A NEW DESIGN OF A PWR FUEL ASSEMBLY FOR DIRECT RECYCLING OF SPENT FUEL

N. MOHAMED
Atomic Reactors Department, Atomic Energy Authority
Cairo, Egypt
Email: nader.mohamed@eaea.org.eg

Abstract

A new design for the PWR fuel assembly has been proposed, in a previous work, for direct use of the PWR spent fuel without chemical or dry processing has been proposed. The proposed designed assembly consists of four zircaloy-4 tubes. Each tube contains 7 or 8 CANDU fuel bundles stacked end to end. The zircaloy-4 tube has the same inner diameter of CANDU pressure tube. The PWR spent fuel bundles will be transferred directly to CANDU reactors without processing. The CANDU reactor is preferably be built in the same site to avoid the problem of transportations. In the current work, a different case has been studied for improving the uranium utilization and for reducing the high level waste. Generally, the calculations resulted in that the burnup would be increased by about 35%. The proposed strategy would reduce the high level waste. Moreover, direct recycling of the spent fuel would degrade the plutonium vector which enhances the proliferation resistance.

1. INTRODUCTION

Recycling of spent nuclear fuel has an importance for improving the uranium utilization, for reducing the high level nuclear waste and for reducing the amount of plutonium produced in spent fuel per unit energy. Extraction of fissile isotopes from the spent fuel using chemical processing for recycling in reactors has been proposed early when the commercial power plants were built. Since two or three decades, some countries like USA stopped reprocessing as a political consideration of weapons proliferation. Also, reprocessing is not economically attractive [1].

The Direct Use of Spent PWR Fuel In CANDU Reactors (DUPIC), proposed in Korea, employs dry processing to convert spent LWR fuel into CANDU fuel. The general method of DUPIC is re-fabricate the PWR spent fuel in a DUPIC plant such as AIROX [2,3] for CANDU bundles in which the cladding is punctured and fission gasses are captured. The spent fuel pellets are reduced to a fine powder in furnaces and then milled, shaped and sintered into CANDU fuel pellets. The estimation of the economics of DUPIC cycle is difficult because of the complexity of DUPIC processing facility and the transportation of highly radioactive materials from the PWR to this facility and from this facility to the CANDU reactor [4]. One simple way of recycling the PWR spent fuel is by cutting the fuel elements into CANDU length (~50 cm) and welding the end-caps and then constructing the CANDU bundles from 48 or 61 element.

In a previous work [5, 6], a new PWR design has been proposed for direct recycling of the PWR spent fuel without processing. The PWR spent fuel bundles will be transferred directly to CANDU reactors (after a certain cooling time) without processing. The CANDU reactor is preferably be built in the same site to avoid the problem of transportations. The proposed designed assembly consists of four zircaloy-4 tubes. Each tube contains 7 or 8 CANDU fuel bundles stacked end to end. The zircaloy-4 tube has the same inner diameter of CANDU pressure tube. The space between the tubes contains 44 low enriched UO2 fuel rods and 12 guide tubes as shown in Fig. 1. Almost, the same pitch to rod diameter ratio inside the zircaloy-4 tubes and between them is considered. The new design changes the fuel rod configuration from square lattice to be approximately hexagonal lattice. The assembly has the same pitch as the 17x17 Westinghouse fuel assemblies (21.5 cm). The PWR built using the new fuel assembly can be considered as a vertical tubes reactor but with a number of UO2 fuel rods between the tubes under the same pressure. The new design applies the Integrated Fuel Burnable Absorber (IFBA) on the outer ring of each fuel bundle as a mean of reactivity control. The length of the assembly is 396 cm for 8 CANDU bundles. Table 1 give a comparison between the reference and proposed assemblies.

