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<Title> **Development of advanced PIE technique for fuel debris using X-Ray Computer Tomography**

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Abstract

The X-ray computer tomography (X-ray CT) technique widely used in the medical field is one of the most powerful non-destructive test tools available for the characterization of an inner structure. This technique has been applied to the inspection of irradiated fuel assemblies to observe fuel pellet restructuring in irradiated fuels. In this X-ray CT system, a 9 MV X-ray pulse is used in synchronization with a switch-on of the detector to minimize the effects of the gamma ray emissions from the irradiated fuel assemblies. In addition, one hundred X-ray detectors and a collimator, which has one hundred microscopic slits (width: 0.1mm), were utilized to obtain high resolution images.

Following the Fukushima Daiichi Nuclear Power Plant accident, a feasibility study on the application of X-ray CT technique for observation of the inner condition of the fuel debris was initiated. First, a preliminary test was performed using a dummy specimen of irradiated fuel pellets, which was heated to 2373 K. As a result, we obtained high resolution X-ray CT images in which the small pieces of fuel pellets could be clearly distinguished from one another. Analyzing these X-ray CT images enables us to know the density distribution of the fuel debris.

This X-ray CT method has the advantage of enabling the collection of multiple data from the fuel debris in a short time without the need for sample preparation.

1. Introduction

A nondestructive method using X-ray computer tomography (X-ray CT) has been applied to post irradiation examination of fast breeder reactor (FBR) fuel assemblies. In this X-ray CT system, a 9 MeV X-ray pulse was used in synchronization with a switch-on of the detector to minimize the effects of gamma ray emissions from the irradiated fuel assemblies. Application of the developed technique should provide enhanced resolution of measurements and simplify fuel PIEs [1] [2] [3].

After the Fukushima Daiichi Nuclear Power Plant accident, a feasibility study on the application of X-ray CT technique to observe fuel debris was initiated. In this study, a preliminary test was performed using a simulated fuel debris specimen of irradiated fuel pellets.

In this paper, we describe the following items; (1) development of high resolution X-ray CT technique for PIE, (2) the result of applying high resolution X-ray CT technique to the simulated fuel debris.

2. Development of a high resolution X-ray CT technique for PIE

An X-ray CT apparatus was installed in the hot laboratory called Fuel Monitoring Facility, of the O-arai Research and Development Center. Figure 1 shows an outline of the X-ray CT apparatus. An irradiated fuel assembly was axially transferred using the elevator from the hot cell to the measurement position between the X-ray source and the detector of the X-ray CT machine in the CT test room. The scanner, that has an X-ray source and detector, is positioned on a table rotating around the fuel assembly. The X-ray intensity measured by the detector is converted to the X-ray CT image by means of the image-processing computer. All systems of the apparatus are controlled by the main computer, allowing X-ray CT images to be taken on any cross section. The following are the details of this apparatus.

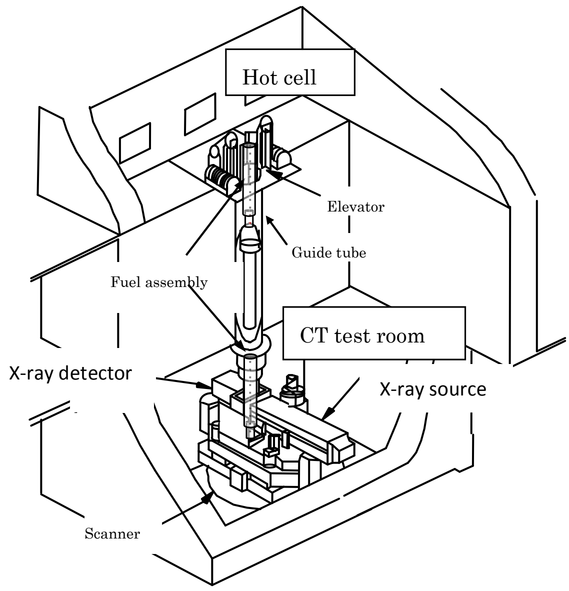

Figure 1 Outline of X-ray CT apparatus

2.1 Scanner

Photo.1 shows the scanner device. The scanner device is composed of an X-ray source and an X-ray detector unit.

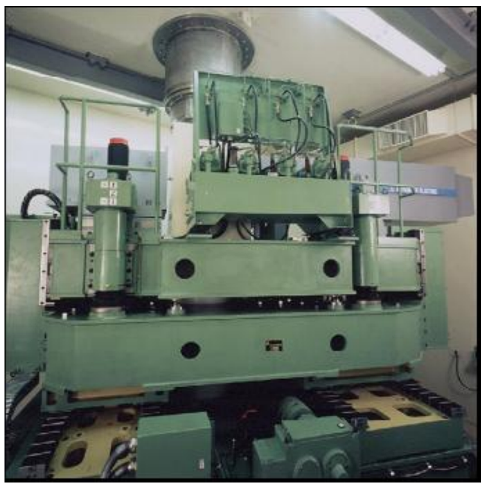

Photo.1 Scanner device

2.2 X-ray source

In order to obtain sufficient X-ray intensity through the high-density specimens, a high power and high energy (9 MeV) X-ray source, which is the maximum source used for commercialized X-ray linear accelerators, was selected. The pulses of high energy X-rays that are generated by an accelerator were applied to the scanning.

