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ARTICLE

Measurement and Analysis of In-vessel Component Activation and Gamma Dose Rate Distribution in Joyo

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The in-vessel gamma dose rate was measured in the experimental fast reactor Joyo to evaluate the activation of reactor structural components and the radiation exposure of the fiber scope used for in-vessel visual inspection. The measurement system, which requires a wide sensitivity range and high durability in a high-temperature environment, was specifically developed for use in the sodium cooled fast reactor. The gamma-ray detector was calibrated by simulating the actual temperature conditions in Joyo. Using this system, the in-vessel gamma dose rate with cooling times of 450 and 720 days after reactor shutdown was measured in Joyo, which has been operated for 71,000 hours over approximately 30 years. The gamma dose rate was calculated using QAD-CGGP2 code with the gamma source intensity obtained by the ORIGEN2 code. The neutron flux used as input to the ORIGEN2 was evaluated by the Joyo dosimetry method. The ratio between the calculated and experimental values ranged from 1.1 to 2.4, confirming the accuracy of gamma dose rate and component activation calculation.

KEYWORDS: experimental fast reactor, Joyo, gamma dose rate, activated products, QAD-CGGP2, ORIGEN2

I. Introduction[1]

During the 15th periodic inspection of the experimental fast reactor Joyo of the Japan Atomic Energy Agency, the irradiation test subassembly (S/A) was bent and became an obstruction in the reactor vessel (R/V), and the upper core structure (UCS) was damaged. This incident made it necessary to perform an in-vessel visual inspection using an optical fiber scope. This inspection revealed that the UCS needed to be replaced for Joyo re-start. A critical task in restoring Joyo was evaluating the activation of the UCS; this was necessary to design the transportation cask for the damaged UCS. However, it is difficult to directly obtain samples of the highly irradiated components in the R/V.

In order to obtain experimental data and to evaluate the accuracy of radiation dose calculation, in-vessel gamma dose rate measurements were conducted in the experimental fast reactor Joyo. The measured gamma dose rate was compared with the values calculated using the QAD code and the ORIGEN2 code with the JENDL-3.2 cross section library.

II. Plant Description of Joyo

Joyo first attained initial criticality in 1977 using a MK-I breeder core. It was the first sodium cooled fast reactor in Japan. Joyo has now been upgraded to the high performance MK-III irradiation test bed[1, 2].

Figure 1 shows the structure of the R/V. It is approximately 10 m high and has an internal diameter of approximately 3.6 m. The R/V includes S/As and the in-vessel structure components (an UCS, a core support plate, an in-vessel storage rack etc.). The top of the R/V is covered by the rotating plugs (R/Ps), and they consist of the large and small R/P as shown in **Fig. 1**. The small and large R/Ps have diameter of approximately 2,870 mm and 4,730 mm, respectively, and they are approximately 3,200 mm high. As shown in **Fig. 1**, there are six control rod drive mechanism (CRDM) holes on the UCS, an in-vessel inspection hole (A), and a fuel handling hole on the small R/P, and an in-vessel inspection hole (B) on the large R/P. All these holes are available for in-vessel measurements.

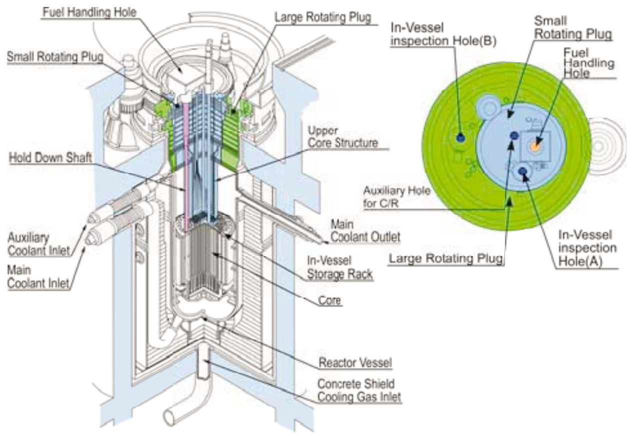

Fig. 1 Structure of Joyo reactor vessel

III. Measurements

1. Measurement Equipment and Evaluation Method

An in-vessel gamma dose rate measurement system was designed to be inserted in the R/V while preserving the reactor cover gas boundary. The system consists of a long sealed pipe enclosing the ion chamber, a k-type thermocouple, and a shaft to seal the cover gas boundary.

