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A feasibility study on fast reactor with low-enriched uranium fuel at Kyoto University Critical Assembly

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ABSTRACT

Research with fast reactors has drawn interest in the investigation of their characteristics, their applications involving fast neutrons, and such. In this study, to examine the feasibility of the fast core design with the use of three low-enriched uranium (LEU) fuels (Al-alloy LEU, Metal-LEU and U10Mo) at the Kyoto University Critical Assembly (KUCA), numerical simulations with the MCNP6.1 code are conducted with 3-D assembly model of one fuel assembly in the infinite lattice of fuel assemblies to determine 1) performance of the candidate LEU fuels; 2) effect of reflectors and 3) combination of fuel and other plates in the fuel region. Based on the results, the reactor characteristics are analyzed through the full 3-D core model. Consequently, the fast reactor meeting the safety regulations at KUCA is found feasible with the use of the Metal-LEU fuel together with graphite and lead plates, while the other LEU fuels present difficulty in achieving criticality in the designed fast reactor. Finally, the design analyses could offer basic data for onward plans and operation of the KUCA core for fast reactor experiments.

1. Introduction

The Kyoto University Critical Assembly (KUCA) is a research reactor that uses highly-enriched uranium (HEU) fuels. KUCA has three cores: A, B and C. A-core is a solid-moderated and –reflected one where accelerator-driven system (ADS) experiments are carried out. Using the pulsed neutron generator installed in A-core, numerous pertinent experiments have been carried out (Taninaka et al., 2011; Pyeon et al., 2014, 2015). B-core is a solid-moderated core similar to A-core, except that an isotope-based external source, not ADS, is used. C-core uses light-water moderators for static and kinetics experiments related to light-water reactors. Of particular mention is the configuration of fuel, moderator and reflector assemblies that can easily be changed in the cores: the configurations have been arranged to meet the purposes of the numerous experiments carried out in the thermal reactor cores.

Research on fast reactors and fast neutron-induced reactions has been actively pursued worldwide. Numerous studies on design and analyses of fast reactors have been carried out (Kim et al., 1999; Sekimoto and Miyashita, 2006; Dumaz et al., 2007). With the use of fast neutron spectra in fast reactors, transmutation studies of radioactive materials have been conducted on ADS using fast neutron-induced reactions (Takizuka et al., 2002; Gokhale et al., 2006). Furthermore, a large number of application studies on fast reactors has been conducted on materials and in the field of basic physics (Little and Stow, 1979; Yano et al., 2004; Furuta et al., 2012). At KUCA, studies with the use of fast neutrons have been conducted for the validation of Pb nuclear data using a specific core configuration that can locally generate fast neutrons in the core of the thermal reactor (Pyeon et al., 2016).

Also at KUCA, experiments will be expanded with fast reactor cores and fast neutron spectra for surveying transmutation technology, estimating irradiation properties, analyzing neutronics of fast reactors and others. Nevertheless, for experiments based on a fast reactor, a limitation in the design of the current HEU fuel was noted in that the number density of ^{235}U was not sufficient to achieve criticality with the present configuration of the fast reactor core. Moreover, in the growing efforts toward non-proliferation throughout the world, low-enriched uranium (LEU) is considered first and used in designing reactor cores (Alferov et al., 2015; Hartman et al., 2013; Lyons et al., 2015). In future research related to fast reactor cores, some candidate fuels based on LEU have been

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considered by the KUCA research team.

In this study, feasibility of three candidate fuels based on LEU was carried out for the design of the fast reactor core at KUCA. As a model of the assembly, the basic characteristics of the core using the LEU fuels were investigated with various reflector and fuel combinations. Also, based on the results of two full core models, the applicability of the LEU fuels was analyzed from the aspect of criticality and neutron energy spectra. Furthermore, to evaluate whether the LEU fuels can meet the safety regulations for operating KUCA cores, control rod worth, excess reactivity, shutdown reactivity and kinetics parameters were estimated through full core models. Finally, the feasibility of the LEU fuels for the core design was assessed.

2. Overview of KUCA core and fuels

2.1. Core overview

The representative core configuration at KUCA is shown in Fig. 1 (Pyeon et al., 2015). In the KUCA A-core, HEU fuel, natural uranium (NU) fuel, thorium fuel, polyethylene (PE), graphite (Gr), beryllium, lead (Pb), aluminum (Al), and others plates (or blocks) are used for experimental purposes. The information on the major materials used in this study is given in Table 1. With the combined use of the plates, experiments are mainly conducted in the thermal reactor core as follows:

- Static and kinetics analyses of ^{235}U-loaded ADS
- Neutronic analysis of ^{232}Th-loaded ADS
- Estimation of nuclear data-induced uncertainty
- Response analysis of optical fiber detector with ^{6}LiF
- Reaction rate analysis of nuclear spallation reactions with proton accelerator

All the experiments were carried out in thermal reactors with the use of moderator plates. For experiments using the fast neutron spectrum, a specific thermal reactor was designed in that the fuel assemblies, from which the moderators were removed, were locally inserted in the core. Nonetheless, the core configuration was basically a thermal reactor with some limitations in the study of fast reactors. Some difficulties were encountered in designing a fast reactor with the current fuel plates in that the HEU fuel is an Al alloy and has a low ^{235}U atom density compared with other fuels used in research reactors. Achieving criticality was, therefore, relatively challenging in designing the fast reactor at KUCA.

