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Gadolinia-bearing Assembly Design for Reduction of Critical Boron Concentration in APR 1400

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1. Introduction

At the beginning-of-cycle (BOC) of reactor operation, high levels of critical boron concentration (CBC) is required to suppress excess reactivity such that core remains critical, which in turn causes the moderator temperature coefficient (MTC) to become less negative or more positive. Burnable poisons such as Gadolinium (Gd) rods are typically utilized for partial control of excess reactivity and to help lower CBC levels.

The objective of this study is to develop a systematic approach to further reduce CBC at BOC and ultimately making MTC more negative, while maintaining cycle length and keeping pin peaking factor below the 1.55 safety limit. The methodology uses fuel assembly (FA) designs that contain both low and high Gd w/o rods.

The APR 1400 fuel assembly and core design for Shin-Kori Unit 3 Cycle 1 (SK3C1), which is of PWR type, is used as reference case. The Gd-bearing assembly types in SK3C1, namely B1, B2, B3, C1, C2, and C3, uses Gd rods with 8 w/o gadolinia (Gd_2O_3) admixed in UO_2, and 2 w/o U-235 enrichment. FA and core depletions are simulated using CASMO 3.0 and MASTER 3.0 design codes, respectively.

2. Fuel assembly optimization

2.1 Effects of Gd rod on reactivity

Reactivity and pin peak behaviors in FA depletions are governed by many parameters associated with Gd rods. The low-Gd and high-Gd w/o used are 2 w/o and 8 w/o, with 4.1 w/o and 2.2 w/o U-235 enrichment, respectively. The number of low-Gd rods, *L*, and high-Gd rods, *H*, is varied between 4 and 36, such that the total number does not exceed 48. The assembly average Gd w/o and Gd rod number ratio are:

$$Avg.\ Gd\,w/o = \frac{(L \times low\,Gd\,w/o) + (H \times high\,Gd\,w/o)}{total\,number\,of\,fuel\,pin\,cells\,in\,FA} \quad (1)$$

$$Gd\,rod\,number\,ratio = \frac{L}{H} \quad (2)$$

The placement of Gd rods in FA pin cells is arranged such that they are evenly distributed in the surrounding regions of high neutron leakage, i.e. the water holes, and that no two or more Gd rods positioned adjacently. Variations of these parameters are simulated while keeping the average U-235 enrichment constant according to SK3C1 assembly designs.

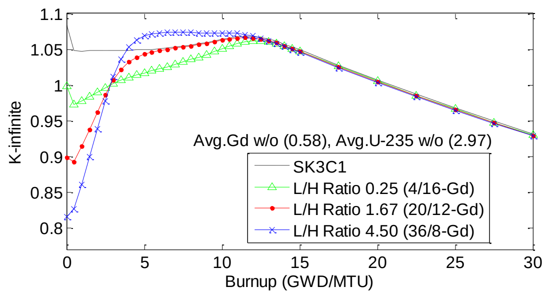

Fig. 1. K-inf behavior for varying Gd rod number ratios (B1)

Fig. 1 reveals that higher number of low-Gd rods significantly suppresses more reactivity at BOC, whereas effects of high-Gd rods are seen at middle-of-cycle (MOC). Simulation results also showed that reactivity decreases with increasing average Gd w/o, as expected. Pin peak behaviors did not show any conclusive trends for all simulated test cases.

2.2 Reactivity equation

A new method to predict reactivity and hence CBC at BOC is proposed in this paper. This idea is based on the fact that CBC level is dependent upon the correlation between average Gd w/o, Gd rod number ratio, and reactivity at BOC. Despite its complexity, it is possible to approximate the correlation via regression analysis. The least squares method (LSM) is applied using data and results of simulated test cases. LSM calculations of a quadratic bivariate model equation yielded solutions in the form of:

$$k_{FA} = a_0 - a_1 x - a_2 y + a_3 x^2 + a_4 y^2 - a_5 xy, \quad (3)$$

where x is average Gd w/o, y is Gd rod number ratio, k_{FA} is infinite multiplication factor at BOC, and a_i are constants. The correctness of the solutions is verified by simulating FA depletions with various combinations of x and y, and comparing the k-infinite results against k_{FA} values predicted in Eq. (3). The k-infinite errors between simulated and calculated values were found to be within 1% or roughly ±0.01, which is fairly accurate.

Fig. 2 illustrates that k-infinite increases linearly with higher assembly U-235 enrichment at all values of average Gd w/o and Gd rod number ratio combinations.

