Optimization of Burnable Poison Design for Pu Incineration in Fully Fertile Free PWR Core

Emil Fridman, Eugene Shwageraus, and Alex Galperin,
Department of Nuclear Engineering, Ben-Gurion University of the Negev, Beer-Sheva, Israel

Abstract

The design challenges of the fertile-free based fuel (FFF) can be addressed by careful and elaborate use of burnable poisons (BP). Practical fully FFF core design for PWR reactor has been reported in the past [1]. However, the burnable poison option used in the design resulted in significant end of cycle reactivity penalty due to incomplete BP depletion. Consequently, excessive Pu loading were required to maintain the target fuel cycle length, which in turn decreased the Pu burning efficiency.

A systematic evaluation of commercially available BP materials in all configurations currently used in PWRs is the main objective of this work. The BP materials considered are Boron, Gd, Er, and Hf. The BP geometries were based on Wet Annular Burnable Absorber (WABA), Integral Fuel Burnable Absorber (IFBA), and Homogeneous poison/fuel mixtures.

Several most promising combinations of BP designs were selected for the full core 3D simulation. All major core performance parameters for the analyzed cases are very close to those of a standard PWR with conventional UO2 fuel including possibility of reactivity control, power peaking factors, and cycle length.

The MTC of all FFF cores was found at the full power conditions at all times and very close to that of the UO2 core. The Doppler coefficient of the FFF cores is also negative but somewhat lower in magnitude compared to UO2 core. The soluble boron worth of the FFF cores was calculated to be lower than that of the UO2 core by about a factor of two, which still allows the core reactivity control with acceptable soluble boron concentrations.

The main conclusion of this work is that judicial application of burnable poisons for fertile free fuel has a potential to produce a core design with performance characteristics close to those of the reference PWR core with conventional UO2 fuel.

KEYWORDS: Pu incineration, fertile free fuels, burnable poisons, three-dimensional core analysis

1. Introduction

Existing stockpile of separated Pu represents immediate proliferation and long-term environmental concerns. The current practice of Pu recycling as Mixed Oxide U-Pu (MOX) fuel is not effective because additional Pu is being generated from U238 as original Pu is being burned. The Pu destruction rate can be increased dramatically in comparison with MOX fuel if Fertile Free Fuels (FFF) is used in existing Light Water Reactors (LWR).

A number of well known nuclear and material design challenges of the FFF question the practicality of using the FFF in existing LWRs. The nuclear design challenges of fertile free Pu fuel include primarily the reduced reactivity worth of the reactor control materials and considerably degraded reactivity feedback coefficients.

These challenges can be addressed by careful and elaborate use of burnable poisons (BP). Practical fully FFF core design for PWR reactor has been reported in the past [1]. However, the burnable poison option used in the design resulted in significant end of cycle reactivity penalty due to incomplete BP depletion. Consequently, excessive Pu loading were required to maintain the target fuel cycle length, which in turn decreased the Pu burning efficiency.

In this work, we performed a systematic evaluation of commercially available BP materials in all configurations currently used in PWRs. The BP materials are Boron, Gd, Er, and Hf. The considered BP geometries were based on Wet Annular Burnable Absorber (WABA), Integral Fuel Burnable Absorber (IFBA), and Homogeneous poison/fuel mixtures.

In order to determine the optimal burnable poison design, we calculate the effect of each design option on the major PWR core characteristics. The core characteristics of interest, which ultimately determine the feasibility of the core design, are:

- possibility of excess reactivity control
- acceptable reactivity feedback coefficients
- minimal cycle penalty due to the use of burnable poison

Table 1 presents a matrix of possible geometry-BP material arrangements analyzed and reported in this document.

