ISPMNA5 (5th International Symposium on Probabilistic Methodologies for Nuclear Applications)
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Keynote Lecture

The Progress and Current Situation of PFM Application in Japan

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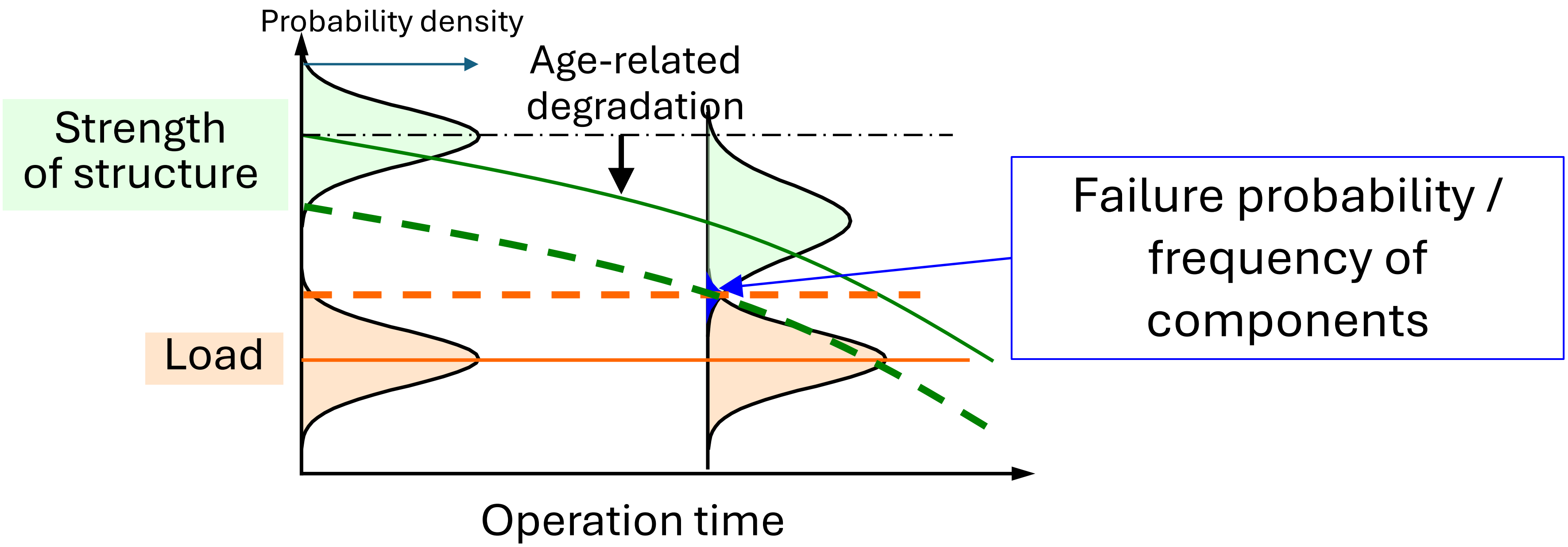
Contents

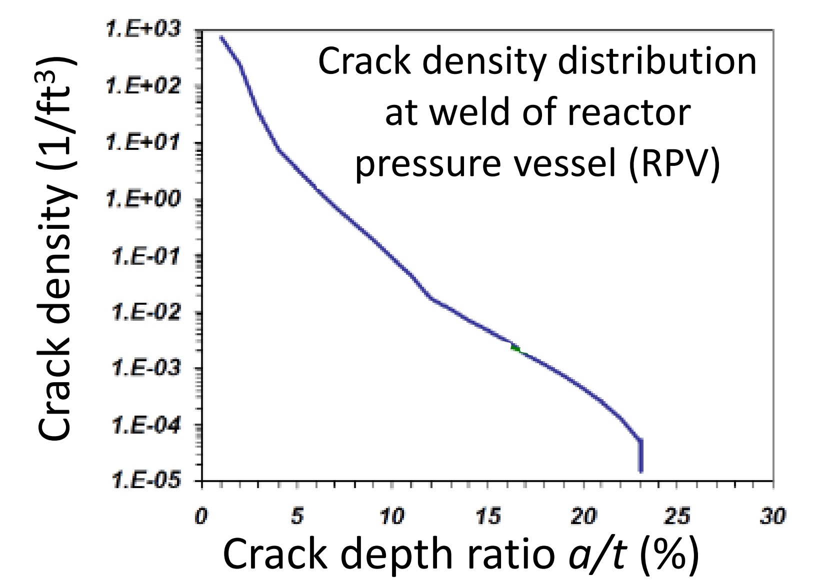
Merits of PFM application

PFM approach

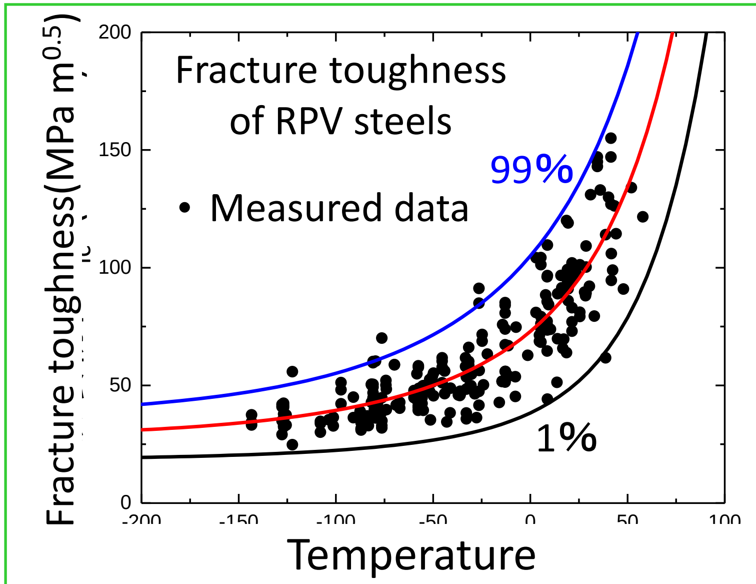
- A structural integrity assessment methodology for structural components based on a probabilistic approach
- Available for supporting the deterministic structural integrity assessment



