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Impact of integral burnable absorbers on SMART reactor behaviour under normal and anomalous operational conditions

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ABSTRACT

Burnable poisons are used to safely prolong reactor core cycle time. They are effective alternatives to regulate power peaking factor and to reduce soluble boron concentration. One of common materials employed for this purpose is Gd_2O_3 dispersed homogenously in UO_2 fuel material. The amount of Gd_2O_3 content impacts directly on thermophysical properties of integral burnable absorber rods. Therefore, especial care must be taken at the design stage of the reactor core. In this paper, the effects of various Gd_2O_3 contents, as a burnable poison, on neutronic and thermal hydraulic behaviour of a SMART reactor are investigated. MCNPX 2.6 code is used to perform neutronic simulations of the core. The COBRA-EN with modified MATPRO subroutine is employed for calculating integral burnable absorber rods temperature in normal operation and control rod withdrawal accident. Results show that 12 percent of weight fraction for Gd_2O_3 lead to the suitable neutronic design which does not break the thermal hydraulic and safety constraints. The performance of the core design is evaluated in steady state and transient conditions in details in the paper.

1. Introduction

A promising and advanced small modular reactor (SMR) is System-integrated Modular Advanced ReacTor (SMART) (Carelli and Ingersoll, 2015) with nominal thermal power of 330 MW_{th} which is considered as a reference case study in the present work. Advanced features and practical combination of proven technologies are incorporated in the design of the reactor. The safety of the reactor is enhanced by implementing inherent safety features and reliable passive safety systems. As the reactor is a commercial type, the economy of the utilization is improved through system simplification, component modularization, saving of construction time and high plant availability (Carelli and Ingersoll, 2015). Long life cycle and reduced need for refuelling is one of the advantages pointed out for these reactors. This feature highlights the importance of burnable absorber presence in the reactor design.

The reactor capacity factor is an important feature in commercial power plants which is determined by reactor core cycle time. To improve this feature burnable absorbers are used to compensate the excess reactivity of the core during the reactor core operation. Simply, burnable absorbers are the materials which have strong neutron absorption cross section. They are converted into less neutron absorbing nuclides after neutron capture interaction. General purpose neutron absorbers are Gadolinium, Samarium, Europium, Erbium and Dysprosium. In these absorbing materials, Gadolinium and Erbium are more common used to construct integral burnable absorbers (IBAs) (Rogers, 2008).

Galahom (Abdelghafar Galahom, 2016) has studied the neutronic effects of IBA rods on the thermal neutron flux and normalized power in pressurized water reactor (PWR) assemblies to increase the cycle length. In another work done by Renier and Grossbeck (2001), detailed analysis on the performance of different isotopes in various forms are performed. The residual negative reactivity left over at the end of cycle (EOC) is studied by the authors. In some other works (Khoshahval et al., 2016; Obara and Onoe, 2013), for flattening of fuel burnup reactivity, in radial and axial directions, different burnable absorber loading patterns are assessed.

Studies on application of Erbium and Gadolinium as IBA materials show that smaller neutron absorption cross section of Erbium leads to more favourable power flattening in the core. However, Erbium is ineffective to supress the high initial excess reactivity of long life SMRs. Gadolinium has the advantage of high neutron absorption cross section. This feature makes Gadolinium as a suitable absorber material for the purpose. The high initial excess reactivity compensate efficiently by the

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Gadolinium strong absorber. However, higher power peaks in the core with Gadolinium are unavoidable (Franceschini and Petrović, 2009).

The addition of Gd_2O_3 in the fuel structure changes thermophysical properties of the IBA rods. Particularly, thermal conductivity and melting temperature of the material are decreased (IAEA, 1995). No study has been done on the degrading effect of adding burnable poisons such as Gd_2O_3 on thermal hydraulic behaviour of the IBA rods. The purpose of this paper is to investigate the effect of different Gd_2O_3 contents on the main neutronic and thermal hydraulic behaviour of SMART reactor under normal and anomalous operational conditions.

2. Materials and methods

2.1. SMART reactor core as a case study

SMART reactor core is designed based on commercial PWR assemblies. The core consists of 57 fuel assemblies. Each fuel assembly is an arrangement of 17 by 17 UO_2 ceramic fuel rods with Zircaloy cladding material. Each square array holds 264 fuel rods, 24 control rod guide tubes, and one instrumentation thimble. The fuel enrichment is less than 5 wt% which provides enough fissile material for continuous 36 months at power operation. For the sake of reducing the boron concentration, IBA rods are employed in the form of solid $(U,Gd)O_2$ (Carelli and Ingersoll, 2015). Note that the uranium enrichment of the IBA rods is lessen (1.8 wt%) due to their thermophysical properties. Table 1shows the general specifications of SMART reactor. In Fig. 1, core configuration of the reactor is illustrated. On the left, positions of shutdown and regulating control rod banks are shown. Among regulating control rod banks, R_1 has the largest reactivity worth. On the opposite side of the figure, locations of hot fuel assemblies with 24 IBA rods are highlighted. Adequate explanations about neutronic features of the core are given in the following sections. It is noticeable that each fuel assembly is a square array of rods (289 rods in total). In the hot fuel assembly shown in Fig. 2, there are 25 guide tubes. One of them is dedicated to instrumentation thimble and the others are reserved for insertion of the control rods.