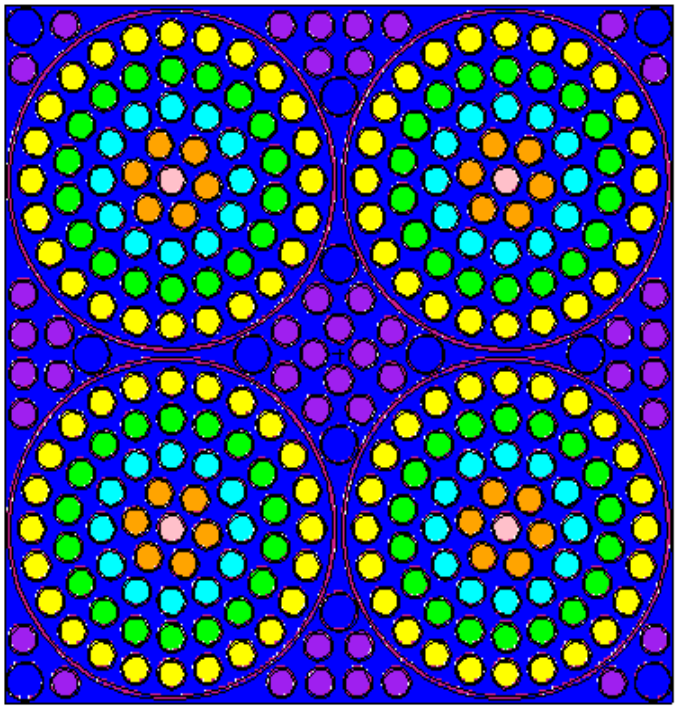

FIG. 1. The Proposed PWR assembly as simulated using MCNPX Code.

TABLE 1. REFERENCE AND PROPOSED PWR ASSEMBLIES [5]

Parameter	Reference PWR assembly	Proposed PWR assembly
Construction	17x17 UO_2 fuel rods bundle: - 264 fuel rods. - 25 guide tubes.	- Four zircaloy-4 tubes contain 7 or 8 CANDU fuel bundles stacked end to end. - 44 low enriched UO_2 rods between the zircaloy-4 tubes. - 12 guide tubes.
fuel rod configuration	Square lattice	Approximately hexagonal lattice.
Dimensions	Fuel rod inner/outer diameter: 8.19/9.5 mm. Fuel cladding thickness: 0.57 mm Assembly pitch: 21.5 cm. Fuel active length: 3.66 m.	Zircaloy-4 tube inner/outer diameters: 5.17/5.3 cm. Fuel rod inner/outer diameter: 8.19/9.5 mm. Fuel cladding thickness: 0.57 mm Assembly pitch: 21.5 cm. CANDU fuel bundle length: 49.53 cm.
Burnable poisons	IFBA coating on fuel pellet surfaces (of around 100 fuel rods).	IFBA coating on fuel pellet surfaces of outer fuel ring of each fuel bundle.
Operating power	~ 17.5 MW	~ 17.5 MW

The proposed new PWR fuel assembly design has the advantages of recycling directly the spent fuel without any processing that eliminates the need of re-fabricating the spent fuel for the CANDU fuel bundles. The fuel cycle strategy using this new design enables to operate the PWRs with the single-batch loading strategy for longer core cycle. Recycling directly the spent PWR fuel will increase the fuel burnup keeping it at the limits of PWR multi-batch loading strategy or higher.

CANDU-6 has advantage of that it is fuelled with natural UO2 but it discharges the spent fuel at low burnup of about 7.5 MWd/kgU and therefore the quantities of high level waste that are produced per unit energy from CANDU-6 reactors is much higher than that produced from Light Water Reactors (LWRs). Also, with this low burnup, the quality of plutonium in CANDU-6 spent fuel is high which is against the proliferation resistance. The proposed strategy of recycling the PWR spent fuel in CANDU-6 reactor would reduce the high

level waste. Moreover, direct recycling the spent fuel would degrade the plutonium vector which enhances the proliferation resistance.

In this paper, it is assumed that the proposed assembly will build a three-batch loading PWR and the spent bundles will be recycled in the on power refuelling CANDU-6 reactor focusing on uranium utilization improvement, reduction of high level waste and proliferation resistance enhancement. The effect of this new design on the moderator temperature coefficient of reactivity, power peaking and CANDU coolant void reactivity have been calculated in the previous work [5,6].