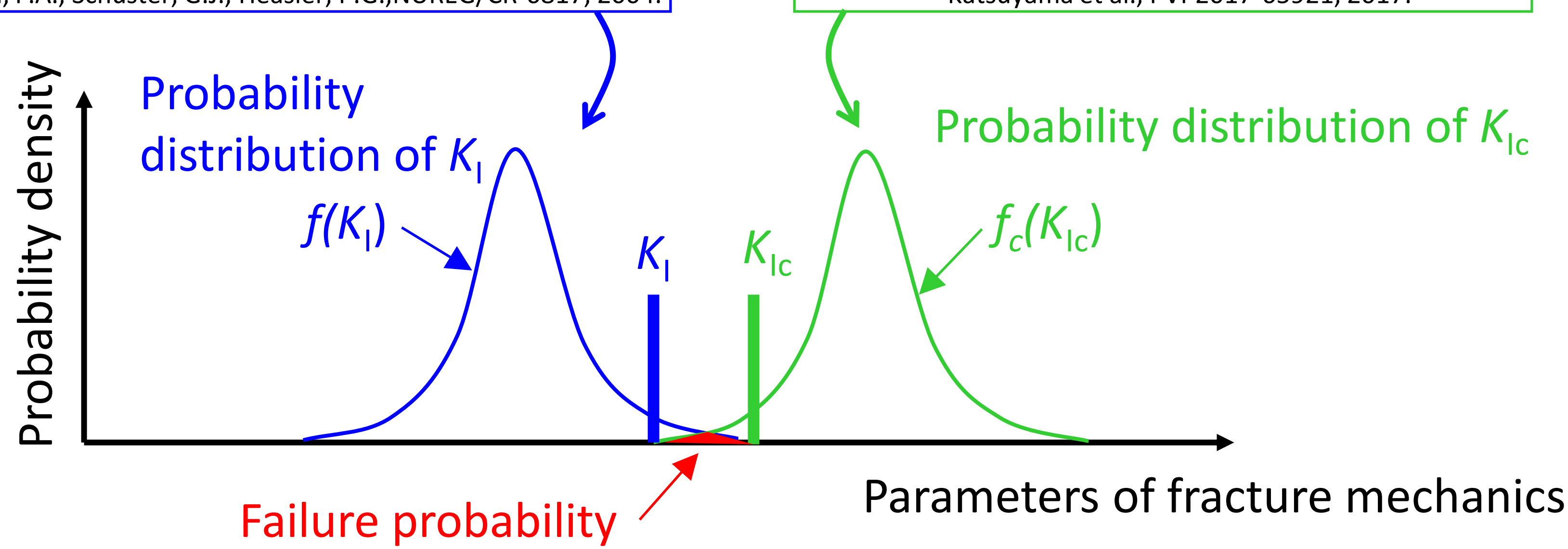
Example of structural integrity assessment (RPV)



* Simonen, F.A., Schuster, G.J., Heasler, P.G.,NUREG/CR-6817, 2004.



* Katsuyama et al., PVP2017-65921, 2017.



Merits of PFM approach

- **Rational Evaluation:** Consideration of uncertainty as probability distribution
- **Quantitative Evaluation:** Failure probability/frequency, Comparison with acceptance criteria, Safety margin
- **Relative Comparison:** Among different components, or codes & standards

World-wide PFM applications

World-wide PFM applications

- In the United States and Europe, PFM analysis has been used for decision making in addition to its application to risk assessment as follows:
  - ✓ Pressurized thermal shock (PTS) rule (RPV)
  - ✓ Necessity of immediate regulatory action
  - ✓ More rational inspection (RPV, piping, nozzle)
  - ✓ Feasibility evaluation of the leak-before-break (LBB) (Piping)
- In the United States, PFM has been used in various regulatory actions.
  - ✓ Issuance of regulatory guide for PFM application (RG1.245)

PTS rule in US based on PFM and PRA

PFM code

FAVOR v04.1

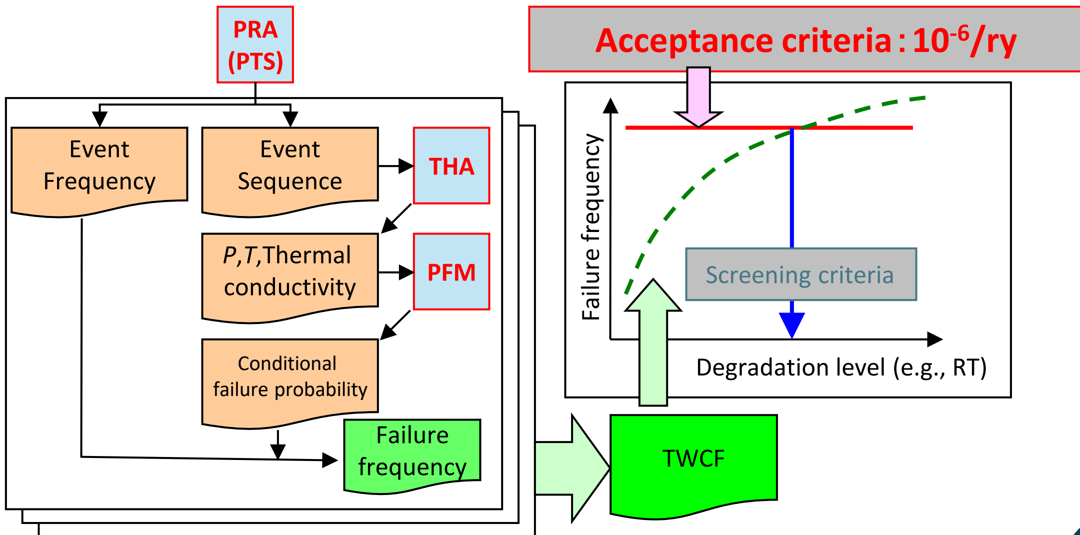
FAVOR v06.1

FAVOR v16.1

NRC project

NUREG-1806 (PTS re-evaluation project,2006)

- Based on the latest knowledge, technical basis for screening criteria was investigated using PFM analysis



NUREG-1874（Establishment of PTS screening, 2007）

- TWCF was re-evaluated under the revised analysis conditions for the establishment of PTS screening criteria.

PTS rule

10CFR50.61 (1984)

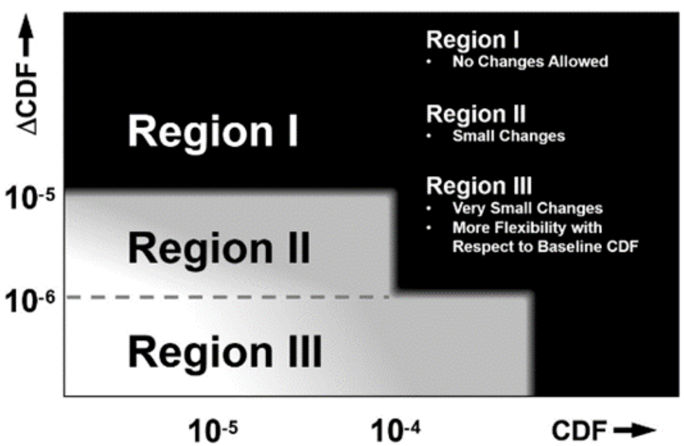
10CFR50.61a (2010)

Risk-informed decision-making using PFM

- In accordance with "Integrated Risk-Informed Decision-Making Process for Emergent Issues," NRC has performed a risk-informed evaluation of the potential safety significance of the recent French stress corrosion cracking (SCC) operational experience to the US fleet.

⇨The NRC performed a PFM analysis to bound the annual frequencies that SCC in the SIS piping could initiate loss of coolant accidents (LOCA). <u>The core damage frequency (CDF) was calculated by PRA using the failure frequency estimated by PFM as input data</u>.

⇨Based on the risk-informed analyses, the level of risk increase is low and acceptable. Then, NRC recommended Option 2 (the agency takes no programmatic actions to address this potential cracking) since <u>it provides reasonable assurance of safety in an efficient and economical manner</u>.



U.S.NRC, Risk-informed Assessment of French Stress Corrosion Cracking Operational Experience Relative to US Fleet, ML23236A080 (2023)
NRC, An approach for using probabilistic risk assessment in risk-informed decisions on plant-specific changes to the licensing basis. RG1.174, 1998.

