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Dissolution, Reactor, and Environmental Behavior of ZrO2-MgO Inert Fuel Matrix: Neutronic Evaluation of ZrO2-MgO Inert Fuels

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Neutronic Evaluation of MgO-ZrO_2 Inert Fuels

Progress Report

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I. Summary

This report presents the results of the Task 3, defined in working program as: evaluation of burnable poison designs. Adopting the basic design of a standard PWR and Pu loadings required for 18-month cycle (results of Task 2), this part of the program is aimed to estimate performance of each BP design and BP material to address challenges of Fertile-Free Fuel (FFF) Concept. Finally, an optimal BP design will be developed and an overall feasibility of FFF concept will be determined. Basically, the main challenge encountered in neutronic design for a FFF core is to develop reactivity control system which is capable to satisfy performance and safety criteria of existing PWR plants.

Heavy Pu loadings combined with absence of fertile isotopes with capture resonances result in low reactivity worth of existing control mechanisms and inadequate temperature coefficients. The main solution adopted by several previous design efforts is based on increased content of BP materials with capture resonances. The BP designs proposed and analyzed in previous designs are based on such elements as: Gd, Hf, and Er, located in fuel cell, either as a homogeneous mixture or as a thin ring (IFBA-type geometry). This approach results in a large residual reactivity penalty due to an incomplete burnup of the BP material (especially Hf and Er).
Description and parameters of the BP designs considered in this work are presented in section II.

In this report, an extensive set of calculations was carried out to assess the potential of the main BP materials - B, Gd, Hf, and Er, utilized in three main geometrical arrangements: Wet Annular Burnable Absorber (WABA) type, Integral Fuel Burnable Absorber (IFBA) type, and Homogeneous fuel-BP mixture.
Heavy loadings of BP materials in non-standard geometries combined with high Pu content in a fertile-free matrix necessitated additional verification of the calculational tools. Verification of the calculational modeling and parameters are presented in section III. A full scope of calculations is presented in section IV of this report. All cases are arranged according to geometry-type and BP material. The results and analysis of these calculations, presented and summarized in Section V, serve as a basis for a comprehensive assessment of BP potential to address challenges of the FFF concepts.

Three main performance parameters of the BP designs will be evaluated:

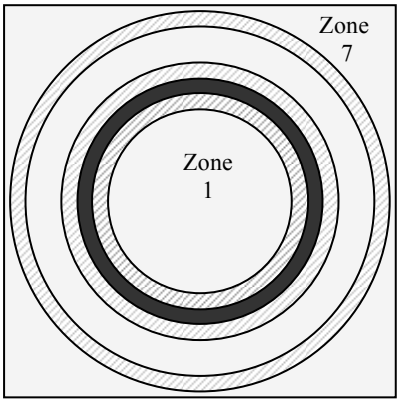
1. Maximum critical soluble boron concentration (CBC) required during the cycle,
2. Acceptable fuel and moderator temperature coefficients (will be evaluated in Task 4),
3. Residual reactivity penalty associated with incomplete depletion of the BP material.

Summary and Conclusions are presented in section VI.

II. Burnable Poison Designs – Description and Basic Data

This section presents general description of different BP designs, including geometrical arrangements and isotopic compositions. The standard BP design geometries and compositions of WABA and IFBA type absorbers were adopted from Reference 1.

