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The Effect of PWR Fuel Management Strategy on DUPIC Fuel Cycle

Wei Shen and Daniel Rozon
Institut de Génie Nucléaire
Ecole Polytechnique de Montréal
C.P. 6079, Succ. Centre-ville
Montréal (Québec), Canada H3C, 3A7

ABSTRACT

In the DUPIC fuel cycle, spent PWR fuel is recycled directly into CANDU reactors. Because of evolving fuel management strategies, the spent PWR fuel composition is expected to be different from one cycle to the next. Variations in reload fuel enrichment, loading patterns, and batch sizes, can thus result in nominal DUPIC core performance that will vary. In order to evaluate the sensitivity of the DUPIC fuel cycle on PWR fuel management strategy, we have made a preliminary study based on the linear reactivity model. A generic study of DUPIC fuel was then carried out by DRAGON/OPTEX-4/DONJON with ENDF/B-V library, for various spent PWR fuel types. The initial enrichment in PWR varied from 3.2 w/o to 4.5 w/o with the discharge burnup ranging from 30000 MWD/T to 52000 MWD/T. Our 3D full core calculations show that all nominal DUPIC cores have similar peak power, adjuster worth, CPPF, even similar average exit burnup regardless of initial enrichment in PWR fuel. It was found that the total discharge burnup of the tandem cycle (PWR+CANDU) is constant for the nominal DUPIC fuel cycle with a given initial enrichment in PWR. The increase in total burnup is entirely attributable to the PWR leg of the tandem cycle. This implies that the DUPIC fuel cycle may not be economical beyond a certain initial enrichment in PWR because of the fixed discharge burnup in CANDU and the rapidly increasing DUPIC fuel fabrication costs associated to the radioactivity of the spent PWR fuel.

I. Introduction

The use of DUPIC fuel in CANDU can lead to performance different from natural uranium fuel because both the initial reactivity and the reactivity decline curve with burnup are different. As fresh DUPIC fuel is made of spent PWR fuel, the nominal CANDU core performance may vary depending on the specification of the reference PWR fuel. Appropriate fuel management strategies will be key to ensuring acceptable costs, as well as to maintaining bundle and channel powers within acceptable limits in the CANDU reactor. Such fuel management strategies have been studied in recent studies of the DUPIC fuel cycle.[1, 2] The initial enrichment and discharge burnup of the reference spent PWR fuel used in our previous study[2] are 3.2 w/o and 32500 MWD/T, which reflect current typical 17x17 French standard 900 MWe PWR fuel assembly at the Daya Bay site in China when a 1/3-batch size and an Out-In loading pattern design are used.[3]

Spent PWR fuel composition varies from one cycle to the next, and from one reactor to another, depending on the specific fuel management strategy adopted. Variations in reload fuel enrichment, in loading patterns, and in batch sizes, can thus result in nominal DUPIC core performance that will vary. The current trend in PWR fuel management strategies is to use higher reload enrichments with a In-Out loading pattern design in order to achieve longer cycle length (18 months and more) and a higher discharge burnup. In order to evaluate the sensitivity of the DUPIC fuel cycle on PWR fuel management strategy, a parametric study was carried out based on the linear reactivity model. The initial PWR enrichment varied from 3.2 w/o to 4.5 w/o with the discharge burnup ranging from 30000 MWD/T to 52000 MWD/T. Each spent PWR fuel type represents a specific PWR fuel management strategy.

In this generic study of the DUPIC fuel cycle, calculations for a CANDU 6 reactor are carried out using the DRAGON/OPTEX-4/DONJON[4-6] chain of codes with the ENDF/B-V cross section library. In order to provide a coherent basis for the evaluation and comparison of the DUPIC fuel cycle for various spent PWR fuels, optimized burnup distributions were obtained for all cases with a 6-burnup-zone time-average model, followed by instantaneous DONJON calculations. The characteristics of different DUPIC cores such as average exit burnup, power peaking, CPPF and adjuster worth for various axial refueling schemes are summarized and compared to those of the 8-bundle shift (8BS) natural uranium core. From these, we may see the effect of various PWR fuel management strategies on the DUPIC fuel cycle.

II. Method for the Study of DUPIC Fuel Cycle

A 17x17 French standard 900 MWe PWR Fuel was used as reference PWR fuel for the DUPIC fuel cycle study. The geometry of a typical PWR fuel assembly is showed in Figure 1. The fuel assembly comprises 264 fuel rods distributed over 289 cell locations in an eight-of-square symmetry. This assembly has three distinct types of cell: 264 fuel rod cells, one instrumentation cell and 24 guide tube cells. The initial enrichment and discharge burnup of spent PWR fuel varies depending on specific PWR fuel management strategy adopted, as will be discussed in Section III.

The calculations of DUPIC fuel cycle in a CANDU 6 reactor are carried out with DRAGON/OPTEX-4/DONJON chain of codes in three steps, illustrated in Fig. 2:

- The few-group cross section database of DUPIC fuel is generated by the multi-group transport code DRAGON using an 89-group ENDF/B-V microscopic cross section library. PWR assemblies, CANDU cluster cells (bundles) and CANDU supercells were all modeled by the same code (DRAGON) with a single library with the same nuclide and group structures. The drawback of using potentially inconsistent computational codes and cross section libraries of previous studies will thus be avoided. The DRAGON options used for modeling of 2D PWR assembly, CANDU 2D-cluster cell and 3D supercell are illustrated in Table 1.