Table 1: Matrix of calculated BP designs

BP Material / BP Geometry	B	Gd	Hf	Er
WABA-type	WABA-B	WABA-Gd	WABA-Hf	WABA-Er
IFBA-type	IFBA-B	IFBA-Gd	IFBA-Hf	IFBA-Er
Homogeneous Fuel/BP	-	Hom-Gd	Hom-Hf	Hom-Er

For each of the BP design options several sub-cases were analyzed, by varying the number of BP rods per assembly, volume and/or BP material density. It should be noted that the scope of calculations was defined in order to deduce the potential of each design to address design challenges of the FFF cores and sensitivity of the performance parameters to a specific BP design parameter

The work was divided into two stages: first – a comprehensive set of BP design options was analyzed by performing 2D assembly-level burnup calculations and application of modified linear reactivity model [3], and second – a full core 3D analysis for a few selected designs.

2. Methodology

Most of the calculations performed in the framework of this project were performed by utilizing the ELCOS code system [2]. This system provides a capability to perform a full core 3D analysis of a LWR core. Three main modules of the system are executed sequentially:

- ETOBOX – generates a library of microscopic cross-section for all relevant isotopes,
- BOXER – performs 2D assembly-level burnup calculations to produce assembly-averaged macroscopic cross-sections libraries dependent on a selected set of independent lattice parameters,
- SILWER – a full core 3D code with thermal-hydraulic feedback.

The first stage of the project, namely scoping calculations for all possible BP calculations were carried out by running the BOXER code and applying the modified (non-linear) reactivity model. Modification of the standard linear reactivity model to account for distinctively non-linear behavior of the reactivity rundown curves characteristic to FFF fuel lattices is presented in Reference 3.

At the second stage of the project (detailed full core analysis) the main analysis tool – SILWER computer code – was modified to account properly for thermal conductivity of the fuel.

It should be noted that in the original version of SILWER assumes UO_2 by default for all analyzed fuel types. Thermal conductivity of FFF varies greatly with the matrix material composition and differs from UO_2. Moreover, the original version of the SILWER code accepts only sold fuel pellet geometry, which in case of annular pellets also results in inaccurate fuel temperature calculation.

Thus, the following modifications were made in thermal-hydraulic module of the code:

- Thermal conductivity of the fuel as a function of temperature is specified by user as a set polynomial coefficients,
- An adjustment of the spatial temperature distribution model to include annular as well as solid fuel pellet geometries was added.

Sensitivity analysis and verification of the modifications of the calculational methodology (application of non-linear reactivity model and adjustment of the temperature profile model) was carried out. The results indicated that significant errors in results were avoided.

3. Results

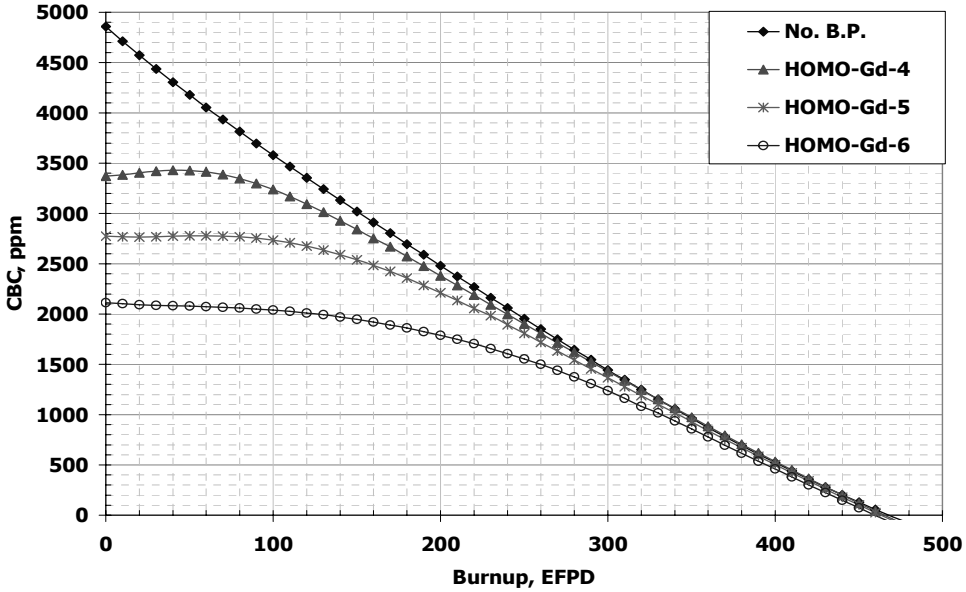
The results of the calculations are presented below in two parts. First, the scoping calculations are summarized and general conclusions are presented. Second, the most promising BP designs are further analyzed by performing a 3D full core analysis in order to verify the conclusions of the first stage.

