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Burn-up characteristics and criticality effect of impurities in the graphite structure of a commercial-scale prismatic HTGR

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ABSTRACT

This study investigates the burn-up characteristics and the criticality effect of impurities in the graphite structure of commercial-scale prismatic High Temperature Gas-cooled Reactor (HTGR), and thereby reconsiders the necessity of high-grade graphite material. In an HTGR, the core is filled with the graphite, and the impurities in the graphite have a non-negligible poison effect on the criticality. To account for the effect of the reflector blocks deployed adjacent to the fuel blocks, GTHTR300, commercial-scale HTGR, employed fine purified grade graphite material IG-110. Ideally, the fuel blocks should also employ IG-110; however, for economic purposes they are constructed from an un-purified grade graphite material IG-11. The poisoning effect of the impurity (which behaves like ^{10}B burn-up and is expressed in boron equivalents) decreases exponentially and eventually saturates at 1% of the initial boron equivalent. However, the reactivity worth of the fuel and reflector blocks with 0.03 ppm boron equivalents (equivalent to 1% of IG-11) is negligible (i.e., $< 0.01\%\Delta k/kk'$). Because the poisoning effect of the impurity mimics that of naturally occurring boron, it was evaluated in whole-core burn-up calculations with the impurities represented by naturally occurring boron.

According to the results, the criticality of the commercial-scale HTGR is unaffected by the impurity levels (even in the un-purified grade IG-11) because the impurities burn cleanly until the End of Cycle (EOC). Therefore, the economy of electricity generation by HTGRs can be improved by using the un-purified grade IG-11 instead of the fine purified grade graphite IG-110.

1. Introduction

The Japan Atomic Energy Agency (JAEA) has built a High Temperature Engineering Test Reactor (HTTR) (Saito et al., 1994), which is a prismatic-type High Temperature Gas-cooled Reactor (HTGR) that generates 30 MW thermal power. On the basis of the accumulated design, construction, and operational experience, JAEA has been conducting a design study of GTHTR300 series (Yan et al., 2003), it is a series of commercial-scale HTGRs with annular cores and thermal power outputs of 600 MW.

In the first experimental assessment of the HTTR, which was conducted by the fuel addition method at room temperature, the amount of fuel required for criticality has been predicted by many researchers; however, the amount was insufficient. In the core, dummy graphite blocks constructed from the un-purified grade graphite material IG-11 were replaced with fresh fuel blocks from the outer core region in the form of fuel columns. Other fuel and reflector blocks were constructed from the fine purified grade graphite material IG-110. The first criticality was achieved in an annular core comprising 19 fuel columns. However, in the simulation by using MVP (Nagaya et al., 2006), the first criticality was predicted in a core with 16 fuel columns (Nojiri et al., 1998). The MVP code simulates neutron transport by a Monte Carlo method (Nagaya et al., 2006).

After the experimental assessment, many researchers reevaluated the approach to criticality, which has now become a benchmark problem (IAEA, 2003). In one re-evaluation (Tanaka, 1999), the model was refined to achieve criticality in a core with 18 fuel columns; however, one of the fuel column deviated from the experimental data. The researchers attributed this discrepancy to an underestimation of the impurity in IG-11. In this way, high-grade graphite is important for criticality, and employed in the core structure of GTHTR300 design.

The neutron capture cross-section of graphite is sufficiently low to achieve criticality even in Calder-Hall-type reactors (Centaur Communications Ltd, 1956), which are natural uranium fueled reactors. Therefore, the poisoning effect of the impurity is non-negligible. In the GTHTR300 design, where the criticality effect is regarded as important, the reflector blocks adjacent to the fuel blocks are constructed from the fine purified grade graphite IG-110. However, the fuel blocks, which

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should also employ IG-110, are constructed from the un-purified grade graphite IG-11 for economic purposes.

Furthermore, the burn-up characteristics of the impurity were not considered in the nuclear design. In the criticality calculations of GTHTR300, the poisoning effect is expressed in equivalents of unburnable boron, treating the impurity as a constant composition of naturally occurring boron. However, because the impurity is infinitely diluted by the graphite material, its criticality value (i.e., its boron equivalent (IAEA, 2002)) should be reduced by transmutation during burn-up without shielding effects. If sufficient impurity nuclides with large cross-sections are converted to nuclides with small cross-sections by End of Cycle (EOC), the poisoning effect does not problematically affect the achievable burn-up and/or cycle length.

The present study investigates the necessity of employing IG-110 in commercial-scale HTGR from a criticality viewpoint. To this end, it evaluates the burn-up characteristics and criticality of impurity. Section 2 explains the core geometry of GTHTR300 and the calculation method. Section 3 investigates the burn-up characteristics of the impurity, which are necessary for evaluating the burnable impurity effect in the core calculations. In Section 4, the implications of the criticality effect for nuclear design are evaluated by whole-core burn-up calculations.

2. Calculation method

2.1. Core geometry of GTHTR300 and calculation model

The major specifications (Nakata et al., 2003) of GTHTR300 are listed in Table 1. GTHTR300 is a commercial-scale HTGR design with a 600 MW thermal power output. Its annular core, which comprises two batches of fuel blocks, is packed with 14 wt% enriched uranium fuel. The cycle length is 730 days.