II.1 WABA-type BP



Zone Number	Region	Zone Radii (cm)
1	Moderator	0.28575
2	Clad	0.35306
3	BP	0.40386
4	Clad	0.48387
5	Moderator	0.56896
6	Clad	0.61468
7	Moderator (cell pitch)	1.26000

G.T.	Fuel	Fuel	WABA	Fuel	Fuel	WABA	Fuel	Fuel	water
Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	water
Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	water
WABA	Fuel	Fuel	WABA	Fuel	Fuel	WABA	Fuel	Fuel	water
Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	water
Fuel	Fuel	Fuel	Fuel	Fuel	WABA	Fuel	Fuel	Fuel	water
WABA	Fuel	Fuel	WABA	Fuel	Fuel	Fuel	Fuel	Fuel	water
Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	water
Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	water
water	water	water	water	water	water	water	water	water	water

Fig. 1: Reference WABA Design: pin cell and assembly positions (1/4 assembly)

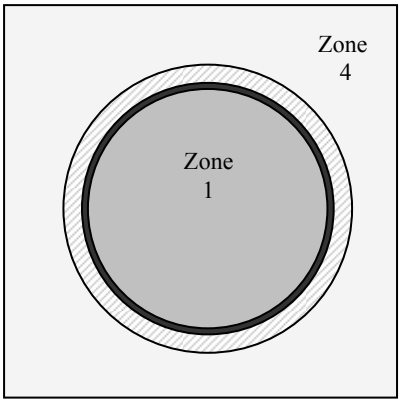
Table 1: Reference WABA absorber design description

Number of BP absorber pins	24
BP material	Al_2O_3 - B_4C
Active material	B_4C
Inert material	Al_2O_3
BP material density, g/cm^3	2.593
Active material density, g/cm^3 (theoretical)	2.52
Inert material density, g/cm^3 (theoretical)	3.965
Weight fraction of active material in BP, w/o	14.0%
Weight fraction of inert material in BP, w/o	86.0%

Table 2: Reference isotopic composition of WABA absorber

Isotope	**Fraction of isotope in material composition** weight %	**Number density** # / (barn · cm)
B-10	2.0	3.0722E-03
B-11	9.0	1.2764E-02
C	3.0	3.9590E-03
Al	45.5	2.6331E-02
O	40.5	3.9497E-02

II.2 IFBA-type BP



Zone Number	Region	Zone Radii (cm)
1	Fuel	0.40950
2	BP	0.41065
3	Clad	0.47500
4	Moderator (cell pitch)	1.26000

G.T.	Fuel	IFBA	G.T.	IFBA	Fuel	G.T.	IFBA	Fuel	water
Fuel	IFBA	Fuel	IFBA	Fuel	IFBA	IFBA	Fuel	Fuel	water
IFBA	Fuel	IFBA	Fuel	IFBA	Fuel	IFBA	Fuel	Fuel	water
G.T.	IFBA	Fuel	G.T.	Fuel	IFBA	G.T.	IFBA	Fuel	water
IFBA	Fuel	IFBA	Fuel	IFBA	IFBA	IFBA	Fuel	Fuel	water
Fuel	IFBA	Fuel	IFBA	IFBA	G.T.	Fuel	IFBA	Fuel	water
G.T.	IFBA	IFBA	G.T.	IFBA	Fuel	IFBA	IFBA	Fuel	water
IFBA	Fuel	Fuel	IFBA	Fuel	IFBA	IFBA	Fuel	Fuel	water
Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	Fuel	water
water	water	water	water	water	water	water	water	water	water

Fig. 2: IFBA Reference design (116 BP pins): pin cell locations (1/4 assembly)

Table 3: Reference IFBA absorber description

Number of IFBA pins per assembly	116
BP chemical form	ZrB_2
BP density, g/cm3	6.085

Table 4: Reference isotopic composition of IFBA coating

Isotope	Fraction of isotope, weight %	Number density # / (barn · cm)
B-10	3.5	1.2149E-02
B-11	15.6	4.8902E-02
Zr	80.9	3.0526E-02

III. Calculational Model – Verification of modeling and model parameters

Non-standard applications of several BP materials, such as Gd in different geometrical arrangements necessitated verification of calculational parameters of the BOXER code, which was used in this work as a main computational tool. Different zone condensation schemes, division of poison region into different number of mesh points, and comparison of depletion calculations results with those of an alternative fuel assembly burnup code – CASMO [2], are considered and presented in this section.

