Development of X-ray system for irradiated fuel in hotcell

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ABSTRACT

A non-destructive test for irradiated fuel is very important to understand its in-pile behavior. An X-ray system is useful to observe the fuel shape without destruction. In addition, using the 3-D software and CT technology, the fuel shape can be intuitionally observed.

450kV and 160kV X-ray system were installed and operated in the Irradiated Materials Examination Facility (IMEF) hotcell. Because of a high penetrating power, the 450kV X-ray system is appropriate for observing a macroscopic shape of the fuel rod. The 160kV X-ray system using a relatively low voltage is suitable to a micro-scale sample, and high resolution images can be obtained. Through these X-ray systems, macroscopic shapes of various fuel rods irradiated in HANARO and microscopic fuel shapes such as a coated particle fuel were successfully observed. These results have been used as the in-pile behavior data of the irradiated fuel and as reference data when the destructive test.

1. Introduction

A non-destructive test using the X-ray system is very useful to observe the deformation and defect of the fuel rod without destruction. In addition, the dimensions of the fuel rod can be measured. Also, using a 3-D software and CT technology, the fuel shapes can be intuitionally observed. This information is used to understand the in-pile behavior of the fuel and allows researcher to prepare specimens effectively during a destructive test.

The X-ray system has been used world-wide, and a high resolution image can be obtained easily because of the development of image processing methods using a computer system. Several hotcell facilities such as CEA and JMTR have been operating the X-ray system. In Korea, the need to develop an X-ray system is increased to obtain a reliable and high resolution image.

In IMEF, various types of fuel rods irradiated in HANARO have been tested. Therefore the X-ray systems possible to observe not only a macro-scale sample but also a micro-scale sample are needed. The 450kV and 160kV X-ray systems were installed and operated in IMEF. Using these X-ray systems, the X-ray inspection of various fuels has been performed.

2. Experimental

2.1 450kV X-ray system setup

The 450kV X-ray system [1] was installed in the M1 hotcell as shown in Figure 1. An X-ray tube, Line Detector Array (LDA), and sample bench were installed in hotcell and a hydraulic-oil cooler was installed on the roof in the service area. PLC and computer system were installed in the operating area for convenient use.

The specifications of the 450kV X-ray system are shown in Table 1. The system was designed based on the fuel rod, which has a diameter of 10mm and a length of 40cm. In addition, the fuel rod is filled with a UO_2 pellet. A high penetrating power is needed to inspect the fuel rod, and which is why the 450kV X-ray tube was chosen. To reduce the radiation damage of an image pickup device, the LDA covered housing for shielding and a tungsten slit were used. In addition, for CT inspection, a sample bench was designed to move up and down and rotate. Figure 2 shows the 450kV X-ray system layout and installation in hotcell.

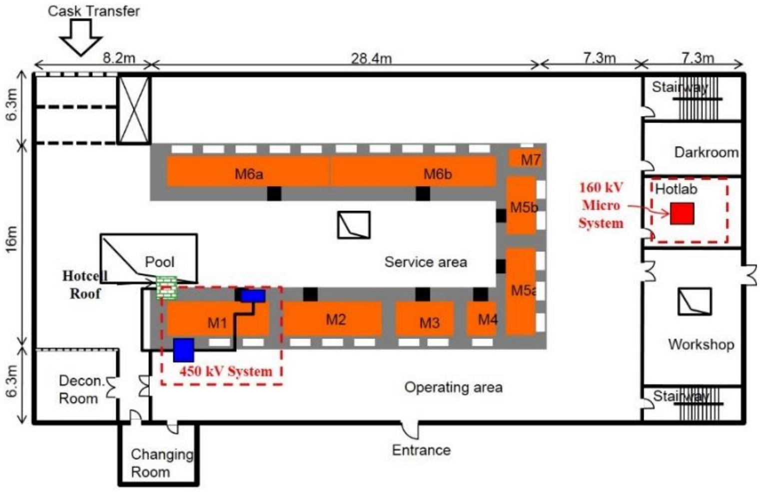

Figure 1. Installation place of the 160kV and 450kV X-ray systems

Table 1. Specifications of the 450kV X-ray system

X-ray Tube	Voltage	20 – 450 kV
	Current	0 – 15 mA
	Focus size	0.4 / 1.0 mm
Line Detector Array (LDA)	Length	500mm (effective), non-curved
	Pitch	254 µm pitch, 1984 elements in 32 modules
	Layout	(up to) 450 kV
	Scintillator	CdWO4
	Collimator	1mm, tungsten