- The 3D-fuel management optimization code OPTEX-4 is used to obtain optimized discharge burnup distributions at equilibrium refueling for different DUPIC core. The optimization step is introduced to provide a coherent basis for comparison of various DUPIC core performances (i.e. the same form factor for the power distribution).

- Finally, instantaneous calculations were performed with the 3D diffusion code DONJON, from which both the channel power peaking factor (CPPF) and peak powers are estimated.

III. Preliminary Study of French 900MWe PWR Fuel Management Strategy

A. Linear Reactivity Model

Cycle-by-cycle scoping calculations provide the basic data for a utility to establish the long-term fuel management strategy. Basically, there are two standard methods for multi-cycle scoping calculation: one is the zero-dimensional linear reactivity model,[7] another is an exact 2D or 3D coarse mesh diffusion model. In the linear reactivity model, all spatial detail below that of the batch average level is suppressed and the principal focus is on the batch-wise rather than assembly-wise fuel depletion behavior. The linear reactivity model has been used widely in the past because of its simplicity and efficiency, since it does not require a core-loading pattern that needs to be determined through a formidable procedure. The linear reactivity model is used in this paper to predict the cycle lengths and the batch-averaged discharge burnup for each cycle when the proper input data such as batch enrichment, initial batch burnup, batch size and reloading strategies are given.

Batch Reactivity

For a reactor with I batches, the individual batch-average physics features are represented by fuel batch reactivity $\rho_i(\varepsilon_i, Bu_i)$, which can be approximated as linear function of the specified batch burnup Bu_i, for a given batch enrichment ε_i, and not of the detailed burnup history:

$$\rho_i(\varepsilon_i, Bu_i) = a_i + b_i * Bu_i \qquad i=1,\ldots I \tag{1}$$

The coefficients a_i and b_i are obtained by curve fitting from the DRAGON output, as shown in Figure 3, for the standard 17x17 PWR assembly illustrated in Fig. 1 (without burnable poisons).

Core Reactivity

For a reactor with I batches, the static core reactivity can be computed from the power weighted reactivity average of individual batches:

$$\rho_c(\rho_i, f_i, V_i, \rho_L) = \sum_{i=1}^{I} f_i V_i \rho_i \Big/ \sum_{i=1}^{I} f_i V_i - \rho_L \qquad i=1,\ldots I \tag{2}$$

Where

f_i = batch-wise power sharing of batch I
V_i = individual volume of batch I
ρ_L = the core leakage reactivity, which can be separated into radial and axial components. Strictly speaking, ρ_L is dependent on batch-wise power sharing f_i, loading pattern design, cycle burnup behavior.

Core Depletion

The batch-wise burnup at the end of cycle (EOC) can be computed easily from the assumption that batch-wise increment is proportional to its power sharing, that is

$$Bu^i_{EOC}(Bu^i_{BOC}, f_i, T_n) = Bu^i_{BOC} + f_i * T_n \qquad i=1,\ldots I \tag{3}$$

Where

Bu^i_{EOC} = Individual burnup of batch I at EOC, MWD/T
Bu^i_{BOC} = Individual burnup of batch I at beginning of cycle (BOC), MWD/T
T_n = Cycle length of cycle n, MWD/T

For the given batch enrichment, batch size, batch burnup and batch-wise power sharing, the cycle length can be calculated by a standard iteration technique, as shown in Figure 4.

A computer program (named SCOPE) was written for the multi-cycle scoping calculation described above. Results obtained with the linear reactivity model for cycles 1 to 4 are compared in Table 2 to the design reference data of the Daya Bay NPP.[8] The results demonstrate that the linear reactivity model based on DRAGON assembly calculations is quite reasonable for a multi-cycle PWR fuel management study.

B. Impact of Fuel Management Control Variables on Cycle Length and Discharge Burnup

For the PWR fuel cycle, the main fuel management control variables are reload enrichment, batch size and loading pattern if the cycle length or the discharge burnup is used as the objective function. A parametric study was performed with the SCOPE model introduced above for an Out-In loading pattern design. Results are shown in Fig. 5. The horizontal dashed lines in Figure 5 represent operating calendar months with an 80% capacity factor.

Reload Enrichment

For any PWR reload core with given batch size and loading pattern, reload enrichment is decided by the desired cycle length or discharge burnup. For the current 3.2 w/o reload enrichment with 1/3 batch size (52 fresh assemblies out of 157 total) and the out-in loading pattern design used at Daya Bay NPP, the equilibrium cycle length and discharge burnup are 271 equivalent full power days (EFPD) and 32.5 MWD/T respectively. As can be seen in Fig. 5, the cycle length could be extended to 400 EFPD if the reload enrichment is increased to 4.4 w/o. Assuming 80% capacity factor, the plant could then operate for 16 to 18 calendar months with an average discharge burnup at near 47000 MWD/T.