2.2. Fuel description

At KUCA, three LEU fuels are considered candidates for fuel in a future A-core. The enrichment of the Al-alloy and U10Mo LEU fuels was set by 19.9 w/o considering the maximum limitation of LEU (<20 w/o), and that of Metal-LEU fuel was determined by 19.3 w/o considering the neutron multiplication ability. Details of the material of LEU and HEU fuels are shown in Table 2. The fuel is a 2″ x 2″ x 1/8″ (50.8 × 50.8 × 3.18 mm) plate with an Al sheath (55.3 × 55.3 × 1524 mm). The Al-alloy LEU fuel is of the same chemical composition as that of the current HEU fuel. While the use of chemically stable fuels in KUCA experiments is advantageous, the Al-alloy LEU fuel has a drawback at critical mass in that the atomic density of ^{235}U is significantly low compared with that of the currently used HEU fuel. U10Mo LEU fuel (Aliberti et al., 2013) is considered the second next-generation candidate fuel at KUCA; it has been developed as an alternative to HEU; however, there is a drawback to the aluminum cladding used for protecting U10Mo. In our test result, the biases of multiplication factors in using the homogenization of the cladding and U10Mo were within a few hundred pcm which can be easily adjusted by the experimental

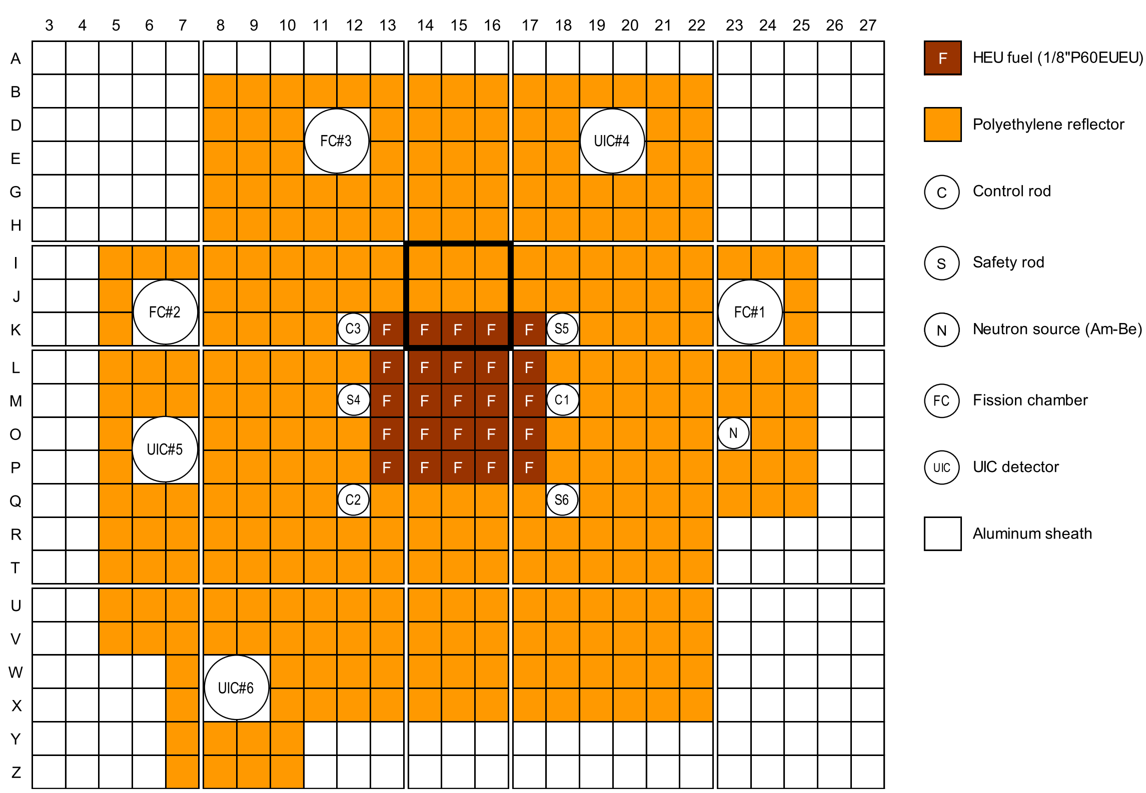

Fig. 1. Top view of A-core configuration at KUCA.