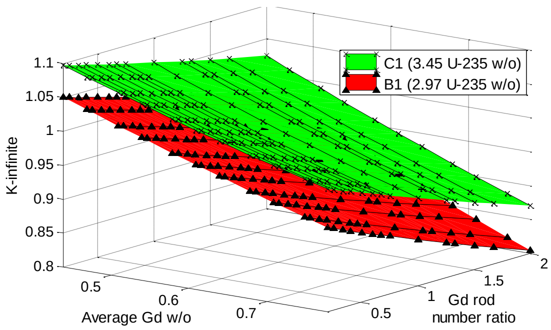

Fig. 2. Quadratic model surface plot of B1 and C1 assemblies

Simple linear difference calculations showed that k-infinite changes by a factor of 0.11 for every unit change in FA fuel enrichment. This factor, coupled with the low error of LSM quadratic model solutions, allows for reasonably accurate k-infinite predictions at BOC for different FA fuel enrichments of any *x* and *y* pair.

2.3 Selection of optimum design

The difference between the actual k-infinite of a reference FA and those predicted in Eq. (3) at selected *x* and *y* pairs can be calculated to obtain a set of Δk_{FA} values at BOC. For example, Table I shows a physically realizable solution space derived for B1 type assembly when the target Δk_{FA} is 0.076. It can be seen that two options of *x* and *y* combinations exists which can yield the desired reactivity reduction. The validity of the chosen pairs is verified using Eqs. (1) and (2). Hence, the optimum average Gd w/o and Gd rod number ratio for B1 assembly design can be determined.

y \ x	0.47	0.51	0.54	0.58
0.20	0.045	0.061	0.073	0.088
0.25	0.047	0.064	0.075	0.091
0.33	0.052	0.068	0.080	0.096
0.40	0.055	0.071	0.084	0.099
0.50	0.060	0.077	0.089	0.105
0.60	0.065	0.082	0.094	0.111

Table I: Δk_{FA} values for B1 assembly with 2.97 w/o U-235

2.2 Determination of core reactivity

As an example, to reduce CBC at BOC for SK3C1 by 300 ppm, the corresponding core reactivity difference, Δk_{core}, is calculated to be 3142 pcm. It is assumed that Δk_{core} is equal to the average k-infinite difference at BOC of all FAs in the core. Since only Gd-bearing assemblies have any effect on k-infinite:

$$\Delta k_{core} \cong \frac{n}{N} \Delta k_{FA} \tag{4}$$

where Δk_{FA} is the average k-infinite difference of individual assemblies, *n* is the number of Gd-bearing assemblies, and *N* is the total number of assemblies in the core. Consequently, optimum FA designs should aim to reduce k-infinite by Δk_{FA} from SK3C1 reference values, which was analytically calculated to be 0.076.

3. Core depletion

The methodologies described in Section 2 are applied to assemblies B1, C1 and C3. Interpolation of these assemblies' quadratic model equations is performed using the 0.11 factor to obtain Δk_{FA} tables for B2, B3 and C2 assemblies. Once the design of all Gd-bearing assemblies are determined, core depletion is simulated.

The summary of core depletion results is shown in Table II. It is clear that CBC at BOC is successfully reduced in the optimized core case, as also evident in Fig. 3. The amount of CBC reduction is less than the predicted 300 ppm. This is attributed to neutron leakage in core depletion simulation. The actual Δk_{FA} computed using results of the optimized core simulation is 0.078, which is well within the 1% error of the quadratic model solutions and close to the analytically calculated value. Thus, the assumption made in Eq. (4) is validated.

	Average Gd w/o (%)	Critical Boron Concentration at BOC (ppm)	Effective Full Power Day (days)	Maximum pin peaking factor
SK3C1	0.26	841	479	1.41
Optimized	0.32	608	471	1.52

Table II: Core data and depletion results

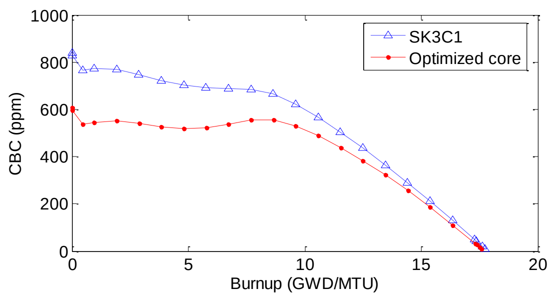

Fig. 3. Boron letdown curves of SK3C1 and optimized core

4. Conclusions

The goal of reducing CBC at BOC while maintaining cycle length and satisfying the pin peak safety limit was successfully achieved by employing a mix of low-Gd and high-Gd w/o rods in fuel assemblies. Optimization of Gd rod placement to further reduce k-infinite and pin peaking factor is a viable area of future research work to gain added improvements in Gd-bearing FA designs.

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