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Evaluation of burnable absorber rods effect on neutronic performance in fuel assembly of WWER-1000 reactor

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ABSTRACT

In pressurized water reactors dissolving a soluble neutron absorber in the moderator and varying its concentration with time serves to compensate for excess reactivity. Burnable poisons embedded in the fuel or other core constituents offer an additional means for limiting excess reactivity as well as mitigating localized power peaking. Indeed, burnable absorber rods are one of the most important control elements in with respect to the nuclear reactor safety. We investigated the burnup characteristics of a fuel assembly by varying the concentration of burnable poison in a fuel rod, and the number of burnable poison rods in an assembly. Furthermore, examined the burnable poison distribution pattern and the influence of changing poison material on the main neutronic parameters of the fuel assembly. The performance of chromium diboride and gadolinium oxide was also analyzed in this study. The WWER-1000 reactor was used as our test case.

1. Introduction

Long term reactivity control comprises the compensation of the reactivity effects of fuel burn up. An elegant way for such control is the use of burnable poison (BP) in fuel elements. By carefully balancing the reactivity loss associated with fuel burnup by the reactivity gain caused by the poison burnup, a flattening of the reactivity to time curve can be obtained (Van Dam, 2000). In addition, one can also use distributed burnable poisons to flatten out the power peaking (Duderstadt and Hamilton, 1976).

The use of boric acid in the moderator, B_4C-Al_2O_3 rods as fixed burnable poison, boric coated UO_2 fuel, and Gd_2O_3-UO_2 fuels are the main methods for the insertion of burnable poisons into the reactor core. The use of burnable poison rods instead of soluble poisons gives another advantage. In pressurized water reactors, PWRs, high boron contents in the moderator gives a positive moderator temperature coefficient. By mainly controlling the reactor by means of burnable poisons, the boron content is reduced and positive moderator temperature coefficient avoided. The latter aspect has not been studied though in this work. Burnable poisons remove the excess reactivity, flatten the flux, and harden the neutron spectrum causing more Pu-239 production and hence yield increased core age (Gunduz and Ajwah, 1989).

Much work has been focused on this issue. Among them, some studies have been optimized fuel assembly design using different methods. Hirano et al. (1997) and Lim and Leonard (1977) studied the optimization of fuel rod enrichment distribution for BWR fuel assemblies using non-linear functional minimization techniques. Francois et al. (2003) applied Tabu search techniques for radial BWR fuel lattice design. Martin-del-Campo et al. (2007) optimized BWR fuel lattice enrichment and gadolinia distribution using genetic algorithms. In addition to radial optimization, axial optimization has also been considered for BWR FAs; see, for instance, (Martin-del-Campo et al., 2001).

Haibach and Feltus (1997) optimized integral fuel burnable absorber using genetic algorithm in a PWR fuel assembly, Yilmaz et al. (2006) optimized the Gadolinium concentration using the genetic algorithms, Alim et al. (2008) optimized burnable poison placement using genetic algorithm in PWRs and Rogers et al. (2009) optimized fuel assembly radial enrichment and burnable poison location based on adaptive simulated annealing in PWRs.

There have been few works, which investigate the influence of burnable poison on the neutronic parameters. There are several schemes used for introducing control absorption into a nuclear reactor core. One common way is to insert movable rods of absorbing material into the core. Such movable control elements not only can be used to adjust the core power, but because of their rapid response can also be used for scramming the reactor, as well as for shim and power shaping. Fixed absorbing materials are

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sometimes fabricated into the core, aiming such absorption will gradually burn out along with the fuel. These burnable poisons help to extend the initial core lifetime of reactors. As said earlier, another very popular control mechanism in Light Water Reactors (LWRs) involves dissolving a poison such as boric acid in the coolant. Such a soluble poison provides a very uniformly distributed shim control which minimizes spatial power profile perturbations (Duderstadt and Hamilton, 1976). If the boric acid concentration become higher than the critical concentration (threshold concentration due to positive coolant temperature coefficient of reactivity), burnable poison rod usually is used.

We investigated the burnup characteristic of the WWER-1000 fuel assembly varying the concentration of burnable poison in a fuel rod, the number of burnable poison rods in an assembly, burnable poison distribution pattern and the influence of changing poison material on the main neutronic parameters of the fuel assembly.

2. Burnable absorbers

In order to increase the allowable initial core fuel loading, it is common to load into the core materials characterized by high neutron absorption cross sections (poisons) that compensate for such an excess reactivity during the early stages of core life. Such absorbers are chosen such that they "burn out" (i.e., are transmuted by neutron capture into isotopes with low capture cross sections) somewhat faster than fuel burnup, so that later in core life they contribute negligible negative reactivity. Hence these burnable poisons can nearly match the time behavior of the excess fuel reactivity as it decreases over core life, thereby allowing larger initial fuel inventories without a corresponding increase in control requirements (Duderstadt and Hamilton, 1976).

Thus burnable poisons possess a number of advantages. They increase core lifetime without any decrease in control safety, reduce the amount of mechanical control required, and if they are distributed in a proper fashion, can also improve core power distributions, for example, by suppressing reactivity in high flux regions, such as near coolant channels (Duderstadt and Hamilton, 1976).