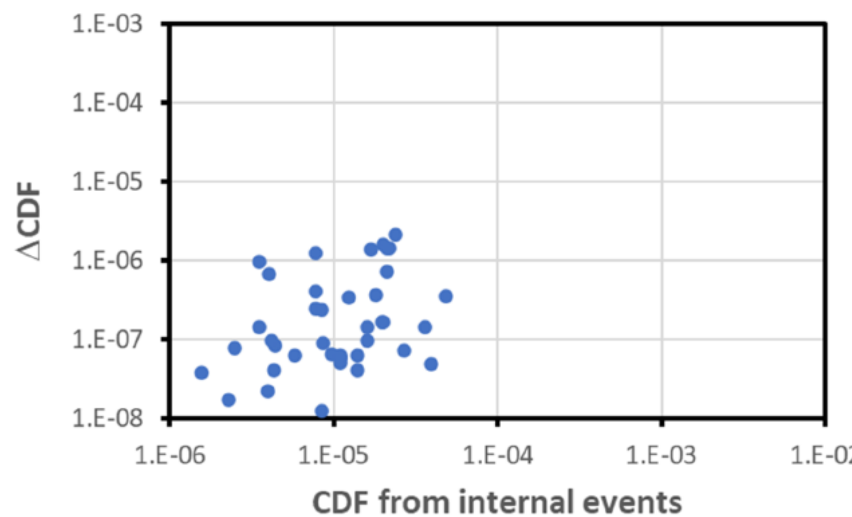


Figure 3 Impacts of SBLOCA on CDF for all PWRs Considered

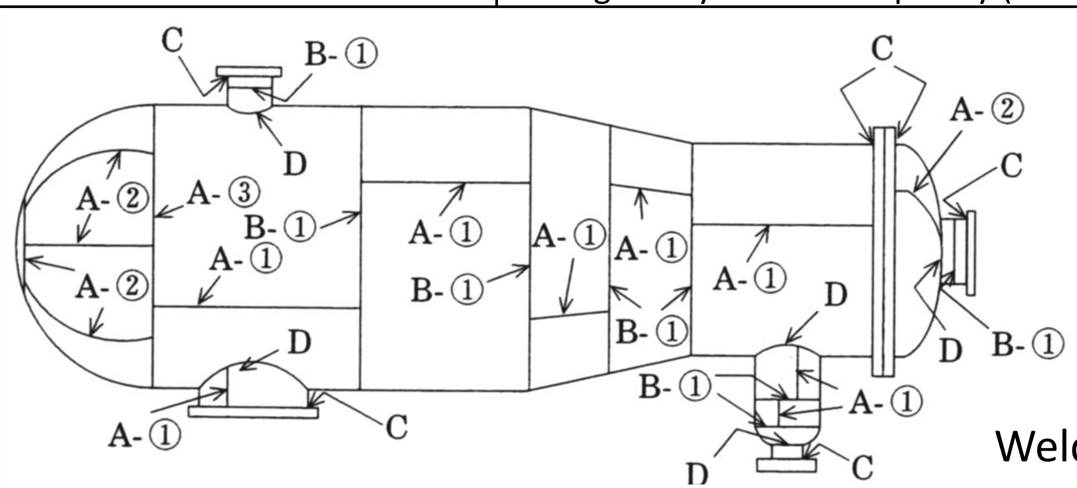
Using the result from PFM analysis as an input for PRA, risk can be quantitatively evaluated. PFM can be used for decision-making for the optimization of resource.

Reduction of the extent of examination in RPV shell welds in BWR (1/2)

*1 BWRVIP: BWR Vessel and Internals Project
*2 BWRVIP-05

- BWRVIP[*1] is proposed to reduce the extent of inspection of RPV shell weld based on the PFM analysis result[*2].
- In response to the proposal, NRC independently performed PFM analysis to investigate whether the proposal was technically-justified.

Item	Contents
Contents of investigation	Reduction of extent of examinations of 100% required in 10CFR50.55a
Investigated parts	RPV shell welds in BWR
Aging degradation	Neutron irradiated embrittlement
Considered events	Design basis events, Low-temperature over pressure (LTOP) event
Acceptance criteria	· Applying acceptance criteria for failure frequency of RPV of PWR caused by PTS event (in 1998): $<5 \times 10^{-6}$ /ry [NRC RG1.154] · Core damage frequency (CDF): $<10^{-4}$ /ry [NRC RG1.174] · Large early release frequency (LERF): $<10^{-5}$ /ry [NRC RG1.174]



Weld lines in RPV in BWR

Reduction of the extent of examination in RPV shell welds in BWR (2/2)

* BWRVIP-05

- The table below summarizes the history and conclusion of the investigation for RPV circumferential shell welds.

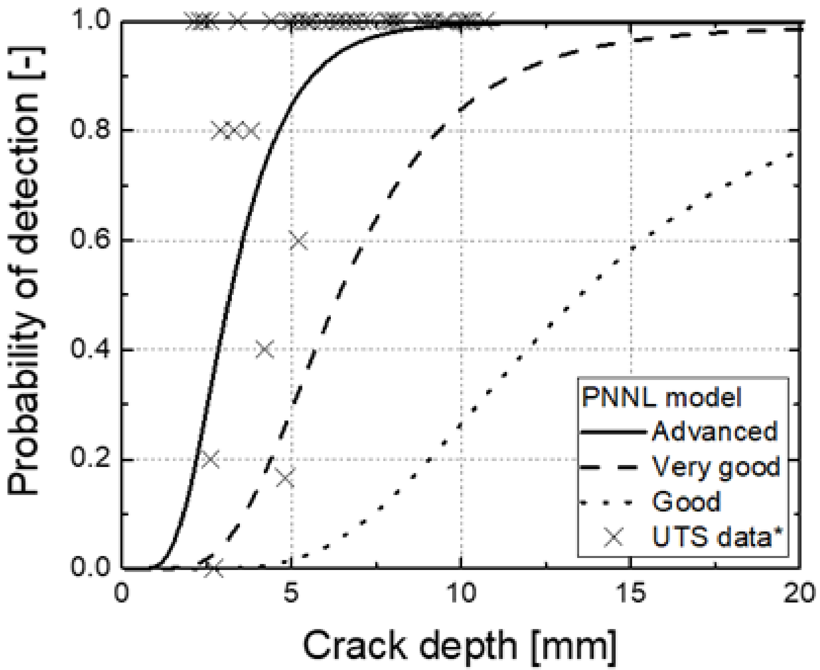
Year	Organization	Contents
1995	BWRVIP	BWRVIP calculated failure frequency as 2.2×10^{-41}/ry by considering design basis events and proposed to reduce to inspection of 0% of circumferential shell welds.
1997	NRC	NRC requested for BWRVIP to consider LTOP event because LTOP event occurred at the overseas BWR fabricated in the United States.
1997	BWRVIP	BWRVIP calculated CPF as 1×10^{-6} and failure frequency as 9×10^{-10}/ry by considering LTOP events and proposed to reduce to inspection of 0% of circumferential shell welds.
1998	NRC	• NRC calculated as CPF = 8.2×10^{-5}, failure frequency = 8.2×10^{-8} /ry. It was confirmed that failure frequency was less than criteria of RG1.154 as well as the criteria of RG1.174 regarding CDF and LERF. • NRC concluded that the proposal of BWRVIP is acceptable.

