JAEA Research Program on the Assessment of Structural Integrity of Reactor Pressure Vessels for Safe Long-term Operation

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Contents

● Introduction

● Current Structural Integrity Assessment Method
  ➢ Technical issues and necessary improvements

● Exploring Irradiation Embrittlement Mechanisms
  ➢ 3-dimensional atom probe (3DAP) and positron annihilation techniques to highly irradiated materials
  ➢ Accelerated MTR irradiation tests

● Validating Fracture Toughness Evaluation Method
  ➢ Master Curve approach from mini- to large-CT specimens
  ➢ Irradiation study program utilizing refurbished JMTR

● Toward Probabilistic Structural Integrity Assessment
  ➢ Model RPV analysis using PASCAL3 code

● Summary and Future Work
Introduction

- After the severe accidents in Fukushima-daiichi NPPs, the safe long-term operation of nuclear power plants has become more important.
- Accordingly the measures for aging degradation to maintain or improve the function and performance of systems, structures and components in the plant, are necessary.
- The structural integrity of a reactor pressure vessel (RPV) is the most critical issue to maintain the operation safety of NPPs.
- We have been performing researches on the evaluation methods to predict material degradation due to long-time operation and to assure the structural integrity of RPV as the following;
  1. Mechanistic study on neutron irradiation and thermal embrittlement with applying nano-scale microstructural analyses,
  2. Validation of the method to evaluate fracture toughness based on Master Curve method for the structural integrity assessment.
  3. Development of a rational evaluation approach based on probabilistic fracture mechanics (PFM) analysis to evaluate brittle fracture initiation and through-wall cracking probabilities.
Structural Integrity Assessment Method for RPV during PTS

Material Data
- Chemical Composition of Material (Cu, Ni)
- Fracture Toughness (RT_{NDT}, Measured K_{Ic}, Surveillance test data)

Embrittlement Prediction
(Fluence, Flux, Temperature)

Operation Data
- Neutron Fluence at Evaluation
- Attenuation in RPV Wall

PTS Transient Data
- Change in Coolant Temperature
- Change in System Pressure
- Thermal Analysis (Temperature distribution in RPV wall)
- Stress Analysis (Stress due to pressure and temperature change with time)
- Fracture Mechanicas Analysis (Change in K_i with time)

Master Curve
- Fracture Toughness K_{Ic} Curve at Evaluation (Lower bound curve)
- Fracture Toughness K_{Ic} at Crack Tip
- Temperature

Postulated Crack
(Axial semi-elliptical surface crack)

Current Approach: Deterministic!

Structural Integrity Assessment
(Comparison of K_{Ic} and K_i)
Irradiation Embrittlement Mechanisms

$$\Delta T = \sqrt{(\Delta T_{SC})^2 + (\Delta T_{MD})^2}$$

- $\Delta T_{SC}$: Contribution of Solute Clusters (SCs)
- $\Delta T_{MD}$: Contribution of Matrix Damage (MD)

- The contribution of SCs is divided into two sub-mechanisms; irradiation induced clustering and enhanced one.
- Embrittlement prediction equation in JEAC 4201-2007 is based on these mechanisms using rate equations and optimized coefficients.

- Contributions of SCs can be observed as a volume fraction of SCs by using a 3D AP technique.
- MD Contribution is not so significant compared to SCs.
- Intergranular embrittlement due to Phosphorus segregation will not occur in Japanese A533B-1 steels. (Nishiyama et al.)
One of the key features is irradiation embrittlement of high Cu containing steels with high fluence.

Neutron irradiation of the A533B-1 steel with 0.16 wt.% Cu (Steel A) at JMTR

The neutron fluence for each stage was controlled by timing of lift out.
Si, Mn, Ni, Cu Atoms Map by 3DAP

Steel A (0.16wt%Cu, 0.68wt%Ni, 0.015wt%P)

0.32 (x 10^{19} n/cm^2)

3.9 (x 10^{19} n/cm^2)

9.9 (x 10^{19} n/cm^2)

Number of Cu atoms in each cluster

Total number of Cu, Si, Mn and Ni atoms in each cluster

Note the rising up of the slope from not origin at 9.9\times 10^{19} n/cm^2

- The Cu-rich solute clusters formed even at 0.32\times 10^{19} n cm^{-2} and start coarsening at around 3.9\times 10^{19} n cm^{-2} in the high-Cu steel, while the Mn-Ni-Si-Clusters formation was retarded until \approx 1\times 10^{19} n cm^{-2} and still grow at around 1\times 10^{20} n cm^{-2} in the low-Cu steel.