Reload Batch Size

The effect of batch size on average discharge burnup and cycle length is illustrated in Fig. 5 and compared with the traditional 1/3 batch size design in Table 3. We note that if batch size changes from 1/3 to 1/4 (i.e. the number of fresh assemblies goes from 52 to 40), the average discharge burnup increases by 6% while cycle length decreases by 19%. Thus the advantage of better fuel utilization leads to a somewhat reduced plant capacity factor. The optimum batch size is thus related to technical and operational conditions. It can be adjusted from cycle to cycle to satisfy electricity demand and maintenance schedule. For example, with 4.2 w/o reload enrichment and 1/2.5 batch size design, the plant can operate on extended 18 calendar months, with a 42000 MWD/T average discharge burnup. However, if 1/4 batch size is used instead, the plant can operate on 13 calendar months only, but the average discharge burnup can be increased up to 48000 MWD/T.

Reload Core Loading Pattern

The above results were obtained assuming an Out-In loading pattern (LP), illustrated in Fig. 6. The Out-In LP, currently used for Daya Bay, is helpful for power flattening but leads to higher leakage and lower discharge burnup. On the other hand, the Low-Leakage Loading pattern, also called In-Out LP, is beneficial for extension of cycle length. The L3P pattern, also shown in Fig. 6, is currently practiced in over half of PWR cores around the world. In-Out LP design is an effective procedure to increase cycle length and discharge burnup because the fresh fuel assemblies are positioned in the inner-core where neutron importance is greater. For 1/3 batch size design, both equilibrium cycle length and average discharge burnup could increase by as much as 5-6% if L3P is used instead of Out-In LP. We note that the L3P pattern requires the use of burnable poisons in the fresh assemblies to suppress power peaking during the first cycle.

The current trend in PWR fuel management strategy is to use higher reload enrichments with an In-Out loading pattern design in order to achieve a longer cycle length (18 months and more) and a higher discharge burnup. Thus, with an appropriate combination of reload enrichment, batch size and LP design, the fuel management strategy will lead to the desired cycle length and discharge burnup

IV. Effect of PWR Fuel Management Strategy on DUPIC Core Performance

From the calculations reported in the previous section, we see that the spent PWR fuel type, as distinguished by initial enrichment and discharge burnup, varies from one cycle to the next depending on the specific fuel management strategy adopted. These variations in spent PWR fuel composition can result in varying nominal DUPIC performance in CANDU. We shall now study the DUPIC core performance with various spent PWR fuel types, each fuel type representing a specific PWR fuel management strategy.

A. Selection of Spent PWR Fuel Types

Each point in Figure 5 represents a typical PWR fuel management strategy, and correspondingly produces a different spent PWR fuel type. It is impractical for us to simulate all possible spent PWR fuel types for the DUPIC fuel cycle study. Five initial enrichments, ranging from 3.2 w/o to 4.5 w/o, are selected as representative enrichments in this study. For each enrichment with the Out-In LP design, variation in batch size from 1/2.5 to 1/4 can result in quite large differences in discharge burnup of the spent PWR fuel as shown in Table 4. We shall therefore consider fifteen spent PWR fuel types, with the discharge burnup ranging from 30000 MWD/T to 52000 MWD/T. Since the difference in discharge burnup caused by loading pattern variation (ex. Out-In vs. In-Out) is of the same order as the difference introduced by changing the batch size, we will not model this type of fuel separately.

Results obtained in CANDU with these 15 PWR fuel types are given in Table 5. Some CANDU lattice K-infinity curves of these DUPIC fuels are also illustrated in Figures 7 and 8. For the same initial enrichment in PWR, we note that the smaller batch size produces a higher discharge burnup in spent PWR fuel, and thus leads to lower the initial CANDU lattice K-infinity in the corresponding DUPIC fuel, as shown in Figure 7. On the other hand, for the same 1/3-batch size design in PWR, a higher enrichment produces a higher discharge burnup in spent PWR fuel, but very similar K-infinity curves in CANDU as shown in Figure 8. This suggests that a similar exit burnup in the CANDU core will be obtained, regardless of the initial enrichment in PWR.

B. Various DUPIC Core Performance

Prediction of the time-average power distribution under equilibrium refueling is essential for the DUPIC-fueled CANDU core design because it ensures that limits on the fuel will not be exceeded during normal operation of the reactor. In order to provide a coherent basis for comparison of various DUPIC core performances, we wish to find the optimal time-average fueling rate distribution over the reactor that minimizes fueling costs and meets the same operating constraints.

With the traditional 2-burnup-zone approach for the time-average model, the core is divided into two radial zones and the discharge burnup of two zones are determined manually such that the reactor is critical and the peak channel power is minimized or at least is acceptable. In this paper, the time-average equilibrium core performance was calculated with a 6-burnup-zone design instead of the simple 2-burnup-zone approach, as shown in Figure 9. The optimized radial discharge burnup distributions of different DUPIC cores were calculated by OPTEX-4 to achieve minimum fueling costs (i.e. maximize average discharge burnup) with a 6.5 MW limit imposed on maximum channel power. During the optimum search, all 14 ZCU water levels were assumed to remain at nominal 50% for calculation simplicity.

The time-average equilibrium core is not the actual core condition during the continuous refueling operation. Thus, the time-average distribution does not yield the actual peaking power resulting from the application of a particular refueling scheme in CANDU reactor. Because of this, instantaneous reactor calculations are required. A simple approach based on the patterned channel age model was implemented in DONJON to allow us to perform instantaneous calculations for various DUPIC cores, from which both the channel power peaking factors (CPPF) and peak powers are estimated.[2]

Results for the 15 different DUPIC cores are presented in Table 5. The characteristics of different DUPIC cores such as average exit burnup, power peaking, CPPF and adjuster worth for various axial refueling schemes are summarized and compared to those of the 8BS natural uranium core. From these, we may see the effect of various PWR fuel management strategies on the DUPIC fuel cycle.