- <u>NRC concluded that the proposal of BWRVIP is acceptable.</u>

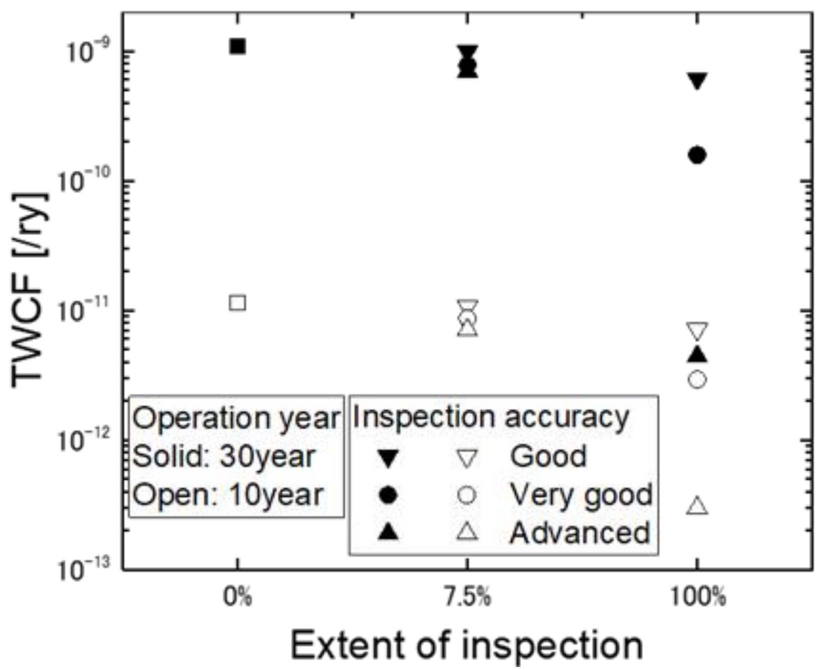
- Regarding the RPV axial shell welds, BWRVIP proposed to reduce the extent of examination of 50% based on PFM analysis results. However, <u>NRC determined that inspection for essentially 100% of axial shell weld is necessary in terms of defense-in-depth.</u>

Technical evaluation of the JSME Code in Japan *1

- For RPV weld line in PWR, sensitivity analyses were performed, regarding the extent of examinations, accuracy, and operation year.
- The results were used as the reference in the technical evaluation of the extent of examination in the Japan Society of Mechanical Engineers (JSME) Code "Rules on Fitness for service for Nuclear Power Plants“.



Inspection accuracy evaluation model*2



Sensitivity analysis results

*1 https://warp.da.ndl.go.jp/info:ndljp/pid/12348280/www.nra.go.jp/data/000255326.pdf
*2 JNES, “Report on the Demonstration Project for Inspection Technology for Nuclear Power Plants (Confirmation of Flaw Detectability and Sizing Accuracy in Ultrasonic Testing) [Summary]” (2005).

Worldwide stakeholders related to PFM applications

Public

Government

- OECD/NEA
- Federal government of the United States
- Cabinet Office of Japan

Regulator

- NRC (U.S.)
- CNSC (Canada)
- NSSC (Korea)
- CSN (Spain)
- NRA (Japan)

Utility

- EPRI, DOE, EDF
- ATENA
- Fabricators (AtkinsRealis, Framatome)

Expert

- Research institutes (VTT, GRS, PSI, UJV,UKAEA, CRIEPI, JAEA, etc.)
- Consultants (EMCC, SIA, DEI, Kiwa, kinectrics, etc.)

Academia

- Universities
- Societies, Associations

Recent activities on PFM in Japan

Stakeholders in JAPAN

Public

Government
- Cabinet Office of Japan
- METI *4

*4: Ministry of Economy, Trade and Industry

Regulator
- NRA*1

*1: Nuclear Regulation Authority

Utility
- ATENA*2
- FEPC*3
- Fabricators

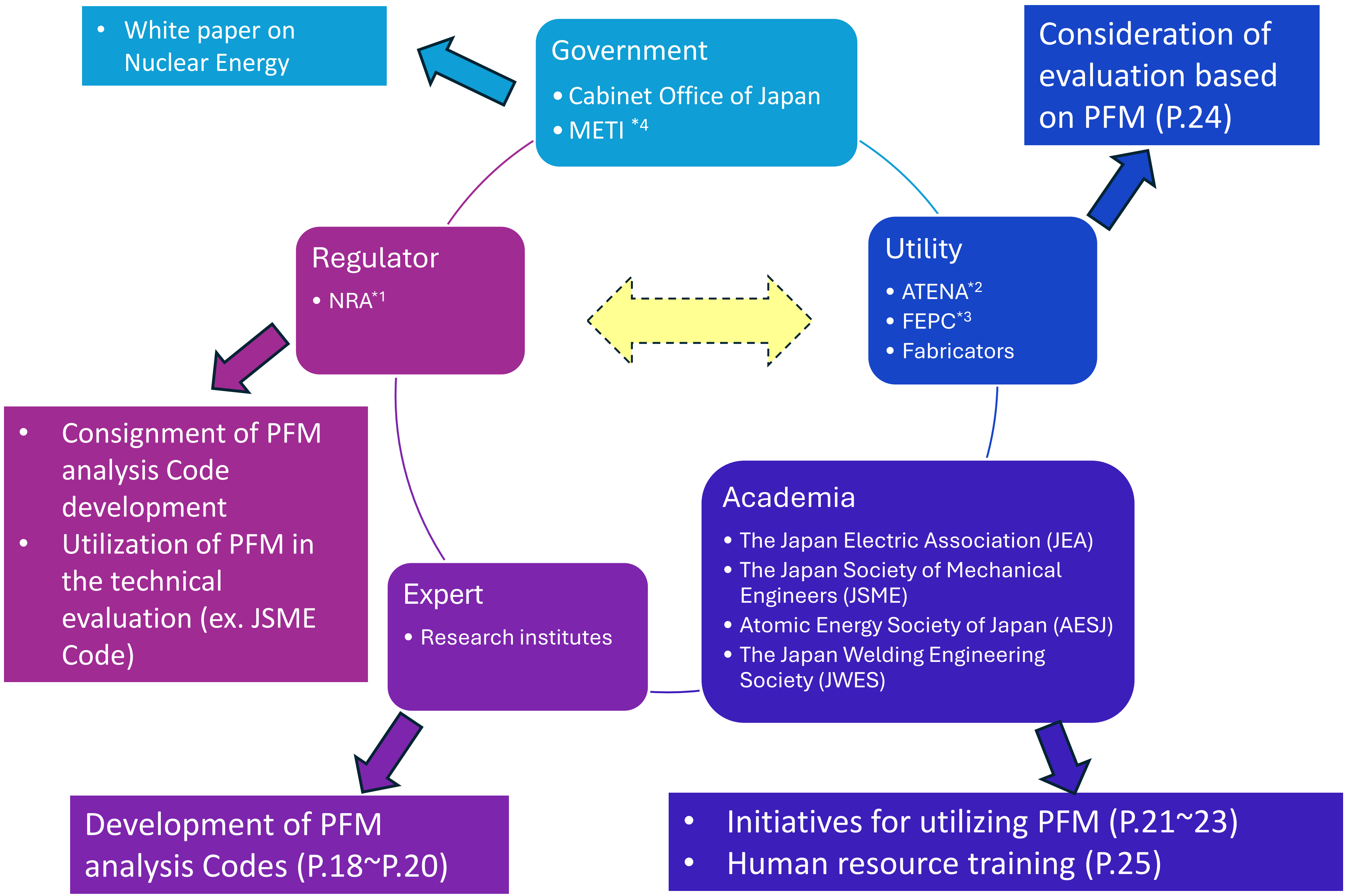
*2: Atomic Energy Association
*3: The Federation of Electric Power Companies of Japan

Expert
- Research institutes

Academia
- The Japan Electric Association (JEA)
- The Japan Society of Mechanical Engineers (JSME)
- Atomic Energy Society of Japan (AESJ)
- The Japan Welding Engineering Society (JWES)

JAEA (External TSO of NRA), CRIEPI

Stakeholders in JAPAN



Development of PFM analysis codes for RPV

Expert

	1970	1980	1990	2000	2010	2020

U.S.

