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New techniques for designing the initial and reload cores with constant long cycle lengths

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ABSTRACT

Several utilities have increased the output power of their nuclear power plant to increase their income and profit. Thus, the utility increases the power density of the reactor, which has other consequences. One consequence is to increase the depletion of the fuel assemblies (FAs) and reduce the end-of-cycle (EOC) sum of fissionable nuclides in each FA, $\sum_{EOC}$. The power density and the $\sum_{EOC}$ remaining in the FAs at EOC must be sufficiently large in many FAs when designing the loading pattern, LP, for the first and reload cycles to maintain constant cycle lengths at minimum fuel cost. Also of importance is the cycle length as well as several other factors. In fact, the most important result of this study is to understand that the $\sum_{EOC}$s in the FAs must be such that in the next cycle they can sustain the energy during depletion to prevent too much power shifting to the fresh FAs and, thus, sending the maximum peak pin power, PPP_{max}, above its constraint. This paper presents new methods for designing the LPs for the initial and follow on cycles to minimize the fuel costs. Studsvik's CMS code system provides a 1000 MWe LP design in their sample inputs, which is applied in this study. The first 3 cycles of this core are analyzed to minimize fuel costs, and all three cycles have the same cycle length of ~650 days. Cycle 1 is designed to allow many used FAs to be loaded into cycles 2 and 3 to reduce their fuel costs. This could not be achieved if cycle 1 was a low leakage LP (Shi et al., 2015). Significant fuel cost savings are achieved when the new designs are applied to the higher leakage LP designs. There are many factors, such as the core power density, cycle length, fuel cost, time between core shutdown and return to power, cost of replacement power during shutdown, loss of income during shutdown, cost of storing used FAs, and the income accrued over the same period of operation, which the utilities must consider when trying to increase their profit. The purpose of this paper is to provide the information to give guidance in making these decisions. Relative cost calculations are presented in establishing this guidance by comparing the utility's profit accrued over a total cycle for the different core designs and cycle lengths.

1. Introduction

Several utilities have increased the output power of their nuclear power plants to increase their income and, thus, their profit. In doing this, the utility increases the power density of the nuclear reactor, which has other consequences. One consequence is to increase the amount of depletion of the fuel assemblies (FAs), reducing the sum of fissionable nuclides in the FAs at the end-of-cycle ($\sum_{EOC}$).

$$\sum_{EOC} = N_{U-235} + N_{Pu-239} + N_{Pu-241}, \tag{1}$$

where N_{U-235} is U – 235 number density in FAs at EOC, N_{Pu-239} is Pu – 239 number density in FAs at EOC, and N_{Pu-241} is Pu – 241 number density in FAs at EOC.

The $\sum_{EOC}$ is the important parameter to be used for reloading the next cycle rather than the FA's K_{inf} (Shi et al., 2015). This important fact was discovered when an FA having a low K_{inf} increased the cycle length when it replaced an FA with a larger K_{inf}. The $\sum_{EOC}$ includes the fission isotopes, which are the energy source and consequently, it is the superior measure of the energy remaining in the FA and not the K_{inf}. The power density, ρ, and the $\sum_{EOC}$ in the used FAs at the EOC must be considered when designing the loading pattern, LP, for the first and reload cycles to maintain constant cycle lengths at minimum fuel cost, which can be explained clearly by referring to the following Eq. (2):

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$$\rho = \frac{P_C}{V_c}, \tag{2}$$

where P_c is the thermal power generated by the reactor, and V_c is the core volume.Increasing P_c while keeping V_c constant increases ρ. The magnitude of the FA's $\sum_{EOC}$ depends on its position in the core. A low leakage core has the low enriched FAs in the core periphery to increase the efficiency of the core design. The K_{eff} of the core is defined as:

$$K_{eff,c} = (K_{inf,c})_{avg.} * NL_c, \tag{3}$$

where $K_{eff,c}$ is K_{eff} of the core, $(K_{inf,c})_{avg.}$ is the average K_{inf} of the core, and NL_c is the core non − leakage probability.

There are two important factors to understand regarding Eq. (3). The first is that placing the low enriched FAs in the core periphery and the higher enriched FAs in the central region of the core forces both the power and the neutron flux to be low in the core periphery. The result is that fewer neutrons leak out of the core so that NL_C is high. Since the $(K_{inf,\ c})_{avg.}$ is approximately independent of the core configuration, the $K_{eff,\ c}$ is higher for this core configuration. This core design, shown in Fig. 1, is called a low leakage core. The second factor is that the loss of the total fissionable nuclides in the core at EOC or the sum of the $\sum_{EOC}$ for all FAs in the core at EOC is independent of the core configuration. However, the $\sum_{EOC}$ is distributed differently among the FAs in the core. Remember a fission reaction of the same nuclide produces the same amount of energy independent of its position in the core, and the Pu production is a function of the FA design in a PWR, which is the same for all FAs in the core. The control rods affect the Pu production in a BWR (Taner et al., 1992) because they are moved inside the core during depletion. The PWR operates with control rods essentially out of the core so that they do not affect the Pu production. Rearranging the FAs in the core by placing the highest enriched FAs in the core periphery and the lower enrichment in the core center increases the power in the core periphery over that of the low leakage core. As a result, the NL_c is reduced, reducing the $K_{eff,\ c}$. Consequently, the FA's enrichment in the high leakage core must be increased if the $K_{eff,\ c}$ and the core cycle length are to be kept constant. As a result, the average $\sum_{EOC}$ in the FAs will be higher for the high leakage core than the low leakage core when the cycle length is the same. The used FAs with higher $\sum_{EOC}$s will have more available energy when reloaded in the next cycle LP to help sustain the cycle length, which is important for LPs with high ρ and long cycle lengths.