The gamma-ray detectors were installed thorough the fuel handling hole, the CRDM hole, and the in-vessel inspection

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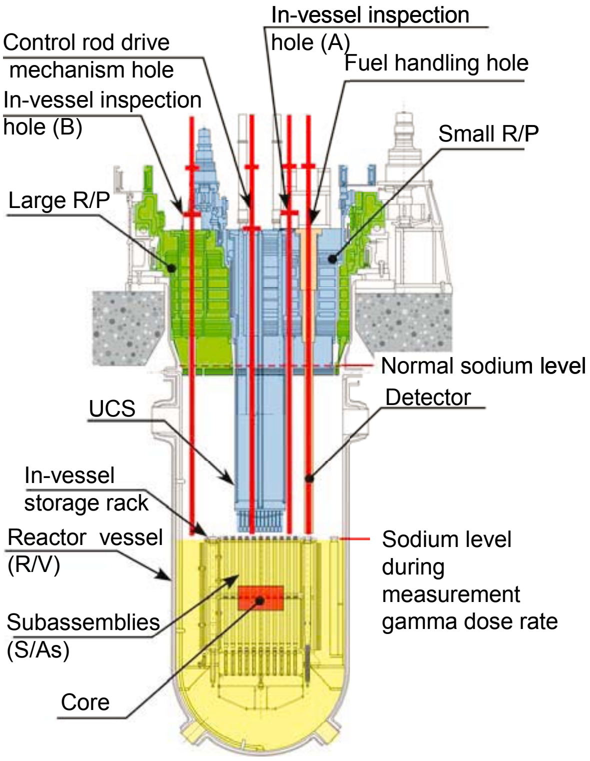


Fig. 2 Measurement of gamma-ray dose rate distribution

holes (A) and (B) on the R/Ps (see **Fig. 2**). The axial measurement range extended from the bottom of the R/Ps to 103 mm above the top of the S/As. In the measurements, only the combined gamma dose rate of various components can be obtained. Therefore, several measurements were performed using different holes; these measured dose rates with different contributions from the various components, enabling the ratio gamma dose rate from each component (e.g., the UCS, the R/V, the S/As and the core barrel) to the total gamma dose rate to be determined.

2. Ionization Chamber Calibration

Calibration of gamma-ray detector and thermal effects on the leakage currents of the ion chamber were evaluated at the cobalt-60 gamma-ray irradiation facilities at Osaka Prefecture University. **Figure 3** shows the calibration curve obtained; it exhibits good linearity for the actual measurement conditions at Joyo (i.e., gamma absorbed dose rates in air in the range 0.1 Gy/h to 1000 Gy/h and temperatures ranging from room temperature to 200 °C). The leakage current increases near 200 °C, but this increase was negligible when the gamma dose rate exceeds 1 Gy/h.

3. Gamma-ray Spectrum Measurement

In order to identify the major gamma-ray sources, the gamma-ray spectra were measured using a Ge detector located 15 cm from the in-vessel inspection hole (A) on the small R/P. **Figure 4** shows the measured gamma-ray spectrum. It was confirmed that the main gamma-ray source was cobalt 60 (energy peaks at 1.173 MeV and 1.332 MeV). The core barrel grid plate is made of stainless steel (SS), which has a relatively high cobalt content of approximately 0.35 wt%. This increases