For a given batch-size design in PWR, although the higher enrichment leads to higher discharge burnup in spent PWR fuel, its effect on initial reactivity of corresponding DUPIC fuel is relatively small, as noted above. Our 3D full core calculations show that these DUPIC cores (numbered 2, 5, 8, 11and 14 in Table 5) have similar peak power, CPPF, even similar average exit burnup regardless of initial enrichment in PWR fuel. On the other hand, significantly different average exit burnup values of 18.5 GWD/T, 15.2 GWD/T and 12.5 GWD/T were found corresponding to 1/2.5 batch, 1/3 batch and 1/4 batch size design in PWR fuel, as shown in Figure 10.

For the given initial enrichment in PWR, the discharge burnup in spent PWR increases when the batch size decreases from 1/2.5 to 1/4. It is also interesting to note that the average exit burnup of DUPIC fuel in CANDU decreases linearly as a function of discharge burnup in PWR, as shown in Figure 11. We therefore conclude that the total discharge burnup (PWR+CANDU) is constant for the DUPIC fuel cycle with a given initial enrichment in PWR. When initial enrichment is varied in PWR from 3.2 w/o to 4.5 w/o, total burnup varies from 47.6 GWD/T to 64.6 GWD/T, as shown in Figure 12. The increase in total burnup is entirely attributable to the PWR leg of the tandem cycle. This implies that the DUPIC fuel cycle may not be economical beyond a certain initial enrichment because of the fixed exit burnup in CANDU and the rapidly increasing DUPIC fuel fabrication costs associated to the radioactivity of the spent PWR fuel. However, limiting values depend on many factors such as the price of natural uranium, the cost of enrichment services, fabrication costs for DUPIC fuel, and of course on waste disposal costs.

The results shown in Table 5 are somewhat conservative because the same amount of natural Dy in the center element was used for all DUPIC fuels to reduce positive void reactivity, regardless of spent PWR fuel types. As a result, more than 3000 MWD/T burnup penalty is introduced for each DUPIC fuel. We could reduce the amount of natural Dy for the DUPIC fuels with lower initial reactivity to obtain higher exit burnup in CANDU.

V. CONCLUSION

Our 3D full core calculations show that all nominal DUPIC cores have similar peak power, adjuster worth, CPPF, even similar average exit burnup, regardless of initial enrichment in PWR fuel. Approximate values of 18.5 GWD/T, 15.2 GWD/T and 12.5 GWD/T were found corresponding to 1/2.5-batch, 1/3-batch and 1/4-batch size designs in PWR. We found that the resulting average exit burnup of DUPIC fuel in CANDU decreases linearly as a function of discharge burnup of spent PWR fuel. As a consequence, the total discharge burnup for the tandem cycle (PWR+CANDU) is approximately constant for the nominal DUPIC fuel cycle with a fixed initial enrichment in PWR. The increase in total burnup with initial enrichment is entirely attributable to the PWR leg of the tandem cycle. This implies that the DUPIC fuel cycle may not be economical beyond a certain initial enrichment because of the fixed exit burnup in CANDU and the rapidly increasing DUPIC fuel fabrication. However, limiting values depend on many factors such as the price of natural uranium, the cost of enrichment services, fabrication costs for DUPIC fuel, and of course on waste disposal costs.

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Table 1: DRAGON Modeling of PWR and CANDU

DRAGON Model	PWR Assembly	CANDU cluster	CANDU supercell
Library	89 Group WIMSLIB ENDF/B-VI		
Geometry	1/8 2D Cartesian 17x17 Pins	2D Cluster 43 Elements	3D Supercell
Self-Shielding	JPMT	EXCELT	EXCELT
Transport calculation	SYBILT	EXCELT	EXCELT
Buckling & leakage	Critical Buckling Search, B_1 Homogeneous Leakage Method with PNL		
Depletion calculation	Yes	Yes	No

Table 2: Comparison of SCOPE Results to Daya Bay NPP Nuclear Design Reference

Cycle	Discharge Burnup (MWD/T) reference SCOPE	Cycle Length (MWD/T) reference SCOPE
1	13296 13258	14100 14048
2	10399 9728	25100 24452
3	9571 9305	28460 27631
4	10680 10674	28026 27512

Table 3: Effect of Reload Batch Size on PWR Core Performance

Batch Size	Relative Discharge Bu	Relative Cycle Length
2	0.82	1.26
2.5	0.93	1.13
3	1.00	1.00
4	1.06	0.81

Table 4: Effects of Batch Size and Loading Pattern on Discharge Burnup (GWD/T)

Enrichment (w/o)	Out-In 2.5 Batch	Out-In 3 Batch	Out-In 4 Batch	In-Out 3 Batch
3.2	30.0	32.5	34.6	34.5
3.5	33.9	36.5	38.9	38.6
3.8	37.3	40.3	42.9	42.5
4.2	42.0	45.4	48.3	47.7
4.5	45.3	48.9	52.0	51.3