2.2. Neutronic simulation and validation

The SMART reactor core is simulated in detail using MCNPX 2.6 nuclear code (Pelowitz, 2008) based on ENDF/VI library. The core is modelled three dimensionally in a quadrant-symmetry. Criticality calculations are performed by 9.9×10^3 active cycles. Each cycle includes 10^4 source histories. The first 10^2 cycles are skipped before beginning of data accumulation. Depletion calculations (materials core inventory including fuel and burnable absorbers) are carried out using BURN card capabilities in assembly-wise approximation. The statistical uncertainty of the result for effective multiplication factor is less than 4 pcm (refer to Table 4). For other calculating parameters, the relative standard deviation is lower than 3% generally.

Table 1
SMART reactor specifications (Carelli and Ingersoll, 2015).

Reactor Thermal Power	330 MW_{th}
Electrical Power	100 MW_e
Number of Fuel Assemblies	57
Lattice Geometry	Square
Active Core Height	2 m
Equivalent Core Diameter	1.832 m
Average Linear Heat Rate	10.97 kW/m
Average Core Power Density	62.60 MW/m^3
Fuel Cycle Length	3 years
Reactivity Control	Burnable Poisons, Soluble Boron, Control Rods
Reactor Operating Pressure	15 MPa
Core Coolant Inlet Temperature	568.8 K
Core Coolant Outlet Temperature	596.2 K

Table 2
Natural Gadolinium isotope composition (Franceschini and Petrović, 2009).

Isotope	% Natural Isotope Abundance	Microscopic Thermal Neutron Absorption Cross Section [barn]
Natural Gadolinium	–	48890 ± 104
^{152}Gd	0.2	735 ± 20
^{154}Gd	2.1	85 ± 12
^{155}Gd	14.8	60900 ± 500
^{156}Gd	20.6	1.5 ± 1.2
^{157}Gd	15.7	254000 ± 815
^{158}Gd	24.8	2.2 ± 0.2
^{160}Gd	21.8	0.77 ± 0.2

Table 3
Gd_2O_3 weight fraction percent for different IBA types.

UO_2-Gd_2O_3	% Weight Fraction	Gadolinium Isotopes Enrichment	Macroscopic Thermal Neutron Absorption Cross Section [cm^{-1}]
IBA Type 1	6	Natural	99.2
IBA Type 2	9	Natural	147.
IBA Type 3	12	Natural	193.
IBA Type 4	6	100% -^{155}Gd	125.
IBA Type 5	6	100% -^{157}Gd	516.

In order to validate the MCNPX 2.6 simulation model, effective multiplication factor is compared with the results obtained by WIMS-D/4 (Taubman and Lawrence, 1980) and CITATION (Fowler et al., 1971) codes. For this purpose, cell averaged homogenized group constants are generated using cluster model for 17 by 17 fuel assemblies by WIMS-D/4. Then they are placed in CITATION code input file to calculate effective multiplication factor. The effective multiplication factor of the SMART reactor core without burnable absorber is obtained equal to 1.39045 using CITATION code. The corresponding multiplication factor calculated by MCNPX 2.6 is 1.38911 ± 0.00004. The difference is about 134 pcm.

Considering the neutronic impacts of burnable absorbers on the behaviour of the reactor core, following objects must be mentioned.

- The extension of the core cycle time is a promising feature which can be optimised by using suitable design of burnable absorbers.
- Two important isotopes of natural Gadolinium with high absorption cross sections are ^{155}Gd and ^{157}Gd. Other natural isotopes of Gadolinium have small absorption cross sections. Table 2 shows detailed information of natural Gadolinium. Depending on the amount of Gd_2O_3 weight fraction, thermophysical properties of the fuel rods are varied. Therefore, enrichment of the main Gadolinium isotopes is an alternative solution for achievement of longer burnout times of the burnable poisons (Renier and Grossbeck, 2001). In Table 3 five different types of material composition of the IBA rods are listed. These IBA types are investigated in this work.
- The amount of critical soluble boron concentration, moderator temperature feedback coefficient, maximum relative power, initial excess reactivity and power peaking factors are affected by Gd_2O_3 weight fraction.

2.3. Thermal hydraulic model

The thermal hydraulic model employed in the present work is based on COBRA-EN code (Basile et al., 1999) which is originally developed for thermal hydraulic analysis of light water power reactors. The "sub-channel analysis" option is utilised to simulate heat transfer between individual fuel rods and bulk of coolant for hot fuel assembly in the SMART reactor. The core is simulated under steady state operational condition and control rod withdrawal accident.