Study on Initial Core Loading Pattern for 50% MOX and 50% UO_2 in iPOWER reactor

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1. Introduction

The Innovative Passive Optimized Worldwide Economical Reactor (iPOWER) is an advanced pressurized water reactor (PWR) with 1,250 MWe capacity which currently is under development. The main characteristic of iPOWER is passive safety features such as the passive emergency cooling system (PECCS) and passive containment cooling system (PCCS) and the accident could be mitigated without operator's action or any electric sources [1].

The iPOWER core consists of 193 Fuel Assemblies (FAs) of the Westinghouse type 17 x 17 lattice fuel. These assemblies consist of 264 fuel rods with 1.25984 cm fuel rod pitch and 426.7 cm active length. Core thermal power is rated at 3,572 MWt with hot full power moderator average temperature of 308.3°C and core inlet moderator temperature of 287.8°C at 15.5 MPa of system pressure.

The objective of this study is to investigate the development of an Initial Core Loading Pattern (ICLP) in iPOWER that uses 50% of FA with Mixed Oxide (MOX) Fuel and the rest of the FAs Uranium Dioxide (UO_2) Fuel. During the ICLP design, it is important to consider the neutronics and thermal characteristics, such as power distribution and reactivity coefficients. The energy extracted from the core should be maximized while power distribution is maintained as flat as possible. The characteristics are important for ensuring performance and safety of nuclear reactor using nuclear design codes system. CASMO-4 and SIMULATE-3 [2-3] design codes were used to conduct the simulations at fuel assembly design and safety evaluation.

2. Description of the Modelled System

2.1. Reactor

The core is designed for an operating cycle of 18 months with discharge burnup of 17,707 MWD/tHM (Tones of heavy metal). The iPOWER core is loaded with 193 FA. Fig. 1 contains the quarter loading pattern reference for the initial cycle; 97 UO_2 FAs with 2.818 wt% of U-235 average enrichment and 96 MOX FAs with 3.644 wt% of average total fissile content (3.537 wt% Pu, 0.382 wt% U-235) were used in the core.

In this model, Gadolinia (Gd_2O_3) is used as the burnable absorber material to suppress excess of reactivity and control power distribution.

	8	9	10	11	12	13	14	15
8	UA0	UA0	MA3	UA0	UB3	MA3	UC3	MB0
9	UA0	MA3	UA0	UB3	UA0	UB3	MB4	MB0
10	MA3	UA0	UB3	MA3	UB3	MA3	UC3	MC0
11	UA0	UB3	MA3	UC3	UA0	UC3	MB4	MC0
12	UB3	UA0	UB3	UA0	MA3	UC3	MC0	
13	MA3	UB3	MA3	UC3	UC3	MB4	MC0	
14	UC3	MB4	UC3	MB4	MC0	MC0		
15	MB0	MB0	MC0	MC0				

Fig. 1. Quarter core loading pattern reference for MOX and UO_2 fuel assemblies.

2.2. Fuel Assemblies

In total, 7 types of FAs were generated; Table I and II display the information of the enrichment and distribution of the assemblies. Each FA is 17 x 17 lattice fuel with 264 fuel rods.

Table I: FA design for UO_2 fuel

UO_2 Fuel									
FA		Fuel Rods				Blanket	BA Rods		
Type	No	wt% High	wt% Low	No. High	No. Low	wt%	wt% (U-235)	wt% (Gd_2O_3)	No.
UA0	33	2.00		264		-	-	-	-
UB3	32	3.30	2.80	184	64	2.20	2.20	10.0	16
UC3	32	3.80	3.30	184	64	2.20	2.20	10.0	16
Total	97								

Table II: FA design for MOX fuel

MOX Fuel									
FA		Fuel Rods				Blanket	BA Rods		
Type	No	wt% High	wt% Low	No. High	No. Low	wt%	wt% (U-235)	wt% (Gd_2O_3)	No.
MA3	32	2.20	1.70	200	40	-	2.20	4.00	24
MB0	12	4.40	3.40	200	64	2.20	-	-	-
MB4	20	4.40	3.40	200	32	2.20	2.20	4.00	32
MC0	32	5.40	4.40	200	64		-	-	-
Total	96								

3. Method

The simulations have been carried out using CASMO-4/SIMULATE-3. Several sets of comparisons were made with varying the numbers of feed fuel assemblies, and optimization of the fuel management strategy was performed to reach the following design criteria: 18 months cycle length (17,707 MWD/tHM), Critical Boron Concentration (CBC) less than 1000 ppm and Maximum Pin Peaking Factor ($F_{\Delta H}$) less than 1.55.

