Development of X-Ray CT Apparatus for Irradiated Fuel Assembly

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Mission of JAEA

Technical establishment of nuclear fuel cycle

- R&D of Fast Breeder Reactor
- R&D of Nuclear fuel for FBR
- R&D of Reprocessing
- R&D of Treatment and disposal of HLW

Prototype fast-breeder reactor “MONJU”

X-Ray CT Apparatus was installed in FMF for developing the FBR fuel

Experimental fast reactor “JOYO”

Hot Laboratory “Fuel Monitoring Facility” (FMF)
Introduction

- X-ray CT technique:
  - The most powerful non-destructive test tool in the fields of medical and industrial inspections

- Purpose of this study:
  - Application of this technique to the Post Irradiation Examination (PIE) of FBR fuel assembly irradiated to high burn-up

- Content of this presentation:
  - Development of X-ray CT Apparatus for PIE
  - PIE Results of Irradiated FBR Fuel Assembly
Development of X-ray CT apparatus

X-ray CT technique has not been applied to the PIE of irradiated fuel assemblies

- Major problems in the development:
  - Strong gamma ray emissions from the irradiated fuel assembly
  - High resolution X-ray CT image
Development of X-ray CT apparatus

- Comprehensive package of measures to solve major problems
  - High energy X-ray pulse (12MeV) as a source
  - Synchronizing detection system with the pulse of high energy X-ray
  - High sensitivity CdWO₄ as scintillation detector material
  - A small width of collimator slit (0.3mm × 2mm)
Outline of X-ray CT apparatus

Bird’s-eye view of X-Ray CT Apparatus for PIE

Hot Cell

CT Test Room

Fuel assembly

Elevator

X-Ray Detector

X-Ray Source

Scanner Device

CT Control Room

Fuel Monitoring Facility
Outline of X-ray CT system
PIE Results and Analyses

- Two-dimensional X-ray CT image
  (Transverse cross sectional images of fuel assembly)

- Three-dimensional X-ray CT image

- Analyses of X-ray CT image
  - Distribution of central void size in fuel pellet
Specimen for PIE

- FBR core fuel assembly irradiated in “JOYO”
- Maximum Burn-up: 66 GWd/t
- Fast neutron fluence: $8.92 \times 10^{22}$ n/cm$^2$ ($E>0.1$ MeV)
- MOX fuel pellet:
  - Pu content 30 wt%
  - Density 94 % T.D.
Two-dimensional X-ray CT image

Transverse cross sectional X-ray CT image of the axial center of core fuel column

- Duct tube
- Fuel pin
- Cladding
- Fuel pellet
- Central Void
- Wrapping wire

(Metallography)
Three-dimensional X-ray CT image(1)

3D image of irradiated fuel assembly extracted a core fuel region

The configuration of all fuel pins and the outer surface of duct tube can be seen clearly.
**Three-dimensional X-ray CT image (2)**

3D image look into the inside of fuel assembly

It is possible to observe the condition of fuel pin bundle without destructive method
Three-dimensional X-ray CT image(3)

3D image obtained on the transverse cross section at the axial center of core fuel column

Displacement of all fuel pins
Central void size in the fuel pellet
Three-dimensional X-ray CT image (4)

3D image obtained on the oblique cross section around the axial center of core fuel column

Configuration of fuel pins and duct tube
Soundness of fuel assembly
Three-dimensional X-ray CT image (5)

- 3D image of the fuel pins loaded in the center line of the assembly
- Surface condition of cladding
- 3D image of the fuel pellet
- Surface condition of fuel pellet
- Cut longitudinally at the center of fuel pellet
- 3D image cut longitudinally at the center of fuel pellet
- Axial distribution of central void of all fuel pellets

- $\pm 5$ mm from the axial center of core fuel column
- Removed duct tube and cladding
- Duct tube
- Fuel pin
- Fuel pellet
- Central void

Hot Laboratories and Remote Handling
Central void (example of fuel performance)

The pores migration along steep temperature gradient in the fuel pellet

Central void formation !!

Central void size: Estimation of fuel temperature

Analyses of X-ray CT image

The central void size was determined from the CT counts distribution within an error of ±0.1 mm

Distribution of central void sizes of all fuel pins in a fuel assembly without fuel pin sectioning
Radial distribution of central void size

Central void sizes are vary widely from 0.1 to 0.4 mm
Central void size has a tendency that its size increases when the fuel pin position approaches to the reactor center
The distribution of central void size as a function of L.H.R.

Central void sizes slightly increased with LHR
Central void sizes are vary from 0.1 to 0.4 mm
Axial distribution of central void size

The central void sizes are vary from 0.2 to 0.4 mm in the axial direction (±5 mm)

The relocation of fuel pellets in the cladding at the beginning period of irradiation

Now, we try to analyze!!
Conclusions

- Non-destructive X-ray CT technique for PIE was successfully developed using a pulsed high energy X-ray source.

- The detail of structural change in the fuel assembly can be observed from any direction.

- This technique can substitute some items of destructive PIEs for non-destructive PIEs.

- Compared with the microstructural data obtained by the metallography, very large number of PIE data can be supplied to the analyses of fuel performance.

- This innovative technique can be applied not only to the irradiated FBR fuel assembly, but also to other irradiated reactor assembly and component.
Axial distribution of central void size

This 3D image is consist of transverse cross sectional image obtained by 1mm pitch of axial direction.

