Modelling the Fuel Shuffling Process Using Spent Fuel

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Abstract

In this study, the AP1000 core was modeled using neutronic code packages (LEOPARD, TLINX, and 2DB) to simulate the fuel shuffling process over three cycles. In the first cycle, 157 fresh fuel assemblies with three different enrichments of U-235 (2.35%, 3.45%, and 4.45%) were used. For the second cycle, 104 spent fuel assemblies were reused, and one fresh fuel assembly with 2.35% enrichment was placed at the center, while 52 fresh fuel assemblies with 4.45% U-235 enrichment replaced the assemblies with 2.35% enrichment. In the third cycle, the configuration was similar, with 104 spent fuel assemblies reused, one fresh assembly with 2.35% placed at the center, and 52 fresh assemblies with 4.45% U-235 replacing those with 3.40% enrichment. In each cycle, all fuel assemblies were shuffled (relocated).

In this study, two simulation cases were considered: one with a clean core (no poisons), and another with burnable poisons to analyze the effect of burnable poison distribution on criticality.

KEYWORDS: Fuel shuffling; LEOPARD; TLINX; 2DB; AP1000; Burnable absorbers;

BOC; EOC; Poisoned core; clean core; IFBA; k_{eff}>

Introduction:

Fuel shuffling in nuclear reactors improves efficiency by periodically rearranging fuel assemblies within the reactor core. This process involves relocating assemblies as they become less effective at neutron production due to depletion. Shuffling allows fresh fuel to be placed in optimal zones for maximum neutron production, while spent fuel is relocated to less demanding areas. This strategy not only extends the operational life of the fuel and increases power output but also simplifies reactor control.

Additionally, fuel shuffling serves as an effective spent fuel management technique, reducing the total amount of spent fuel generated and supporting sustainability goals within the nuclear industry.

1. Fuel shuffling Benefits:

1.1.Environmental Benefits:

Fuel shuffling can greatly reduce the generation of spent fuel assemblies, resulting in less radioactive waste that requires long-term storage and disposal. This reduction helps lessen the environmental impact of nuclear waste management. Furthermore, by reducing the need for fresh fuel assemblies, fuel shuffling decreases the demand for uranium mining. This in turn decrease the environmental impact of mining activities by minimizing land disturbance, the potential for water contamination, and the greenhouse gas emissions associated with ore extraction and processing.

1.2.Economic Benefits:

Fuel shuffling enhances the efficient use of existing fuel assemblies, reducing the need to purchase and manufacture new ones. This results in significant cost savings throughout the nuclear fuel cycle. Additionally, it can extend the reactor operation, allowing it to run for longer periods before needing refueling. This reduction in refueling downtime leads to fewer outages and supports more continuous electricity generation.

AP1000 reactor core [1], [2]

The Westinghouse AP1000, belonging to the advanced Generation III+ class of reactors, utilizes a highly efficient and optimized core design. Fuel rods, fabricated from ZIRLO® zirconium alloy tubes containing UO_2 fuel pellets, are arranged in a 17x17 array within each fuel assembly. As shown in the figure (1), a typical assembly houses 264 fuel rods alongside 24 rod cluster control thimbles and an in-core instrumentation thimble.

Initially, all fuel rods within a single assembly possess the same uranium enrichment. However, for balanced power distribution, the overall core utilizes 157 fuel assemblies [3] with three distinct enrichment levels: 2.35 w/o, 3.40 w/o, and 4.45 w/o. These enrichments are arranged strategically, with the two lower enrichments forming a checkerboard pattern in the central region and the highest enrichment surrounding the periphery. This figure (1) further illustrates the core layout and fuel assembly details [4].

For Westinghouse AP1000 design fuel assemblies are certified to a maximum burnup of around 62 GWD/MTU [9][10].

