Overview of Safety Research on Metal Aging due to Neutron Irradiation in S/NRA/R

International Workshop on Age-Related Degradation of Reactor Vessels and Internals

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Previous research programs(*) on metal aging due to neutron irradiation

No.	projects	Outline
1	Prediction of irradiation embrittlement for highly irradiated reactor vessel steels (2005-2010)	- Verification of the domestic prediction formula of irradiation embrittlement in the high fluence region through conducting tests using materials with accelerated irradiation
2	Repair welding technology of irradiated materials (1997-2004)	- Verification of the integrity of irradiated stainless-steel welding of reactor internals ✓ Relationship between helium content, welding heat input and crack occurrence - Proposal of technical guides to repair the welding of reactor internals

(*)Note: These programs were conducted by Japan Nuclear Energy Safety organization (JNES).

Previous research programs(*) on metal aging due to neutron irradiation (Cont'd)

No.	projects	Outline
3	Evaluation of irradiation assisted stress corrosion cracking (2000-2008)	[BWR] - Evaluation of IASCC susceptibility in L-grade SSs - IASCC crack-growth database of neutron irradiated L-grade SSs - Development of crack-growth rate disposition curves for BWR normal and hydrogen water chemistry (IASCC evaluation guide) [PWR] - IASCC initiation data of baffle former bolt (BFB) in PWR primary water (<70dpa) - Development of a lifetime evaluation method for BFB (IASCC evaluation guide)
4	Evaluation of neutron irradiation effect on SCC crack growth of L-grade stainless steel (2007-2013)	[BWR] - Evaluation of the synergy effect of low neutron fluence and weld hardening on SCC crack propagation - Improvement of SCC evaluation method in terms of neutron irradiation

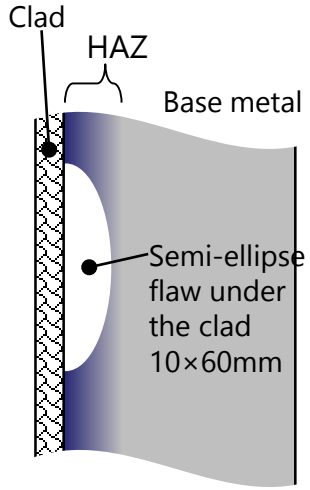
(*)Note: These programs were conducted by Japan Nuclear Energy Safety organization (JNES).

Current research programs on metal aging due to neutron irradiation

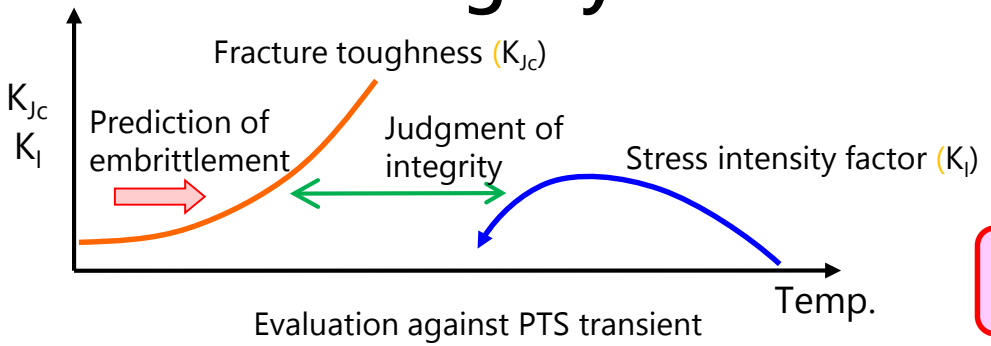
- Reactor Pressure Vessel (RPV) embrittlement
- Probabilistic Fracture Mechanics (PFM)

RPV Embrittlement

Flow of RPV integrity evaluation



Cross section of RPV



Evaluation against PTS transient

Determination of Transition curve of PTS (K_I) postulating underclad flaw

Determination of Transition curve of fracture toughness (K_{Jc}) at the evaluated period

- Prediction of embrittlement

- Effect of confining of flaw, biaxial loading and residual stress of clad welding
- Adequacy of formula for stress intensity factor formula for underclad flaw

$K_{Jc} > K_I$ — Yes → Allowed to operate until the evaluated period

No

$dK_I/dt < 0$ (WPS) — Yes → Allowed to operate until the evaluated period

- Adequacy of WPS evaluation

No

$K_{Ia} \geqq K_I$ (Crack arrest) — Yes → Allowed to operate until the evaluated period

