Metallography and microanalysis of Qinshan NPP spent fuel rods in CIAE Hot Cells

J. Qian
Senior Engineer
China Institute of Atomic Energy

HOTLAB 2015 conference
OUTLINE

- Introduction

- The process of the metallography preparation

- Results and Analysis
  - The macrostructure and crack of fuel
  - Porosity
  - Grain
  - Waterside oxide film of cladding
  - Inner surface corrosion of cladding and the gap between cladding and pellets
  - Hydride of the cladding

- Conclusions
1. INTRODUCTION

Qinshan Phase I NPP (QNPC)
Type: PWR (CNP-300)
Electric Power: 298MW
Operation time: 1991

FA-300 fuel rod assembly
<table>
<thead>
<tr>
<th>Item</th>
<th>parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>The length of fuel rods</td>
<td>3200 mm</td>
</tr>
<tr>
<td>The diameter of fuel rods</td>
<td>Φ10 mm</td>
</tr>
<tr>
<td>The thickness of the cladding</td>
<td>0.7 mm</td>
</tr>
<tr>
<td>The height of fuel pin</td>
<td>10 mm</td>
</tr>
<tr>
<td>The diameter of fuel pin</td>
<td>Φ8.43 mm</td>
</tr>
<tr>
<td>The cumulative height of fuel pins</td>
<td>2900 mm</td>
</tr>
<tr>
<td>The type of cladding</td>
<td>Zr-4</td>
</tr>
<tr>
<td>The type of fuel pin</td>
<td>UO2 with the enrichment of 3.4%</td>
</tr>
<tr>
<td>Fuel Assembly No.</td>
<td>YQ-30BZ</td>
</tr>
<tr>
<td>------------------</td>
<td>---------</td>
</tr>
<tr>
<td>Position of rod</td>
<td><strong>A-15</strong></td>
</tr>
<tr>
<td>Load date</td>
<td>2000-12-24</td>
</tr>
<tr>
<td>Unload date</td>
<td>2006-6-25</td>
</tr>
<tr>
<td>Cooling time(Year)</td>
<td>6.0</td>
</tr>
<tr>
<td>Enrichment of U-235(%)</td>
<td>3.4</td>
</tr>
<tr>
<td>Burrup(GWd/tU)</td>
<td><strong>40</strong></td>
</tr>
<tr>
<td>Core Cycle</td>
<td>9</td>
</tr>
</tbody>
</table>

**NDE**
- Visual inspection
- Dimensional measurement
- Eddy current test
- Axial Gamma scanning
- X radiography

**DE**
- Puncture and FG analysis
  - **Metallography and Ceramography**
- Tensile
- Other test
Contents of metallography and microanalysis

- The macro- and micro-structure of the fuel pellets;
- The corrosion of the outer and inner face of the cladding;
- The observation of the Pellet and Cladding Interaction (PCI);
- The observation of the hydride of the cladding and the analysis of hydrogen content.
Transportation of fuel rods from Qinshan to CIAE: 2012
2. METALLOGRAPHY PREPARATION

Cutting and Sampling

MET1-C  MET2-C  MET3-C  MET4-C  MET5-C  MET6-C  MET7-C

Cross section: 7  Axial section: 2
Grinding

Polishing

Observation after polishing

Observation after cladding etched

Observation after fuel etched

- Cladding corrosion;
- morphology, crack, porosity of fuel pellets;
- PCI, gap between cladding and pellets

- Morphology, distribution, content of hydride

- Grain of fuel pellets
Metallography in hotcell

Grinding and polishing machine
Struers TegraPol-11

Remote control optical microscope
Olympus-GX51
3. RESULTS AND ANALYSIS

- **Morphology and crack of pellets**

- The cracks of the pellets mainly are radial except MET7-C.
- No phenomenon of the black ring on the pellets reveals the FGs bubbles did not migrate and accumulate and the temperature of the fuel is not over 1200°C.
the shape of the pellets is not changed clearly
Porosity

In the process of the metallography preparation, some fuel grains dropped out and the holes looked like pore leave on the sample surface. So, porosity calculation is required to exclude these false “gray spots”
Porosity

- the “gray spots” of 0.25~3um size follow the law of Gaussian Distribution
- the average size of the true porosities is 1um
The change of the fuel porosity in the axial direction of the fuel rod

The porosity is a range of 1.4~3.6%; the average value is 2.3%;
Fuel Grain

-The grains are equiax crystal
The phenomenon of the UO2 grain growth is not obvious

There are more small gas bubbles of inner crystal in rim region than in other region