3.1. Assembly level calculations – critical boron concentration and cycle length

Assembly burnup calculations performed by the BOXER code produced criticality rundown curves as a function of accumulated burnup. Modified linear reactivity model was applied to produce the core soluble boron dependence on burnup. The 3% leakage was assumed and cycle length values were obtained. The critical boron concentration (CBC) at BOC, and cycle length

were used as the main core performance parameters. A typical presentation of calculational results is shown in Fig. 1 for several homogeneous Gd BP designs. A detailed compilation of the results for all considered cases may be found in Reference 3.

Figure 1: CBC as a function of burnup for selected cases



The results of calculations for different BP designs were collected, analyzed and produced the conclusions summarized below:

WABA-type

- Utilization of all BP materials in WABA-type geometry cannot significantly reduce the core CBC.
- The residual fuel cycle length penalty is minimal because WABA absorbers are physically removed from the assembly after first out of three irradiation cycles.

IFBA-type

- IFBA-type BP designs with Hf and Er can reduce maximum CBC to 3,000 ppm.
- IFBA-type BP design with Gd, 264 BP rods/assembly may reduce maximum CBC to 2,400 ppm. Assembly pin-power peak exceeds in this case value of 1.2.
- IFBA design alone cannot reduce maximum CBC below 2,000 ppm even if 100% of fuel pins in the core are IFBA pins.

Homogeneous fuel-BP

- Homogeneous Gd/fuel BP designs are capable of reducing the maximum CBC to less than 2,000 ppm. It was demonstrated that about 4 kg of Gd per fuel assembly distributed among 132 or 264 pins results in a relatively low penalty on fuel cycle length of 8 full power days.
- A significant reduction of maximum CBC, below 2,000 ppm, may also be achieved by utilizing 4 - 6 v/o of Hf or Er mixed in 132 or 264 fuel rods.

- However, the major problem with using Hf and Er BP is the large residual penalty in the range of 40 to 150 full power days per cycle.

The possible solution to this problem is utilization of an enriched Hf or Er isotopic compositions.

3.2. Assembly level calculations – reactivity coefficients

One of the major design challenges associated with utilization of FFF is deterioration of the temperature coefficients and control materials reactivity worth caused by high thermal cross-section of Pu and consequent hardening of the neutron spectrum. The purpose of the investigation reported in this section is to estimate the potential of addition of different burnable poison (BP) materials to improve reactivity feedback coefficients without significant deterioration of control materials worth. Three main parameters of the Fertile-Free Fuel (FFF) lattices were calculated: Moderator Temperature Coefficient (MTC), Fuel Temperature Coefficient due to Doppler Effect (DC), and soluble Boron reactivity worth (BW). The soluble boron concentration was assumed as 2000 ppm, and 0 ppm at BOL and EOL respectively, in order to approximate conditions close to realistic core. All reactivity coefficients were calculated at Hot-Full-Power (HFP), Xe-equilibrium, All-Rods-Out (ARO) operating conditions.

3.2.1 Moderator temperature coefficient

The MTC relates a change in reactivity to a change in reactor coolant temperature. It is defined as the change in reactivity per degree change in moderator temperature and calculated as:

$$\frac{\Delta\rho}{1^{\circ}C} = \frac{k_{\inf}(T_2) - k_{\inf}(T_1)}{k_{\inf}(T_1) \times k_{\inf}(T_2) \times (T_2 - T_1)} \times 10^5 \left[\frac{pcm}{^{\circ}C}\right]$$

where T_1 and T_2 are two moderator temperature values, $k_{inf}(T_1)$ and $k_{inf}(T_2)$ are corresponding criticality values, while MTC values are attributed to the middle of the corresponding (T_1 - T_2) range and is measured in terms of pcm per 1°C.

