Post-irradiation Examination Using TEM Method for Swelling Evaluation of Baffle Plate in PWR Core Internals

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Contents

1. INTRODUCTION

2. EXPERIMENTAL PROCEDURE
   (1) Material
   (2) Sampling Position from the Test Coupon
   (3) TEM* Samples Preparation
   (4) Post-irradiation Examination by TEM*

3. RESULTS AND DISCUSSIONS
   (1) Swelling Measurement by TEM* Method
   (2) Comparison with Swelling Evaluation Equation

4. CONCLUSIONS

   * TEM ; Transmission Electron Microscope
Contents

1. INTRODUCTION

2. EXPERIMENTAL PROCEDURE
   (1) Material
   (2) Sampling Position from the Test Coupon
   (3) TEM Samples Preparation
   (4) Post-irradiation Examination by TEM

3. RESULTS AND DISCUSSIONS
   (1) Swelling Measurement by TEM Method
   (2) Comparison with Swelling Evaluation Equation

4. CONCLUSIONS

   TEM ; Transmission Electron Microscope
1. INTRODUCTION

- **Void Swelling** possibly affects the functionality of reactor internals, especially of a baffle former assembly for PWR.
- **Void Swelling** in a baffle and former assembly leads to the deformation of baffle plates and that applies bending load to baffle former bolts (BFBs).
- **Irradiation Assisted Stress Corrosion Cracking (IASCC)** of BFBs in PWR. It is an important issue for plant conservation in the world.
- It is known that swelling deformation (volumetric expansion) greatly affects the stress of BFBs for the Type 304 stainless steel baffle plate fastened by the BFBs.

![Diagram of PWR core internal components](image-url)
1. INTRODUCTION

- However, the **void swelling** evaluation equation improved to PWR based on the data which has been modified in the Fast Breeder Reactor (FBR) EBR-II in the past (modified dpa rate corrected Foster-Flinn equation) has been under consideration.

- In order to evaluate the actual PWR plant, data expansion using BFBs which is the same steel type (austenitic) and cold-worked Type 316 stainless steel of flux thimble tube (FTT) as the post-irradiation examination (PIE) is under way.

- In this research, as a part of the research using the Spanish decommissioned material conducted Zorita Internals Research Project (ZIRP) of the Electric Power Research Institute (EPRI), the results of directly analysis of dose and irradiation temperature for **304 stainless steel baffle plate** based on the hot laboratory of Nuclear Development Corporation (NDC)

- Micro sampling from the test coupon of **baffle plate** was carried out and data expansion by swelling measurement using a **Transmission Electron Microscope (TEM)** systematically.

- The validity of the **swelling evaluation equation** was verified.
1. INTRODUCTION

2. EXPERIMENTAL PROCEDURE
   (1) Material
   (2) Sampling Position from the Test Coupon
   (3) TEM Samples Preparation
   (4) Post-irradiation Examination by TEM

3. RESULTS AND DISCUSSIONS
   (1) Swelling Measurement by TEM Method
   (2) Comparison with Swelling Evaluation Equation

4. CONCLUSIONS
   TEM ; Transmission Electron Microscope
Material

- **Decommissioned plant**
  - “ZORITA” PWR in Spain (160MWe)
  - Single loop reactor coolant system by WH design
  - Operated about 40Years (26EFPY), shutdown in 2006

- **Test coupon**
  - Cut out from 304SS baffle plates at reentrant corner
  - Provided by EPRI (via Studsvik in Sweden)

![Baffle plates (304SS)](image)

- Baffle plate thickness
  - 29mm
  - 36mm
  - 12mm

![Pictures of the test coupon](image)
Dose and Temperature Distributions

- Dose and irradiation temperature distribution of the test coupon (provided by EPRI)

<table>
<thead>
<tr>
<th>Dose distribution</th>
<th>Irradiation temperature distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>50dpa</td>
<td>295°C</td>
</tr>
<tr>
<td>25dpa</td>
<td>Maximum temp. cycle</td>
</tr>
<tr>
<td>29mm Baffle plate thickness</td>
<td>289°C</td>
</tr>
<tr>
<td>29mm</td>
<td>Minimum temp. cycle</td>
</tr>
<tr>
<td>[dpa]</td>
<td>327°C</td>
</tr>
<tr>
<td>310°C</td>
<td></td>
</tr>
</tbody>
</table>

Depend on γ-heating

Calculation dose and irradiation temperature for the test coupon
Measured at 9 points to cover the wide range of dose and irradiation temperature.