All calculations described in this section were carried out in a simplified geometry, which was judged adequate for comparison and verification purposes. The geometry, shown in Fig. 3, is a 3x3 lattice, with central position occupied by a WABA (or other BP) rod.

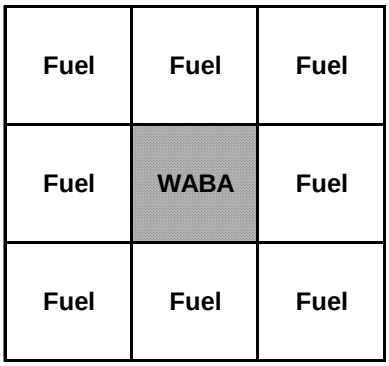


Fig. 3: Lattice arrangement

III.1 Zone condensation options for Resonance Absorption - Gd WABA-type design

This item was investigated due to potential influence of condensation scheme on BP resonance cross-section. In BOXER code, cell resonance calculations are performed in 2 or 3 zones. The WABA cell geometry includes 7 material zones, as shown in Fig. 1. The WABA type absorber with Gd as a BP used in this exercise along with its material composition is described in Tables 5 and 6.

Three options were considered: *Option 1* – 2 zones, BP material mixed with external cladding and water materials, *Option 2* – 3 zones, BP material was considered as a separate zone, and *Option 3* – 2 zones, BP material mixed with internal water and cladding. The comparison of the calculated options with No-BP case is shown in Fig. 4.

Table 5: Description Gd WABA

BP material	Al_2O_3 - Gd_2O_3
Active material	Gd_2O_3 (Nat. Gd)
Inert material	Al_2O_3
BP density, g/cm3	5.403
Active material density, g/cm3 (theoretical)	7.410
Inert material density, g/cm3 (theoretical)	3.965
Weight fraction of active material in BP, w/o	65.1
Weight fraction of inert material in BP, w/o	34.9

Table 6: Material composition: Gd WABA

Isotope	Fraction of isotope, weight %	Number density # / (barn · cm)
Gd154	1.30	2.7825E-04
Gd155	8.20	1.7303E-03
Gd156	11.5	2.3932E-03
Gd157	8.80	1.8297E-03
Gd158	14.1	2.9041E-03
Gd160	12.6	2.5557E-03
Al	18.5	2.2239E-02
O	25.0	5.0895E-02