- Adequacy of K_{Ia} evaluation for irradiated material

- Relation of transition temp. shift (ΔT_o vs ΔT_{41J})
- Size dependency of fracture toughness

Work items

- Pressurized Thermal Shock (PTS) experiments with cladded specimens (JFY2016-2019)
- Warm Pre-Stress (WPS) effect (JFY2014-2019)
- Correlation of transition temp. shift (JFY2014-2019)
- Size dependency of fracture toughness (JFY2014-2019)
- Prediction of irradiation embrittlement (JFY2017-2019)

PTS experiments

Background

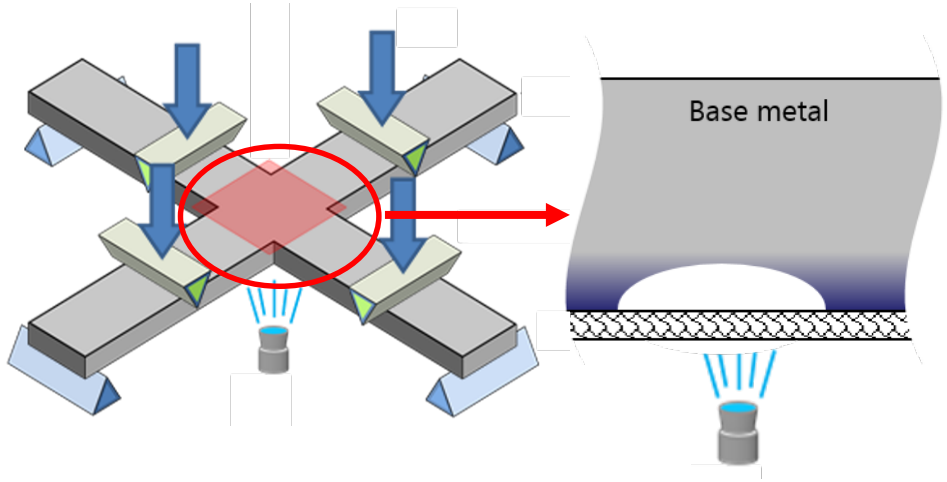
- The location of the postulated flaw was changed from an inner surface to an embedded flaw under the clad in the newly proposed code(JEAC4206-2016).
- The crack tip constraint of the postulated underclad flaw is lower than that of the test specimen, making the critical load lower.
- Biaxial load should be considered in the actual plant.
- WPS effect under biaxial loading has not been verified in a large test specimen.

Objective

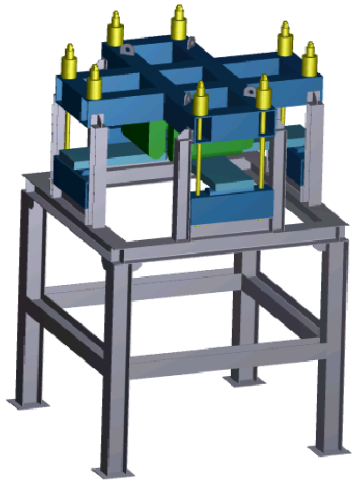
- To confirm the effect of biaxial loading and underclad flaw

PTS experiments (Cont'd)

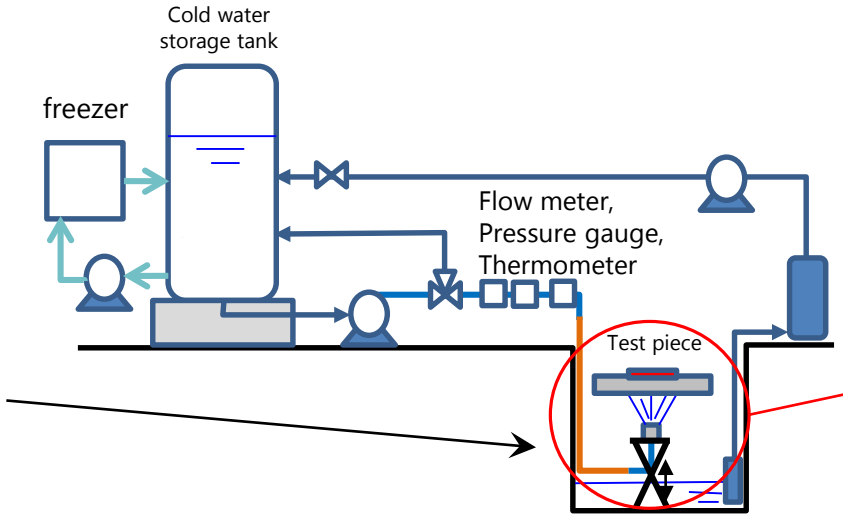
- Biaxial bending tests are conducted under simulating PTS conditions using low-toughness material.
- Test parameters such as flaw size, load, and cooling rate are determined via FEM analysis.