2. CASE STUDY AND SIMULATION

The 3411 MWth Westinghouse PWR has been selected as a reference case in this paper. The reactor core is built from 193 assemblies with 17x17 pins fuel assembly. CANDU-6 reactor was used as a reference reactor for recycling of the PWR spent fuel bundles. The Monte Carlo code MCNPX2.7.0 [7] has been used in this research for the calculations. The code is compatible with MCNP5 with many additional capabilities including material depletion/burnup calculations. All standard evaluated nuclear data libraries used by MCNP can be used by MCNPX 2.7.0.

The fuel lattice cells of the two reactors of interest have been simulated using the code. A criticality calculation (KCODE calculations) and the BURN cards are used to calculate the system criticality and the burnup of the fuel and fuel inventory after time intervals. A total of 150 cycles per burnup step of which 30 were skipped and 5000 histories per cycle were used to reach standard deviation of the $k\infty$ values less than 0.1%. In BOPT card the Tier 3 fission products, which comprise fission products in ENDF/B-VII.0 library was selected. The best matching temperature for the fuel is 900 K and for the cladding and moderator is 600 K. Figs. 1-3 show the MCNPX simulation of the lattice cells of the proposed and reference PWR assemblies and CANDU-6, respectively.

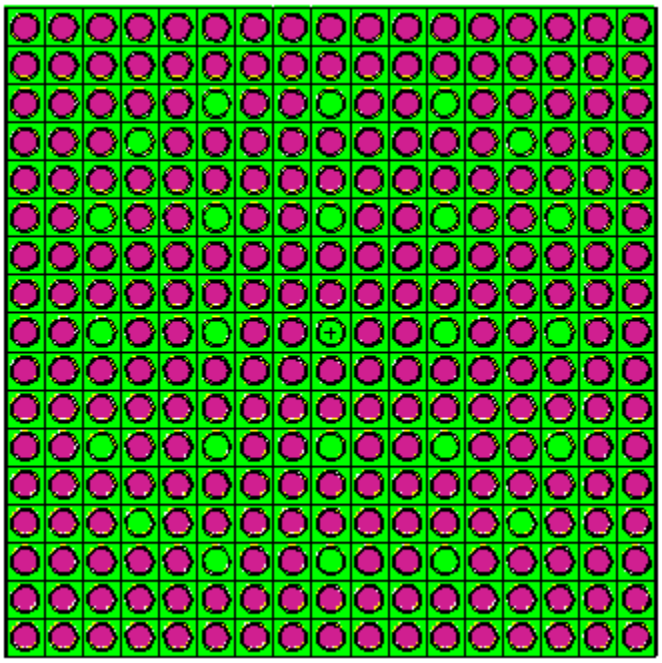

FIG.2. MCNP model of the reference PWR fuel assembly.

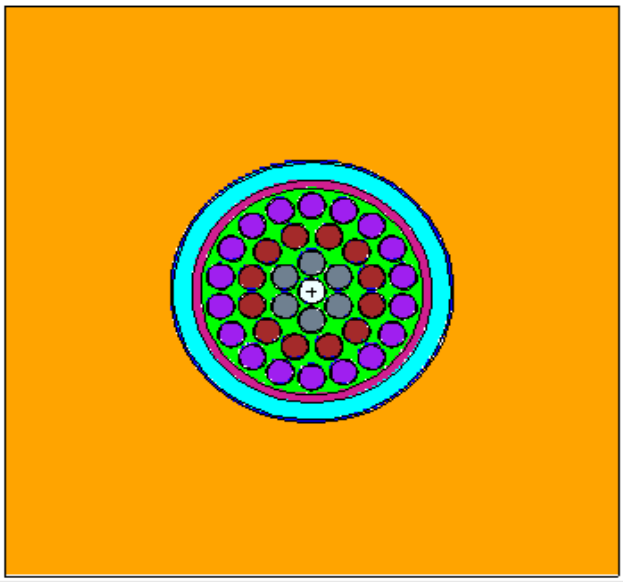

FIG. 3. MCNP model of CANDU-6 lattice cell.

3. RESULTS AND DISCUSSIONS

Considering a 3% leakage effect in PWRs, the single batch discharge burnup can be calculated where the infinite medium eigenvalue, k∞ decreases to 1.03. For three-batch core and 450 Effective Full Power Days (EFPD) core cycle length, each fuel batch spends 1350 EFPD in the reactor with average discharge burnup of 51.7 MWd/kgU.