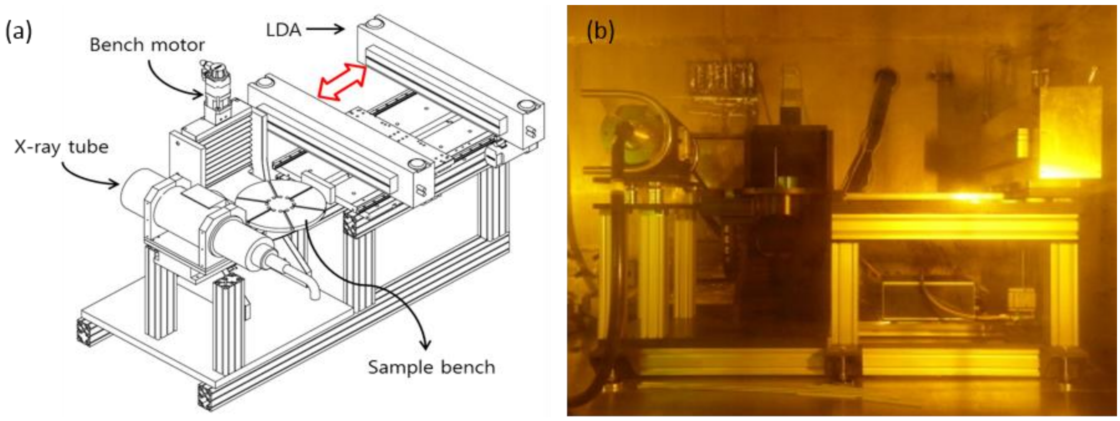

Figure 2. 450kV X-ray system (a) layout and (b) installation in hotcell

2.2 Performance test of the 450kV X-ray system

To inspect the x-ray system, the resolution was measured using a standard wire sample after an alignment of the X-ray tube and the LDA was conducted. The standard wire sample is composed of lines with different thicknesses and spaces. The purpose of this test is to confirm the detectability of the X-ray system. As shown in Figure 3, the resolution of the X-ray system was group D. This means this X-ray system can distinguish at up to 0.130mm.

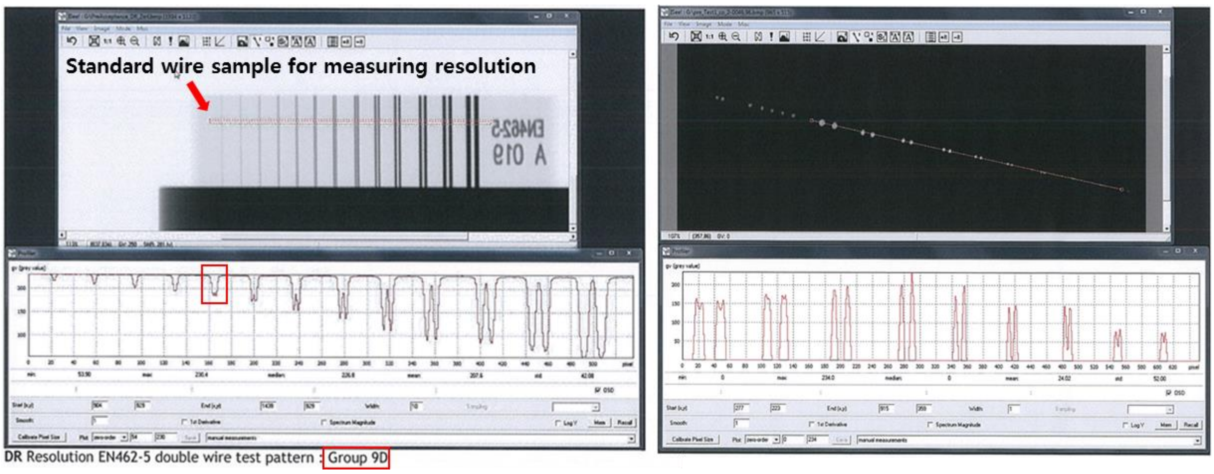

Figure 3. Resolution measuring results of the 450kV X-ray system (Group 9D: 0.130 mm)

2.3 X-ray inspections of the irradiated fuel rod and material using 450kV X-ray system

After the setup was completed, an X-ray inspection of the irradiated fuel rod was performed. Because of the concern regarding radiation damage of the LDA although it is shielded, a fuel rod and material that have a relatively low burnup or low radiation were chosen first.

