DEVELOPMENT OF HIGH RESOLUTION X-RAY CT TECHNIQUE FOR IRRADIATED FUEL ASSEMBLY

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1. Abstract

In order to observe the structural change in the interior of irradiated fuel assembly, the non-destructive post irradiation examination technique using X-ray computer tomography (X-ray CT) was developed. In this X-ray CT system, the 12 MeV X-ray pulses were used in synchronization with the switch-in of the detector to minimize the effects of the gamma ray emissions from the irradiated fuel assembly. This method was applied to a fuel assembly irradiated in the experimental fast reactor “JOYO,” and images were successfully obtained of transverse cross sections at different heights of fuel assembly along its axis for the first time in the world.

This X-ray CT technique can substitute non-destructive PIEs for a number of destructive PIEs. This has a great advantage to enhance efficiency of PIE.

2. Introduction

In the field of post irradiation examination (PIE), the information on the structural changes of nuclear fuel assembly during irradiation in nuclear reactor is basically important to the safety of nuclear reactor. These data have generally obtained by the non-destructive and destructive PIE in hot cell\(^1\),\(^2\).

At the beginning of 21st century in our Institute, a powerful X-ray computer tomography (X-ray CT) technique was installed as a non-destructive PIE technique of irradiated fuel assembly. This technique has been improved year by year. In this paper, the basic concept of this technique and its improvement are described.

3. Development of high resolution X-ray CT technique

3-1. Basic concept\(^3\),\(^4\)

Until the development of this X-ray CT technique, it had been believed among many researchers over the world that X-ray CT technique cannot be applied to the PIE of irradiated materials because of strong intensity of radioactivity (especially gamma ray). We have succeeded in the application of X-ray CT technique to the PIE of irradiated fuel assembly by using the following techniques.
An outline of X-ray CT apparatus developed in our Institute is shown in Fig.1. X-ray CT apparatus is set up in a hot cell and a CT test room, which protect workers from strong intensity radioactivity. The irradiated fuel assembly is inserted into a guide tube by an elevator.

The introduced fuel assembly is irradiated by the pulsed X-ray of maximum energy 12 MeV. The X-ray transmitted through the irradiated fuel assembly are divided into 30 channels by the collimator of 0.3 mm in the width and 2 mm in height and then each X-ray intensity are measured by a detector of CdWO$_4$ scintillator. The system of X-ray source, the collimator and detector can rotate around the guide tube and move laterally from one end to the other of the irradiated fuel assembly.

It is generally considered that the strong intensity of gamma-ray emitted from the irradiated fuel assembly interferes so much the X-ray CT measurement. From the reason, it is necessary to reduce the effect of the gamma-ray in order to obtain a clear X-ray CT image. We succeeded in a drastic reduction of the gamma-ray effect by using the pulsed X-ray of high energy 12MeV. The pulse width of X-ray is 4.5 microseconds and its interval is 10 milliseconds. In addition, the detection of X-ray passed through the collimator is synchronized with the emission of X-ray by the linear accelerator.

3-2. Upgrading

In order to obtain the high resolution X-ray CT image, previous X-ray CT technique was upgraded. First, the collimator slit width was decreased from 0.3 mm to 0.1 mm. Secondly, the material of X-ray detector was changed from a CdWO$_4$ scintillator to a high sensibility of silicon semiconductor, and the number of detector was increased from 30 channels to 100 channels. Finally, the X-ray focus shape was fitted to the collimator slit shape to increase the detected X-ray intensity. These upgrades made it possible to obtain the high resolution X-ray CT image.

The X-ray CT image is constructed by analyzing many digital data (CT values). This analytical method was innovated to observe the more accurate fuel performance.
4. Result and discussion

4.1 Examination specimen

The outline of fuel assembly that was irradiated in the fast reactor “JOYO” is shown in Fig. 2. 127 fuel rods were assembled as a fuel assembly. The main specifications of a fuel assembly are shown in Table 1. The fuel pellets loaded into the fuel rod were mixed oxide (MOX) fuel of uranium and plutonium which had the diameter of 4.63 mm and the high of 5 mm. The fuel rod has the length of 1533 mm and its cladding is made of the stainless steel. The total length of the mixed oxide fuel pellet is 550 mm. In the other parts in the fuel rod, the blanket $\text{UO}_2$ fuel pellets are inserted and the remaining part is plenum where fission gas can be accumulated.

The average burn-up of fuel assembly was 53.5 GWd/t, and maximum linear heat rating of the fuel pellet was 401 W/cm in the fast reactor.

