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Cosmic-ray muon radiography for reactor core observation

Kuniyoshi Takamatsu [a,*], Hiroaki Takegami [a], Chikara Ito [b], Keiichi Suzuki [c], Hiroshi Ohnuma [c], Ryutaro Hino [a], Tadahiko Okumura [d,e]

[a] Nuclear Hydrogen and Heat Application Research Center, Japan Atomic Energy Agency, 4002 Narita-cho, Oarai-machi, Higashiibarakigun, Ibaraki 311-1393, Japan
[b] O-arai Research and Development Center, Japan Atomic Energy Agency, 4002 Narita-cho, Oarai-machi, Higashiibarakigun, Ibaraki 311-1393, Japan
[c] Kawasaki Geological Engineering Co., Ltd., 2-11-15, Mita, Minato-ku, Tokyo 108-8337, Japan
[d] Engineering Advancement Association of Japan, 3-8-19, Tranomon, Minato-ku, Tokyo 105-0001, Japan
[e] Energy Society of Japan, 2-3-7, Shimbashi, Minato-ku, Tokyo 105-0004, Japan

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ABSTRACT

One of the critical problems that have arisen from the accident at TEPCO's Fukushima Daiichi nuclear power plant is the removal of fuel debris. For solving this problem, an examination of the internal reactors has been planned to identify the fuel debris. However, the high radiation dose around the reactors has necessitated the development of a remote sensing method that would enable observation of the internal reactors from the outside. In our study, we focused on a nondestructive inspection method by which cosmic-ray muons could be used to observe the internal reactor from outside the reactor pressure vessel (RPV) and containment vessel (CV). We conducted an observation test on the high-temperature engineering test reactor (HTTR) at the Japan Atomic Energy Agency to evaluate the applicability of the method to the internal visualization of a reactor. We also analytically evaluated the resolution of existing muon telescopes to assess their suitability for the HTTR observation, and were able to detect the major structures of the HTTR based on the distribution of the surface densities calculated from the coincidences measured by the telescopes. Our findings suggested that existing muon telescopes could be used for muon observation of the internal reactor from outside the RPV and CV.

1. Introduction

We focused on the use of cosmic-ray muons as a nondestructive method for observing the internal reactor of a nuclear power plant (NPP) from outside the RPV and CV. Because muons can travel long distances through materials (Nagamine, 2003), they have been used in a nondestructive method for inspecting large structures (Minato, 1986). Although this method has been applied in the investigation of underground structures (Suzuki et al., 2011), volcanoes (Tanaka et al., 2010), and underground rocks (Shiratori et al., 2010), its application to in-reactor inspection is at a very early stage (Morris et al., 2014). The use of the method to distinguish among Pb, Fe, and C in a mass-conserved system has also been demonstrated (Shoji et al., 2011). In the present study, we conducted an observation test on a high-temperature engineering test reactor (HTTR) at the Japan Atomic Energy Agency (JAEA) to evaluate the applicability of the method to the internal visualization of a reactor. We also analytically evaluated the resolution of the measurement apparatus used for the HTTR observation.

2. Experiments

2.1. Overview of the HTTR

The HTTR was built at the Oarai Research and Development Center of the JAEA, and is the first HTGR in Japan (Saito et al., 1994). The main specifications of the HTTR are listed in Table 1. The reactor consists of the core and internal components, which are contained in an RPV of height 13,200 mm and diameter 5500 mm (Fig. 1). The fuel assemblies are of the pin-in-block type, as shown in Fig. 2. Fig. 3 shows a horizontal cross section of the HTTR. The core comprises fuel assemblies, CR guide blocks, and replaceable and permanent reflector blocks, as shown in Figs. 1 and 2. A perpendicularly stacked row is referred to as a column, and the core consists of 61 columns. The core is divided into a fuel region, which includes fuel assemblies (Figs. 1 and 2) and a replaceable reflector region that surrounds the fuel region. Control rod guide blocks are installed in both regions. The active core,

* Corresponding author. Tel.: +81 29 266 7718.
E-mail address: takamatsu.kuniyoshi@jaea.go.jp (K. Takamatsu).

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which is 2900 mm high and has an effective diameter of 2300 mm, consists of 30 fuel columns and seven control rod guide columns.

2.2. Overview of the experiments

The applicability of the use of muons for in-reactor inspection was evaluated by an inner reactor observation test conducted on the HTTR using existing muon telescopes that were developed for subsurface exploration.

2.2.1. Structures of the muon telescopes

The muon detector of the apparatus used for the test consisted of two plastic scintillators, two photo-multipliers, two discriminators, a coincidence circuit, and a counter. The major specifications of the three telescopes are listed in Table 2. The entry of a muon into the scintillator causes light emission, and the light is then converted into an electrical signal, which is multiplied by the photo-multiplier. The discriminator is used to remove the environmental gamma rays.

The employed telescope uses the coincidence method to selectively detect a muon coming from the observation direction (Fig. 4) (Akiyama et al., 1991). The method counts the muons passing the two scintillators simultaneously, and the extension of the line that connects the two scintillators constitutes the measurement direction.