NRC

- [ORNL]
  - ▪OCTAVIA
  - ▪OCA-I
  - ▪OCA-II
  - ▪OCA-P
- [PNNL]
  - ▪VISA
  - ▪VISA-II

▪FAVOR First edition [ORNL]

Integration Improvement

Code improvement →

▪FAVOR v16.1

▪FAVPRO v1.0 [NRC]

— Maintained for PTS of PWR*1

— Extension application for BWR*2 LTOP*3 event, start-up, shut-down, etc.

Utility

▪Code by Gamble & Strosnider

▪VIPER [EPRI, SIA]

—Analysis for in service inspections

Japan

[JAEA]

▪PASCAL First edition

Code development(PASCAL2, 3, 4) →

— Maintained for PTS of PWR

— Extension for BWR*2 LTOP*3 event, start-up, shut-down, Evaluation of HAZ, cracks on outer surface , etc.

▪PASCAL5

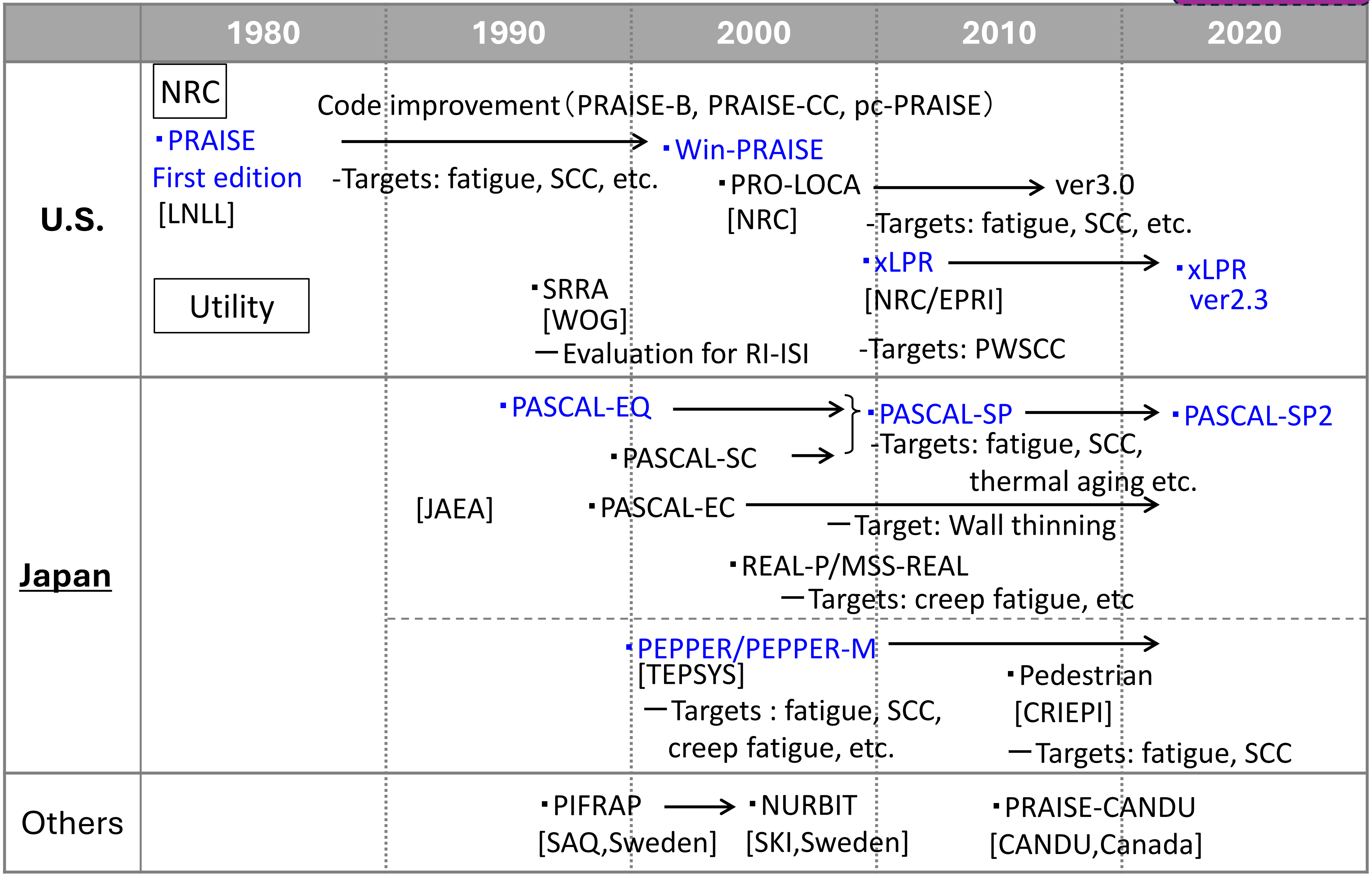
▪FERMAT [CRIEPI]

— Targeting PWR

*1PWR : Pressurized water reactor, *2BWR : Boiling water reactor, *3LTOP : Low temperature over pressure

Development of PFM analysis codes for piping

Expert

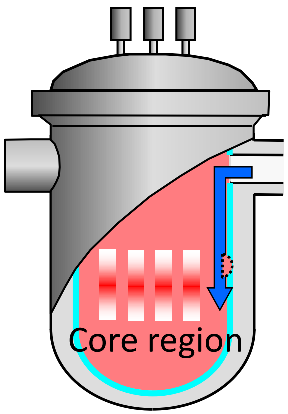


Development of PASCAL Codes in JAEA

- In JAEA, as a part of research on probabilistic structural integrity assessment for light water reactor (LWR) components, PFM analysis code series "PASCAL" were developed.

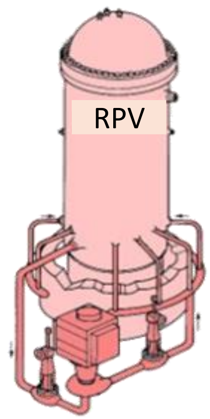
*__PASCAL__: PFM Analysis for Structural Components in Aging LWR

PASCAL5



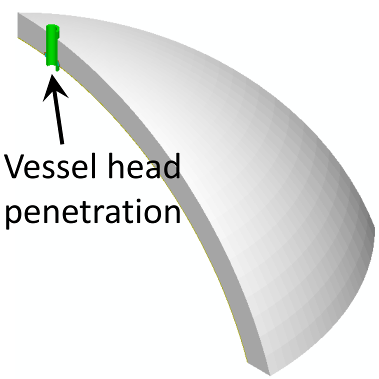
PFM analysis code for RPVs in both PWR and BWR considering neutron irradiation embrittlement & transient events such as pressurized thermal shock (PTS)

PASCAL-SP2



PFM analysis code for piping systems considering stress corrosion cracking (IGSCC, PWSCC, NiSCC), fatigue and thermal embrittlement.