- The formation of low-Cu SCs similar to MNSCs is suggested at the highest fluence in the high-Cu steel. This phase may cause the additional embrittlement at the very high fluence.
Future Direction on Embrittlement Mechanism Study

- High Neutron Fluence
  - Establishing reliable prediction method based on better understanding mechanisms

- Neutron Flux Effect
  - Using surveillance test materials
  - Comparison of results between MTR irradiation and surveillance

- Other Concerns
  - Overlay cladding
  - Heat affected zone
  - Inhomogeneous material property
Fracture Toughness Specimen Irradiation

Series of highly-neutron irradiation on up-to 1 inch thickness-CT specimens of Japanese A533B and A508 steels, and welds will be performed.

Verify fracture toughness Master Curve issues, e.g., specimen size effect, Master Curve shape change of highly neutron embrittled steels.

<table>
<thead>
<tr>
<th>Steels</th>
<th>Specimens</th>
<th>Neutron fluence</th>
<th>Estimated shifts of DBTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>A533B-1 Welds</td>
<td>PCCv, 0.16T-CT, 0.4T-CT, 1T-CT</td>
<td>1T-CT: (~1 \times 10^{20} \text{n/cm}^2)</td>
<td>Mostly 100~200°C</td>
</tr>
<tr>
<td>A508-3</td>
<td></td>
<td>Others: (~2 \times 10^{20} \text{n/cm}^2)</td>
<td></td>
</tr>
</tbody>
</table>
Details of fracture toughness tests

- Comparison of $K_{JC(1T)}$ data with master curve

$K_{JC(1T)}$ [MPa√m]

Test temp. - Ref. temp., $T - T_o$ [°C]

$T_o$ determined by 1T specimens
Valid data are plotted
### Master Curve Reference Temperature $T_o$ of Unirradiated Steels

**Comparison of $T_o$ values obtained from different sizes of specimens using multi-temp. method of Master Curve method**

- Specimen size effect seems to be material dependent.
Probabilistic Fracture Mechanics (PFM) analysis is quite useful for the structural integrity/reliability assessment of aged components containing a crack/cracks.

A PFM analysis code for the structural integrity assessment of RPV during PTS has been developed in JAEA, called PASCAL: PFM Analysis of Structural Components in Aging LWR. (The version is currently 3-1.)

PASCAL ver. 3 evaluates the conditional probability of failure of a reactor pressure vessel (RPV) under transient loading conditions such as pressurized thermal shock (PTS).

Using the latest version of PASCAL, some sensitivity analyses were performed for model RPVs during typical PTS events. Results obtained from the study are presented.
Main Flow Chart of PASCAL ver. 3

Main flow chart

Start

Data input

Crack sampling

Definition of crack size

Calculation of the probability of detection by non-destructive inspection

Sampling of chemical compositions, fluence, \( RT_{NDT} \), \( K_{lc} \) and \( K_{la} \)

Evaluation of crack growth

Total number of crack

Evaluation of the conditional probability of crack initiation and through-wall cracking (fracture)

End

Flow chart of crack growth

Start

The end of transient

Update the time of transient

Stress, Toughness, Crack distribution, ...

Crack initiation

Calculation of new crack depth and length

Vessel failure

Recalculation of \( \Delta RT_{NDT} \) and deviation of \( K_{lc} \) and \( K_{la} \)

Crack arrest

Monte Carlo simulation

End
**PFM Analysis Conditions**

- Probabilities of conditional crack initiation and through-wall cracking for several cases are calculated by **PASCAL3** code using basically the default conditions below.

<table>
<thead>
<tr>
<th>Item</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_i$ for semi-elliptical crack</td>
<td>Influence function method</td>
</tr>
<tr>
<td>$K_i$ for embedded crack</td>
<td>CRIEPI equation</td>
</tr>
<tr>
<td>$K_{lc}$ and $K_{la}$ equation</td>
<td><em>Weibull distribution model</em></td>
</tr>
<tr>
<td>$RT_{NDT}$ shift equation</td>
<td><em>JEAC 4201 equation</em></td>
</tr>
<tr>
<td>Chemical composition</td>
<td><em>Cu, Ni</em></td>
</tr>
<tr>
<td>Failure criterion</td>
<td>$K_{lc}/K_{la}$ and plastic collapse</td>
</tr>
<tr>
<td>Warm pre-stress</td>
<td>No crack initiation after and below the maximum SIF during PTS</td>
</tr>
<tr>
<td>Decrease in upper shelf toughness</td>
<td><em>JEAC 4201 equation</em></td>
</tr>
</tbody>
</table>
PFM Analysis Results for Model RPVs

Analysis conditions for model RPV Nos. 1 to 3
(B: Base metal, W: Weld metal)