The fuel rod irradiated in HANARO has a thermocouple to measure the temperature in real time, and the five UO_2 fuels have holes for measuring the temperature. The fuel burnup is about 4,000 MWD/MTU, and the fuel was irradiated for the burnup evaluation. Figures 4 (a), 4(b) and 4(c) show a UO_2 fuel rod, 3-D scan image and 2-D scan image, respectively. The 3-D images of the fuel rod were scanned by rotating 360 degrees at 1 mm intervals. The scanned images were integrated using VG Max2.2, which is a 3-D image analysis program.

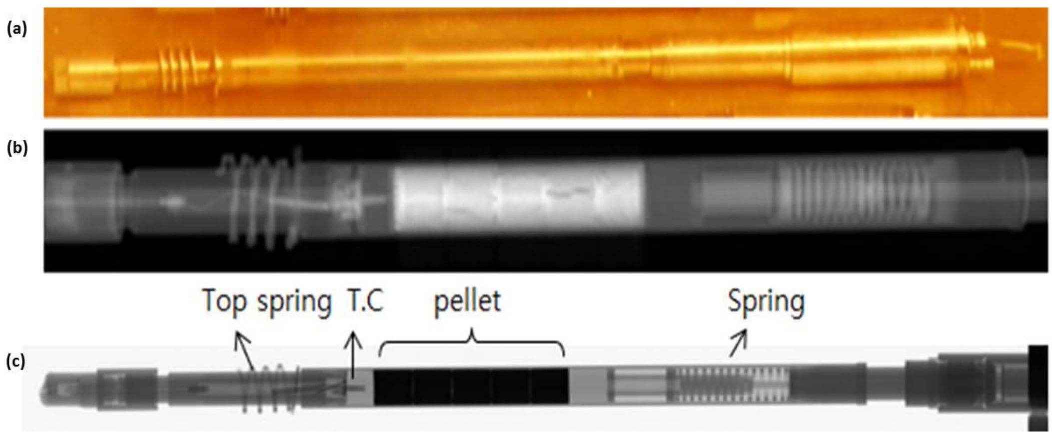

Figure 4. (a) UO_2 fuel rod (b) 3-D scan image (c) 2-D scan image

An X-ray inspection of the irradiated material was also performed for the performance test under the radiation conditions. Figure 5 shows the irradiated PWR spacer grid. After scanning the 2-D image of the spacer grid, a 3-D image scan only a part of the spacer grid was performed based on the 2-D information. From these results, intervals of the inner spring were able to be measured.

It was confirmed that a high resolution image can be obtained under the radiation conditions using the 450kV X-ray system. Nowadays the X-ray inspection of various types of fuel rod such as a plate fuel, VHTR compact fuel, and so on, have been actively performed.

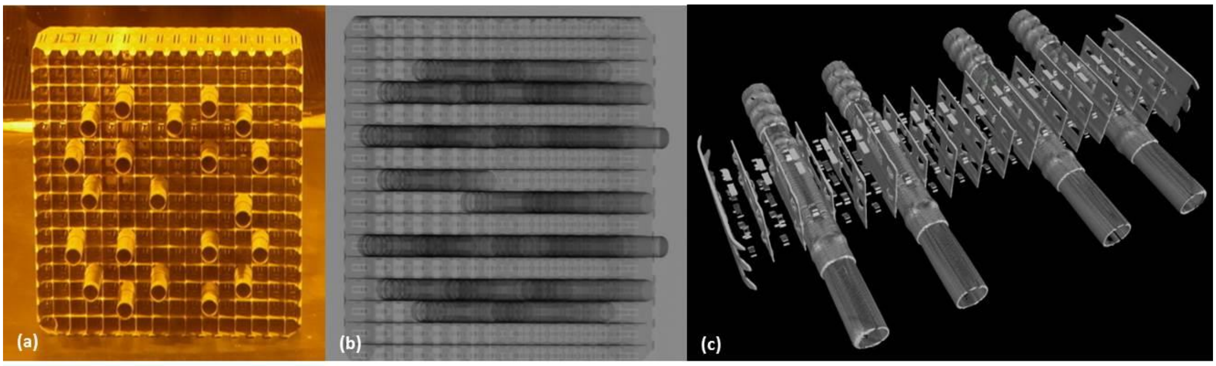

Figure 5. (a) PWR spacer grid, (b) 2D scan image and (c) a part of the spacer grid 3D scan image

2.4 160kV X-ray system setup

The 160kV X-ray system was installed for a micro-scale sample such as a coated particle fuel. This X-ray system using a relatively low voltage is suitable to a micro-scale sample, and high resolution images can be obtained. The system was installed in a hotlab to easily handle the small sample. In addition, the operation in hotlab is possible because the irradiated coated particle fuel has a low radiation.