Table 5: Characteristics of Different DUPIC Core Performance with Various Spent PWR Fuel Types

Initial Enr. in PWR	Batch Size in PWR	DUPIC Fuel Types	Fueling Scheme in CANDU	Equilibrium Discharge Burnup (GWD/T)			Instantaneous Calculation		CPPF
				In PWR	In CANDU	Total	Peak Channel Power (kW)	Peak Bundle Power (kW)	
Nat. U	---	---	8	0	7.45	7.45	6799	866	1.074
3.2 w/o	1/2.5	1	2	30	17.71	47.71	6821	857	1.074
			4		17.96	47.96	7297	936	1.156
	1/3	2	2	32.5	15.10	47.60	6754	837	1.062
			4		15.26	47.76	7181	879	1.136
	1/4	3	2	34.6	13.00	47.6	6741	806	1.056
			4		13.10	47.7	7084	850	1.119
3.5 w/o	1/2.5	4	2	33.9	17.75	51.65	6814	853	1.072
			4		17.99	51.89	7286	926	1.154
	1/3	5	2	36.5	15.08	51.58	6759	837	1.062
			4		15.23	51.73	7165	876	1.133
	1/4	6	2	38.9	12.72	51.62	6718	794	1.054
			4		12.81	51.71	7055	848	1.114
3.8 w/o	1/2.5	7	2	37.3	18.24	55.54	6813	852	1.072
			4		18.48	55.78	7294	924	1.154
	1/3	8	2	40.3	15.19	55.49	6754	831	1.061
			4		15.33	55.63	7156	871	1.131
	1/4	9	2	42.9	12.66	55.56	6703	793	1.053
			4		12.74	55.64	7039	848	1.111
4.2 w/o	1/2.5	10	2	42.0	18.63	60.63	6812	849	1.072
			4		18.86	60.86	7291	917	1.154
	1/3	11	2	45.4	15.20	60.60	6743	820	1.060
			4		15.33	60.72	7138	865	1.128
	1/4	12	2	48.3	12.42	60.42	6690	799	1.050
			4		12.48	60.78	7011	847	1.106
4.5 w/o	1/2.5	13	2	45.3	19.07	64.37	6817	849	1.072
			4		19.31	64.31	7293	914	1.154
	1/3	14	2	48.9	15.46	64.36	6741	818	1.059
			4		15.59	64.49	7135	864	1.127
	1/4	15	2	52.0	12.51	64.51	6684	802	1.049
			4		12.57	64.57	7000	847	1.104