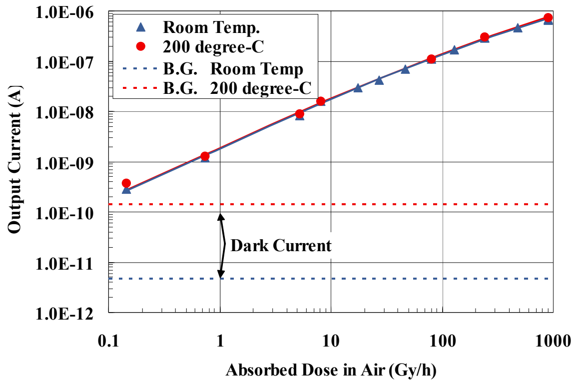


Fig. 3 Calibration of the ionization chamber

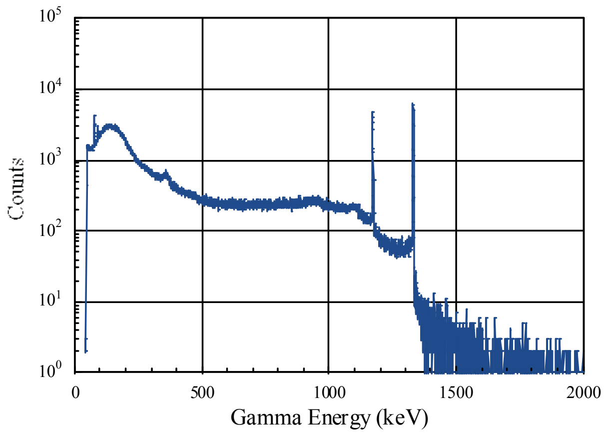


Fig. 4 Gamma-ray spectrum

the gamma dose rate in the radial direction. No peaks were observed from fission products in the driver fuels, indicating that gamma-rays from fission products are well shielded by the fuel components (the handling head, etc.) and sodium.

IV. Gamma Dose Rate Calculation

1. Gamma-ray Intensity

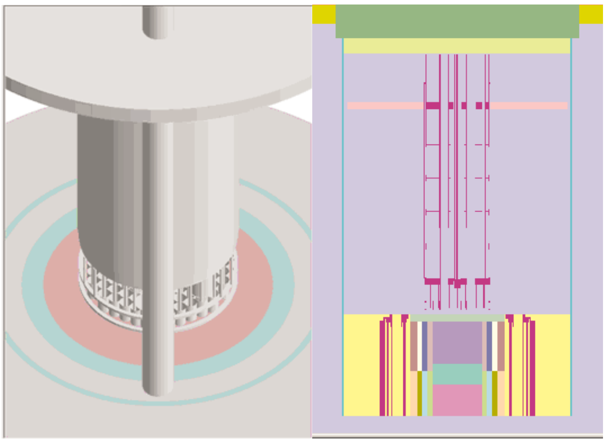
The gamma-ray intensities per unit weight (photon/s/g) in approximately 80 regions were calculated by the ORIGEN2[3) code using the JNDC-V2[4) decay data and fission yield data library. The cross section used in the ORIGEN2 code was collapsed from the JENDL-3.2 library[5) using the 100 group neutron spectrum in each region. The 100 group neutron flux was calculated using the DORT[6) code. The neutron fluence was used as an input to the ORIGEN2 was also calculated by the DORT two-dimensional transport code in the RZ geometry. The transport equation is solved as a fixed source problem with P_3 expansion of the angular dependence of the scattering cross sections, and an S_8 symmetric quadrature set. The cross section data were JSSTDL library[7) (100-neutron and 40-gamma groups) made from the nuclear data file JENDL-3.2. The neutron source distribution was obtained from the Joyo MK-III core management code system HESTIA[8), and it was used as an input to the DORT code.

When calculating the activation of SS, the cobalt content was considered as an impurity of base metal, it was taken to be the same of that in the mill sheet. When the cobalt content was not recorded, it was taken to be between 0.05 and 0.35

wt% based on the data provided by the manufacturer.

2. Gamma Flux and Dose Calculation

The point kernel code QAD-CGGP2[9)] was applied to analyze the gamma flux and absorbed dose rate distribution in the R/V. It was based on the detailed structure and the weight and composition of materials recorded in the design drawing of Joyo. **Figure 5** shows the calculation model. The gamma-ray intensities were obtained from the ORIGEN2 results by multiplying them by the component amounts, which were considered small amounts of materials such as Stellite (Co-Cr-W-C alloy) used in the control rod latch finger and in-vessel storage rack. The dose conversion coefficients from gamma flux to the absorbed dose rate in air given in ICRP Pub. 74 were applied.