### Table 1 Main specifications of fuel assembly

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specification data</td>
<td></td>
</tr>
<tr>
<td>Number of fuel rod</td>
<td>127</td>
</tr>
<tr>
<td>Diameter of cladding</td>
<td>5.5 mm</td>
</tr>
<tr>
<td>Diameter of fuel pellet</td>
<td>4.63 mm</td>
</tr>
<tr>
<td>Pellet density</td>
<td>94% T.D.</td>
</tr>
<tr>
<td>Plutonium content</td>
<td>16 wt%</td>
</tr>
<tr>
<td>Irradiation data</td>
<td></td>
</tr>
<tr>
<td>Average burn-up (assembly)</td>
<td>53.5 GWd/t</td>
</tr>
<tr>
<td>Maximum linear heat rating</td>
<td>401 W/cm</td>
</tr>
</tbody>
</table>

4.2 X-ray CT image of the irradiated fuel assembly

When the fuel rod is irradiated at a high linear heat rating, the steep temperature gradient along the radial direction appears, leading to the formation of cracks. In addition, pores in the sintered fuel pellet moves towards its radial centre, resulting in the redistribution of density and evolution of central void. Fig. 3 shows an X-ray CT image obtained on the transverse cross section of the irradiated fuel assembly (Fig. 3 (a)), together with an enlarged image (Fig. 3 (b)) and its metallographical microstructure (Fig. 3 (c)) obtained on the transverse cross section of fuel rod located in the centre of fuel assembly. In the X-ray CT image of Fig. 3 (a) and 3 (b), the fuel pellet, cladding tubes of 0.4 mm in thickness, wrapping wires of 0.9 mm in diameter and wrapper tube of fuel assembly can be clearly distinguished from each other.
The central void and crack in the fuel pellet on the X-ray CT image (Fig.3 (b)) can be clearly as same as metallographical microstructure (Fig.3 (c)).

The knowledge on the central void size and density redistribution along the radial direction are very important to evaluate the irradiation performance of fuel rod. Until now, the central void size and density redistribution have been evaluated on only the metallographical

Fig.3 X-ray CT image of fuel assembly obtained on the transverse cross section at the axially central position, together with the X-ray CT image obtained in the transverse cross section of fuel rod and the metallographical microstructure as the destructive examinations.

Since it needs a long time to carry out destructive examinations, the number of results obtained by destructive examination is limited. In the other hand, a number of data on the central void sizes can early be obtained in a short time by the X-ray CT technique. 2413 central void sizes obtained on 19 traverse cross sections of all fuel rods as a function of linear heat rating during irradiation is shown in Fig.4. It can be seen that the central void begins to evolve at nearly 300 W/cm and the sizes increases with the linear heat rating.

Also, the radial redistribution of density in the fuel pellet after irradiation could be evaluated more accurately by the X-ray CT technique than by metallographical method. Generally in the metallographical microstructure, the irradiated fuel region excluding the central pore has been radially divided into three regions from the low temperature side, the undisturbed, equiaxial, and columnar regions. Since it is assumed that the density of each region is constant, the radial redistribution of density is discontinuous evaluated.

![Fig.3 X-ray CT image of fuel assembly](image-url)
While in the evaluation by the X-ray CT technique, the radial redistribution of density could be continuously evaluated from the relationship between the densities and CT values, which was obtained by plotting the CT values of 11 standard materials having known densities as their densities. A typical example evaluated using a transverse cross section of irradiated fuel rod and the metallographical image are shown in Fig.5.

A splendid merit of this X-ray CT technique is to be able to obtain three dimensional X-ray CT image (3D image) of irradiated fuel assembly. This 3D image could be obtained by combining several two dimensional X-ray CT images. A typical example of irradiated fuel assembly are shown in Fig.6. This 3D image can be observed from various angles as shown in Fig.6 (a) and can be observed without wrapper tube and cladding tube as shown in Fig.6 (b). Therefore, the 3D image made it possible to observe the surface of cladding tube and fuel pellet and the central void in fuel pellet.
In addition, fine and large 3D images of fuel assembly can be obtained by changing the interval between transverse cross sections on which X-ray CT image is obtained. Using these 3D images, many fuel performances such as the deformation of fuel rod, the bundle-duct interaction and so on can be examined.

5. Conclusion

A high resolution of X-ray CT technique, which can be applied to the irradiated fuel assembly, could be successfully developed in our Institute.

Using this high resolution X-ray CT technique, a number of central voids evolved in the fuel pellet during irradiation could be observed and the more reliable relationship between their size and linear heat rating could be obtained. The radial redistribution of density after irradiation could be continuously evaluated. In addition, 3D image could be obtained by combining several 2D images, from which many fuel performances can be evaluated.

A further improvement of this X-ray CT apparatus is under progress. It is greatly expected in a near future that the more detail data on the fuel performance can be obtained.

6. References