The Pennsylvania State University (PSU) performs the calculations using the university version of the Studsvik Scandpower Code System (CMS), which is for research and education purposes. This version of Studsvik CMS has input core depletion examples for students to study and understand the CMS and has the CASMO-4 and SIMULATE-3 codes for core calculations (CASMO-4E, 2009 and SIMULATE-3, 2009). The core configuration available in the Studsvik's examples is used by Penn State (Levine et al., 2015) and only the LP designs are changed. The ρ for the Studsvik core is 0.42 kW/cm^3 whereas the TMI-1 ρ is 0.20 kW/cm^3, so that there will be a much larger rate of depletion in the core presented in this paper than in the TMI-1 core. Also, the FA's $\sum_{EOC}$ will be much smaller in the Studsvik core than in the TMI-1 core. As stated previously, the $\sum_{EOC}$ must be sufficiently large in many FAs so that in the next cycle they can sustain the energy during depletion to prevent too much power shifting to the fresh FAs during the cycle, and, thus, sending the PPP_{max} above its constraint. There is insufficient energy in the used Studsvik's core FAs at the end of a long cycle length to maintain the cycle length when loaded into the next cycle LP if the initial cycle LP is low leakage (Shi et al., 2015). As explained in Shi et al. (2015), depletion of the low leakage cycle 1 LP results in very low concentrations of the $\sum_{EOC}$ in almost all of the FAs at the EOC. Hence, it became necessary to reload cycle 2 with almost all fresh FAs to maintain the same cycle length in cycle 2.

As stated above, Shi et al. (2015) showed that designing a low leakage LP for cycle 1 prevented designing cycle 2 from attaining the same cycle length without reloading cycle 2 with an excessive number of fresh FAs. This was also true for other Studsvik's sample inputs, which were not low leakage but had higher leakage core (equilibrium) designs. The very large 0.42 kW/cm^3 ρ in the Studsvik LPs produces this even for the higher leakage cores. In addition, maintaining a constant cycle length in later cycles was more difficult for low leakage LPs. This is because the burnup distribution of the FAs at EOC for low leakage LPs is spread more evenly across the core. The used FAs at EOC cycle 1 essentially all have a low $\sum_{EOC}$ when the initial LP has a low leakage design. Any attempt to reload cycle 2 without using an excessive number of fresh FAs required the fresh FAs to have high enrichments to maintain the same cycle length as in cycle 1. As a consequence, it was impossible to design the cycle 2 LP with used FAs to maintain the same cycle length as in cycle 1without exceeding their maximum peak pin power (PPP_{max}) during the cycle. The depleted FAs cannot stay at high enough power (Radial Power Fraction, RPF) during the cycle to prevent excess power shifting to the fresh FAs later in cycle 2. Thus, a higher leakage LP design has to be developed for the initial cycle using FAs which have increased enrichments if the second cycle is to meet both its cycle length and its PPP_{max} constraint. The higher leakage LP has the highest enriched FAs, which have the larger BOC fissionable nuclides, placed in the core periphery where the FAs receive less burnup.

There was no problem in designing a low leakage core for the TMI-1 reloads that had a cycle length of 2 years because of its

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1							A02	A03	A04						
2					A05	A06	B06	B01	B07	A07	A08				
3				A09	C03	B02	A17	C12	A18	B04	C06	A10			
4			A11	B05	C11	C07	C01	B19	C02	C08	C14	B08	A15		
5		A16	C09	C10	A12	B12	B03	C13	B13	B14	A14	C15	C16	A19	
6		A20	B10	C17	B18	C22	C04	B09	C05	C23	B20	C18	B16	A23	
7	A24	B17	A21	C19	B23	C20	B11	A13	B15	C25	B28	C26	A22	B21	A25
8	A26	B22	C21	B26	C29	B24	A27	A01	A28	B29	C24	B27	C32	B31	A29
9	A30	B32	A33	C27	B25	C28	B38	A42	B42	C33	B30	C34	A34	B36	A31
10		A32	B37	C35	B33	C30	C48	B44	C49	C31	B35	C36	B43	A35	
11		A36	C37	C38	A41	B39	B40	C40	B50	B41	A43	C43	C44	A39	
12			A40	B45	C39	C45	C51	B34	C52	C46	C42	B48	A44		
13				A45	C47	B49	A37	C41	A38	B51	C50	A46			
14					A47	A48	B46	B52	B47	A49	A50				
15							A51	A52	A53						
					1.5%		2.0%		2.5%		3.2%				

Fig. 1. PSU low leakage core configuration.

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