The fuel enrichment in the reference PWR assembly is 4.5 w/o U-235 and for the proposed assembly it is 4.7 w/o U-235 in the rods inside the zircaloy-4 tubes and 3.4 w/o enriched UO2 rods in the spaces between the tubes and therefore the average enrichment is 4.5 w/o U-235 in the whole fuel. In the reference fuel assembly, it is assumed that the IFBA is applied on the all rods with concentration of 0.31 mgB-10/cm while in the proposed assembly it is applied on the outer rings of the CANDU bundles inside the zircaloy-4 tubes with concentration of 0.62 mgB-10/cm Fig. 4 shows the depletion history (k∞ vs. EFPD) for the reference and proposed fuel assemblies. While the reference assembly discharges the fuel with burnup of 51.7 MWd/kgU, the proposed assembly will discharge the fuel with burnup of 42.8 MWd/kgU (see Table 2). This is because the amount of UO2 fuel in the proposed assembly is increased.

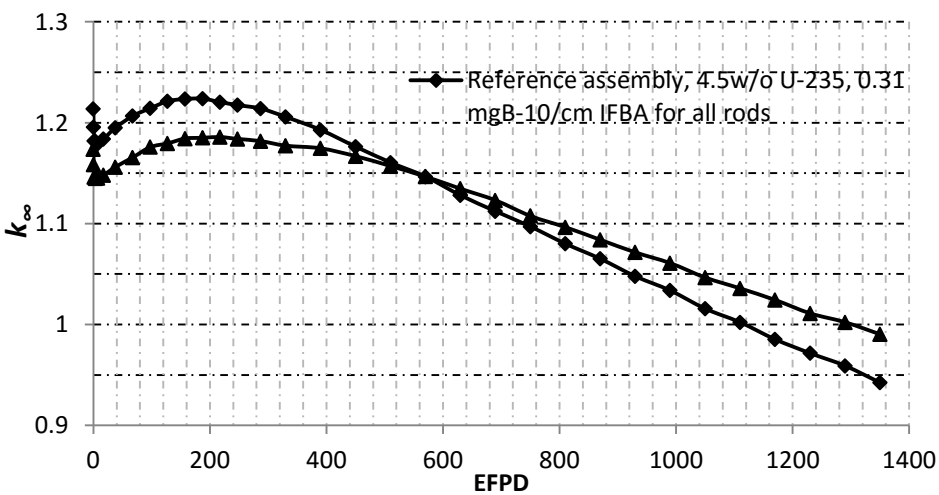

FIG. 4. Depletion history of the reference and proposed PWR assemblies.

TABLE 2. CALCULATION RESULTS

Data	Reference Cases		Studied case	
	PWR fuel assembly	CANDU-6 fuel bundle	Proposed PWR fuel assembly	RPSFB
Enrichment	4.5w/o 235U.	0.71w/o 235U.	4.5w/o ^{235}U in the bundles and 3.4 w/o ^{235}U in the rods between the bundles.	Spent PWR fuel of the proposed design.
Burnable poisons	0.31 mgB^{10}/cm IFBA applied on all rods	Poisons free	0.62 mgB^{10}/cm IFBA applied on the elements in the outer ring.	Residual of the IFBA
Power per assembly/channel	17.67 MWth	5.3 MWth	17.32 MWth	5.3 MWth
Average burnup (MWd/kg U)	51.7	7.5	42.8	30
EFPD	1350	330	1350	1020
Fissile materials at discharge (g/kg U)	235U: 8.4 239Pu: 6.22 241Pu:1.8	235U: 2.16 239Pu: 2.52 241Pu:0.21	235U: 13 239Pu: 7.3 241Pu:1.7	235U: 1.8 239Pu: 2.9 241Pu:0.95
Average$^{139,\ 241Pu}$ produced per MWd (g/MWd)	0.155	0.364	0.055	