2.3 X-ray detector unit

The X-ray detector unit was placed in a scanner, and consists of a collimator and semiconducting detectors. Silicon alloy was selected as semiconducting detector material because of its high sensitivity. Detection of X-rays transmitted through the fuel assembly is synchronized with the pulses of high energy X-rays to minimize the effect of gamma ray from the fuel assembly. This improvement allowed a reduction in the number of detected photons emitted from an irradiated fuel assembly (maximum radioactivity: 2×10^{16} Bq) to a negligible level.

In order to improve the CT image, the collimator made of tungsten alloy, which has microscopic slits (width: 0.1 mm/ height: 2 mm), was prepared for this apparatus and the collimator was arranged in front of the X-ray detectors. Tungsten alloy was selected as collimator material because of its high shielding effect.

2.4 Result of the irradiated FBR fuel assembly

Representative cross-sectional images obtained from the fuel assembly irradiated in the experimental fast reactor Joyo at the core center elevation are shown in Figure 3 (a). In the figure, the 127 fuel pins are arranged systematically in the hexagonal wrapper tube, and this observation makes it possible to grasp the displacement of the fuel pins. Furthermore, in the close-up figure (Figure 3 (b)), the wrapping wires, cladding and MOX pellet with a central void and cracks are distinguished. Figure 3(c) shows the metallography of a fuel pin obtained by the destructive examination after fuel pin sectioning. The fuel pellet restructuring observed in figures (b) and (c) agree fairly well with each other.

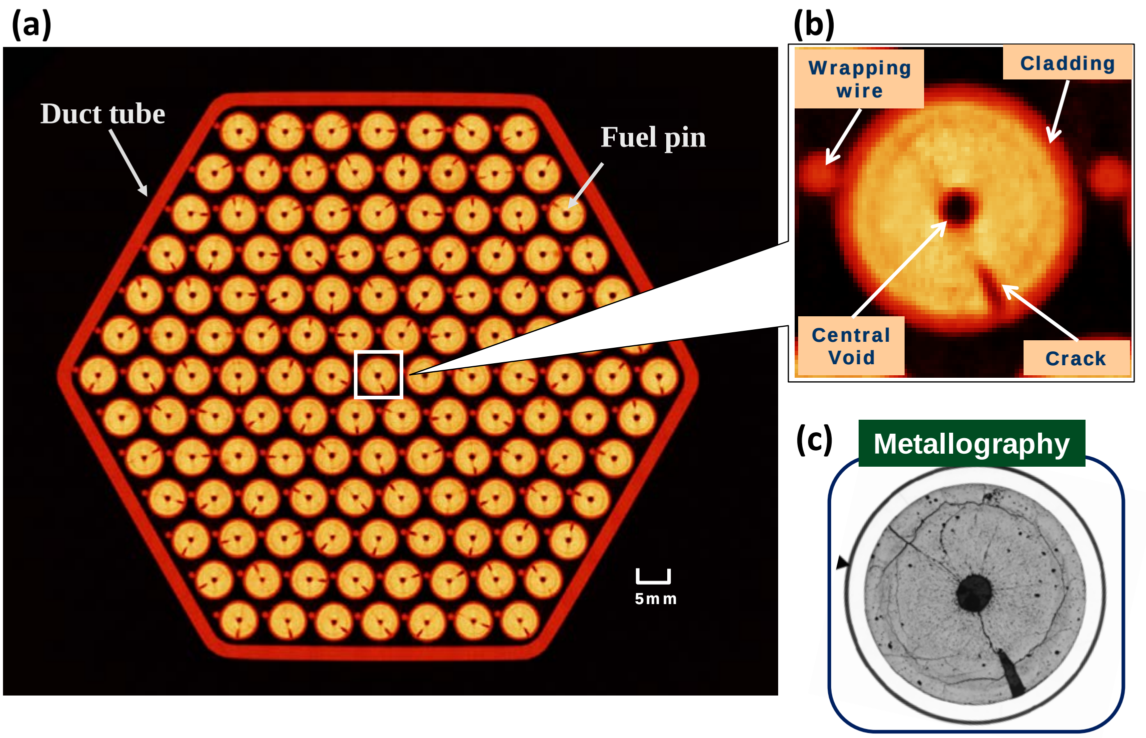

Figure 3 Cross-sectional X-ray CT images obtained from the irradiated fuel assembly

3. Preliminary test for the fuel debris

After the Fukushima Daiichi Nuclear Power Plant accident, a feasibility study on application of X-ray CT technique to observe the inner condition of fuel debris was initiated. In order to clarify the applicability of X-ray CT technique to fuel debris, a preliminary test was conducted using simulated fuel debris specimen. The specimen, which was examined for the high-temperature reaction test between irradiated MOX fuel and cladding material [4], was provided for a preliminary test as simulated fuel debris.

