - 2 directions: axial flaw (axial), circumferential flaw (circ)

* name in brackets will be used in the figures from next page.
ex. "base_surf_axial" means surface axial flaw in base metal.

Comparison of TWCF for each event and each flaw type (Comparison of mean values on log axes)

- The 8 types of flaws are indicated by color of symbols, and the 61 PTS events are shown as multiple symbols with the same color.
- Although some plots seems outliers, their differences are less than 10^{-10}.
  ⇒ Those differences were plotted on linear axis in the next page.

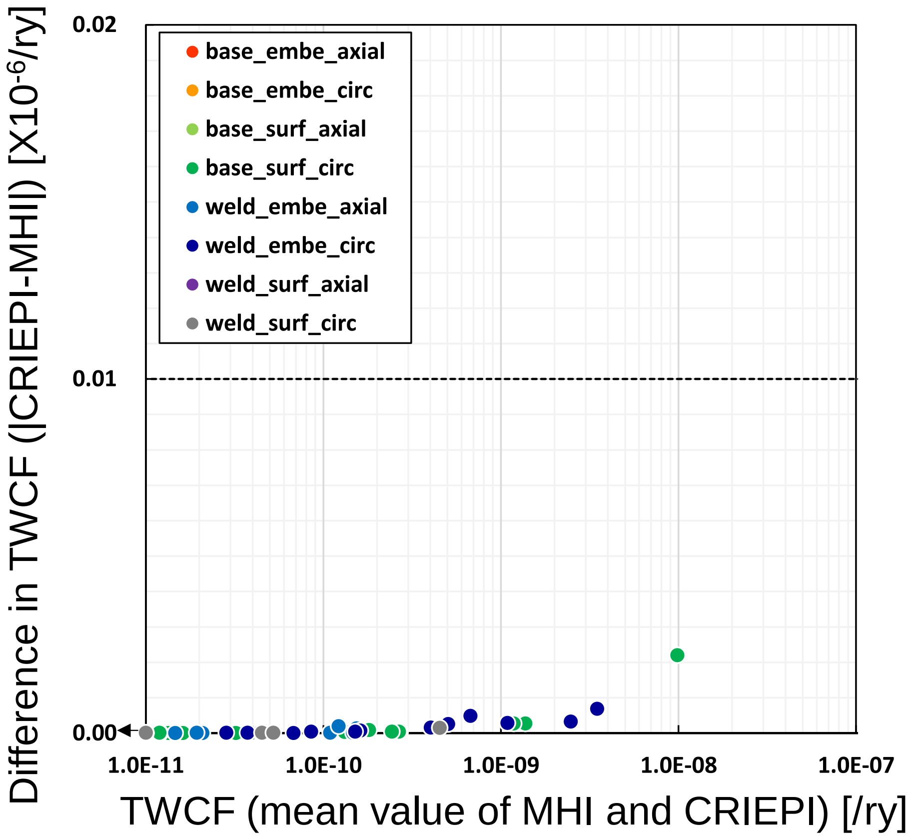


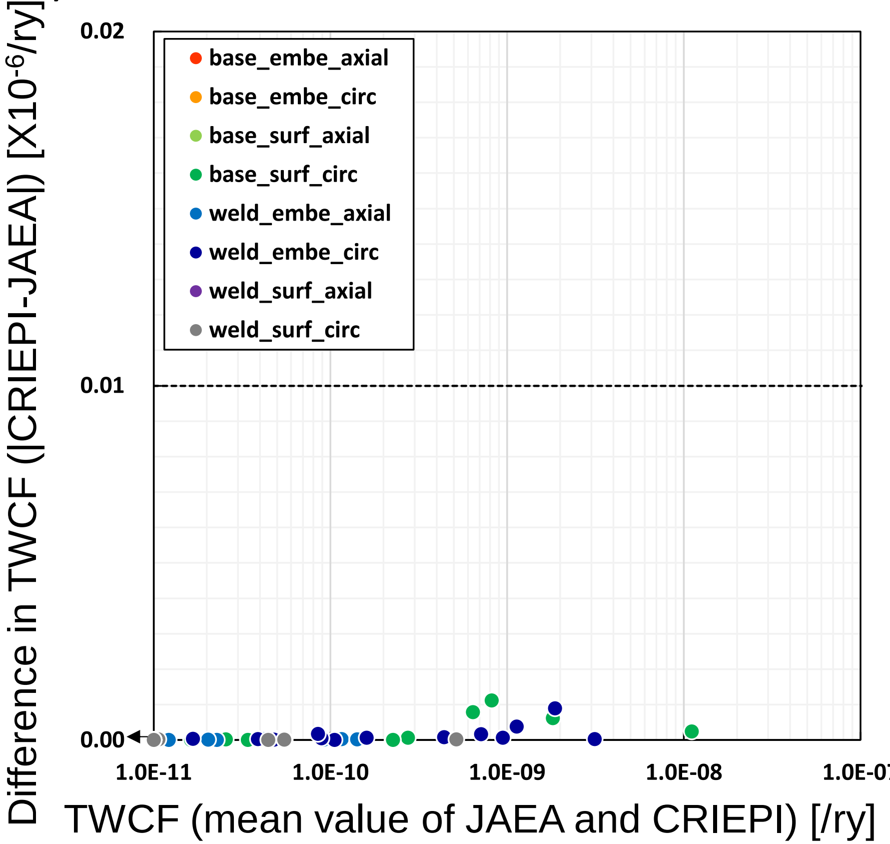


* Results less than 1.0×10^{-25} are not shown.

Comparison of TWCF for each event and each flaw type (Comparison of difference in mean values on linear axis)

- Difference in TWCF is smaller for event/flaw type combination with lower TWCF.
  ⇒ The differences in TWCF for the order less than 10^{-10} is very small.
- The maximum difference for one event/flaw type combination was less than 1% of 1.0×10^{-6} (acceptance criteria of the US).





* Results less than 1.0×10^{-11} are shown as 1.0×10^{-11} .

Comparison of analysis conditions (input files made by each participant)

- Input files of all participants were compared after benchmark analysis.
- The difference in input files were shown in the following table.
  - Those differences cause differences in calculated failure frequency.

Parameter	MHI	JAEA	CRIEPI