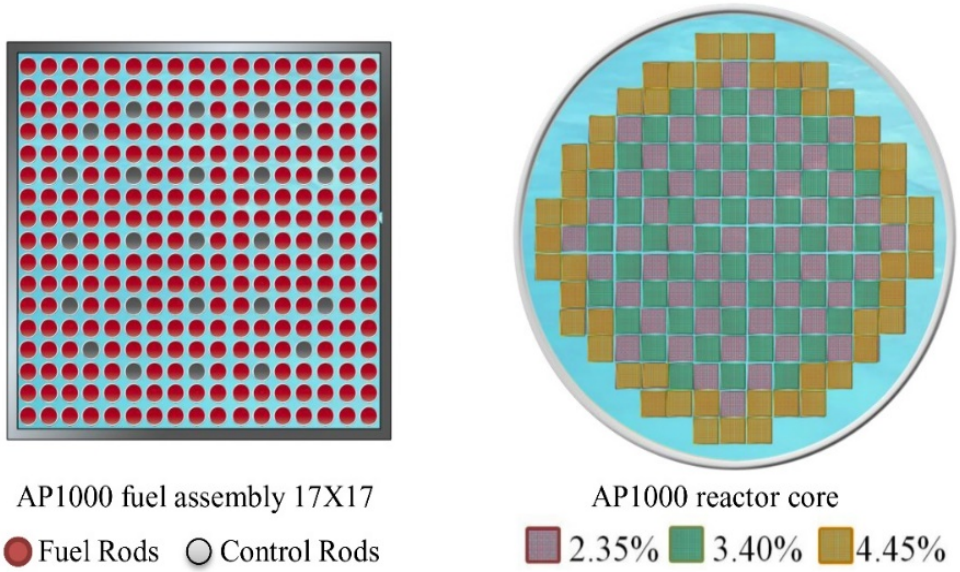


Figure 1 AP1000 reactor core & fuel assembly

Integrated Burnable Absorbers (IFBA) [5]:

Adding another layer of sophistication to the AP1000 core design is the incorporation of Integrated Burnable Absorbers (IFBA). These burnable poison materials, typically Boron-10, are discreetly embedded within specific fuel rods of certain assemblies. As the reactor operates, the burnable absorber gradually depletes, mitigating excess reactivity at the beginning of the fuel cycle and facilitating a more stable power profile throughout. This clever technique optimizes fuel utilization and extends the operating cycle between refuelling.

The specific distribution of IFBA rods within the AP1000 core varies depending on the assembly type. Some assemblies may have IFBA in selected peripheral rods, while others might incorporate them throughout the central array. This tailored approach ensures optimal reactivity control and fuel efficiency across the core.

Nuclear Codes Packages

In this study, computer code packages written in FORTRAN were used to simulate the AP1000 fuel shuffling process. These packages apply numerical methods to calculate parameters based on diffusion and transport equations.

1.1.0. LEOPARD Code:

LEOPARD [6] is a unit-cell code that calculates neutron spectra and group constants for various materials in light water reactors. It utilizes two- or four-energy group cross-section sets and was used to evaluate material cross-sections for the fuel meat, cladding, water channel, and an extra region within fuel assemblies. LEOPARD calculates few-group cross sections for all types of fissile and fertile materials and for any combination of H_2O and D_2O.

The evaluated nuclear data (ENDF) is the primary data source. The ETOM and FLANGE programs process this basic data into the multi-group data required by MUFT (54 groups) calculates the fast and epithermal region spectrum, and SOFOCATE (172 groups) handles the thermal region. Both MUFT and SOFSCATE execute homogenous medium calculations.

Finally, LEOPARD can perform a step-by step burn up calculation. The burns up isotopic histories are useful in their own right, and the cross sections can be employed in higher-dimensional computations. Depletion was accounted for on the assembly level by interpolating macroscopic cross sections as a function of depletion (MWD/MT) for each assembly.

The averaging of the cross sections generated by the fine group structure is based on conserving the reaction rates. The averaging integrals in the case of two group diffusion model are:

$$\sum_1 = \frac{\int_{0.625}^{\infty} \Sigma(E)\phi(E)dE}{\int_{0.625}^{\infty} \phi(E)dE} \text{ and } \sum_2 = \frac{\int_{0}^{0.625} \Sigma(E)\phi(E)dE}{\int_{0}^{0.625} \phi(E)dE}$$

1.4.2 TLINX Code:

TLINX an associated program that prepares cross-section tables from LEOPARD [6] for burnup calculations, making them usable in 2DB. For instance, if the fuel used is UO_2 with enrichments of 2.1%, 2.6%, and 3.1%, there are three distinct fuel materials plus a reflector. In this case, TLINX needs to be run three times, as each of the three materials undergoes burnup. The cross-sections for the reflector must be provided manually.

1.4.3 2DB Code:

It is a two-dimensional (X-Y, R-Z, R-θ) multi-group diffusion code for reactor criticality and burnup analysis. It calculates the effective multiplication factor (k_{eff}), material depletion rates, and can perform calculations using 2 or 4 energy groups. It accepts group constants generated by the cell codes, together with the material and geometrical maps of the reactor core, the user also defined spatial mesh structures, and output edit regions. The fuel shuffling capability in the 2DB code allowed actual operation to be simulated. 2DB code were used for routine calculations of core reactivity, depletion effects, and power and flux distribution.

