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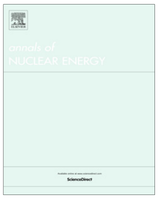

The effect of changing enrichments on core performance

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ABSTRACT

The information presented in this paper has been developed as a follow on to two previous papers published using the same low leakage core configuration with the addition in this paper of evaluating fuel costs. The two previous publications studied the characteristics of this low leakage core with two different enrichment sets, where each enrichment set represents the three batches in the core. The purpose of the two previous papers proved the effectiveness of using the Haling Power Depletion (HPD) method as a guide. The first purpose of this paper is to extend this study to higher enrichment sets to finally attain a core having close to the highest possible cycle length. Three additional similar enrichment sets are studied increasing the number of enrichment sets to five. The ratio between the enrichment sets was maintained constant except for the highest enrichment set. This was done to increase the cycle length to approximately the longest possible cycle length of 800 days for a 1000 MWe reactor limited to a maximum 5% enrichment. The core reactor physics characteristics of these five cores are presented in this paper together with the evaluating of the fuel costs. These core characteristics include radial power fractions (RPF), Haling Power Depletion, RPF distributions, maximum pin peak powers (PPP_{MAX}), and other important data. The HPD RPFs of all 5 cores were similar and used to help develop the burnable poison placement designs for each core. The longest two cycles required an improved technique using more information than the HPD results to develop successful BP placement designs. Also, it was very difficult to find the correct soluble boron ppmB in the HPD input to have the Studvik HPD calculation converge. There is an error in this algorithm. The fuel costs for the five cores were calculated and the results prove that the fuel costs are lower with the cores having the longest cycle lengths. The details observed in this study are presented in this paper.

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1. Introduction

A few papers have been published that are precursors to this paper. The first is (Levine et al., 2012) wherein the core characteristics of a Studvik equilibrium high leakage core design (CMS, 2009) was compared to the same core characteristics of a low leakage core configuration. The low leakage core configuration in Levine et al. (2012)is shown in Fig. 1.The second paper (Levine et al., 2013) was an expansion of the first paper to add an additional analysis of the same low leakage core configuration but with higher enrichments than those shown in Fig. 1.Thus, the same low leakage core configuration was calculated with two different sets of enrichments in Levine et al. (2013). A set of enrichments represents the core's three batches. They were [2.00 2.50 3.20] and [2.10 2.63 3.37], which are the first two enrichments presented in this paper. These two enrichment sets had cycle lengths of 16.050 GWd/MT and 17.044 GWD/T, respectively, whereas their corresponding HPD cycle lengths were given as 16.392 GWd/MT and 17.010 GWd/MT. The results of the Levine et al. (2012) and Levine et al. (2013) studies proved that the power distributions of a low leakage core during depletion followed closely the Haling Power Depletion (HPD) method power distribution, i.e., the HPD radial power fraction, RPF, distribution. The RPF is the same as the normalized fuel assembly power, NP, that occurs in other publications. The HPD RPF distribution follows the step depletion RPF distribution because the low leakage core is designed to maintain its low leakage characteristic to EOC and therefore tends to follow the HPD power distribution especially after some initial burnup steps to EOC. Each HPD RPF depletion curve is a straight line but all non-symmetrical FAs have different RPF magnitudes. Hence, the HPD method is used as a guide in designing low leakage cores. It should be mentioned that originally it was planned in Levine et al. (2013) to develop a cycle length. of ~18 GWd/MT. However, the initial studies were unable to find a BP placement design in this core to satisfy the maximum pin peak power, PPP_{MAX}, of 1.550

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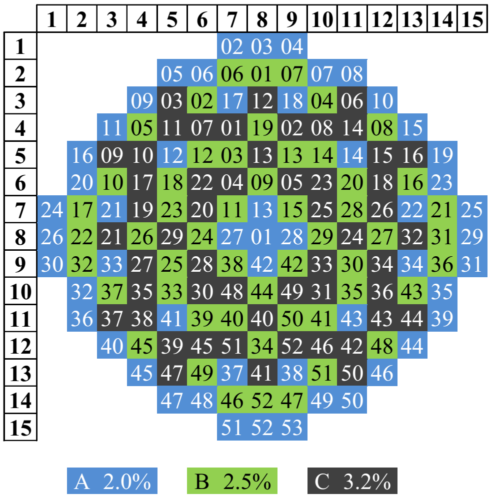

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1							02	03	04						
2					05	06	06	01	07	07	08				
3				09	03	02	17	12	18	04	06	10			
4			11	05	11	07	01	19	02	08	14	08	15		
5		16	09	10	12	12	03	13	13	14	14	15	16	19	
6		20	10	17	18	22	04	09	05	23	20	18	16	23	
7	24	17	21	19	23	20	11	13	15	25	28	26	22	21	25
8	26	22	21	26	29	24	27	01	28	29	24	27	32	31	29
9	30	32	33	27	25	28	38	42	42	33	30	34	34	36	31
10		32	37	35	33	30	48	44	49	31	35	36	43	35	
11		36	37	38	41	39	40	40	50	41	43	43	44	39	
12			40	45	39	45	51	34	52	46	42	48	44		
13				45	47	49	37	41	38	51	50	46			
14					47	48	46	52	47	49	50				
15							51	52	53						

A 2.0% B 2.5% C 3.2%

Fig. 1. PSU core design of the low leakage core.

during depletion. Hence, the cycle length was reduced to the above 17.010 GWd/MT.