The specifications of the 160kV X-ray system are shown in Table 2. In addition, Figure 6 shows the 160kV X-ray system installed in the hotlab. The specimen loaded in a jig can be rotated 360 degrees, and the detector can move along the Z-axis and tilt 180 degrees. The voltage and current of the X-ray tube are 160kV and 10mA, respectively. The target material is tungsten. In addition, a maximum detectability of the system is 1 µm.

Table 2. Specifications of the 160kV X-ray system

X-ray Tube	Tube type	Open micro-focus tube
	Target material	Tungsten
	Voltage range	25 – 160 kV
	Current range	0.01 – 10 mA
	Detectability	< 1 µm
Image Chain	Detector type	Panel 1313 high speed
	Number of pixel	1,004 x 1,004 pixel
	Pixel size	127 µm
	Total magnification	17,000x

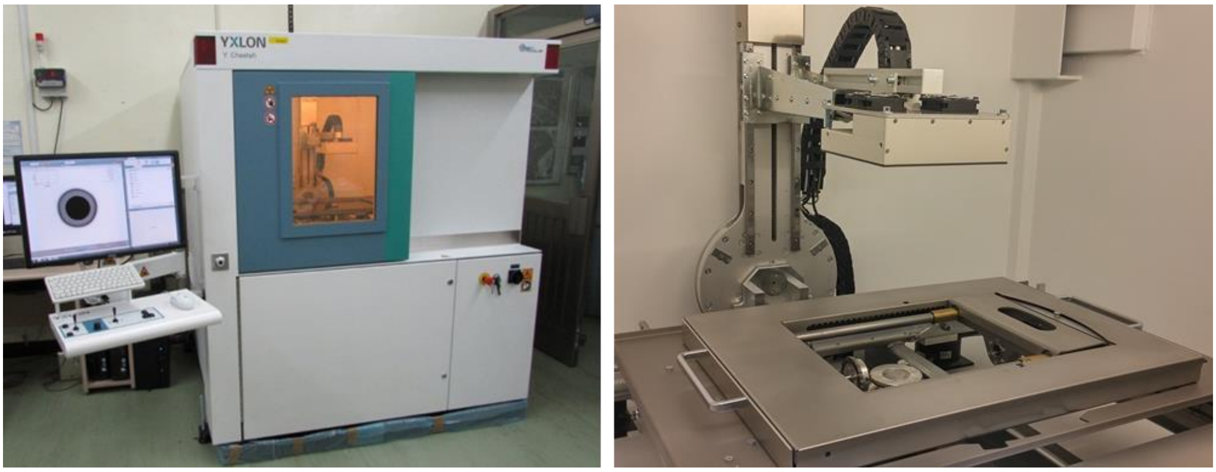

Figure 6. The 160kV X-ray system installed in hotlab

2.5 Performance test of the 160kV X-ray system

To inspect the X-ray system, the resolution was measured using a standard sample which was selected as the standard sample in Japan and has been used world-wide. This standard sample is composed of an image that can confirm sizes from 15 micro to 0.4 micron. As shown in Figure 7, it was confirmed that this system can distinguish at up to 1 μm.