During simulations, different parameters were calculated. These are Fuel Temperature Coefficient (FTC), Moderator Temperature Coefficient (MTC), and Shutdown Margins (SDM); in order to know if the design criteria of the core meets the safety specifications and maintains the level of criticality during operation.

4. Results

The coming evaluations follow the methodology and approach developed by APR-1400 reactor in the Design Control Document (DCD) [4].

4.1. Power Distribution

The Power Distribution could be measured by certain factors, one of them is $F_{\Delta H}$ (Pin Peaking Power) which provides the integral rod power of a fuel rod relative to the average integral rod power. The hottest rod in the core is plotted in Fig. 2, and accounts for the hot channel factors that should be monitoring during power operation. It could notice that the power distribution is maintained as flat as possible, and the maximum pin peaking factor is 1.442 but still, the design operates below 1.55 value [5]. Keeping the power distribution helps to maintain the economical utilization of the fuel and allows operation at high power without reaching Departure from Nuclear Boiling (DNB) in the core. DNB values are still under design stage of iPOWER but this result could provide an input how the fuel will behave during operation [6].

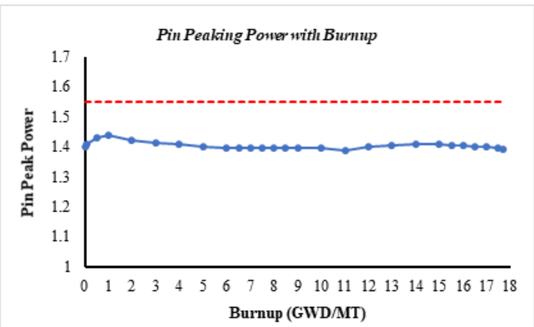

Fig. 2. Maximum rod relative power to core average rod power as a function of burnup.

MOX fuel consists of Pu-239 and Pu-241, has larger fission and absorption cross section than U-235 and generally more neutron absorbing at low energies because of the larger radiative capture and fission cross section of Pu-240 and Pu-242. High absorption cross section behavior has been the reason of neutron spectrum hardening in MOX in comparison of UO_2. On the other hand, the reduction of soluble-boron, control rod and burnable poison worth are affected by the spectrum hardening effect in maintaining the reactor core criticality [7]. In Fig. 3 appears the critical boron concentration during the cycle length. The tendency behaves normally aside the core has a mixture of fuel and keeps the concentration below the 1,000 ppm.

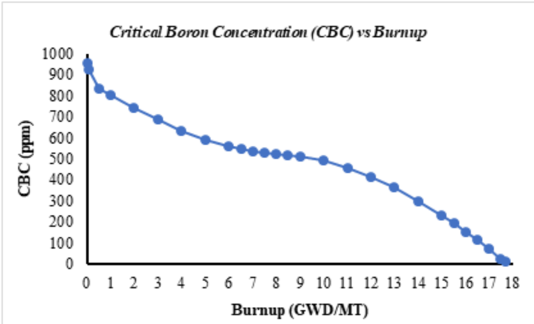

Fig. 3. Boron Concentration as a function of burnup.

4.2. Reactivity Parameters

In this section is shown the reactivity coefficients analysis that was determined for iPOWER. According to the 10 Code of Federal Regulation (CFR) [8] that describes the Energy Regulation, it mentions that “the reactor core and associated coolant systems shall be designed so that in the power operating range the net effect of the prompt inherent nuclear feedback characteristics tends to compensate for a rapid increase in reactivity”.