The multi-group diffusion for steady state non critical reactor is:

$$-\nabla \cdot \boldsymbol{D}_g(\underline{r})\nabla\boldsymbol{\phi}_g(\underline{r}) + \boldsymbol{\Sigma}_{Rg}(\underline{r})\boldsymbol{\phi}_g(\underline{r}) = \frac{\boldsymbol{\chi}_g}{\boldsymbol{K}} \sum_{g'=1}^{G} \boldsymbol{\nu}_{g'}\boldsymbol{\Sigma}_{fg'}(\underline{r})\boldsymbol{\phi}_{g'}(\underline{r}) + \sum_{g'=1}^{G} \boldsymbol{\Sigma}_{sg'g}(\underline{r})\boldsymbol{\phi}_{g'}(\underline{r})$$

Figure (2) presents the flow chart of these code packages.

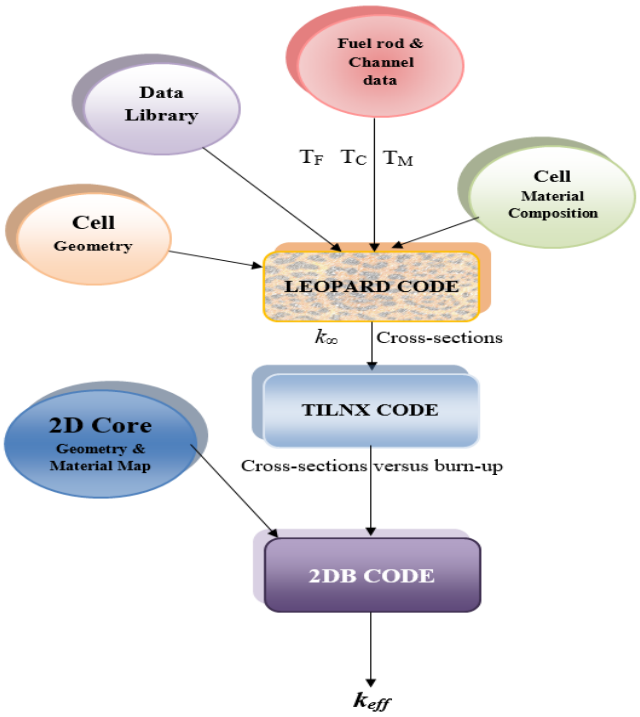


Figure 2 codes packages flowchart

2. Methodology:

This study utilized LEOPARD, TLINX, and 2DB nuclear code packages, to thoroughly simulate fuel shuffling in the AP1000 reactor under both clean and poisoned core conditions.

2.1 Clean core Simulations:

In the clean core scenario, where burnable absorbers or soluble boron are absent, the LEOPARD code was employed. Three input files were created to represent the three fuel enrichments present in the core (2.35%, 3.40%, and 4.45%). Additionally, a separate file for the water reflector was generated, two additional input files were created for the 4.45% enrichment, representing fresh fuel intended for shuffling, as shown in figure 3. A uniform

burnup period of 1095 days was applied across all simulations. Figure 4 shows a simplified diagram of the fuel shuffling process.