The fuel inventory (averaged on the 61-elemnt bundle) from the proposed PWR assembly after 1350 EFPDs followed by 90 days cooling time is simulated in the CANDU-6 pressure channel. Figure 5 shows the depletion histories (reactivity vs. burnup)) for the reference CANDU-6 fuel bundle and the Recycled PWR Spent Fuel Bundles (RPSFB). Since CANDU-6 is fuelled on-power, the equilibrium CANDU core contains fuel with burnups from fresh to exit-burnup. Therefore, the infinite medium reactivity, ρ∞ can be calculated from the following Eq.:

$$\rho_\infty = \frac{\int_0^{exit} \rho_\infty(B)dB}{B_{exit}} \quad (1)$$

where, $\rho_\infty(B)$ is the infinite system reactivity at burnup B and B_{exit} is the burnup at the discharge. The discharge burnup (B_{exit}) of CANDU-6 is 7.5 MWd/kgU, Using Eq. 1 and Fig. 5, ρ_∞ was calculated for the CANDU-6 and found to be 0.05358. In order to find the discharge burnup of the RPSFB, the integration of Eq. 1 was carried out over the burnup until ρ_∞ decreases to 0.05358. At burnup of 30 MWd/kgU of the RPSFB, $\rho_\infty = 0.0534$. This means that the RPSFB would be burnt in the CANDU-6 to around 30 MWd/kgU. Therefore, after the two cycles of burnup in PWR and CANDU-6, UO2 fuel with enrichment of 4.5 w/o can be burnt to around 70 MWd/kgU which represents an increase of about 35% than the burnup in the PWR without recycling in CANDU-6 as given in Table 2.

CANDU-6 has an advantage of that it is fuelled with natural UO2 but it discharges the spent fuel at low burnup of about 7.5 MWd/kgU and therefore the quantities of high level waste that are produced per unit energy from CANDU-6 reactors is much higher than that produced from Light Water Reactors (LWRs). Also, with this low burnup, the quality of plutonium in CANDU-6 spent fuel is high which is against the proliferation resistance. The proposed strategy of recycling the PWR spent fuel in CANDU-6 reactor would much reduce the high level waste. Moreover, direct recycling the spent fuel would degrade the plutonium vector which enhances the proliferation resistance and the produced plutonium per unit energy would be reduced as given in Table 2.

4. CONCLUSIONS

Direct recycling of the PWR spent fuel with the proposed strategy does not need chemical or dry processing. The case studied in this paper showed that the fuel burnup can be increased by around 35%. The proposed strategy of recycling the PWR spent fuel in CANDU-6 reactor would much reduce the high level

waste. Moreover, direct recycling the spent fuel would degrade the plutonium vector which enhances the proliferation resistance and the produced plutonium per unit energy would be reduced.

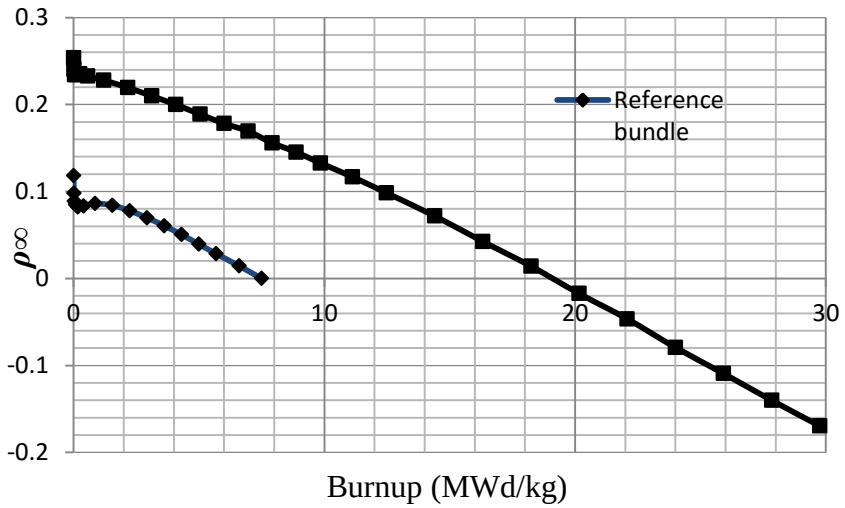

FIG. 5. Depletion history of the reference and RPSFB CANDU-6 bundles.

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