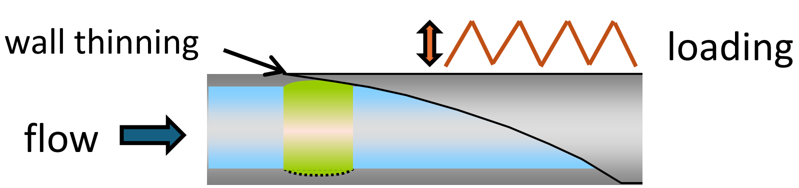
PASCAL-NP



PFM analysis code for complicated structures considering cracks due to PWSCC & NiSCC

PASCAL-EC

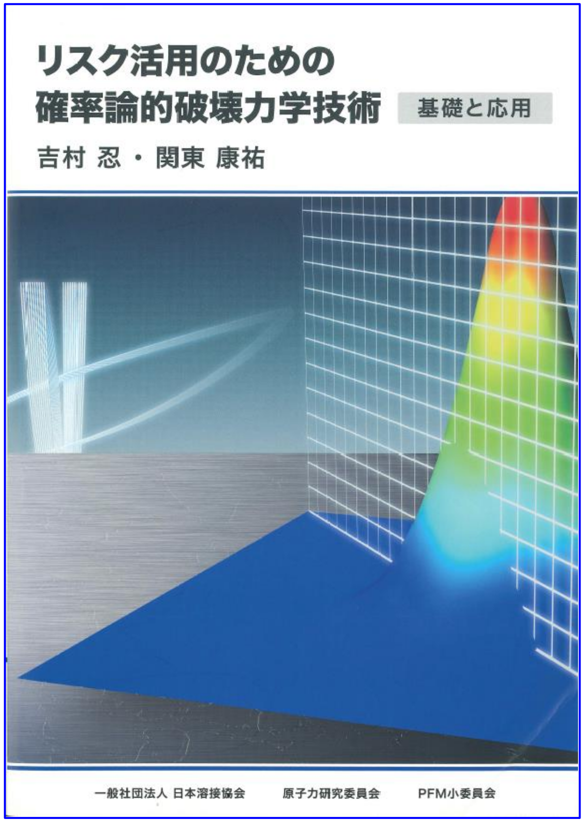
Probabilistic analysis code for carbon steel piping systems with wall thinning due to flow-accelerated corrosion(FAC)

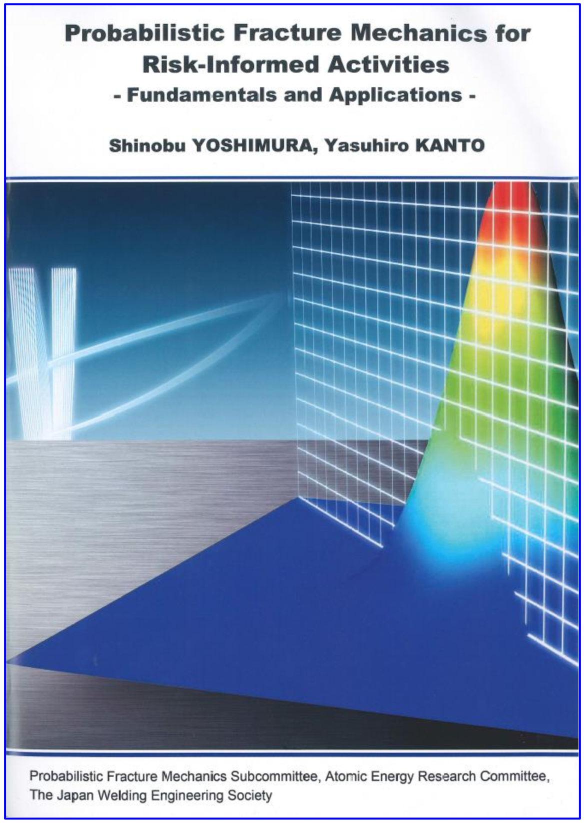


Towards use of PFM in Japan: Initiatives of Academic Societies

Academia

- The Japan Welding Engineering Society (JWES) established the PFM Subcommittee (since 1987) at an early stage, which prompts a wide range of activities such as research on PFM analysis techniques, study of methods, comparative study of analysis codes and applied research, and published PFM books.





http://www-it.jwes.or.jp/ae/index.jsp

Towards use of PFM in Japan: Initiatives of Academic Societies

Academia

- The Japan electric association (JEA) published "Guideline for Calculating the Failure Frequency of Reactor Pressure Vessels Based on Probabilistic Fracture Mechanics (**JEAG 4640-2018**)" for PFM analysis for PTS events in RPVs.

PFM-1000	General descriptions
PFM-1100	Scope of this guideline
PFM-1200	Definition of terminology
PFM-1300	Target components
PFM-1400	Outline of failure frequency evaluation procedure
PFM-2000	Stress intensity factor calculation
PFM-2100	Selection of transients
PFM-2200	Time history of temperature distribution
PFM-2300	Time history of stress distribution
PFM-2400	Weld residual stress distribution
PFM-2500	Potential cracks
PFM-2600	Stress intensity factor
PFM-3000	Fracture toughness
PFM-3100	Neutron fluence
PFM-3200	Chemical composition
PFM-3300	Reference temperature
PFM-3400	Fracture toughness
PFM-3500	Crack arrest toughness
PFM-4000	Treatment of uncertainty

PFM-5000	Failure frequency evaluation
PFM-5100	Evaluation methods
PFM-5200	Decision of failure
PFM-5210	Crack initiation
PFM-5220	Crack arrest
PFM-5230	Through-wall cracking
PFM-5300	Conditional probability
PFM-5310	Conditional probability of crack initiation
PFM-5320	Conditional probability of failure
PFM-5400	Frequency of transient occurrence
PFM-5500	Failure frequency
PFM-5510	Frequency of crack initiation
PFM-5520	Through-wall craking frequency
PFM-5600	Confidence level

Annex
Annex A(regulation):How to verify the analysis code
Annex B(reference):Examples of analysis conditions and analysis method for domestic plants
Aneex C(reference): Example of analysis conditions for transients

Towards use of PFM in Japan: Initiatives of Academic Societies

Academia

- A committee on the actual application of PFM was established voluntarily as academia-industry collaboration, whose secretary is CRIEPI (since December 2018).

  - To conduct PFM analyses based on actual plant conditions, with the goal of actually applying PFM to the design evaluation of structural components and more rational operation and maintenance of actual nuclear power plants.
  - The PFM analysis based on actual plant conditions is being conducted to confirm failure probability level of domestic RPV, and to confirm how different PFM analysis codes and different analysts can lead variations of PFM analysis results.

Towards use of PFM in Japan: Initiatives of Academic Societies

Extraordinary PFM Committee within the Nuclear Standards Committee *of Japan Electric Association (JEA)*

Academia

- In Japan, PFM has been well researched in various ways for many years, but it has not been applied to the operation or regulation of actual plants.
- However, the need for application of PFM among utilities is increasing recently.
- In January 2024, one committee was established within the Nuclear Standards Committee of JEA to comprehensively discuss the issues towards the applications of PFM to actual plants, and to include the results in standards.

  Participating organizations are
  - Universities
  - Research Institutes (JAEA, CRIEPI, etc.)
  - ATENA, Power industries, Fabricators
  - NRA

In the committee, audio during meetings is recorded and minute is published

Towards use of PFM in Japan: Initiatives of utilities

Utility

- In relation to the response to the new regulatory requirements in Japan, the electric utilities stated that they discuss the application of PFM*2, for example non-destructive examinations for RPVs*1, referring to the application examples in the U.S. and other countries.