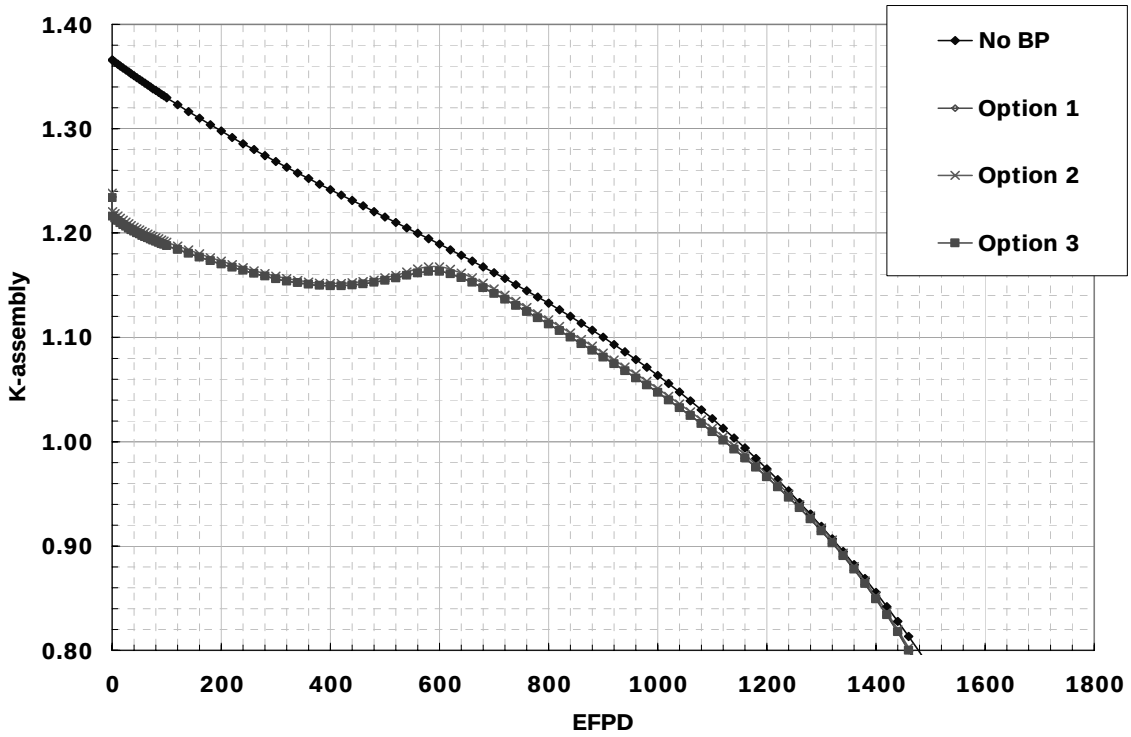


Fig. 4: The results of burnup calculations for different zone condensation schemes

The results clearly indicate that zone condensation scheme has negligible impact on results of depletion calculations. It should be noted however, that in present work, the cross-section group structure was not reduced from cell-level to assembly level calculations. In other words, no collapsing of energy groups was performed and depletion calculations of the assembly were carried out with full 70 energy groups.

III.2 Spatial division of BP region for Gd WABA-type design

Spatial distribution of the absorber material during burnup is essential for accurate prediction of the criticality. This paragraph presents sensitivity of the results of depletion calculation on a spatial division of the poison region, i.e. number of mesh points. In this case three options were considered, where gadolinium region was represented by a 1 mesh point (burnup material), 5 mesh points, and 20 mesh points. It should be noted that each mesh point was designated as a separate material and was depleted separately. Obviously, total amount of materials was conserved for all cases.

A comparison of assembly criticality as a function of burnup is shown in Fig. 5. The main conclusion which may be derived from these results is that 5 spatial regions option is identical to that of 20 spatial regions. In addition, it may be concluded that Gd region may be considered as a single region with a relatively small error of 0.2% ΔK.