4.2.1. Moderator Temperature Coefficient.

Fig.4 contains the MTC calculation results at different boron concentrations in certain periods of the cycle operation. The Beginning of the Cycle (BOC), Middle of the Cycle (MOC) and End of the Cycle (EOC) were analyzed at 0, 9 and 17.7 GWD/tHM, respectively. For MTC, as moderator temperature increases, the moderator density decreases, and reactivity varies. In moderator, boron density plays an important role in controlling the reactivity and power distribution. The boric acid concentration is decreased and it is used to compensate for the decrease in reactivity due to burnup of the fuel. However, boron concentration also may decrease as moderator temperature increases, due to boron dilution in water (coolant) [9].

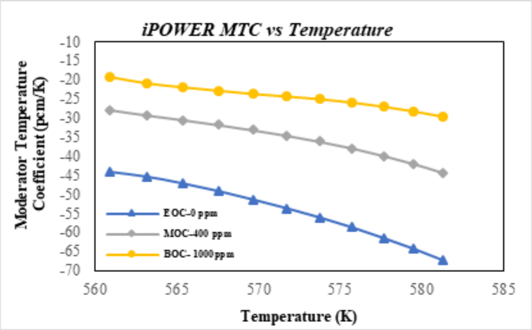

Fig. 4. Moderator Temperature Coefficient in iPOWER.

4.2.2. Fuel Temperature Coefficient.

As it was mentioned in section 4.2.1, the same conditions at BOC, MOC, and EOC were applied to calculate the FTC coefficients. Figure 5 shows the dependence of FTC for different values of fuel average temperature. It could be found that maximum fuel temperature decreases over the time that reactor is operating. As it is described by Westinghouse [10], there are several competing factors affecting fuel temperature over burnup. One of the reasons that could cause fuel temperature increment is the release of fission product gasses into the air gap that is originally filled with helium. As long as helium has relatively high thermal conductivity among other gases, introducing gaseous fission products decrease thermal conductivity of air gap and results in increasing average fuel temperature. However, fuel swelling is one of the most dominant factors over burnup. As a result of swelling, the thickness of the gap between fuel pellet and cladding is reducing, causing contact between fuel and cladding at some point. Consequently, it increases the thermal conductivity of the air gap and therefore reduces fuel temperature. The other observation from the figure shows that the absolute value of FTC decreases over burnup. This could be explained by production of Pu-240 over time operation [11].

This isotope has higher negative impact on FTC compared to U-238 due to higher and larger resonance in an epithermal energy range, which is naturally broadening in hot fuel.

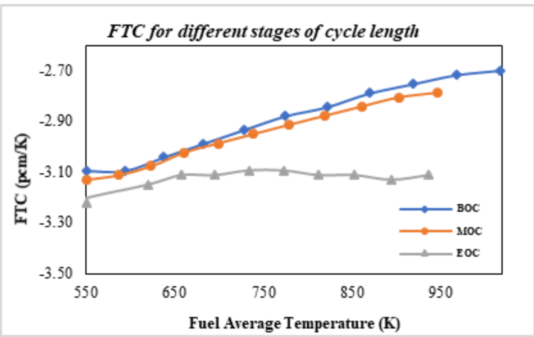

Fig. 5. FTC for different values of fuel temperature at BOC, MOC and EOC.

4.2.3. Shutdown Margin.

Table IV contains the SDM value that was calculated for ILCP. From the safety requirements and analysis for the licensing process of a commercial nuclear reactor; the SDM calculation assures that the reactor will be capable of shutdown during an accident scenario and to maintain the subcriticality in the core. It was found that the Shutdown Thermal Margin satisfied the design criteria of SDM value should be ≥ 5500 pcm from APR1400 design [4].