*1 https://www.nra.go.jp/data/000272590.pdf

*2 https://warp.da.ndl.go.jp/info:ndljp/pid/12348280/www.nra.go.jp/data/000279468.pdf

Human resource training for PFM in Japan

Academia

- Collaborative course between the University of Tokyo and JAEA
  - ✓ Established a special course in UTokyo, with lectures, including PFM, by UTokyo & JAEA experts + external lecturers
  - ✓ Symposia and seminars to disseminate information and to communicate with industry, academia, regulatory agencies, and the public.
- PFM subcommittee in Japan Welding Engineering Society (JWES)
  - ✓ Symposia on PFM technique and utilization strategies
- Human resource development project of CRIEPI and Tohoku University commissioned by the Agency for Natural Resources and Energy
  - ✓ Training sessions to develop human resources for the practical application of 'decision-making using risk information' in conservation activities, and to develop the tools on 'a probabilistic assessment method for material degradation'.

Issues on promoting the use of PFM in Japan (1/5)

1. **Interpretation of calculated probabilistic values**
   Even if the analysis target is the same, the calculated probability values will be different if analysis conditions are different. Even if both of the analysis target and conditions are the same, respectively, the calculated values will be different if the analysis codes are different. Under such circumstances, how do we make engineering judgement such as "almost the same value, larger, or smaller" for probability values?
2. **We cannot perform Verification & Validation (V&V) of PFM analysis codes through the comparisons with experiments**
   What should Validation of PFM be? (Same issues are encountered in PSA)
3. **Gaps in understanding between experts and the public regarding the utilization of probabilistic values**
   How do we bridge the gaps?
   ➡ The public also uses the probability or risk information in making decisions in finance, insurance, health, accidents, examinations, etc.
   ➡ The utilization of risk information should not be closed in a nuclear-specific issue. A broader perspective is important !

Issues on promoting the use of PFM in Japan (2/5)

4. **Establish a standard analysis procedures for target phenomena**
5. **Establish the rule and acceptance criteria based on probabilistic values**

   How should safety goal be set. Is it possible to regulate based on probabilistic values even if there is no safety goal like in Japan?
6. **Accumulate experiences on decision making based on risk information**
7. **Collect, share and utilize the actual data such as initial crack distribution, non-destructive examination results obtained in actual power plants in Japan, etc.**

Issues on promoting the use of PFM in Japan (3/5)

1. Interpretation of calculated probability values

Examples)

- How to judge the meanings of failure frequencies between 10^{-6} /ry and 10^{-8} /ry?
  , or $2x10^{-6}$ /ry and $4x10^{-6}$ /ry / $2x10^{-8}$ /ry and $4x10^{-8}$ /ry?
- How to judge the differences in failure frequencies, when the same problem was evaluated by PASCAL and FAVOR?

➡ The Committee on Actual Application of PFM in Japan, whose secretariat is CRIEPI, plan to release a technical report by the end of this fiscal year.

2. We cannot perform V&V of PFM analysis codes through the comparisons with experiments

➡ Quantitative comparisons of failure probability / frequency obtained by multiple codes, investigation of the reasons for the differences, and social sharing through the publication of analyis results.

3. Gaps in understanding between experts and the public regarding the utilization of probabilistic values

➡ The public also uses the probability or risk information in making decisions in finance, insurance, health, accidents, examinations, etc.

➡ The utilization of risk information should not be closed in a nuclear-specific issue. A broader perspective is important !

Issues on promoting the use of PFM in Japan (4/5)

4. Establish a standard analysis procedures for target phenomena

➡ JEAG 4640-2018 of the Japan Electric Association (JEA) is available as a guideline for calculating failure frequency of RPVs. The JEA is currently discussing revisions of the guideline for expanding the target or renewal.

5. Establish the rule and acceptance criteria based on probabilistic values

How should be safety goal set. Is it possible to regulate based on probabilistic values if there is no safety goal like in Japan?

➡ It is recommended to set safety goal, but for example,

➡ Is an approach possible to replace the existing deterministic-based criteria with the equivalent criteria based on failure probability calculated by PFM ?

Issues on promoting the use of PFM in Japan (5/5)

6. Accumulate experiences on decision making based on risk information

➡ Comprehensive judgement considering several influences, for example the effect of change in the extent of examination on failure probability vs the radiation exposure to inspectors.

➡ The relationship between extension of the operation period and failure probability.

7. Collect, share and utilize the actual data such as initial crack distribution, non-destructive examination results obtained in actual power plants in Japan, etc.

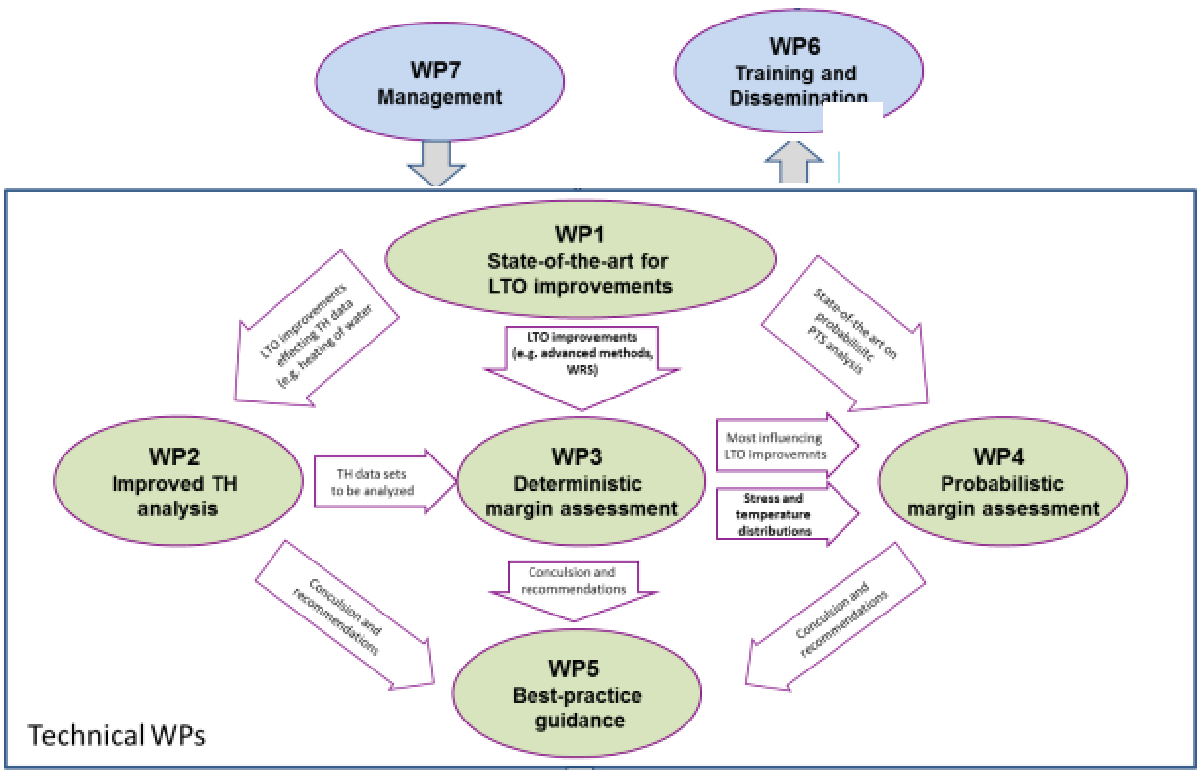
International activities for PFM utilization

International Collaborations

- Advanced Assessment Methods for Long-Term Operation (APAL Project) in EU
  - ✓TH-PFM Coupling
  - ✓Benchmark
  - ✓Educational Program
- International Benchmark on PFM Analysis
  - ✓Identify the effect of differences in the design of analysis codes
  - ✓Improve the reliability of analysis codes

EU's APAL Project (1/2)

- The EU research project APAL has been proceeded to develop advanced safety assessment methods for long-term operation of NPPs.
- There are 14 European partners and 2 international partners (US and Japan).
- The project aims to develop advanced thermal-hydraulic (TH) assessment methods with considering uncertainties, advanced deterministic and probabilistic fracture mechanics analysis methods, and education program.