Nevertheless, it was subsequently decided to study step wise what happens when three higher sets of enrichments, [2.15 2.69 3.44], [3.00 3.75 4.80], and [3.20 4.00 5.00] are involved with this same core configuration. In doing this, the ratios of the enrichments were kept constant for the first four enrichment sets. For example, the lowest enrichment set ratios were 2.50/2.00 = 1.25 and 3.20/2.50 = 1.28. The highest enrichment set ratios are 1.25 and 1.25 to increase the cycle length to approximately its maximum when constrained by the highest allowed enrichment of 5%. A ratio of 1.28 between the two highest enrichments in this enrichment set would lower the total amount of ^{235}U in the core reducing the cycle length. The core power was 1000 MWe. The third enrichment set, [2.15 2.69 3.44], was increased slightly above the second set to allow more experience in designing the BP placements for higher enrichment cycles. Thus the core with the third enrichment set was the first studied for this report. The remaining two were studied in sequence to attain experience in making the BP placements to satisfy the PPP_{MAX} constraint. These BP placement designs became more difficult to establish to prevent the PPP_{MAX} constraint from being violated as the enrichment sets were increased. The problem of designing the core BP placement to meet the PPP_{MAX} of 1.550 was solved for the two the highest enrichment sets by developing new core BP placement techniques. These techniques are described in this paper. Of importance is the need to understand the differences that occur between the HPD results and the corresponding step depletion results if the HPD method is to be used as a guide. Complications arise as the cycle lengths are increased requiring a better understanding of these results.

Nuclear reactor power will not be used unless its operation costs are competitive with the costs of producing electricity with coal and natural gas power plants. It is, therefore, important to compare the fuel costs of these five cores and determine the lowest fuel costs. A result of this study shows that the calculated fuel costs decrease with increase in cycle length.

The study shows that the enrichments at the two highest enrichment sets, the maximum radial power fraction (RPF_{MAX}) in the Haling Power Depletion (HPD) calculation decreases somewhat from the other lower enrichment sets. That is, the maximum fuel assembly power, RPF_{MAX}, in the HPD, becomes smaller with increase in enrichment at the two highest enrichments. On the other hand, the actual pin peak power, PPP, continues to be close to 1.55 in the step depletion calculation for all five different enrichment sets. This suggests that the allowed HPD RPF max in the higher enriched cores should be lower than that allowed for the shorter cycle cores. The core cycle length increases, as expected, with increase in enrichment. These results have significant implication on how to use the HPD as a guide in working on these higher enrichments. Only three different batches are involved in a core to allow easy reload designs. One of the major findings in this study is that the best core design established with the HPD RPF_{MAX} at the lowest enrichment remains valid for all five enrichment sets provided the ratio of enrichment sets remain approximately constant.

It should be mentioned that although the CASMO-4/ SIMULATE-3 codes (User's Manual, 2009; SIMULATE-3, 2009) are excellent when calculating the step depletion option, it is not necessarily precise when calculating the HPD option, especially at the very high enrichments. This is because the HPD EOC did not converge at 10 ppmB for the two highest enrichment sets but at higher ppmB as explained later. Their HPD algorithm should make all calculations at the EOC and the Studvik HPD algorithm does not do this. It makes some intermediate calculations so as to make the EOC be at 10 ppmB. Nevertheless, the Studvik HPD option caused no difficulty in using the HPD results as a guide for the two highest enrichments. The real problem was finding the correct ppmB for the input. Much time was required to find this ppmB value so that the HPD calculation converged.

An attempt was made to further increase the cycle length of the core with the highest enrichment set by interchanging FAs near the core periphery with lower enriched FA's near the core center. Unfortunately, it was impossible to make the HPD calculation converge, and, therefore, could not be used as a guide. The step depletion calculation was successful but its results were confusing. The step depletion did not give a longer cycle after these core changes were made even though the changes were expected to increase the cycle length. The step depletion results had large RPF_{MAX}'s and corresponding PPP's that exceeded the 1.550 maximum allowed. No further analysis would be successful without having an HPD calculation to guide the changes and help determine if the calculation could be successful. This calculation was terminated.

The purpose of this paper is to present the results of this study and expand the knowledge on how to use the HPD as a guide in developing optimum low leakage core configurations by studying cores with the higher enrichments and longer cycle lengths. Another purpose is to determine the fuel costs as a function of cycle lengths.

2. Results of the calculations

The HPD is used as a guide in designing optimum low leakage cores. It is, therefore, important to compare the relative maximum fuel assembly power in the HPD, the HPD RFP_{MAX}, with the corresponding step depletion RFP_{MAX} and then to compare their cycle lengths. The HPD is used as a guide when its RPF_{MAX} can result in the PPP_{MAX} in the step depletion calculation to fall within its constraints. This has been found to be true for the 3 lowest enrichment cores if the HPD RFP_{MAX} is not to be greater than 1.38 (CMS, 2009; Levine et al., 2013). The HPD cycle length should also compare favorably with the actual cycle length. A higher HPD RPF_{MAX} was not allowed because at the higher HPD RPF_{MAX} values it would not be possible to develop the placement of BPs to prevent the PPP_{MAX} from exceeding 1.55. The HPD cycle length simulates what the cycle length will be for this core configuration, which is useful. These two parameters are compared in Tables 1 and 2.

The HPD RPF_{MAX} and the step depletion RPF_{MAX} for Enr.Set #1 maintain the same core position (11, 8) during the step depletion where the RPF_{MAX} is 1.443 in the RPF distribution as shown in Fig. 2. This core position will be referred to as the reference core

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