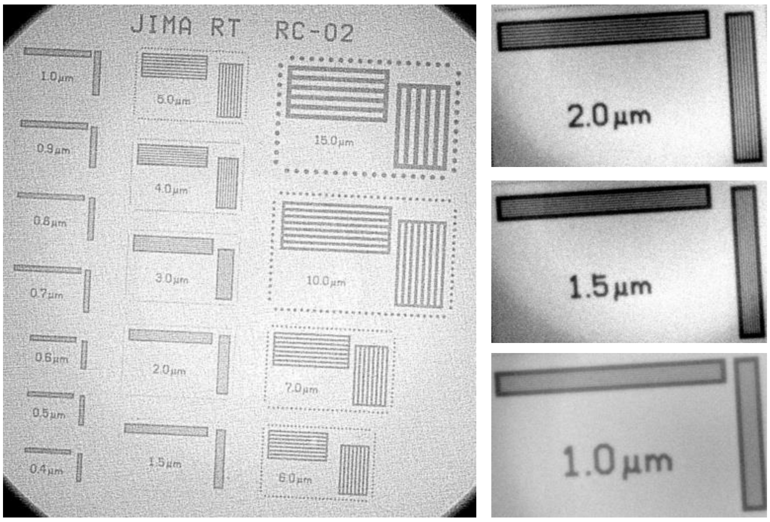

Figure 7. Resolution measuring result of 160kV X-ray

2.6 X-ray inspection of the irradiated fuel using 160kV X-ray system [2]

The un-irradiated fuel compact and the coated particle fuel were prepared as a sample. Also, the irradiated coated particle fuel was prepared. The fuel burnup was about 40,000 MWd/tU. The coated particle fuels were separated from the fuel compact through a heating test. In the case of the irradiated fuel, the X-ray inspection of the coated particle fuel was only performed to reduce the radiation damage to the X-ray system and researchers.

Figure 8 shows the X-ray images of the un-irradiated fuel compact, the un-irradiated coated particle fuel and the irradiated coated particle fuel. Graphite, which is the structural material of a fuel compact, had a relatively bright color because of a low density. In addition, it was confirmed that the coated particle fuels were evenly distributed in the graphite. Although the density of a buffer and IPyC is slightly different, the OPyC, SiC, Buffer, IPyC and Kernel could be distinguished under these test conditions. In addition, the clear X-ray image of the irradiated coated particle fuel was obtained without the radiation damage. In the case of the irradiated fuel, the OPyC was not observable because the OPyC was removed during the heating test.

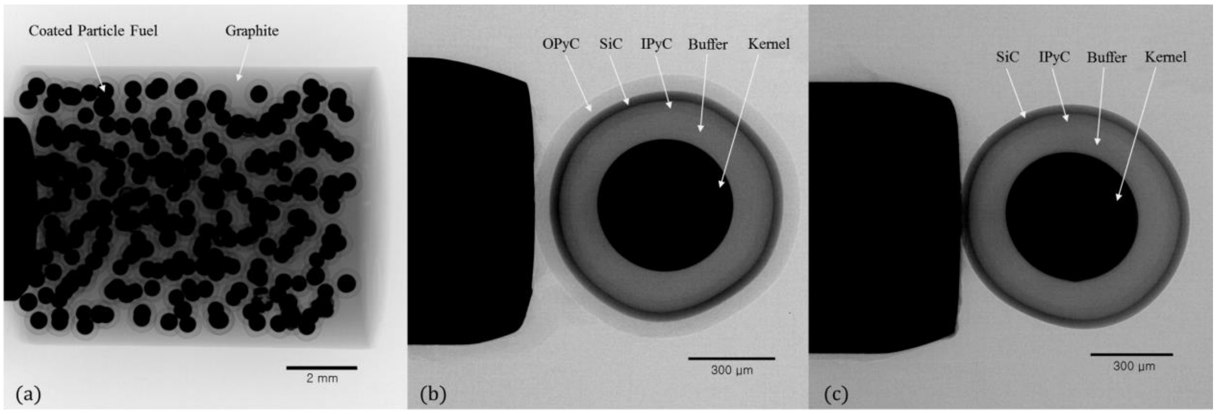

Figure 8. X-ray image of (a) Un-irradiated fuel compact, (b) Un-irradiated coated particle fuel, and (c) irradiated coated particle fuel

3. Conclusion

X-ray systems were developed for a non-destructive test of various fuel types. Calibration and performance tests were successfully performed. According to the results of the performance test, the 450kV X-ray and 160kV X-ray systems can observe up to 0.130mm and 1µm, respectively. In addition, based on the results of the X-ray inspection of an irradiated fuel and material, a high resolution image can be obtained without radiation damage. Through the development of X-ray systems, the various and accurate in-pile test data of the irradiated fuel and material can be obtained and an effective specimen preparation can be performed for a destructive test. These X-ray systems will be continuously used to obtain the in-pile test data.

4. Reference

[1] H.M.Kim et al., Development of X-ray Inspection System for Irradiated Fuel Rod in a Hotcell, Transactions of the Korean Nuclear Society Spring Meeting, 2014.

[2] Y.J.Kim et al., Non-destructive test for VHTR fuel using 160kV X-ray system in Hotcell, Transactions of the Korean Nuclear Society Spring Meeting, 2016.