- Max. dose position with the temperature above 320°C (①)
- Max. temperature position (②,③) and its near position (⑤,⑥,⑦,⑧)
- Max. dose position (⑨)
- Middle dose and temperature between ① and ② (④)

**Dose distribution**

**Irradiation temperature distribution**

**Swelling examination sampling position from test coupon**

*: Calculated temperature at the maximum temperature cycle
## Sampling Position from Test Coupon

- Measured at 9 points to cover the wide range of dose and irradiation temperature

<table>
<thead>
<tr>
<th>No.</th>
<th>Sampling positions on the top side</th>
<th>Dose (dpa)</th>
<th>Dose rate (dpa/s)</th>
<th>Irrad. Temp. (℃)</th>
</tr>
</thead>
<tbody>
<tr>
<td>①</td>
<td>Max. dose position (over 320°C region)</td>
<td>39</td>
<td>4.8x10^-8</td>
<td>319</td>
</tr>
<tr>
<td>②</td>
<td>Max. temp. position</td>
<td>34</td>
<td>4.1x10^-8</td>
<td>327</td>
</tr>
<tr>
<td>③</td>
<td>Max. temp. position as same as No.② position</td>
<td>35</td>
<td>4.3x10^-8</td>
<td>327</td>
</tr>
<tr>
<td>④</td>
<td>Middle of No.① and No.② position</td>
<td>37</td>
<td>4.5x10^-8</td>
<td>324</td>
</tr>
<tr>
<td>⑤</td>
<td>Near max. temp. No.② position</td>
<td>33</td>
<td>4.0x10^-8</td>
<td>326</td>
</tr>
<tr>
<td>⑥</td>
<td>Near max. temp. No.② position</td>
<td>36</td>
<td>4.4x10^-8</td>
<td>325</td>
</tr>
<tr>
<td>⑦</td>
<td>Near max. temp. No.② position</td>
<td>36</td>
<td>4.4x10^-8</td>
<td>325</td>
</tr>
<tr>
<td>⑧</td>
<td>Near max. temp. No.② position</td>
<td>33</td>
<td>4.0x10^-8</td>
<td>326</td>
</tr>
<tr>
<td>⑨</td>
<td>Max. dose position (all region)</td>
<td>47</td>
<td>5.7x10^-8</td>
<td>299</td>
</tr>
</tbody>
</table>
TEM Sample Preparation

- TEM sample preparation of micro sampling from a baffle plate coupon by NDC
- In order to reduce radiation exposure due to radioactivity during TEM observation, punching to φ1mm size with a die was performed.

![Diagram of TEM sample preparation process](image)
Post-irradiation Examination by TEM

- TEM observation, a JEOL JEM-2010F instrument with an acceleration voltage of 200kV was used
- High magnification TEM cavity images of the distinction between helium (He) bubbles and voids

(a) Under focus
(b) Just focus
(c) Over focus

(1) He bubble

In case of helium bubble (cavity diameter: \( \leq 3 \text{nm} \)), the shape does not change even at each focus position, and it looks like a sphere shape
- At under focus, it looks like a white sphere shape
- At over focus, it looks like a black sphere shape

(2) Void

In case of void (cavity diameter: \( >3 \text{nm} \)), different shape at each focus position, polygonal shape and fringes visible
- At under focus, it looks like a white polygonal shape and external bright fringes
- At over focus, it looks like a black polygonal shape and internal bright fringes
1. INTRODUCTION

2. EXPERIMENTAL PROCEDURE
   (1) Material
   (2) Sampling Position from the Test Coupon
   (3) TEM Samples Preparation
   (4) Post-irradiation Examination by TEM