The core configuration is shown in Fig. 1. The fuel columns are composed of eight fuel block layers aligned in the axial direction. Each fuel block is approximately 1 m high, yielding an approximate core height of 8 m. Because of the axial arrangement of the GTHTR300 core parts, an axial fuel reloading is assumed. As the loading pattern for GTHTR300 design, JAEA devised and implemented a method called sandwich refueling (Yan et al., 2003). The fuel blocks are divided into irradiated and fresh fuel batches. The irradiated fuel blocks are sandwiched between the fresh fuel blocks, as shown in Fig. 2. In addition, the uranium inventory is slightly reduced from its original 7.09 t (Nakata et al., 2003), as the fuel structure was revised from the viewpoint of fuel fabrication (Fukaya et al., 2015). The target cycle length and average discharged burn-up are 730 days and 120 GWd/t, respectively.

To compare the criticality effect of the impurity, the core was divided into several parts as shown in Fig. 1. For the burn-up calculations in Section 4, the side reflectors and fuel blocks were divided into layers. The residence time of the reflector blocks is approximately 10 years (Sumita et al., 2003), However, to simplify the problem and obtain conservative results, the present study assumed that the reflectors were replaced at each refueling.

Table 1
Major specifications of GTHTR300.

Item	Value
Thermal power (MWt)	600
Electric generation (MWe)	
Gross:	280
Net:	274
Uranium inventory (ton)	7.01
^{235}U enrichment (wt%)	14.0
Cycle length (days)	730
Number of batch	2
Discharge burn-up (GWd/t)	120

2.2. Calculation method

In this study, the burn-up characteristics and criticality of impurity were assessed by core burn-up calculation implemented in MVP (Nagaya et al., 2006), a Monte Carlo neutron transport code with evaluated nuclear data of JENDL-4.0 (Shibata et al., 2011). Moreover, the double heterogeneity of Coated Fuel Particles (CFPs) was directly analyzed using a statistical geometric model (Murata et al., 1997). The MVP calculations were implemented in three-dimensional whole-core models. The representative burn-up characteristics of the impurity and the detailed criticality effect (presented in Sections 3 and 4, respectively) were evaluated using two different models. The burn-up characteristics were determined by a one-batch core model, in which the whole fuel element was reloaded with fresh fuel without burn-up to generate libraries of ORIGEN code (Croff, 1983), and to determine the neutron flux level for the burn-up calculations. The criticality value of the impurity during operation, and the achievable cycle length, were evaluated using a two-batch core model with equilibrium cycles. To evaluate the impurity criticality effect accurately, the Burnable Poisons (BPs) and control rods were not modeled in these calculations.

The representative burn-up characteristics of the impurity were determined using the ORIGEN code as mentioned above. This code models the reactions of 394 nuclides. If transmutations of these nuclides are included, the number of activation products increases to 688. To generate the requisite library of one-energy group cross-sections (Fukaya et al., 2013), we condensed the 108-energy group infinite dilution cross-sections processed using the NJOY code (MacFarlane and Kahler, 2010), with the neutron fluxes obtained by MVP calculations in the one-batch core model.

To prepare the cross-sections condensed by HTGR spectra for all activation products, multiple evaluated nuclear data libraries implemented in the NJOY code were employed. In order of descending priority, these libraries were JENDL-4.0 (Shibata et al., 2011) (311 nuclides), JEFF-3.1.2 (Koning et al., 2011a) (18 nuclides), JENDL/A-96 (Nakajima, 1991) (17 nuclides), JEFF-3.1/A (Koning et al., 2006) (30 nuclides), and TENDL-2011 (Koning and Rochman, 2011) (18 nuclides). JENDL-4.0 and JEFF-3.1.2 are the most reliable ones that can be utilize for criticality calculations. JENDL/A-96 and JEFF-3.1/A were prepared to cover activation products, which have many nuclides and are not so important for criticality. TENDL-2011 covers the most number of nuclides because those are provided by the nuclear model for direct use basic physics, and those are less reliable compared with the evaluated nuclear data generated with experimental data such as JENDL-4.0 and JEFF-3.1.2.

2.3. Conversion method impurity to equivalent boron

The burn-up composition can be evaluated by ORIGEN code and the ORIGEN libraries generated in the manner described in Subsection 2.2. However, the burned impurity composition, which includes many nuclides, is difficult to take into account the poison effect to the core calculation by MVP. To perform this, extensive renovations would be necessary for code system of MVP, and it is not realistic. On the other hand, the reactivity worth of the impurity in the graphite is expressed by boron equivalent, which is weight fraction of equivalent naturally occurring boron, and has been treated as unburnable boron for core calculation as described in Section 1. The definition of the boron equivalent (IAEA, 2002) can be written as follows,

$$\mathrm{BE} = \sum_{i=1}^{n} \frac{\sigma_\mathrm{i}}{\sigma_\mathrm{B}} \frac{\mathrm{M_B}}{\mathrm{M_i}} \mathrm{w_i}, \tag{1}$$

where,

BE: boron equivalent (ppm),
σ_B: microscopic thermal absorption cross-section for naturally