Some of the burnable poisons isotopes commonly, used today are boron-10, gadolinium-157 and erbium-167. Boron is used both in ZrB_2 coatings on fuel pellets and in B_4C/Al_2O_3 fixed BPRAs. The gadolinium and erbium are used in mixed Oxides (Gd_2O_3 and Er_2O_3) within the fuel pellet. Other isotopes with high cross sections for thermal neutron absorption are europium, dysprosium, and palladium. Fig. 1 shows microscopic absorption cross sections and natural abundance for several isotopes of burnable poison materials generated using a NITAWL 238 group library that used source data from the Evaluated Nuclear Data Files from Brookhaven National Laboratories version five (ENDF/B-V). The primary region of interest for a burnable poison is the absorption of thermal neutrons. Thermal neutrons are those whose energies are located within a Maxwellian distribution functions and are normally assumed to have a most probable energy (ET) and their speed based on the temperature of the system. A temperature of 293 °K corresponds to ET = 0.025 eV and vT = 2200 m/s while a reactor operating temperature of 590 °K results in ET = 0.051 eV and vT = 3100 m/s. A high natural abundance for a material is normally associated with a lower manufacturing cost. Not all of the natural isotopes are shown in Fig. 1. For instance, the Gadolinium has seven naturally occurring isotopes but only the most commonly used parent (Gd-157) is shown to make the data easier to interpret (Glagolenko1 et al., 2010).

Two general types of burnable absorbers (BAs) are used with PWR fuels:

(1) Integral burnable absorbers (IBAs)
(2) Burnable poison rods (BPRs)

IBAs are non-removable, neutron-absorbing materials used as components of a fuel assembly. BPRs, however, are rods that contain neutron-absorbing materials that can be inserted in PWR assembly guide tubes. Both types of BAs can be used to control core reactivity and local power peaking and optimize fuel utilization. In general, both types of BAs are designed to function during the first cycle of irradiation of a fresh, unirradiated fuel assembly. After one cycle of irradiation, the BPRs are typically removed from the fuel assembly allowing primary coolant to occupy the guide tube volume displaced by the BPRs. In the case of IBAs, the rods remain in the fuel assembly throughout its lifetime and usually account for a small reactivity penalty at the end of life, due to incomplete consumption of the neutron-absorber material (Patrick et al., 2001). These two types of absorbers have been described basically in the following sections.

2.1. Integral burnable absorbers

IBAs are a non-removable or integral part of the fuel assembly once it is manufactured. PWR fuel uses several different types of integral burnable absorbers. For example, in some IBAs, neutron absorbers such as gadolinia (Gd_2O_3) or erbia (Er_2O_3) are mixed directly with the uranium dioxide (UO_2) fuel in selected rod locations within an assembly. The Westinghouse-designed integral fuel burnable absorber (IFBA) rods contain uranium pellets with a thin coating of zirconium diboride (ZrB_2). Other integral absorbers, such as boron carbide (B_4C), are mixed in alumina-based (Al_2O_3) pellets and placed in rods that replace uranium fuel rods in some control element (CE) designed fuel assemblies. The Westinghouse and CE-type fuel assemblies have all used gadolinia in IBAs for some specific fuel designs. Presently, only Westinghouse-fabricated fuel assemblies use IFBA fuel rods. Until recently, IBA rods were generally loaded symmetrically in a fuel assembly with similarly loaded assemblies symmetrically located within the core. Recently, aggressive core designs have been incorporating asymmetric IBA loadings to "fine-tune" fuel assembly local power peaking concerns. Fuel designs using gadolinia may incorporate as many as 20 Gd_2O_3-UO_2 fuel rods in a single fuel assembly. Fuel designs using erbia may incorporate approximately 90 Er_2O_3-UO_2 fuel rods in a single fuel assembly. It is notable that, about one-half of the rods in some Westinghouse fuel assemblies may contain IFBA rods. Moreover, some CE-designed fuel assemblies contain B_4C-Al_2O_3 rods that may replace approximately 20 uranium fuel rods. The fuel vendors usually consider the exact details of poison concentration, the number of poison rods and rod locations to be proprietary information. For this reason, the concentrations have been omitted and only general numbers of poison rods have been described to give a relative idea of the possible variations in designs (Patrick et al., 2001).

2.2. Burnable poison rods (BPRs)

As said before, BPRs are rods containing neutron absorbing material that are inserted into the guide tubes of a pressurized water reactor (PWR) assembly during normal operation and are commonly used for reactivity control and enhancing fuel utilization.

Several general types of BPRs have been applied in PWR fuel. Framatome Cogema Fuels (FCF) use BPRs composed of B_4C-Al_2O_3 pellets contained in zircaloy tubing. The Westinghouse configuration for BPRs uses hollow Pyrex glass (B_2O_3-SiO_2) tubing sealed in stainless steel cladding. More recently, Westinghouse has applied Wet Annular Burnable Absorbers (WABAs) that are similar