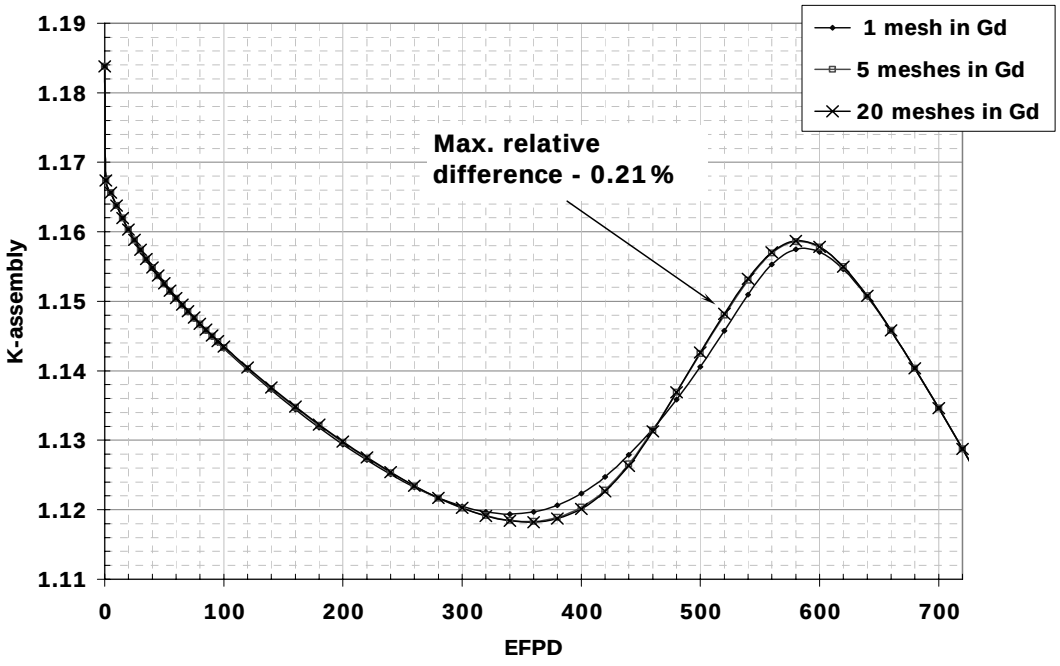


Fig. 5: K-assembly burnup curves for different spatial division of the Gd region (WABA)

Results of the Gd depletion in 5 regions provide an interesting insight into burnup behavior of the BP cells. Fig. 6 presents spatial dependence of the Gd-157 concentrations for 5 (equivalent-volume) regions (rings) of BP region. Region 5 is an external region adjacent to the water ring, and region 1 is an internal region adjacent to the water inside the BP ring (see Fig. 1). It may be noted that strong self-shielding effect of the Gd causes almost complete depletion of external layers of Gd around 300 EFPD's, while mid-part is depleted at about 450 days. This phenomenon strongly affects the burnup-dependent behavior of the criticality.

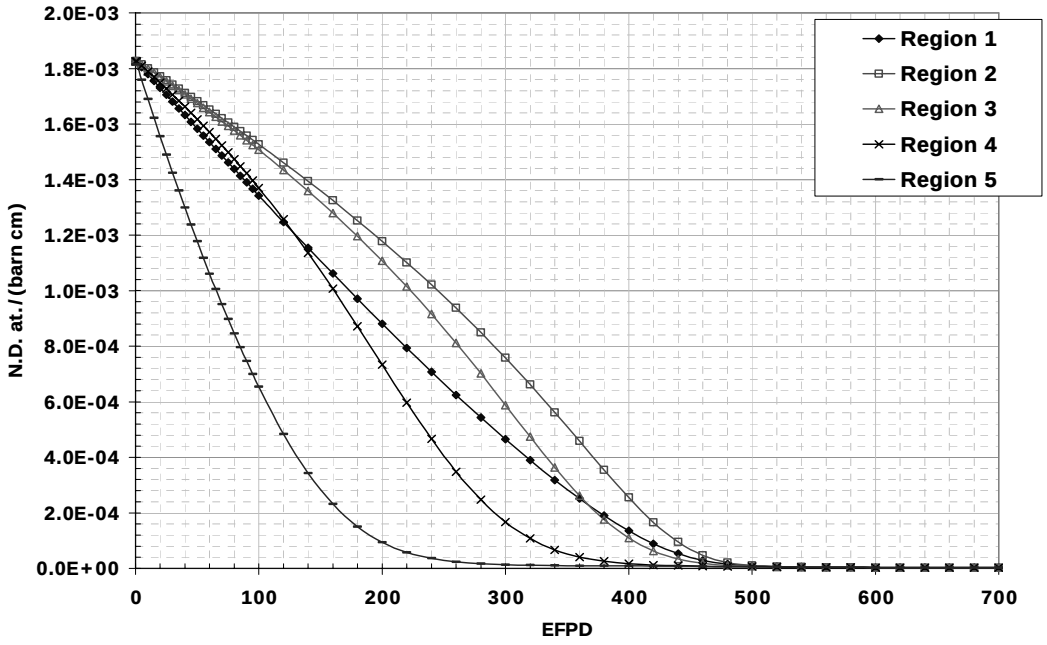


Fig. 6: Gd-157 concentration for different Gd burnup regions

III.3 Time-step length for Gd depletion

It is well known that one of the modeling parameters for depletion calculations is the duration of the time step. In this work adequate length of the depletion time step was verified by a straightforward comparison of the results of two cases with following time-steps (FPD):

- Case 1: 1d + 4d + 5d (19 steps) + 20d (70 steps)
- Case 2: 1d + 4d + 5d (120 steps)

Two different time step duration schemes were compared to check the effect on burnup calculations results. The results of calculations are shown in Fig. 7 and indicate that reduction of the time step to 5 FPD is required to achieve accuracy of about 0.34% ΔK.