Table IV: Shutdown Margin Calculation

Requirements	*BOC (pcm)*	*MOC (pcm)*	*EOC (pcm)*
Control Rod Worth			
All Rods In Worth with Most Reactive Rod Stuck Out (a)	9886	10758	11178
Uncertainty (4.65 %) (b)	460	500	520
Most Reactive Stuck Rod Worth	2781	2139	3454
Total Worth (a) – (b) = (c)	9426	10258	10658
Control Rod Requirements			
Total Power Defect (d)	1518	1652	2790
Rod Insertion Allowance (RIA) (e)*	83	130	367
Total Requirements (d) + (e) = (f)	1601	1782	3157
Calculated SDM (c) – (f)	**7852**	**8476**	**7501**
Requirement SDM	> 5500	> 5500	> 5500

* Inclusion of RIA reduced the value of possible SDM

5. Conclusion

In this paper was investigated the possibility of initial core loading pattern for iPOWER reactor, which currently is still under design stage. This is a proposed design for a suitable core that could be loaded 50% of the FA with MOX fuel and the rest of the FA with UO_2 fuel. The parameters such as cycle length, peaking factor, CBC, reactivity coefficients, and SDM calculation were investigated.

In conclusion, the iPOWER reactor core design with a mixture of fuel is capable to maintain the design specifications and safety requirements for the initial cycle.

Further work should be conducted to continue this design study for the equilibrium cycle stage, in order to prove that the core will be capable to operate for more cycles during these conditions.

ACKNOWLEDGEMENT

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Review Comments

➢ Comments of Reviewer 1

1) Figure 2 shows the pin peaking factors and limit value (1.55) over burnup. If you can, the safety margin and uncertainty of CASMO-4/SIMULATE-3 should be considered.

   Response:

   It was used 17x17 Westinghouse Fuel Assembly type; pin peaking design value limit (1.55) was considered the same as KNF company. It was not considered CASMO-4/SIMULATE-3 uncertainties, the results from the computer code use best estimate approach.

2) The authors said that the CBC should be less than 1000 ppm. However, the CBC at BOC looks like 1000 ppm. How can! you be sure that the design for iPOWER meet criteria?

   Response:

   It was applied KNF design criteria; MTC calculation showed negative results over the whole cycle operation. Shutdown margin calculation and pin peaking factor are maintained during the cycle.

- Note

To whom it may concern:

Thank you very much for your valuable comments. I really appreciate it.

➢ Comments of Reviewer 2

1) In section 4.2, 11 CFR seems to be typo of 10 CFR.

   <u>Response:</u>

   In section 4.2, 11 CFR typo was changed as 10 CFR typo.

2) In Table IV, uncertainty (4.65%) of control rod worth seems to be small compared with KNF core design. It probably needs base of uncertainty (V&V reports).

   <u>Response:</u>

   It was applied 4.65% of uncertainty for the design of control rod worth in Shutdown margin calculation, based on KNF Nuclear Design Report for Shin-Kori unit 3&4.

- Note

To whom it may concern:

Thank you very much for your valuable comments. I really appreciate it.

➢ Comments of Reviewer 3

1) 4.2.1… "Fig. 4 contains the MTC measurements" -> ""Fig. 4 contains the MTC results calculated "

   <u>Response:</u>

   In section 4.2.1, “Fig. 4 contain the MTC measurement” sentence was modified as “Fig.4 contains the MTC calculation results”.

2) 4.2.2… "were applied to measure the FTC" -> "were applied to compute the FTC"

   <u>Response:</u>

   In section 4.2.2, "were applied to measure the FTC" statement was replaced for “were applied to calculate the FTC”.

3) 5.… "in this paper was investigated… iPOWER reactor," -> "In this paper In this paper was studied a possibility of initial core loading pattern for iPOWER reactor with MOX,"

   <u>Response:</u>

   At Section 5, "in this paper was investigated… iPOWER reactor," content was changed for “In this paper was investigated the possibility of initial core loading pattern for iPOWER reactor,”.

4) 5... "The correlations between cycle.." -> "The parameters such as cycle.."

   <u>Response:</u>

   In section 5, "The correlations between cycle.." sentence was modified for "The parameters such as cycle length, peaking factor, CBC, reactivity coefficients, and SDM calculation were investigated".

- Note

To whom it may concern:

Thank you very much for your valuable comments. I really appreciate it.