Height of fuel pellet is 8 mm.
Influenced factor for central void formation

- Pellet density
- Thermal conductivity of pellet
- Gap conductance between the fuel pellet and cladding
- Variation of pellet relocation
Development of X-ray CT apparatus

X-ray CT technique has not been applied to the PIE of irradiated fuel assemblies

- **Major problems in the development:**
  - Strong gamma ray emissions from the irradiated fuel assembly
  - High resolution X-ray CT image
Specimens

- Irradiated or Un-Irradiated Fuel Assembly (FBR, PWR, BWR)
- Length: 4.2m, Width: φ30cm
- Decay heat: 3kW
- Penetration thickness: 20cm (Iron)

Performance of X-ray CT image

- Measurement accuracy of fuel pin position: <±0.05mm
- Identification of defect: >φ0.5mm
The measurement error of X-ray CT image

The error of the measurement between 2 points using the ruler is ±0.3mm.

The error of the central void diameter is ±0.1mm. Because the central void diameter was measured by analyzing of X-ray CT image using CT value.
### Outline of X-ray CT apparatus (2)

**Table 1 Main specification of X-ray CT apparatus for PIE**

<table>
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<tr>
<th>Item</th>
<th>Contents</th>
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<tr>
<td>(1) CT scanning method</td>
<td>The second generation method (Traverse/ Rotate)</td>
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</table>
| (2) Scanner device | 3-Axis drive system  
Rotation moving accuracy \( \leq 0.01 \) sec  
Traverse moving accuracy \( \leq 0.02 \) mm  
Up and down accuracy \( \leq 0.05 \) mm |
| (3) X-ray source | Linear accelerator for Non-destructive Inspection  
Maximum electron energy \( \leq 2 \) MeV  
Maximum power \( \leq 20 \) mC/kg/min at 1m |
| (4) X-ray detector | Scintillates materials \( \text{CdWO}_4 \)  
Collimator slit size \( \leq 0.3 \) mm\((W)\) \(\leq 2 \) mm\((H)\)  
View pitch \( \leq 0.2 \) deg  
Number of channel \( \leq 0, f^* \) |
| (5) Translation pitch | Normal scanning \( \leq 0.3 \) mm  
Low speed scanning \( \leq 0.03 \) mm |
| (6) Measuring time | Normal scanning \( \leq 0 \) min  
Low speed scanning \( \leq 0 \) min |
X-ray detection system synchronized with X-ray pulse

Detection pulse (X-ray detector)

X-ray pulse (X-ray source)

Output from detector
Reduce the influence of gamma-ray

Total $2 \times 10^{16}$ Bq, $1.5 \times 10^{16}$ photon/sec

Photons of gamma-ray from fuel assembly
$9.3 \times 10^4$ photon/sec

Photons of transmitted X-ray from accelerator
$1.83 \times 10^5$ photon/sec

Adoption of the synchronized detection system

Photons of gamma-ray $\rightarrow$ 0.4 photon/shot

Photons of transmitted X-ray $\rightarrow$ 1830 photon/shot
The CT image is composed of 0.3mm×0.3mm dot shown by a CT value. 

CT value is shown as a value in proportion to the density of materials.
Bundle-Duct Interaction

BDI is believed to occur due to the swelling and irradiation creep of structure materials at high burn-up.

- Coolant flow area is reduced
- Local temperature of fuel pin is raised
"JOYO" MK-III PFB110
Specimen No. P50636

Irradiation period: 10 minutes

As-Polished
Axial deflection of fuel pins (2)

Distance from pin bottom (mm)

Wrapping wire position

Fuel pin ID and Deflection

Analysis of coolant flow and irradiation temperature
Hot Laboratories and Remote Handling
Central void distribution

Central void diameter was measured by analyzing of X-ray CT image

Precision: 0.1mm

Distribution of the central void diameter of all the fuel pins in a fuel assembly without pin sectioning

Central void diameter was measured by analyzing of X-ray CT image

Precision: 0.1mm

Distribution of the central void diameter of all the fuel pins in a fuel assembly without pin sectioning
Further applications to LWR fuel

- PIEs of fuel pin and assembly irradiated to high burn-up
  - Irradiation growth, bowing and swelling of fuel pin
  - Relocation of pellets in fuel pin and central void sizes measurements in pellets
  - Easy re-irradiation after interim examination

- PIEs of fractured fuel pin
  - Fracture by the debris
  - Collapse by the fuel densification
  - Fracture by the fretting corrosion

Observation without dismantling assembly
Performance of X-ray CT image (2)
Density discernment performance

Copper (8.96 g/cm\(^3\))

Brass (8.60 g/cm\(^3\))
X-ray CT image for irradiated fuel

Scanogram
Three-dimensional image

Top of fuel pin bundle

(X-Ray CT)  (Visual observation after removing duct)

Fuel pin elongation without DE
Bundle-Duct Interaction

BDI is believed to occur due to the swelling and irradiation creep of structure materials at high burn-up.

Coolant flow area is reduced
Local temperature of fuel pin is raised
Fig. 7 Directions and distances of fuel pin dislodgments
Analyzing the X-ray CT image

Fig.2 Concept of preliminary test on dummy specimen with artificial hole
\[ \pm 0.1\text{mm} \]
Central void distribution

Central void diameter was measured by analyzing of X-ray CT image

Precision: 0.1mm

Distribution of the central void diameter of all the fuel pins in a fuel assembly without pin sectioning

Central void diameter was measured by analyzing of X-ray CT image

Precision: 0.1mm

Low density pellet

Metallography X-ray CT

Central void diameter (mm)

Linear heat rating W/cm
Specimen No.: M22762  
(X/L = 0.99)

30GWD/t

M22742  
(0.50)

M22724  
(0.02)

As-Polished
Neutron CT in HFEF

Reactor for neutron generation uneconomical

X-ray CT in FMF

Accelerator for X-ray