3. RESULTS AND DISCUSSIONS
   (1) Swelling Measurement by TEM Method
   (2) Comparison with Swelling Evaluation Equation

4. CONCLUSIONS

TEM ; Transmission Electron Microscope
Swelling Measurement by TEM Method

<table>
<thead>
<tr>
<th>No.</th>
<th>DPA</th>
<th>Temperature</th>
<th>SW</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>39</td>
<td>319°C</td>
<td>0.041%</td>
</tr>
<tr>
<td>(2)</td>
<td>34</td>
<td>327°C</td>
<td>0.074%</td>
</tr>
<tr>
<td>(3)</td>
<td>35</td>
<td>327°C</td>
<td>0.080%</td>
</tr>
<tr>
<td>(4)</td>
<td>37</td>
<td>324°C</td>
<td>0.051%</td>
</tr>
<tr>
<td>(5)</td>
<td>33</td>
<td>326°C</td>
<td>0.074%</td>
</tr>
<tr>
<td>(6)</td>
<td>36</td>
<td>325°C</td>
<td>0.052%</td>
</tr>
<tr>
<td>(7)</td>
<td>36</td>
<td>325°C</td>
<td>0.073%</td>
</tr>
<tr>
<td>(8)</td>
<td>33</td>
<td>326°C</td>
<td>0.056%</td>
</tr>
<tr>
<td>(9)</td>
<td>47</td>
<td>299°C</td>
<td>0.015%</td>
</tr>
</tbody>
</table>

Temperature distribution

B: He babbles
V: Voids

Under focus TEM images

SW: Swelling ratio
TEM Observation at **High Temp. Position**

Temperature distribution

No. 2 position (34 dpa, 327°C)

**B**: He babbles  
**V**: Voids

Under focus TEM image

- **He bubble**
- **Void**
- **Sparse bubbles**
- **Several voids**
TEM Observation at **Low Temp. Position**

Temperature distribution

No.9 position (47dpa, **299°C**)

**B**: He babbles

**V**: Voids

Under focus TEM image

- Dense bubbles
- No voids
### Swelling Ratio by TEM Method

- **Quantification of swelling amount (Swelling ratio: S)**

\[
S = \sum_{i=1}^{n} \left\{ \frac{4}{3} \pi \left( \frac{d_i}{2} \right)^3 \right\} \left( \frac{A}{At} \right) \times 100
\]

- \( S \): swelling ratio [%]
- \( n \): number of cavities per observed area [-]
- \( d_i \): diameter of a cavity [nm]
- \( A \): observed area [nm²]
- \( t \): average thickness of observed area [nm]

### Table: Swelling Amount

<table>
<thead>
<tr>
<th>No.</th>
<th>Dose (dpa)</th>
<th>Irrad. temp. (°C)</th>
<th>Number of cavities (-)</th>
<th>Ave. diameter of cavities (nm)</th>
<th>Max. diameter of cavities (nm)</th>
<th>Density of cavities (x10²²/m³)</th>
<th>Swelling ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>①</td>
<td>39</td>
<td>319</td>
<td>523</td>
<td>1.2</td>
<td>7.8</td>
<td>13.3</td>
<td>0.041</td>
</tr>
<tr>
<td>②</td>
<td>34</td>
<td>327</td>
<td>298</td>
<td>1.5</td>
<td>7.6</td>
<td>13.7</td>
<td>0.074</td>
</tr>
<tr>
<td>③</td>
<td>35</td>
<td>327</td>
<td>348</td>
<td>1.5</td>
<td>8.8</td>
<td>13.1</td>
<td>0.080</td>
</tr>
<tr>
<td>④</td>
<td>37</td>
<td>324</td>
<td>507</td>
<td>1.3</td>
<td>6.0</td>
<td>15.6</td>
<td>0.051</td>
</tr>
<tr>
<td>⑤</td>
<td>33</td>
<td>326</td>
<td>323</td>
<td>1.5</td>
<td>8.3</td>
<td>12.8</td>
<td>0.074</td>
</tr>
<tr>
<td>⑥</td>
<td>36</td>
<td>325</td>
<td>461</td>
<td>1.3</td>
<td>6.4</td>
<td>14.7</td>
<td>0.052</td>
</tr>
<tr>
<td>⑦</td>
<td>36</td>
<td>325</td>
<td>493</td>
<td>1.5</td>
<td>7.5</td>
<td>13.2</td>
<td>0.073</td>
</tr>
<tr>
<td>⑧</td>
<td>33</td>
<td>326</td>
<td>473</td>
<td>1.3</td>
<td>7.9</td>
<td>11.8</td>
<td>0.056</td>
</tr>
<tr>
<td>⑨</td>
<td>47</td>
<td>299</td>
<td>802</td>
<td>1.1</td>
<td>1.8</td>
<td>21.4</td>
<td>0.015</td>
</tr>
</tbody>
</table>
Size Distribution of He Bubbles and Voids