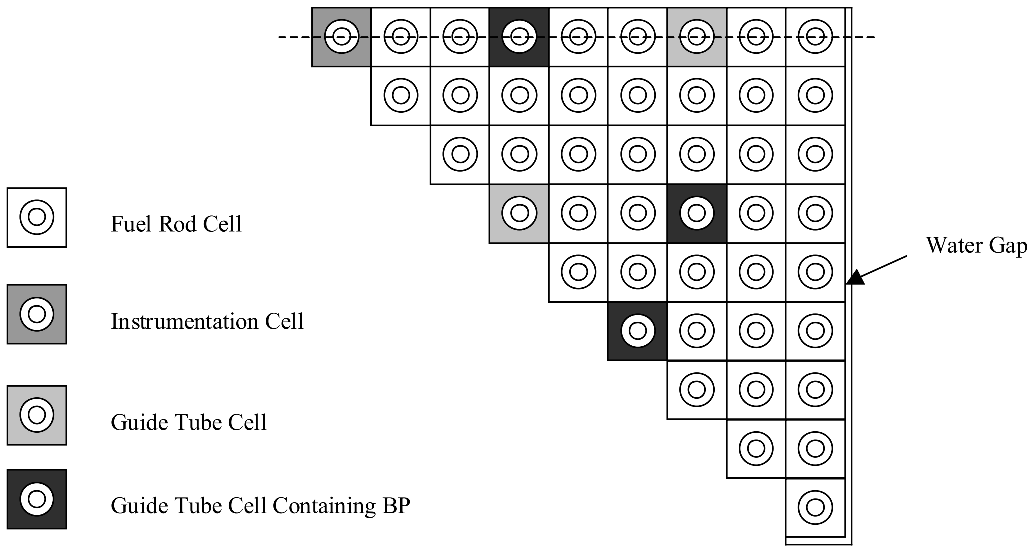

Figure 1: Geometry of One-Eighth PWR BP Assembly

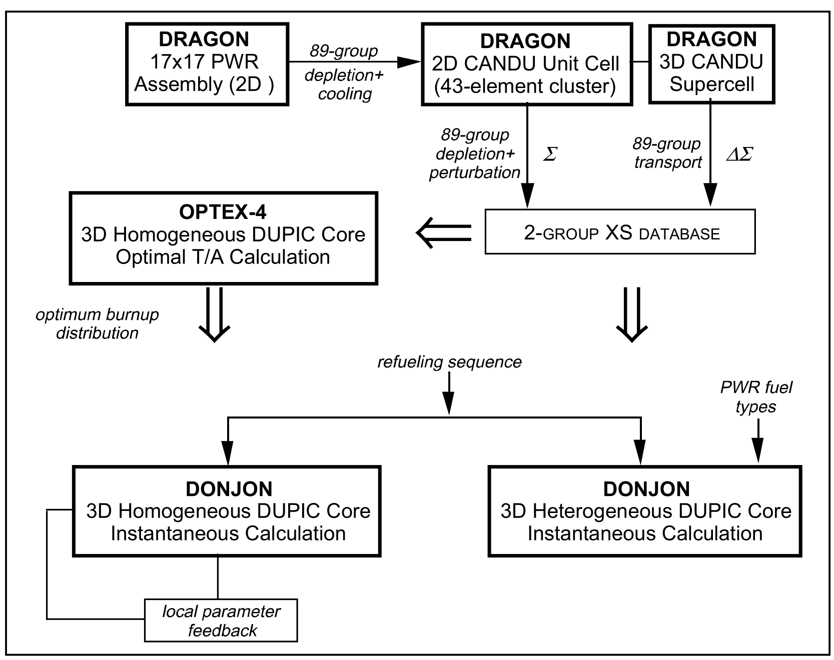

Figure 2: Chain of codes for the study of the DUPIC fuel cycle

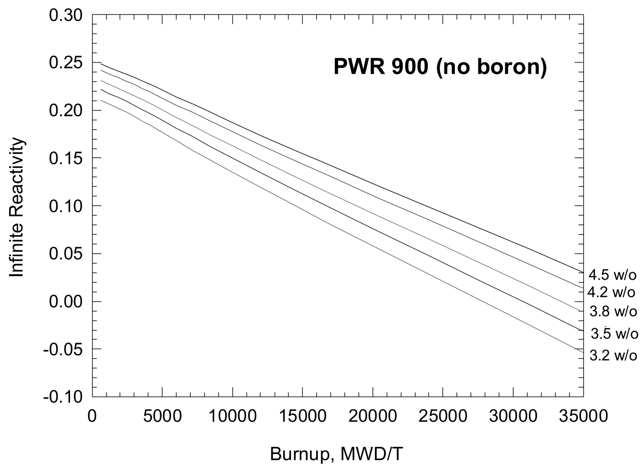

Figure 3: Lattice Reactivity vs. Burnup for 17x17 French Standard PWR Fuel Assembly (DRAGON)

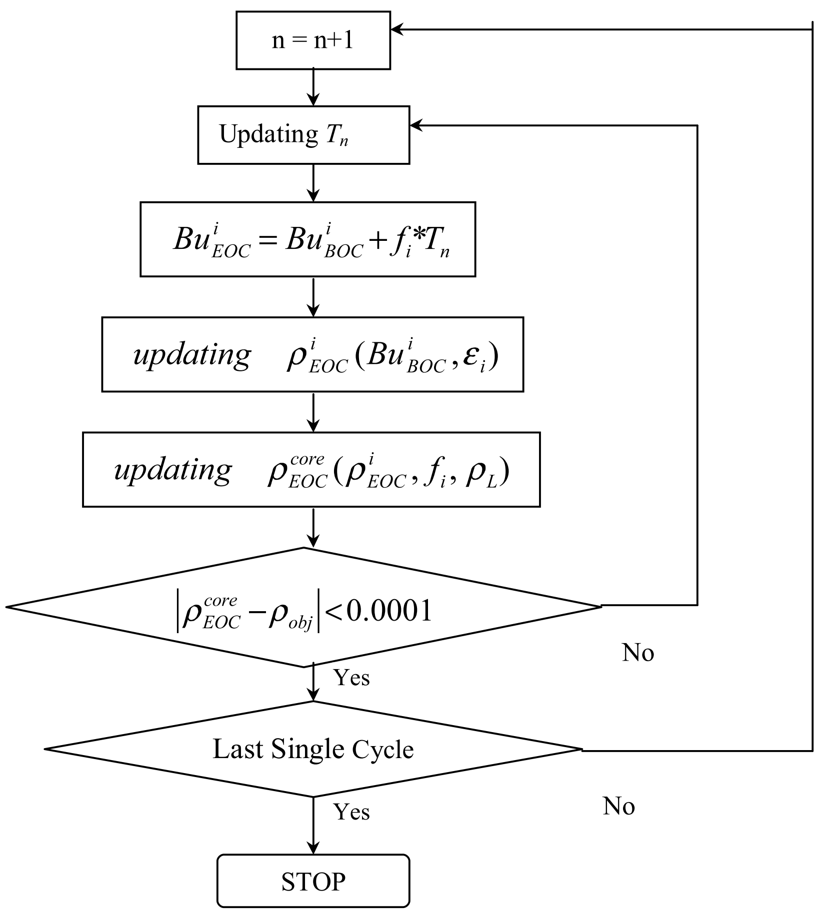

Figure 4: Iteration Diagram for Multi-cycle Scoping Calculation

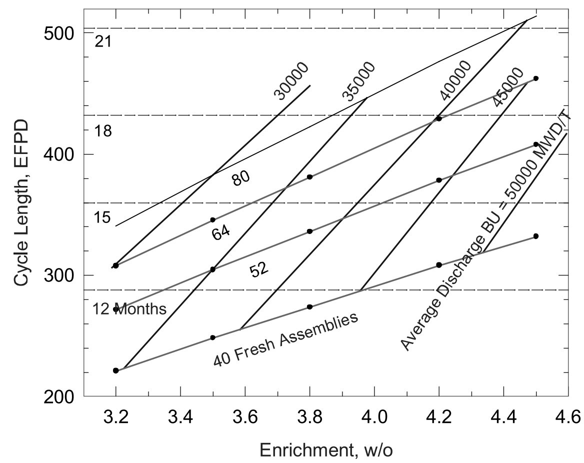

Figure 5: Cycle Length and Average Discharge Burnup vs. Reload Enrichment and Batch Size for French 900 MWe PWR (Out-In Pattern)