Large scale biaxial test specimen
- Length: 3800mm
- Thickness: Base metal 150mm, Clad 5.5mm



Load machine

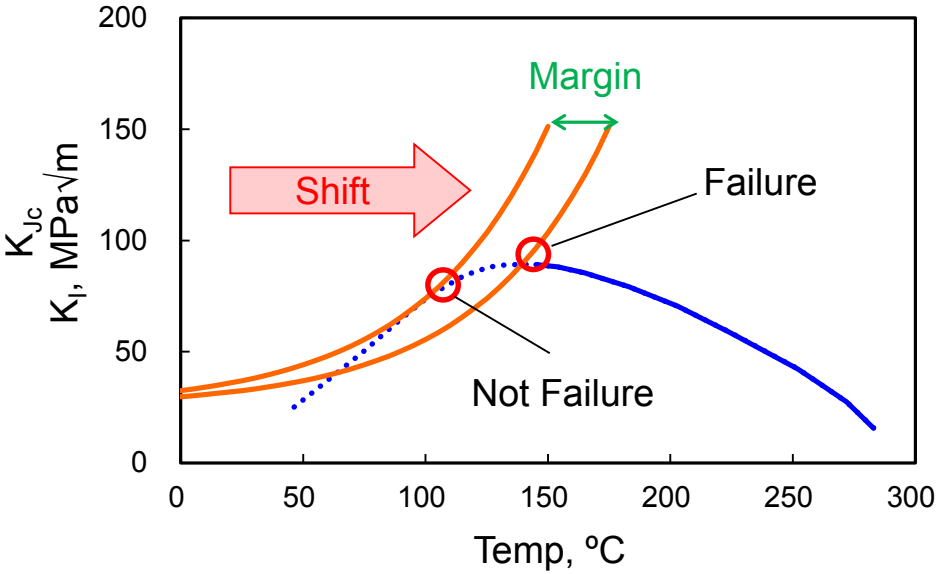


Equipment schematic

Study on WPS effect

Background

- The warm pre-stress (WPS) effect corresponds to no occurrence of crack propagation after pre-stressing in the process that the load is decreased as the temperature is decreased.
- Newly proposed code (JEAC4206-2016) introduces WPS consideration.
- The WPS effect on flaws postulated in the actual plant (underclad, post irradiated) is unknown.



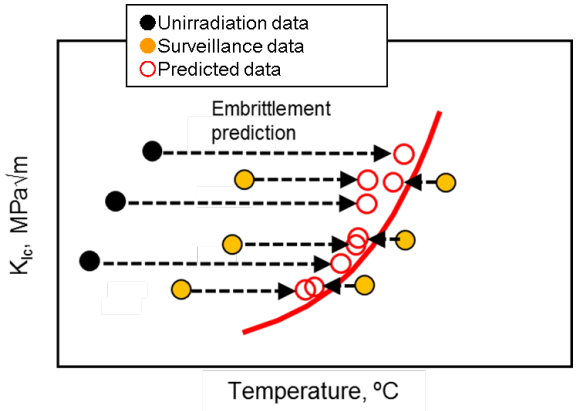
Objectives

- To confirm the adequacy of the proposed code through the experiments using irradiated material
- To develop a method of analysis to evaluate the WPS effect

Correlation of transition temp. shift (ΔT_0 vs ΔT_{41J})

Background

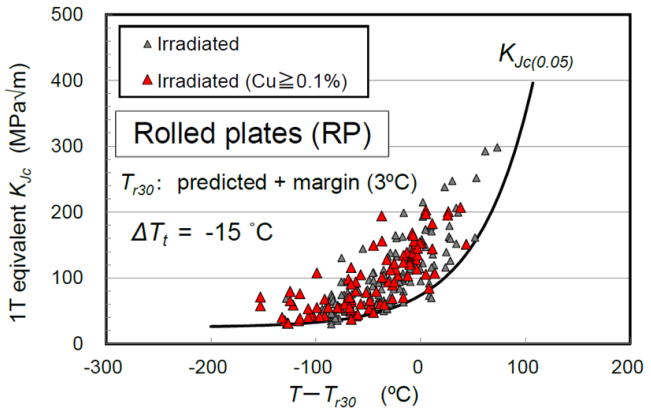
- Both JEAC4206-2007 and the newly proposed JEAC4206-2016 postulate that the temperature shifts of the reference (ΔT_0) and transition (ΔT_{41J}) temperatures are identical for determining the fracture toughness during the evaluated period.