- He bubbles become sparse and large size as the temperature increases

Temperature distribution:

No. 2 position (34dpa, 327°C)

No. 1 position (39dpa, 319°C)

No. 9 position (47dpa, 299°C)

Ave. 1.5nm

Total num. 298

Ave. 1.2nm

Total num. 523

Ave. 1.1nm

Total num. 802
Correlation with Dose and Temperature

- Strong correlation with irradiation temperature
- Swelling ratio showed a tendency to increase markedly from around 320°C
- A poor correlation with the swelling ratio was observed for dose and dose rate in this study since the number of the data points is limited.
Comparison with Literature Data

- Comparable with literature data

- Literature data mainly consist of CW316SS (304SS in this study) from PWR irradiated materials

- Swelling ratios seem to increase with increasing irradiation temperature

- Also, swelling ratio showed remarkably increase from around 320°C

- The clear relation between the swelling ratio and the dose was not observed.
Comparison between Equation and Data

- The swelling equation agrees well with the measured data in this study.
- In the PWR irradiation condition, remarkable swelling ratio was observed at around 320°C. It was possible to clarify the irradiation temperature dependence that transition from He bubbles to voids is observed.
- However, higher irradiation temperatures data is insufficient to improve adequacy.

Comparison between the swelling equation and the measured data for swelling ratio

\[ S = \frac{\Delta V}{V_0} = \exp \left( -1.591 + 0.245T - 1.210T^2 - 1.384T^3 - 1.204T^4 \right) \times \left( \phi / 1.25 \right)^{-0.73} \times \left( F / 4.9 \right)^2 \times 10^{-2} \]

\[ T = (t - 490) / 100 \]

Where,
- \( S \) : swelling ratio [%]
- \( t \) : irradiation temperature [°C]
- \( \phi \) : dose rate [dpa/s × 10^7]
- \( F \) : dose [dpa]


Contents

1. INTRODUCTION

2. EXPERIMENTAL PROCEDURE
   (1) Material
   (2) Sampling Position from the Test Coupon
   (3) TEM Samples Preparation
   (4) Post-irradiation Examination by TEM

3. RESULTS AND DISCUSSIONS
   (1) Swelling Measurement by TEM Method
   (2) Comparison with Swelling Evaluation Equation

4. CONCLUSIONS

TEM ; Transmission Electron Microscope
4. CONCLUSIONS

We investigated swelling (SW) characteristics of a test coupon removed from a Type 304 stainless steel baffle plate of a decommissioned commercial PWR ZORITA plant.

- The measured SW ratio was 0.015% to 0.080%, varying according to the dose (33dpa~47dpa) and irradiation temperature (299°C~327°C) at measurement points.
- SW ratios clearly increase with increasing irradiation temperature, while clear dependency of the SW ratio for dose was not recognized as far as dose variation in this study.
- At lower irradiation temperature 320°C position, 1nm~3nm diameter He bubbles were mainly observed, while at higher temperature (>320°C) positions, over 3nm diameter voids and less dense He bubbles were observed. The growth from He bubbles to voids seems to start from around irradiation temperature 320°C.
- The SW evaluation equation called modified Foster-Flinn equation corresponds well with the obtained SW data.

> In the future, we will try to improve the adequacy of the SW evaluation equation for PWR by expanding irradiation material data at higher irradiation temperatures from baffle plates.
Acknowledgment

This study was done as a joint research program among Japanese PWR utilities and Mitsubishi Heavy Industries, LTD. (MHI).

Grateful to EPRI Zorita Internals Research Project (ZIRP) for providing used coupon from Studsvik and its dose and irradiation temperature distribution calculations.
MOVE THE WORLD FORWARD