Summary of the MTC calculations is presented in Table 2. Description of the specific BP design and a complete set of cases calculated (corresponding to designations of Table 2 may be found in Reference 3).

Observation of the results presented in Table 2 leads to the following conclusions:

- FFF for a No BP case shows small and positive MTC at BOL.
- WABA-Gd shows a negative MTC of a reasonable value close to a standard LWR core.
- IFBA-Gd and HOMO-Gd cases show unacceptably large and positive MTC values.
- Hf and Er BP materials show a potential to improve MTC,.
- For all BP materials and geometries simultaneous burnout of Pu and BP results in acceptable MTC values at EOL time-points.

3.2.2 Fuel temperature coefficient due to Doppler Effect

The DC is defined as the change in reactivity per degree change in effective fuel temperature due to the Doppler resonance broadening and calculated as:

$$\frac{\Delta\rho}{1^{\circ}C} = \frac{k_{\inf}(T_2) - k_{\inf}(T_1)}{k_{\inf}(T_1) \times k_{\inf}(T_2) \times (T_2 - T_1)} \times 10^5 \left[\frac{pcm}{^{\circ}C}\right]$$

where T_1 and T_2 are two fuel temperatures, while k_{inf} (T_1) and k_{inf} (T_2) are corresponding criticality values. The Doppler coefficient is measured in terms of pcm per 1°C. Here, we used T_1=605.0 °C, and T_2=645.0 °C.

A partial list of DC values calculated for all BP designs and materials considered in this task are presented in Table 2. As can be observed from the Table 3, the most effective BP design is Hf in homogeneous geometry. This configuration allows an increase in absolute value of FFF DC from -1pcm/°C for the No BP case to -1.6 pcm/°C for the HOMO-Hf case. Some improvement in DC is also observed for the Er cases. The effect can be explained by the fact that Er-167 is a strong resonance absorber (IR≈3000b) with its first absorption resonance overlapping with fission resonance of Pu-239, so that the DC is enhanced due to the mutual shielding of Pu and Er resonances. Other considered burnable poisons are much less effective and have almost no effect on the Doppler Coefficient.

3.2.3 Boron reactivity worth coefficient

The BW coefficient is defined as the change in reactivity per one ppm change in the soluble boron concentration and calculated as:

$$\frac{\Delta\rho}{1ppm} = \frac{k_{\inf}(B_2) - k_{\inf}(B_1)}{k_{\inf}(B_1) \times k_{\inf}(B_2) \times (B_2 - B_1)} \times 10^5 \left[\frac{pcm}{ppm}\right]$$

where B_1 and B_2 are two boron concentrations, k_{inf} (B_1) and k_{inf} (B_2) are corresponding criticality values, and is measured in terms of pcm per 1ppm. In this case, we used the reference boron concentration ±50 ppm for the values of B_1 and B_2 in each time point.

The results of the soluble boron reactivity worth coefficients (BW) are summarized in Table 4. As already noted, Pu containing fuels have factor of 2 to 3 lower BW than typically observed in the conventional All-U cores due to the fact that Pu is much stronger thermal neutrons absorber than Uranium. Therefore, the BW increases with the depletion of fissile material and corresponding "softening" of the spectrum. This effect is also much stronger in FFF-Pu than in All-U fuel. While the BW of UO_2 fuel increases almost linearly with burnup due the buildup of Pu, the FFF exhibits a sharp increase in BW at EOL when most of the fissile Pu is depleted. This effect may cause a power peaking problem in the FFF-Pu core.

In general, BP material and geometrical arrangement have limited effect on the BW of FFF-Pu fuel. Hf and Er tend to improve the BW slightly (from -2.4pcm/ppm in NoBP case to about -2.5pcm/ppm in Er and Hf cases in IFBA and Homogeneous geometries), while Gd, generally, reduces it. This is due to the competition between Gd and Boron for thermal neutron absorption as both of these materials are mostly thermal neutron absorbers.