JEAC 4206-2007

$K_{Ic} = 20.16 + 129.9\exp[0.0161(T-T_p)]$

- Lower bound curve



JEAC 4206-2016

$K_{Jc} = 25.2 + 36.6\exp[0.019\{T-(T_{r30}+\Delta T_t)\}]$

- Use of Master Curve concept

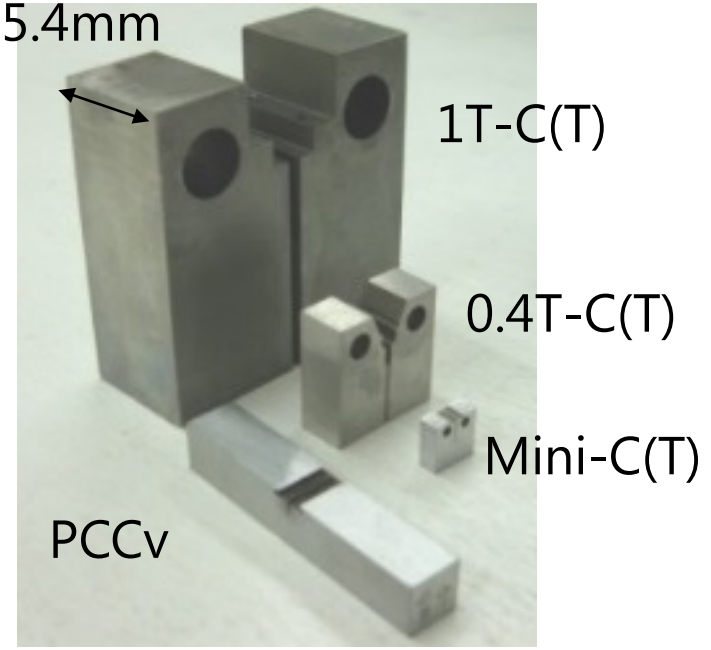
Objective

- To confirm the relationship between ΔT_{41J} and ΔT_0 at high fluence region

Size dependency of fracture toughness

Background

- Using T_0 is allowed to determine a fracture toughness curve in the newly proposed code (JEAC4206-2016).
- To evaluate T_0, it is necessary to conduct the fracture toughness tests using Mini-C(T) cut-off from the surveillance specimen.



Objective

- To ensure that T_0 is adequately evaluated by Mini-C(T) compared with that by 1T-C(T)

Prediction of irradiation embrittlement

-Statistical analysis of surveillance data and microscopic analysis-

Background

- The prediction equation of irradiation embrittlement of RPV steels was revised in JEAC4201-2007 (2013 addendum) reflecting the accumulation of surveillance data in a high fluence region.

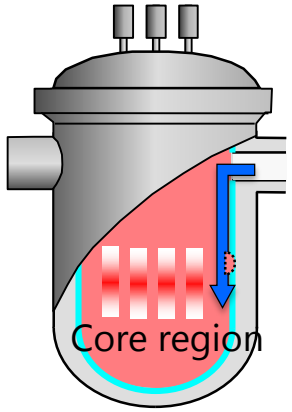
Objectives

- To confirm the conservatism of the prediction model, through the statistical analysis of surveillance data
- To confirm the adequacy of the prediction model in a high fluence region by obtaining microscopic observation data such as clusters of solute atoms and grain boundary segregation
- To identify major parameters potential for improving the prediction accuracy from the aforementioned results

Probabilistic Fracture Mechanics (PFM)

Work items

- Improvement of the functions of PFM analysis code “PASCAL” (JFY2012-2018)
- Development of the PFM guidebook (JFY2012-2017)
- Benchmark analysis with the other PFM analysis code (JFY2016-2017)



PASCAL

PFM analysis code for RPV considering neutron irradiation embrittlement & pressurized thermal shock (PTS) events developed by Japan Atomic Energy Agency (JAEA)