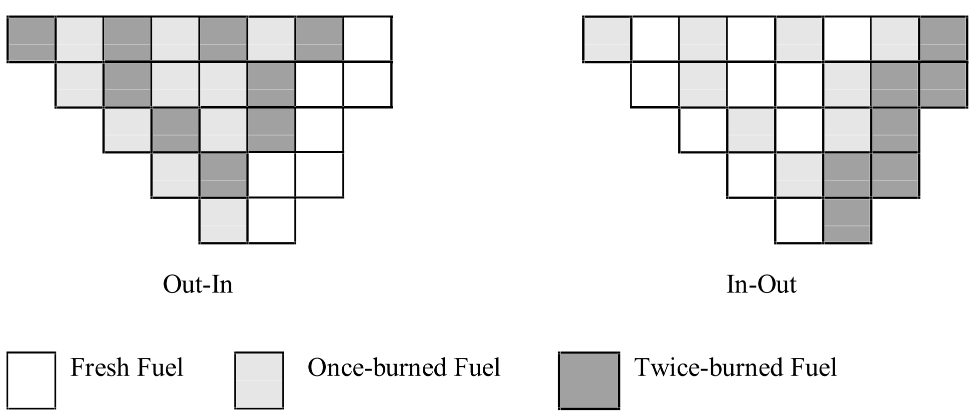

Figure 6: Layout of different Loading Pattern design for Daya Bay NPP

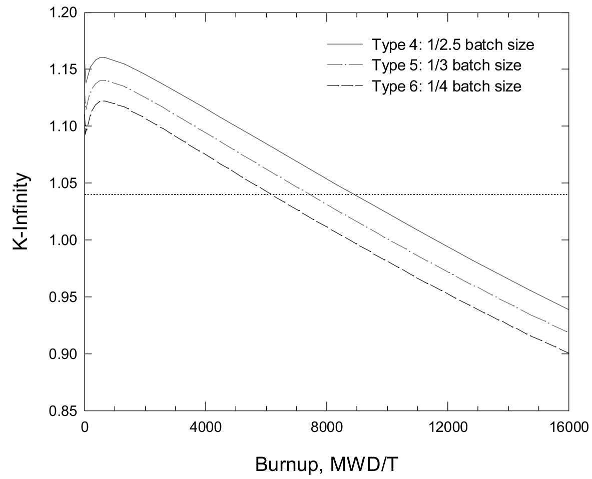

Figure 7: CANDU Lattice K-infinity for Various DUPIC Fuel Types
(3.5 w/o Initial Enrichment with Different Batch Size Design in PWR)

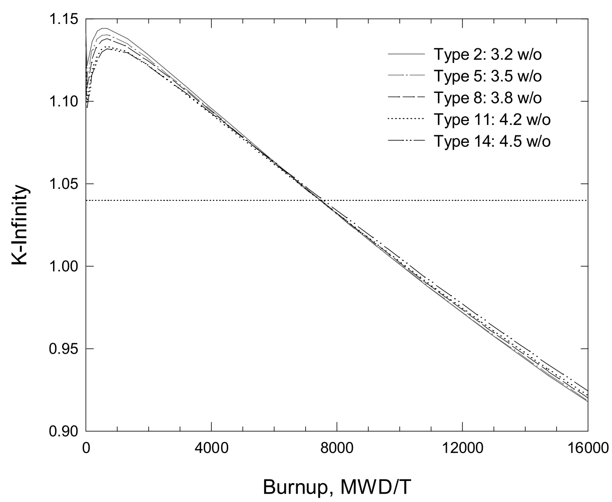

Figure 8: CANDU Lattice K-infinity for Various DUPIC Fuel Types
(Different Initial Enrichment with 1/3 Batch Size Design in PWR)