3.3. Assembly level calculations – conclusions

Based on the performed analysis, it was found that a combination of BP materials and geometries may be required to meet all FFF design goals. However, these findings can be confirmed only by performing a full core 3-dimensional neutronic analysis.

The final result of the next stage of this research will be the choice of acceptable FFF core fraction with appropriate mix of BP designs. This result will be obtained and verified by a full core 3-dimensional simulation and fuel cycle analysis, which is presented in the next section.

Table 2: Reactivity Coefficients Summary

Case Designation	MTC (pcm/°C)		DC (pcm/°C)		BW (pcm/ppm)	
	BOL	EOL	BOL	EOL	BOC	EOC
UO2, e=4.21%	11.2	-59.9	-2.0	-3.4	-5.8	-9.5
No BP	0.61	-27.0	-1.0	-1.5	-2.4	-15.3
WABA-Gd-9	-20.7	-39.6	-1.0	-1.6	-2.2	-12.9
WABA-Hf-3	-17.3	-60.8	-1.0	-1.8	-2.2	-13.8
WABA-Er-3	-12.6	-53.2	-1.1	-1.8	-2.2	-13.3
IFBA-Gd-4	96.9	-32.6	-0.9	-1.5	-1.8	-14.9
IFBA-Hf-1	-9.7	-40.0	-1.2	-1.6	-2.5	-15.4
IFBA-Er-1	-7.0	-34.9	-1.1	-1.5	-2.6	-19.0
HOMO-Gd-3	120.7	-32.0	-1.0	-1.5	-1.8	-15.5
HOMO-Hf-1	-18.8	-43.8	-1.6	-2.0	-2.5	-14.9
HOMO-Er-1	-13.2	-37.8	-1.3	-1.5	-2.6	-14.8

3.4. Full core (3D) calculations – cycle performance

This section presents the results of 3-dimensional whole core analysis of PWR fully loaded with fertile free fuel. Based on the preliminary assembly level calculations, two most promising combinations of BP designs were selected for the full core 3D simulation:

- Hf Homogeneously mixed with fuel – Er IFBA coating – Boron WABA
- Er Homogeneously mixed with fuel – Hf IFBA coating – Boron WABA

The calculations were performed with 3-dimensional nodal diffusion code SILWER. The code is a part of the ELCOS [2] LWR analysis software package. A standard 3-batch fuel management scheme with 18 month cycle length was chosen as a reference fuel management.

For each fuel design option, equilibrium core was approximated through a number of successive fuel reloads starting with initial guess of burnup distribution for the once and twice burned fuel batches. Such iterative process was repeated until the average initial burnup of batch n was equal to the discharge burnup of batch $n-1$ in the same cycle, where $n = 1,2,3$ for the fresh, once, and twice burned fuel batch respectively.

Major core design and operating parameters assumed in this analysis are summarized in Table 3. The fuel designs evaluated in this task are summarized in Table 6. Cases 1, and 2, represent the most promising fertile free fuel designs: homogeneously mixed Hf+IFBA/Er, and homogeneously mixed Er+IFBA/Hf, respectively. Cases 3 and 4 correspond to the PSI FFF core design and standard UO_2 fuel respectively.

Table 3: Parameters of the reference PWR core

Operating parameter	**Value**
Core	
Total thermal output (MWth)	3358
Number of fuel assemblies in the core	193
Average core power density (MW/MTHM)	37.3
Fuel Assembly	
Active fuel height (cm)	366
Assembly array	square 17 × 17 rods
Total number of fuel rods per assembly	264
Assembly pitch (cm)	21.5
Fuel rod pitch, cm	1.26
Fuel Rod	
Cladding outer radius (cm)	0.4750
Cladding thickness (cm)	0.0570
Fuel pellet radius (cm)	0.4095