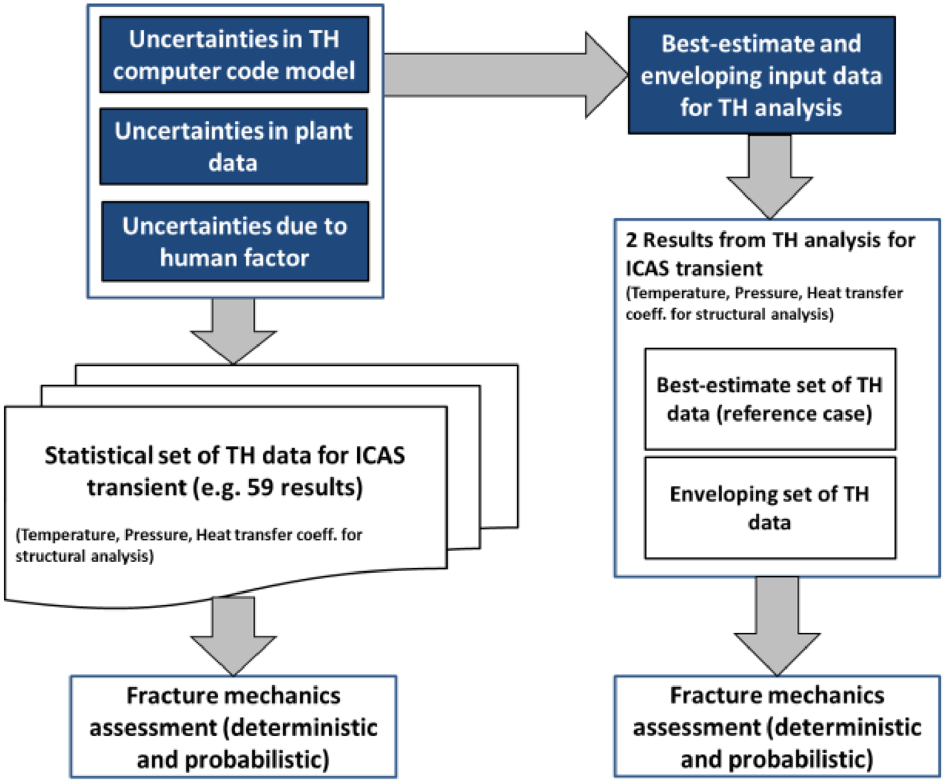
Structure of APAL project

Participant No		Country
1	UJV	CZ
2	FRA-G	DE
3	PSI	CH
4	IPP	UA
5	KIWA	SE
6	TECNATOM	ES
7	GRS	DE
8	BZN	HU
9	EURICE	DE
10	JSI	SL
11	IRSN	FA
12	LUT	FN
13	WUT	PL
14	SSTC	UA

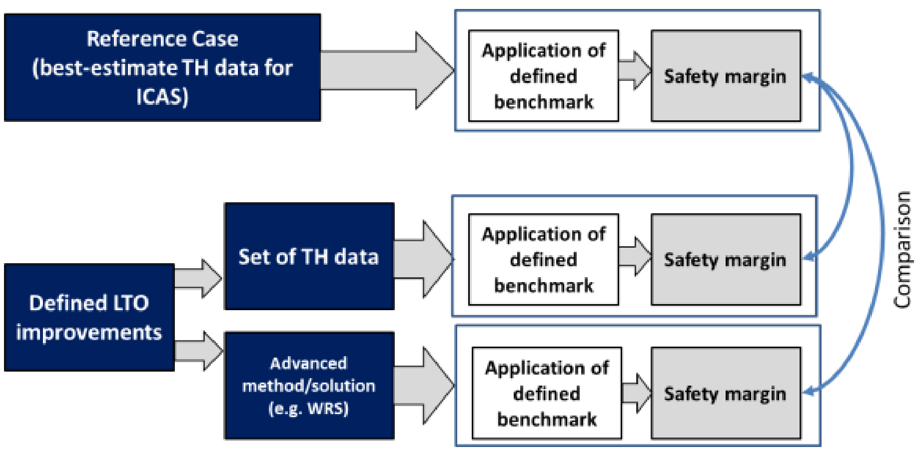
APAL partners

EU's APAL Project (2/2)

- Implementing distinctive initiatives such as the uncertainty assessment in TH analysis, LTO measures, and the evaluation of safety margin.



Uncertainty assessment in TH analysis



Initiatives regarding LTO measures and margin evaluations

International Benchmark on PFM Analysis

- OECD/NEA CSNI PFM Benchmark :
  - ✓ The target is the LBB assessment of nickel alloy welds in PWR nozzles.
  - ✓ Confirm the effects of differences in models and assumptions implemented in PFM analysis codes on analysis results.
  - ✓ There are 15 participants from 12 countries.

Participants of
CSNI PFM Benchmark

Participant		Country
1	SIA	US
2	NRG	NL
3	Kiwa	SE
4	CRIEPI	JP
5	JAEA	JP
6	CEI	CA
7	EMCC	US
8	KINS	KR
9	PSI	CH
10	GRS	DE
11	LEI	LT
12	IPP	UA
13	VTT	FI
14	USNRC	US
15	MPA	DE

Proposal on Further Works

White-Boxing of PFM analysis codes

- To promote the practical utilization of PFM, it is necessary to have white-box PFM analysis codes so that users can add the functions which they need as appropriate.
  - ✓ ADVENTURE, an open-source parallel finite element structural analysis code, is an example of the white-boxing of analysis codes. The ADVENTURE system has been employed in several national projects in computational mechanics and sciences such as the ITBL project on grid computing, the Earth Simulator project, the K-computer, and the Supercomputer Fugaku. It continues to develop in collaboration with CAE software vendors, universities, and research institutes.

(https://adventure.sys.t.u-tokyo.ac.jp/)

International Data Sharing

- Aging degradation caused by long-term operation is a common issue worldwide in near future.
- It is necessary to share the technologies and data that contribute to the structural integrity assessment of components based on PFM, not only within each country, but also around the world. It is also important to keep updating the shared data.

Concluding remarks (1/2)

- PFM is useful not only for operators but also for the public, as it is an important tool for reducing risk.
- For the utilization of PFM, it is necessary for each stakeholder to make efforts not by working independently for themselves, but by visualizing the trends and expectations of other stakeholders and clarifying what needs to be done for other stakeholders.
- It is important that the latest technologies and data on PFM are shared globally and continuously updated, rather than being kept within countries.

Concluding remarks (2/2)

- PFM has matured as a key technology for integrity assessment and risk information utilization. The technical foundation has been established in Japan.
- In Japan, opportunity is increasing towards the actual utilization of PFM. However, more integrated efforts are needed across industry, government, academia, and the public to make this a reality.
- It is possible that in near future, the actual utilization of PFM may suddenly begin. It is important to take this seriously, and to use the PFM to further improve the safety and further rational operation of nuclear power plants.

Thank you for your kind attention.

I strongly believe that ISPMNA5 held in Japan will provide a very good opportunity to kick off the actual use of PFM in Japan.