3D bird eye view Vertical cross section view

Fig. 5 QAD-CGGP2 calculation model

V. Results and Discussion

1. Gamma Dose Rate Measurement

The in-vessel gamma dose rates were measured at cooling times of 450 and 720 days after reactor shutdown. The Joyo had been operated for 71,000 hour since first criticality in 1977. During the measurements, sodium was drained from the R/V until it reached a level of 50 mm below the top of the S/As. All measured values were corrected to the value for a cooling time of 450 days using the decay constant of cobalt 60.

Figure 6 shows the axial absorbed dose rate distribution. In the case of CRDM and in-vessel inspection hole, the detailed axial distributions were measured. The measured values ranged from 0.1 to 210 Gy/h in the axial direction. The high dose rate at the bottom in the case of CRDM hole indicates that the bottom of the UCS is largely activated. The dose rates decreased apart from the top of S/A. In the case of the fuel handling and in-vessel inspection hole measurements, the dose rates were attenuated rapidly by the thermal shielding plate.

Figure 7 shows the results of the radial gamma dose rate distribution measurements. The elevation of the detector was 103 mm from the top of the S/As, which is close to the bottom of the UCS. The radial distance between the

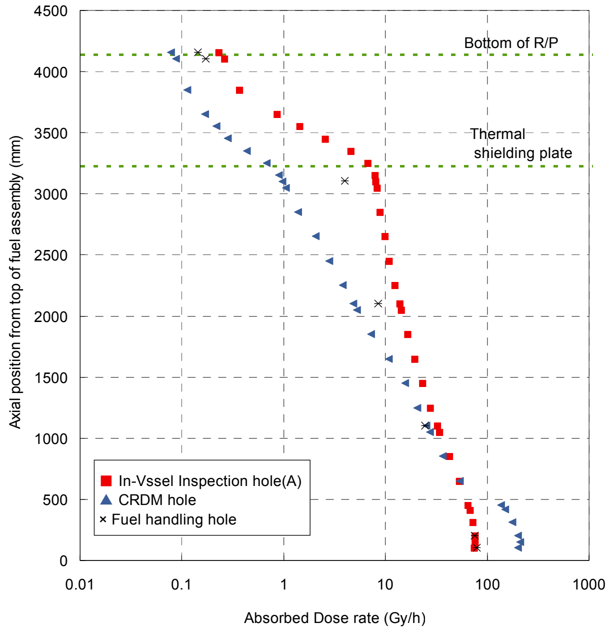


Fig. 6 Axial gamma dose rate distributions

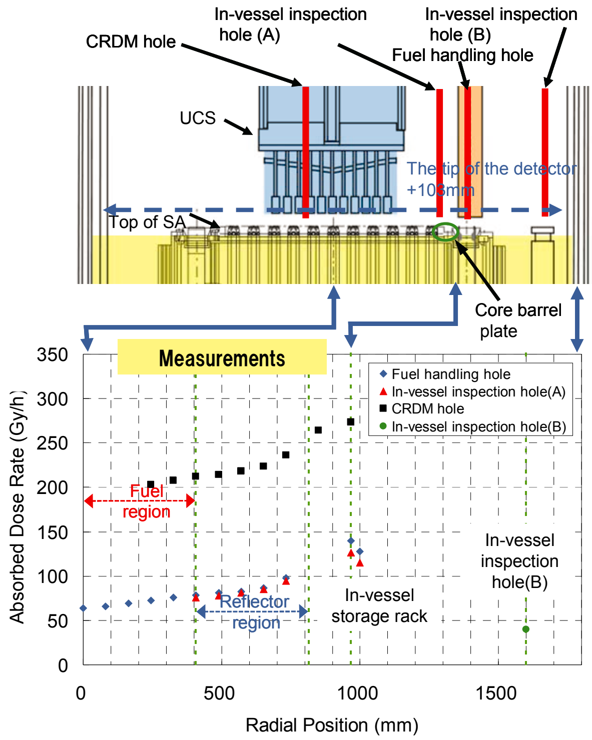


Fig. 7 Radial gamma dose rate distributions

gamma-ray detector and the UCS was constant because there were holes except the in-vessel inspection hole (B) and the UCS on the small R/P. The gamma dose rate distributions measured at the fuel handling and the in-vessel inspection (A) holes ranged from 64 to 140 Gy/h and increased in the radial direction due to the activation of the core barrel plate.

In the case of measure using the CRDM hole on the UCS, the gamma dose rate distribution was relatively flat, lying in the range 203 to 274 Gy/h, because the gamma source intensity from the UCS is dominant, and the CRDM and the

UCS move together.

In all cases, the gamma dose rates were largest above the in-vessel storage rack. On the other hand, the gamma dose rate at the core center (measured using the inspection hole (A)) was similar to that near the R/V (measured using the in-vessel inspection hole (B)). These results demonstrate that the main component of the gamma dose rate in cover gas area was from the in-vessel storage rack support, which is made from a large amount of SS and includes Stellite that contains a large amount of cobalt.