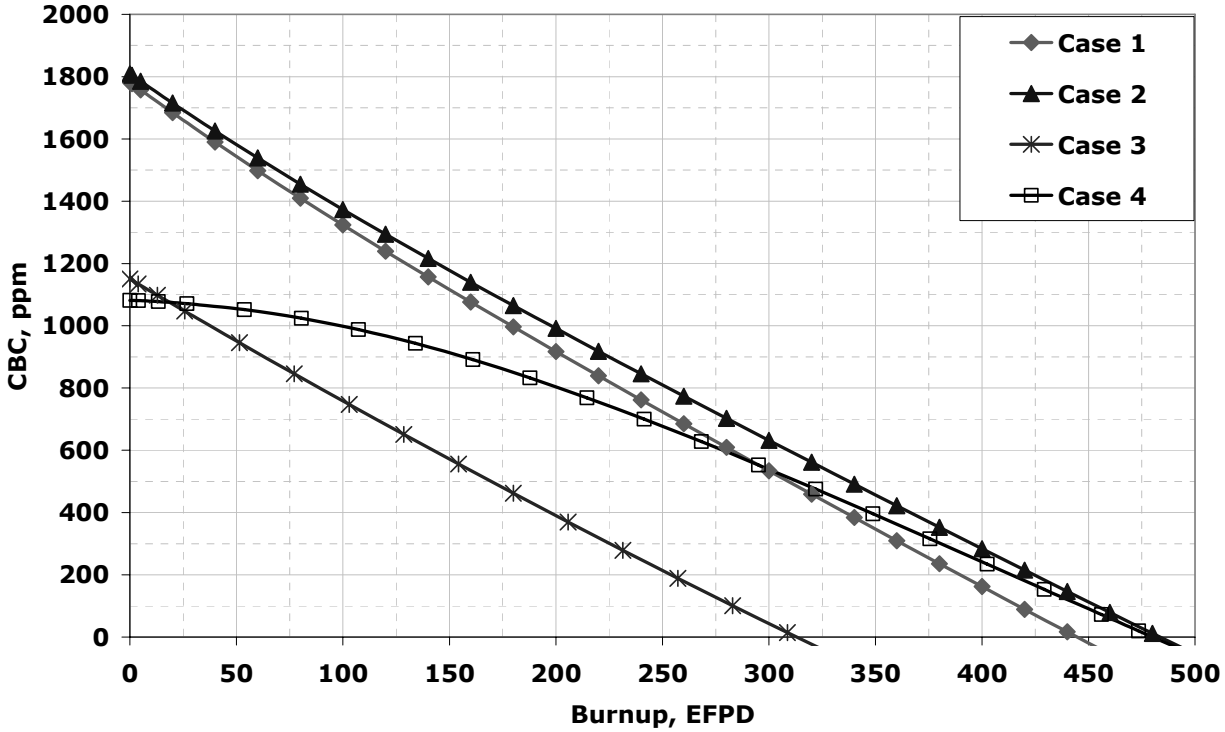
The results of the full core burnup for an equilibrium cycle are presented in Fig. 2 for all cases and described in Table 4. Observation of the CBC curves indicates that all considered BP designs are capable of reducing the maximum CBC value below the 2,000 ppm mark. In addition, the fuel cycle penalty due to incomplete burnout of BP material may be significantly reduced by using a combination of BP designs.

Table 4: Analyzed Fuel Designs Description

Analyzed Case	***1***	***2***	***3***	***4***
Fuel matrix composition, MgO/ZrO_2 (vol.%)	50/50	50/50	0/100	UO_2
PuO_2 content (vol. %)	10.3	10.3	12.6	4.21(*)
Homogeneously mixed BP material	HfO_2	Er_2O_3	Er_2O_3	-
Homogeneously mixed BP content (vol. %)	1.5	1.5	5.4	-
IFBA Coating Material	Er_2O_3	HfO_2	-	ZrB_2
IFBA Coating Thickness, mm	0.0160	0.0160	-	0.0115
Number of IFBA rods in assembly	264	264	-	116
WABA burnable absorber	Al_2O_3 - B_4C		-	Al_2O_3 - B_4C
Number of WABA rods in assembly	24		-	4 - 16
B-10 loading (g/cm of WABA rod)	0.006165		-	0.006165