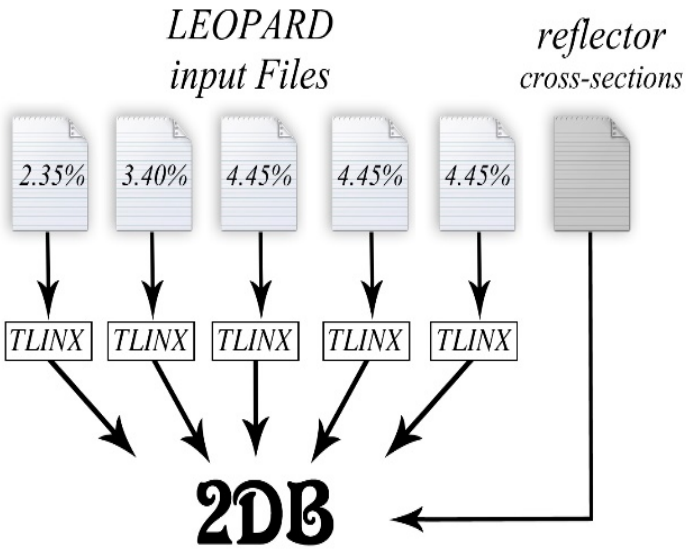


Figure 3 LEOPARD, TLINX and 2DB inputs

2.2 Poisoned Core Simulations: Accounting for Burnable Absorbers:

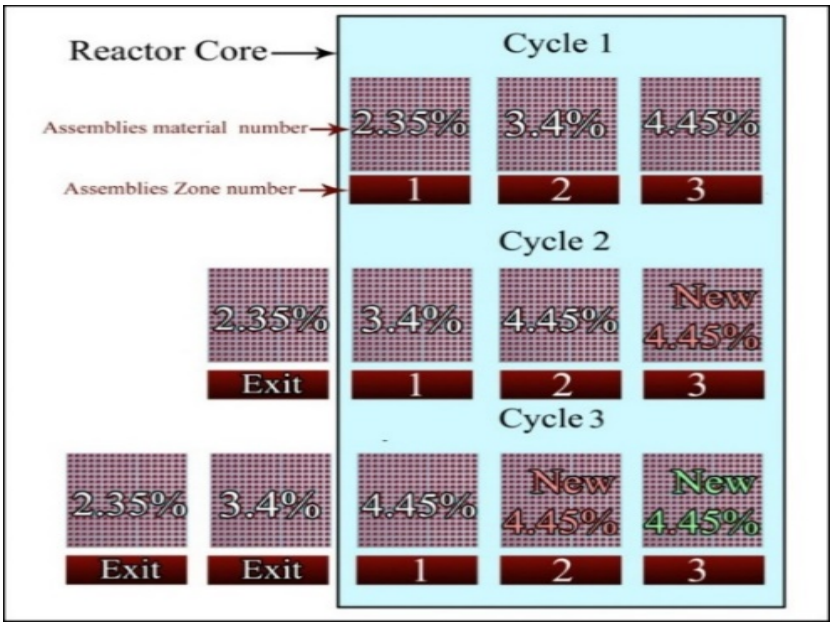
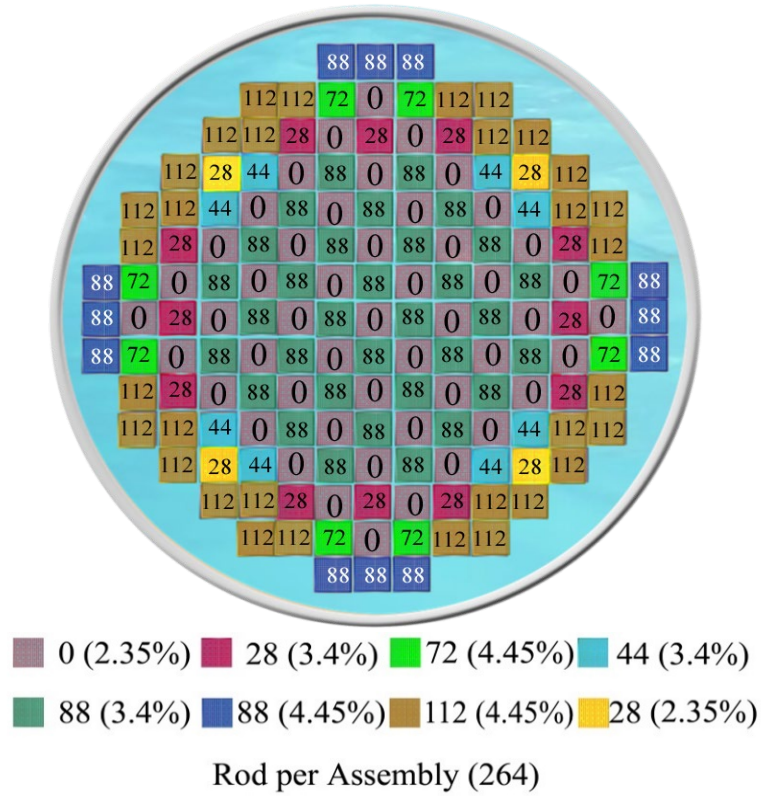


Figure 4 Fuel shuffling mechanism

The AP1000 core utilized Integrated Burnable Absorbers (IFBA), which are strategically positioned within specific fuel assemblies, as shown in Figure 5. This required consideration of

the impact of IFBA rods in the simulations. Due to LEOPARD's limitations in explicitly modeling



individual fuel rods, an alternative approach was implemented to ensure consistency with the clean core simulations. In this approach, all fuel rods were treated as having a uniform burnable poison coating, enabling the use of a consistent set of input files. To address the absence of specific IFBA rod placements, the Boron-10 number density was adjusted accordingly. This simplified methodology focused on analysing the overall criticality impact of the burnable poison.

3 RESULTS:

3.1 Multiplication Factor (k∞) Comparison

Table 1 shows the multiplication factor (k∞) for the three fuel assembly types at room temperature, as calculated by LEOPARD code. The results closely match with the AP1000 reference values from Westinghouse [4].

