Microstructure Analysis of Irradiated NUE and NU Fuel in NPIC Hot Cells

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1. Introduction

- Recycling of spent fuel in HWR
  
  - Improve the uranium resource utilization rate
  
  - Reduce the storage pressure of spent fuel

  - Sustainable development for nuclear power
  
  - Realization of building the closed fuel cycle system

- TQNPC and CANDU Energy put forward the natural uranium equivalent (NUE) fuel development program
1. Introduction

NUE fuel development program

NUE fuel: Homogeneous mixture of recycled uranium (RU) and depleted uranium (DU).

NU fuel: natural uranium

**Similarities**
- Reactor core characteristics
- Main parameters
- Pellet structure
- Physical character

**Differences**
- Composition of fuel pellet
In order to guarantee the security and functional stability of reactor operations, **irradiation test and post-irradiation examination** are required.

a) **Whole Structure**

b) **Section Structure**

**Structure Sketch of Fuel Bundles**
1. Introduction

Post-irradiation examination

1. Visual Inspection
2. Dimensioning Measurement
3. Fission Gas Analysis
4. Microstructure Analysis
5. SEM Analysis
6. Burn-up Analysis
2. Test Method

Specimen Preparation

- The section, sampling, specimen preparation and metallographic examination all should be conducted in hot cell by robotic arm.
- The specimens were sectioned from 4 NUE fuel rods and 3 NU fuel rods by cutting milling machine in the hot-cell, Diamond disk was used to cut.
- A longitudinal specimen containing end cap and a transverse specimen containing the middle spacer pad were cut from each rod.
### Specimen Preparation

#### Sampling Location and Quantity of Fuel Elements

<table>
<thead>
<tr>
<th>Transverse Specimen</th>
<th>Longitudinal Specimen</th>
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<tbody>
<tr>
<td><strong>Rod Code</strong></td>
<td><strong>Sample Code</strong></td>
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<tr>
<td>NUE-1</td>
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<tr>
<td>NUE-2</td>
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<tr>
<td>NU-3</td>
<td>NU-3-H</td>
</tr>
</tbody>
</table>
2. Test Method

Test Method

Section & Sampling → Mounting → Grinding → Polishing

Section Grinding & Polishing Metallographic examination

Grain Size → Grain Appearance → Etching → Pellet Appearance

Preparation and examination process of sample
2. Test Method

Test Method

Specimens were mounted in mounting mould by epoxy resin.

Ground in sequence through size 220#, 600# and 1200# diamond disc and polished in sequence through size 9μm, 3μm and 1μm diamond slurry.

After ground and polished, the distribution of cracks and pores in pellets were examined.

Etched by etchant consists of H₂SO₄:H₂O₂=1:9.

Grain shape and size of UO₂ pellets were examined by Leica MEF4A optical microscopy.
3. Result and Analysis

Transverse Specimens

There were circumferential cracks and no obvious radial cracks inside of the circumferential cracks in NUE fuel rods.

Pellets of both NUE and NU fuel rods were broken in different degree and there were lots of cracks in the surface in different.

There were big radial cracks in the center of NU fuel rods which show that the source of cracks were at the center of pellet.
3. Result and Analysis

Overall Appearances

- There were gaps between pellet and cladding.
- No fragments in the gap and there were no obviously distortion of cladding.

- Graphite coating were relatively intact and well-distributed.
- The thickness of graphite coating ranges from 8μm to 26.7μm.
3. Result and Analysis | Overall Appearances

- Longitudinal Specimens

- There were cracks with different sizes and orientations distributing in pellets of both NUE and NU.
- No obvious difference in the pellet-to-end cap interfaces of six longitudinal specimens.

Overall Appearances of Longitudinal specimens
3. Result and Analysis

Overall Appearances

There were gaps between pellet and the end cap. No abrasive wearing and abnormal fragmentations at pellet-to-endcap interfaces.

There were gaps between two pellets, pellet and the end cap, this shows the size and shape of pellets controlled within a rational range.
3. Result and Analysis

Transverse Specimens

Grain size changed according to areas. From periphery to center, grain size gradually increased.

Microstructures at the Five Different Radial Locations of 1-NUE-1-H
3. Result and Analysis

Transverse Specimens

Section Locations

Pellet Periphery

1/2 Radius

1/3 Radius

1/6 Radius

Center

Microstructure at the Five Different Radial Locations of 1-NU-1-H
3. Result and Analysis | Grain

Transverse Specimens

The grain size distribution in corresponding area of NUE and NU fuel rods was basically the same.

- Size distribution: 5.8 ~ 26.7 μm.

There was significant difference between periphery and the center.

- Center: 21.4 ~ 26.7 μm
- Periphery: 5.8 ~ 7.1 μm

Appropriate grain size can reduce fission gas release, improve pellet's thermal stability and its breaking strength.

Studies showed that grain size within 5 to 35 μm was acceptable.

- Periphery: 5.8 ~ 7.1 μm.

Grain Size for Pellet’s Different Locations in Transverse Specimens
Specimens of NUE and NU show the same trend: grain size increased from the periphery to the center area.
3. Result and Analysis

Grain

Longitudinal Specimens

- The variation in grain size distribution in specimens of NUE and NU was **basically the same**.

- Grain size **changed according to areas**.
  - Pellet periphery area: 4.8~7.5μm.
  - Center area: 6.9~15.5μm.

All results mentioned above show that obvious growth of grain occurred in the NUE and NU pellets during irradiation.
3. Result and Analysis | Grain Growth

- Similar grain sizes in corresponding area of NUE and NU pellets shows they had similar temperature and thermal gradient during irradiation.

- Grain size statistical result shows that there was no obvious changes in UO$_2$ pellet's periphery area after irradiation, which shows that temperature in pellet's surface was not high enough for grain growing.

- More close to the center of the pellet, the grain size became larger.
Pellet generate large volume of heat during radiation

Thermal conductivity of UO$_2$ is very low

The heat will readily transfer from periphery area to surrounding

Large temperature gradient and thermal stress in the center and the periphery

More close to the center of the pellet, the temperature got higher, and it is favorable for the growth of the grain.

Grain size increases gradually from periphery area to the center of the pellets

The process of grain growth
4. Conclusion

1. Lots of cracks were found in NUE and NU pellet. Analysis shows that thermal gradient between the center and the periphery was the main reason for the serious damage.

2. The distribution rule and appearance of grain size in corresponding area of NUE and NU fuel pellet were basically the same. Grain size changed according to areas. From periphery to center, grain size gradually increase.

3. The irradiation swelling of NUE pellet was within the allowable scope, there was no significant difference with NU pellet in pellet's broken degree and growing process.
THANK YOU