(1)-1 Thermal and stress analysis (time steps)	MHI version (Douglas-Peucker)	JAEA version (Douglas-Peucker)	CRIEPI version (Regular intervals)
(1)-2 Thermal and stress analysis (Software)	Abaqus	PrePASCAL	PrePASCAL
(2) Fluence (#Fluence datapoint)	5 points	4 points	4 points
(3) Fluence distribution (#Subregion)	252 X 74	502 X 150	132 X 20
(4) Sample size of event occurrence frequency	1000	100	10
(5) Truncation threshold (#Zero value)	1.0×10^{-20}	1.0×10^{-30}	1.0×10^{-20}
(6) Truncation threshold (#CPFPARAM)	1.0×10^{-16}	1.0×10^{-25}	1.0×10^{-16}
(7) Datapoints of yield stress (#PSSYDT)	11 points	11 points	8 points
(8) Version of PFM code (PASCAL)	PASCAL 20180807	PASCAL4.2A	PASCAL4.1B

* The words after “#” are the name of parameters used in PASCAL4.

Conclusion

- Failure frequency calculated by three participants (MHI, JAEA and CRIEPI) were compared with analysis conditions of a Japanese actual PWR plant.

- Mean value of TWCF was on the order of 10^{-8}. The maximum value was less than 1.2 times of the minimum value.
  - the difference are not considered to affect the judgement, because the TWCF was approximately 2 digits lower than the acceptance criteria in the US (1.0×10^{-6} /ry).

  - Acceptance criteria and/or judgement way other than acceptance criteria have not been determined in Japan. Therefore, treatment of variation and difference in failure frequency should be discussed for application of PFM.

    ⇒We believe that our benchmark analysis provides technical basis for those discussions.