<table>
<thead>
<tr>
<th>RPV No.</th>
<th>Embrittlement prediction</th>
<th>Fracture toughness $K_{ic}$</th>
<th>Chemical comp. (average wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>JEAC4201-2007</td>
<td>Japanese Weibull (PFM)</td>
<td>B: Cu 0.16, Ni 0.61</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JEAC4206-2007 (DFM)</td>
<td>W: Cu 0.14, Ni 0.80</td>
</tr>
<tr>
<td>2</td>
<td>10CFR50.61a</td>
<td>ORNL Weibull (PFM)</td>
<td>B: Cu 0.16, Ni 0.61</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ASME Sec.XI (DFM)</td>
<td>W: Cu 0.14, Ni 0.80</td>
</tr>
<tr>
<td>3</td>
<td>JEAC4201-2007</td>
<td>Japanese Weibull (PFM)</td>
<td>B: Cu 0.16, Ni 0.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td>JEAC4206-2007 (DFM)</td>
<td>W: Cu 0.19, Ni 1.08</td>
</tr>
</tbody>
</table>

Ratio of conditional probability of fracture to the crack initiation (LBLOCA)

Relationship between deterministic temperature margin and CPI
Future Research on RPV Integrity

- Improvement on Deterministic/Probabilistic Structural Integrity Analysis Method
  - Thermal-Hydraulic Analyses (3D-CFD)
  - Selection and Frequency Estimation on Typical Loading Conditions (PTS-PRA)
  - Crack Arrest Evaluation Method ($K_{ia}$ database)
  - Crack Distribution Model Development (Simulation/Experiment?)

- Application of PFM Analysis to Regulatory Framework
  - Verification (and Validation) of PFM Analysis Code (Experts Opinion, Benchmark)
  - Activities toward Establishment of Standards/Guidelines for PFM Analysis in Japan
Summary

- Mechanistic study on neutron irradiation embrittlement:
  - Insights on embrittlement mechanisms using 3DAP and PA particularly for high neutron fluence
- Master curve approach on fracture toughness evaluation:
  - Specimen size effect depending on material used (unirradiated)
  - Irradiation study to be performed at JMTR
- Probabilistic structural integrity analysis
  - Sensitivity Analyses on various parameters
  - Model RPV analyses for PTS events
- Future research items related to technical issues above were presented toward the enhancement of current regulation, codes and standards.
  - These items are supported by the project JAMPSS of NISA.
Details of fracture toughness tests

- $T_o$ values

<table>
<thead>
<tr>
<th>Material</th>
<th>Specimen</th>
<th>$T_o$ [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SteelA</td>
<td>PCCv</td>
<td>-75.6</td>
</tr>
<tr>
<td></td>
<td>016T</td>
<td>-69.5</td>
</tr>
<tr>
<td></td>
<td>1T</td>
<td>-65.8</td>
</tr>
<tr>
<td>SteelB</td>
<td>PCCv</td>
<td>-99.0</td>
</tr>
<tr>
<td></td>
<td>016T</td>
<td>-101.5</td>
</tr>
<tr>
<td></td>
<td>1T</td>
<td>-97.2</td>
</tr>
<tr>
<td>JRH</td>
<td>PCCv</td>
<td>-123.7</td>
</tr>
<tr>
<td></td>
<td>016T</td>
<td>-105.1</td>
</tr>
<tr>
<td></td>
<td>04T</td>
<td>-109.8</td>
</tr>
<tr>
<td></td>
<td>1T</td>
<td>-103.0</td>
</tr>
<tr>
<td>JRM</td>
<td>PCCv</td>
<td>-84.8</td>
</tr>
<tr>
<td></td>
<td>016T</td>
<td>-95.2</td>
</tr>
<tr>
<td></td>
<td>04T</td>
<td>-93.7</td>
</tr>
<tr>
<td></td>
<td>1T</td>
<td>-81.7</td>
</tr>
<tr>
<td>JRL</td>
<td>PCCv</td>
<td>-114.4</td>
</tr>
<tr>
<td></td>
<td>04T</td>
<td>-102.5</td>
</tr>
<tr>
<td></td>
<td>1T</td>
<td>-114.1</td>
</tr>
<tr>
<td>S1</td>
<td>PCCv</td>
<td>-124.0</td>
</tr>
<tr>
<td></td>
<td>04T</td>
<td>-123.1</td>
</tr>
<tr>
<td></td>
<td>1T</td>
<td>-119.5</td>
</tr>
</tbody>
</table>

- Comparison of $K_{JC(1T)}$ data with master curve

Test temp. - Ref. temp., $T - T_o$ [°C]

- $T_o$ determined by 1T specimens
- Valid data are plotted

M4T10です。M4T1～M4T20は、専門部会後に試験実施です。

L1T20とL1T21です。専門部会の資料に載っていました。専門部会で間違っていました。

H4T20です。H4T1～H4T20は専門部会後に試験実施です。

M1T11です。pop-inが発生し低い値です。専門部会では示していませんでした。ASTM規格を見直して載せることとし、Toも計算し直しています。