(*) Max. Uranium enrichment in All-UO_2 fuel case

Figure 2: CBC Letdown Curves



3.5. Full core (3D) calculations – reactivity coefficients

This section presents the results of the reactivity coefficients calculations, soluble boron reactivity worth and fuel temperature distribution in the reactor core. The reactivity coefficients were calculated for the Hot Full Power (HFP), equilibrium Xe, and All Rods Out (ARO) core operating conditions.

The Distributed Doppler Coefficient (DDC) was calculated as the reactivity change associated with a change in fuel temperature with the same spatial distribution as the power divided by the change in the averaged fuel temperature. This reactivity coefficient is considered a conservative estimate of the Doppler Effect.

The MTC of a PWR core was calculated as the reactivity change associated with a change in coolant inlet temperature divided by the change in the core average coolant temperature.

Finally, the BW was calculated as the change in the core reactivity as a result in the change in Soluble Boron concentration in the reactor coolant divided by the core average Soluble Boron concentration.

The summary of the reactivity coefficients in all considered cases is presented in Table 5. The reactivity coefficients are negative at all time points during the cycle for all calculated cores. All fertile free cores exhibit approximately the same negative Doppler feedback, which is determined primarily by the type and the loading of the burnable poison in use. Homogeneously mixed Hf case (Case 1) shows the most negative Doppler coefficient. The magnitude of the Doppler feedback is still somewhat lower than that of the reference UO_2 fuel core (-1.8 -1.5 pcm/°C for the FFF cores versus -3.0 pcm/°C for the UO_2 core). The assessment of the importance and consequences of such a difference is beyond the scope of the current study.

Table 5: Summary of feedback parameters

	Case 1		Case 2		Case 3 (PSI)		Case 4 (UO2)	
	BOC	**EOC**	**BOC**	**EOC**	**BOC**	**EOC**	**BOC**	**EOC**
DDC, pcm/C	-1.8	-1.6	-1.7	-1.5	-1.6	-1.4	-3.0	-3.3
MTC, pcm/C	-28.6	-57.7	-27.3	-56.6	-38.4	-64.2	-33.1	-68.8
BW, pcm/ppm	-2.7	-3.7	-2.7	-3.8	-3.4	-4.4	-7.1	-8.1

4. Conclusion

The main conclusion derived from the results and discussions presented in this paper indicate that the FFF cores with elaborate burnable poison designs are consistent with current LWR design constraints. This conclusion is based on the fact that all calculated FFF core performance characteristics are close to those of the reference PWR core with conventional UO_2 fuel.

Acknowledgments

The work was initiated and supported by the University of Nevada at Las Vegas, Harry Reid Center for Environmental Studies as a part of the "Dissolution, Reactor, and Environmental Behavior of ZrO_2-MgO Inert Fuel Matrix" project.

References

1. U. Kasemeyer, J. M. Paratte, P. Grimm, R. Chawla "Comparison of Pressurized Water Reactor Core Characteristics for 100% Plutonium-Containing Loadings", Nuclear Technology, **122**, 52, (1998).
2. J.M. Paratte, K. Foskolos, P. Grimm, and C. Maeder, "Das PSI Codesystem ELCOS zur stationaren Berechnung von Leichtwasserreaktoren", Proc. Jahrestagung Kerntechnik, Travemunde, Germany, **59,** (1998).
3. E. Fridman, S. Kolesnikov, E. Shwageraus, and A. Galperin, "Dissolution, Reactor, and Environmental Behavior of ZrO2-MgO Inert Fuel Matrix: Neutronic Evaluation of MgO-ZrO2 Inert Fuels," Department of Nuclear Engineering, Ben-Gurion University of the Negev, Final Report for University of Nevada, Las-Vegas (June 2005). Available from: http://aaa.nevada.edu/task19.html