Table 1 values of k_∞ of the three fuel assembly types

Fuel assembly type	k_∞	
	LEOPARD	AP1000 DCD [2]
2.35 %	1.3392	1.3207
3.40 %	1.4306	1.436965
4.45 %	1.4833	1.506579

3.2 Reactivity Change during Shuffling

Tables 2 and 3 present the effective multiplication factor (k_{eff}) for both the clean and poisoned cores at the beginning of cycle (BOC) and end of cycle (EOC), respectively.

Table 2 clean core K_{eff} at each BOC and EOC of fuel shuffling

Cycle	k_{eff}	
First Cycle	BOC	1.34678
	EOC	1.17241
Second Cycle	BOC	1.28639
	EOC	1.13886
Third Cycle	BOC	1.26239
	EOC	1.10632

3.3 K_{eff} TRENDS OVER TIME

Figures 6 presents the K_{eff} evolution throughout the three shuffling cycles, as calculated by 2DB. The expected decrease in K_{eff} over time due to fuel depletion, highlighting the effectiveness of the fuel shuffling strategy in maintaining core reactivity

Table 3 poisoned core K_{eff} at each BOC and EOC of fuel shuffling

Cycle	k_{eff}

First Cycle	BOC	1.250841
	EOC	1.096053
Second Cycle	BOC	1.198532
	EOC	1.067002
Third Cycle	BOC	1.177263
	EOC	1.038033

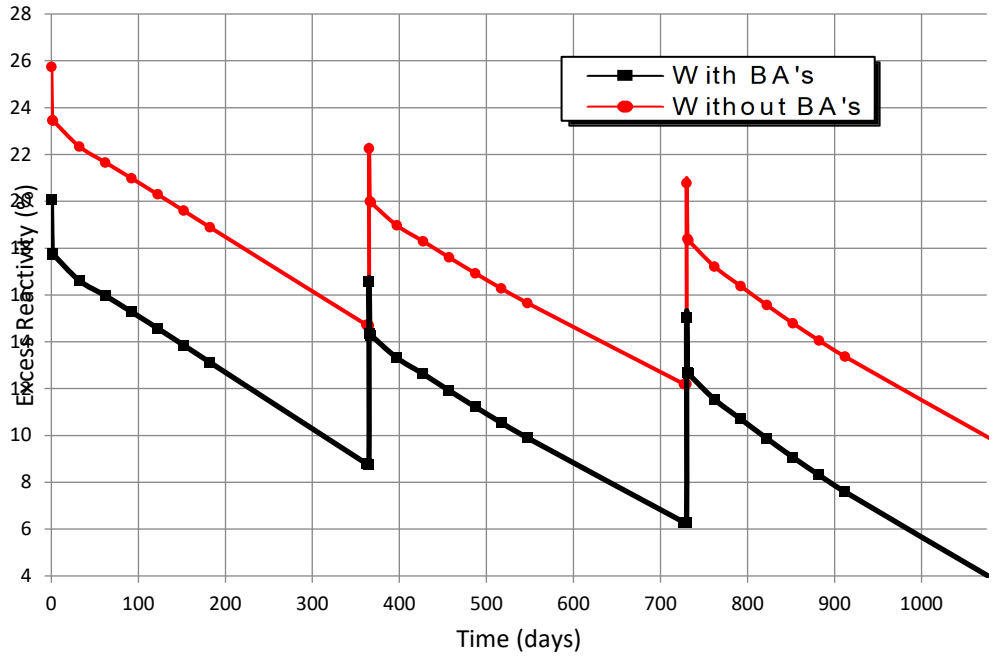


Figure 6 K_{eff} vs time for 3 cycles

4 CONCLUSION

This study demonstrates the effectiveness of fuel shuffling in the AP1000 reactor, offering significant benefits for both fuel consumption and waste management. By strategically rearranging fuel assemblies within the core, the shuffling process reduced the total number of assemblies required for three years of operation from 471 to 263. This translates to a nearly 44.16% reduction in spent fuel generation, additionally reducing environmental impact, minimizing radioactive waste, and simplifying management challenges.

Additionally, the simulations showed a consistent decrease in the effective multiplication factor (k_{eff}) over time due to fuel depletion. highlights the effectiveness of shuffling in maintaining core reactivity and ensuring stable power production.

The code packages used in the study proved to be capable of simulating the fuel shuffling process, suggesting that simpler, less computationally demanding approaches such as LEOPARD and 2DB can be valuable tools for initial assessments and optimization studies.

Building on the insights from this study and exploring further optimization strategies, future research can help develop even more efficient and sustainable fuel shuffling practices for the AP1000 reactor and beyond.

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