The small gas bubbles of inner crystal
<table>
<thead>
<tr>
<th>specimens</th>
<th>Distance from the bottom (mm)</th>
<th>Grain Grade</th>
<th>Grain size (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MET1-C</td>
<td>140</td>
<td>11.8</td>
<td>6.0</td>
</tr>
<tr>
<td>MET2-C</td>
<td>560</td>
<td>10.8</td>
<td>8.5</td>
</tr>
<tr>
<td>MET3-C</td>
<td>1000</td>
<td>11.1</td>
<td>7.7</td>
</tr>
<tr>
<td>MET4-C</td>
<td>1410</td>
<td>11.2</td>
<td>7.4</td>
</tr>
<tr>
<td>MET5-C</td>
<td>1870</td>
<td>11.5</td>
<td>6.7</td>
</tr>
<tr>
<td>MET6-C</td>
<td>2350</td>
<td>11.4</td>
<td>6.9</td>
</tr>
<tr>
<td>MET7-C</td>
<td>2880</td>
<td>11.2</td>
<td>7.4</td>
</tr>
<tr>
<td>AVE</td>
<td></td>
<td><strong>11.3</strong></td>
<td><strong>7.2</strong></td>
</tr>
<tr>
<td>SD</td>
<td></td>
<td><strong>0.3</strong></td>
<td><strong>0.8</strong></td>
</tr>
</tbody>
</table>

**Distribution of grain grade**

The process of the calculation of the grain size by Area method.
The waterside oxide film of the cladding is continuous and dense overall;
In some local positions, the oxide film is porous and cracked.
The relationship of the thickness of waterside oxide film and the position of the fuel rod

Maximun waterside oxide thickness vs. Fuel rod burnup

MAX: 23um
AVE: 11.6um

The maximum measured value (23um)
Inner surface corrosion of cladding

- No corrosion is happened for all samples except MET4-C sample
- there are 4 localized corrosion on inner surface of cladding for the MET4-C;
- the size of maximum corrosion spot is 117um (length) × 9um (depth)．
The change of the gap of cladding and pellets in the axial direction of the fuel rod.

- The gap of cladding and pellets is growing from the bottom to top of the fuel rod.
- The average value of the gaps is 34um, which is 40% of original value (85um).

The change of the gap of cladding and pellet in the axial direction of the fuel rod.
The distribution of hydride

- The hydride distribution on the cross section of cladding:
  - The hydride distribute on the outer wall and near the inner wall of cladding mainly;
  - The hydride orientation is circumferential.
The hydrogen content

standard Zr-4 samples → Build the analysis Curve → Analyze the cladding samples

Hydrogen content analysis curve

\[ H = 43 \times A^{0.75} \]

The area ratio of hydride phase
<table>
<thead>
<tr>
<th>specimens</th>
<th>Distance from the bottom (mm)</th>
<th>A (%)</th>
<th>H (mm)</th>
<th>$f_{45}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MET1-C</td>
<td>140</td>
<td>1.2</td>
<td>49</td>
<td>0.25</td>
</tr>
<tr>
<td>MET2-C</td>
<td>560</td>
<td>2</td>
<td>72</td>
<td>0.21</td>
</tr>
<tr>
<td>MET3-C</td>
<td>1000</td>
<td>2.2</td>
<td>78</td>
<td>0.15</td>
</tr>
<tr>
<td>MET4-C</td>
<td>1410</td>
<td>3</td>
<td>98</td>
<td>0.12</td>
</tr>
<tr>
<td>MET5-C</td>
<td>1870</td>
<td>3.7</td>
<td>115</td>
<td>0.1</td>
</tr>
<tr>
<td>MET6-C</td>
<td>2350</td>
<td>5.3</td>
<td>150</td>
<td>0.1</td>
</tr>
<tr>
<td>MET7-C</td>
<td>2880</td>
<td>2.9</td>
<td>96</td>
<td>0.15</td>
</tr>
<tr>
<td>AVE</td>
<td></td>
<td>2.9</td>
<td>94</td>
<td>0.15</td>
</tr>
</tbody>
</table>

- The maximum hydrogen content is **150ppm** with the sample of **Span 6** of the fuel rod;
- The hydride orientation factor $f_{45}$ is a range of **0.1~0.25**.
- The f45 decreases with the growth of the hydrogen content;
- This phenomenon is advantageous for the property of the cladding.
The change of the hydrogen content in the axial direction of the fuel rod

- The hydrogen content and the thickness of waterside oxide film are proportional relation
- The slope of the fit linear reflect the hydrogen absorption property of the cladding

The relationship of the hydrogen content and the thickness of waterside oxide film

\[ y = a + b \times x \]

Adj. R-Square: 0.89715
Hydrogen absorption properties of the cladding

\[
Zr + 2H_2O \rightarrow ZrO_2 + 4H \quad \text{H: hydrogen generation}
\]

\[
\downarrow \quad \text{H': hydrogen absorption}
\]

the hydrogen absorption factor \( F \):

\[
F = \frac{\text{Hydrogen absorption}(H')}{{\text{Hydrogen generation}(H)}} \times 100\%
\]

\[
H' = \rho_{Zr} \cdot d_0 \cdot W_H
\]

Calculated by hydrogen content

\[
H = \rho_{ZrO_2} \cdot d \cdot \frac{4A_H}{A_{ZrO_2}}
\]

Calculated by the thickness of waterside oxide film

the result of \( F \) is **16.3%** and the value is normal
When the burnup of Qinshan Phase I NPP fuel rod is up to 40GWD/tU:

- The microstructure of the fuel pellets is normal and no PCI phenomenon happens;
- The waterside corrosion and the hydride in cladding is normal;
- In summary, the fuel rod is normal and safety in micro-scale.
Thanks !