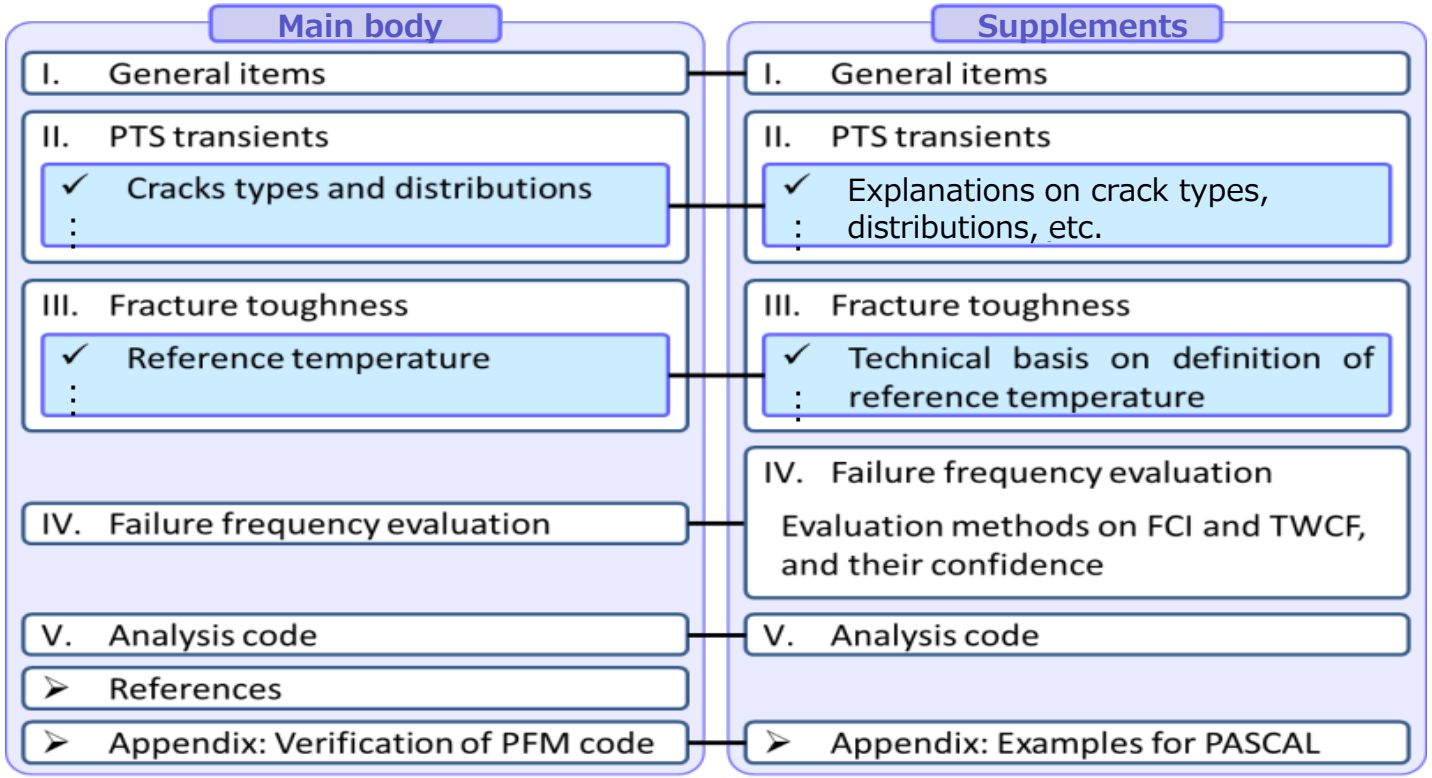
Improvement of the functions of PASCAL

In order to improve the accuracy of PFM analyses, following functions of PASCAL has been improved.

- Irradiation embrittlement prediction method
- Fracture toughness
- Loading conditions under PTS events
- Stress intensity factor K_I calculation
- Evaluation model for Non-Destructive Examination (NDE)
- Evaluation model for warm pre-stress effect

Development of the PFM guidebook

The PFM guidebook for RPVs has been developed to support calculations of probabilistic numerical index such as through-wall crack frequency (TWCF) by PFM analyses.



Reference: Katsuyama, J. et al., Guideline on Probabilistic Fracture Mechanics Analysis for Japanese Reactor Pressure Vessels, PVP2017-65921

Benchmark Analysis

- Benchmark analysis was conducted between PASCAL and FAVOR which has been utilized in the US regulation.
- Same Input data (pressure and temperature transitions, material properties, crack shapes, etc.) were used, and then different analysis models of the two codes were replaced with the same models step by step in the analyses.
- The following was confirmed:
  - the difference of K_I solutions was the most effective factor in the difference of the TWCF obtained from the two codes and
  - the results obtained from the two codes showed good agreement when the same analysis models were used.

Thank you for your attention.