The specimen for a preliminary test consisted of pieces of MOX fuel and cladding. MOX fuel and cladding had been irradiated in the advanced thermal reactor FUGEN, which was moderated by heavy water and cooled by light water. The local burn-up of the fuel pellet was about 43 GWd/t. In as-fabricated condition, the fuel pellets containing 5.6 wt% PuO_2 averaged in diameter and in density respectively around 12.4 mm and 95% theoretical density. The cladding material was standard Zircaloy-2 (Zry-2). The crushed pieces of the fuel pellet were loaded into the crucible and then cut pieces of cladding was put on them. The crucible with irradiated fuel and cladding pieces was loaded into the induction furnace and then it was heated to 2373 K.

Figure 4 shows a three-dimensional X-ray CT image obtained on a transverse cross section cut longitudinally at the center of the specimen. Three-dimensional X-ray CT images were synthesized from two-dimensional X-ray CT images taken on the cross section of the specimen. As a result, high resolution three-dimensional X-ray CT images were successfully obtained in which the small pieces of fuel pellets could be clearly distinguished from one another. Such images show the inner condition of the fuel debris and allow evaluation of the distribution of fuel element in the debris.

Figure 5 shows the density distribution obtained by analyzing an X-ray CT image of the simulated fuel debris specimen. The density distribution in the specimen could be continually measured using the relationship between density and CT values. In the figure, density is indicated by the color scale at the bottom of the drawing, with red being high density and blue being low density. It should be noted that the density of the region corresponding to a piece of fuel pellet is higher than that of the outer region.

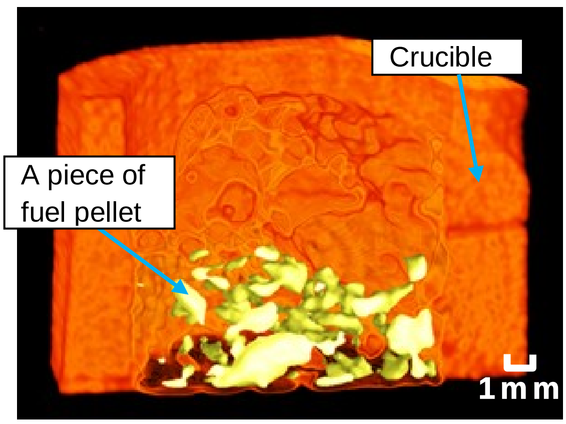

Figure 4 Three-dimensional X-ray CT image of simulated fuel debris specimen

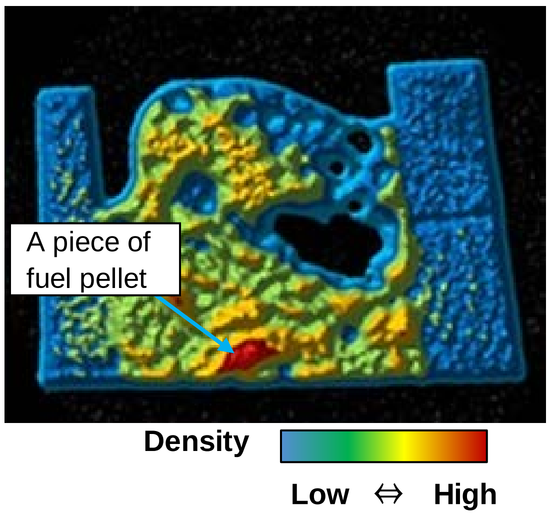

Figure 5 Density distribution obtained by analyzing X-ray CT image

4. Conclusions

The non-destructive examination technique using X-ray computer tomography was developed for the purpose of post irradiation examination. The technique uses high energy X-ray pulses to reduce the effects of gamma ray emissions from an irradiated fuel assembly and to obtain a clear cross-section image.

In this study, we obtained high resolution X-ray CT images of a simulated fuel debris specimen in which the small pieces of fuel pellets could be clearly distinguished from one another. Analyzing these X-ray CT images enables us to determine the density distribution of the fuel debris.

This X-ray CT method has the advantage of enabling the collection of multiple data from the fuel debris in a short time without the need for sample preparation. It is expected to be a powerful tool for use in clarifying a number of fuel debris performance values such as density distribution.

References

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