2. Comparison of Measurement and Calculation Results

The ratios between the calculated and experimental values at the CRDM and the in-vessel inspection hole ranged from 1.1 to 2.4 (see **Fig. 8**). The calculation overestimated the measured value, by a factor of approximately 2.5 times for gamma dose rates in the range 0.1 to 200 Gy/h. This appears to be a systematic discrepancy. This result reveals that the amount and distribution of SS and the gamma-ray intensity distribution were calculated accurately. An increase in C/Es in both holes above 3200 mm was observed. This is considered to be due to an error in the gamma-ray source calculation for the R/V, which greatly affects the gamma dose rate at this position.

This systematic discrepancy seems to be caused by an error in the amount of cobalt in SS or Stellite, because the contribution of Stellite to the gamma dose rate is in the approximate range 30 % and 50 % according to calculations.

These results confirm the accuracy of the gamma dose calculation method by the ORIGEN2 and the QAD-CGGP2. However, the cause of the discrepancy needs to be investigated.

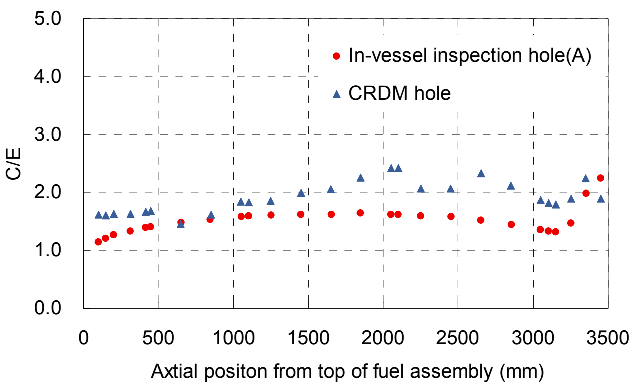


Fig. 8 C/E of gamma dose rate

VI. Conclusion

The in-vessel gamma dose rate was measured in the experimental fast reactor Joyo to evaluate activation of the reactor structural components and to evaluate the radiation exposure of the fiber scope used for in-vessel visual inspections. The gamma-ray detector was calibrated by simulating the actual temperature conditions at Joyo. The measured gamma dose rate at 100 mm above the top of the S/As were in the range 40 to 274 Gy/h.

The gamma dose rate was calculated using the QAD-CGGP2 code using gamma source intensities obtained by the ORIGEN2 code. The ratio between the calculated and experimental values ranged from 1.1 to 2.4, confirming the accuracy of the gamma dose rate and component activation calculations.

These experiments provided valuable information for evaluating the radiation environment of in-vessel inspection or repair, and the results will be applied for the designing the shielding of the cask and for the estimating the radioactive waste of the major components in the R/V.

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