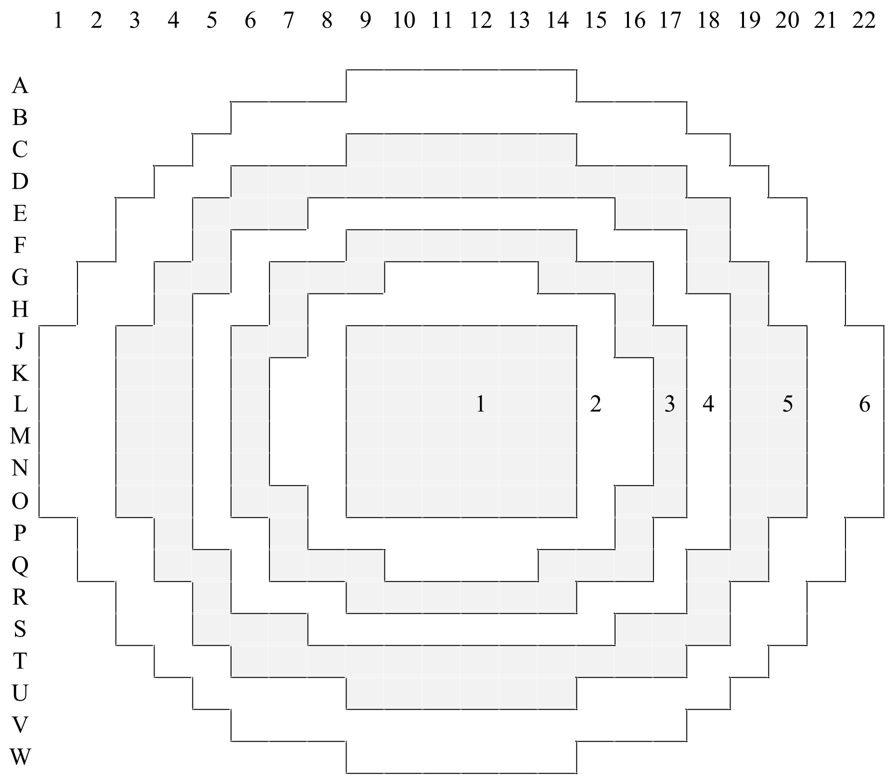

Figure 9: Boundary of 6 Radial burnup zones in CANDU-6 core

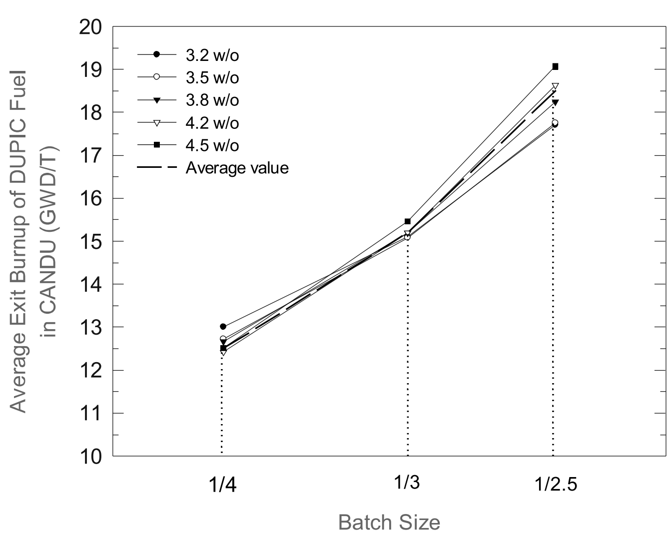

Figure 10: Sensitivity of Average Exit Burnup of DUPIC Fuel on Various Batch Size Design in PWR

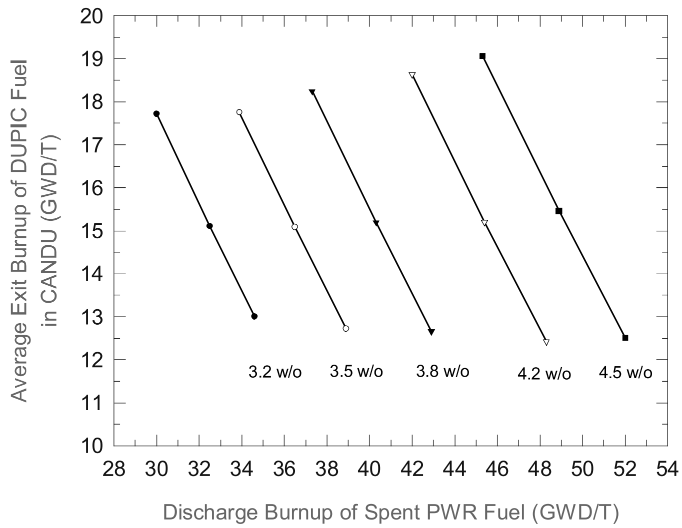

Figure 11: Average Exit Burnup of DUPIC Fuel vs. Discharge Burnup of Spent PWR Fuel

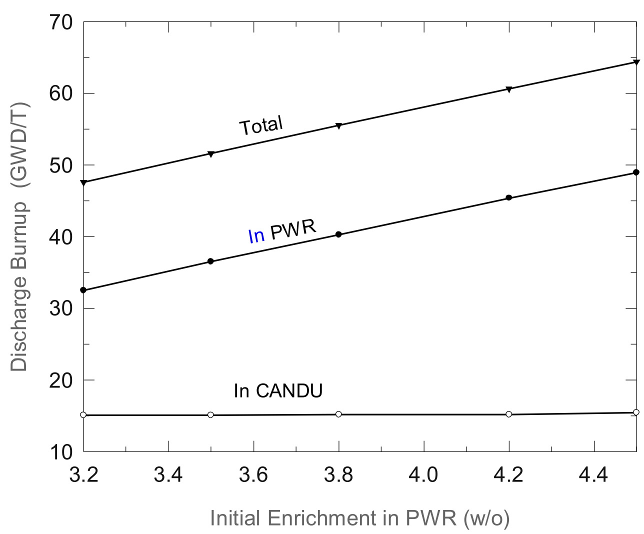

Figure 12: Total Discharge Burnup (PWR+CANDU) for DUPIC Fuel Cycle
with Various Initial Enrichment and Same 1/3 Batch Size Design in PWR