2.2.2. Multichannel-type telescope

Fig. 5 shows photographs of the two types of muon telescopes used for the observation. The first is a multichannel-type telescope, shown in Fig. 5(a), which is capable of simultaneous measurements in five directions using one main spherical detector and five sub-detectors. The sub-detectors were arranged at intervals of 15°.

2.2.3. Single-channel-type telescope

A single-channel-type telescope, shown in Figs. 5(b) and 5(c), has the basic configuration of a muon telescope and uses the coincidence method. The area of the scintillator of single-channel telescope A was approximately half of those of the scintillators of the other telescopes.

Table 1
Main specifications of the HTTR.

Item	Specification
Thermal power	30 MW
Coolant	Helium
Reactor outlet coolant temperature	850 °C[a]
	950 °C[b]
Reactor inlet coolant temperature	395 °C
Primary coolant pressure	4.0 MPa
Primary coolant flow rate	12.4 kg/s[a]
	10.2 kg/s[b]
Core structures	Graphite
Core height	2,900 mm
Core effective diameter	2,300 mm
Power density	2.5 MW/m^3
Fuel	Low-enriched UO_2
Enrichment	3–10 wt%
	(Avg. 6 wt%)
Fuel element type	Prismatic block
RPV	Steel (2 1/4Cr-1Mo)
Number of main cooling loops	1

[a] Rated operation mode: operation at reactor outlet coolant temperature of 850 °C.
[b] High-temperature test operation mode: operation at reactor outlet coolant temperature of 950 °C.

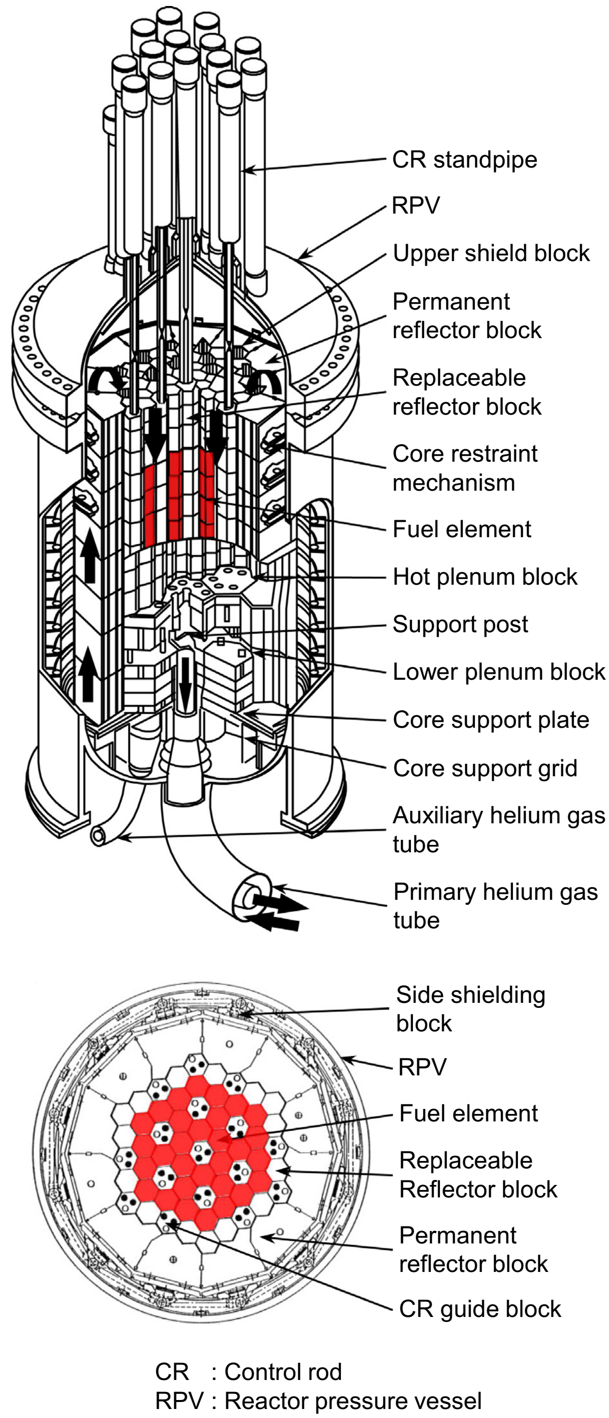

Fig. 1. Core and internal components of the reactor.

2.2.4. Densities of the major structures of the HTTR

The muon coincidence was measured at the periphery of the CV of the HTTR. Table 3 lists the major structures of the HTTR and their material densities. The structures are variously made from graphite, concrete, and steel. Although the densities of graphite and concrete are considerably less than that of steel, the total volume of the structures made from graphite and concrete is comparatively large.

2.2.5. Measurement point

The muons were measured at five different points on the same floor of the HTTR, as shown in Figs. 6(a) and 6(b). Measurement