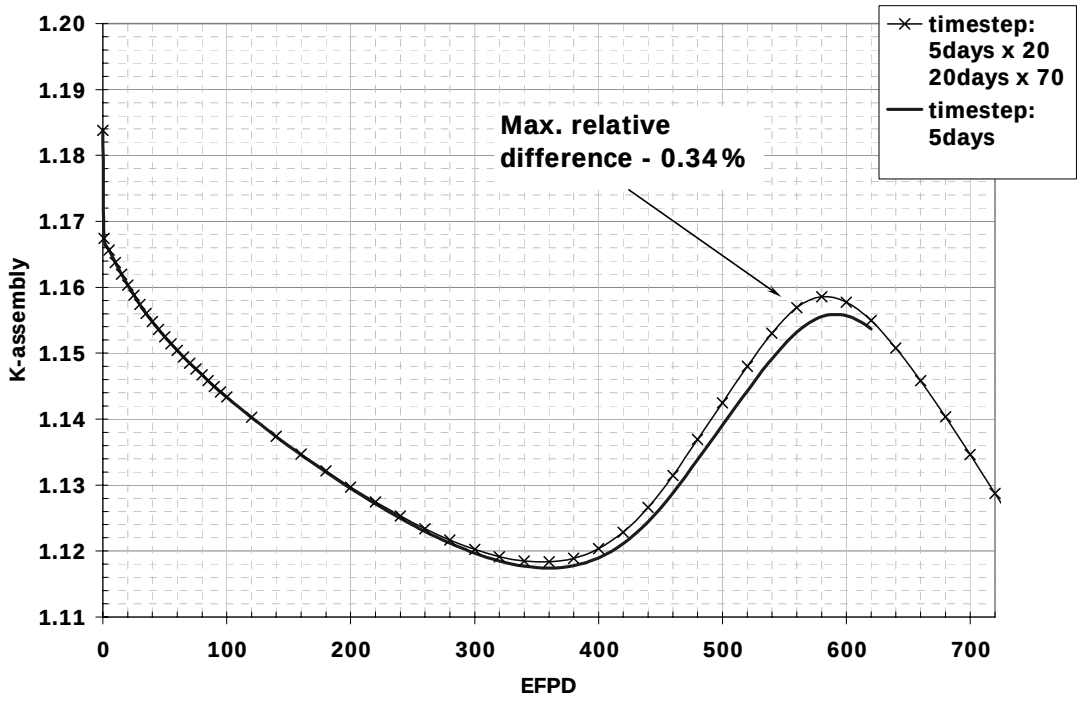


Fig. 7: K-assembly for different time-step length

III.4 BOXER vs. CASMO comparison

Depletion of a reactor lattice with heavy loading of such strong absorber as Gd involves approximations adopted in the calculational model. In order to assess an overall performance of the BOXER assembly burnup model, a direct comparison with widely used assembly code CASMO-4 [2] was carried out. The test was performed for a unit cell with reference IFBA pin geometry. The IFBA rod had a reference BP coating thickness and natural Gd oxide as a BP material. Detailed isotopic composition of Gd oxide coating is presented in Table 7. It should be noted that the BOXER code cross-section library is based on JEF-1 evaluated data file, while CASMO-4 uses JEF-3 based cross-sections. The CASMO-4 calculation was performed at Massachusetts Institute of Technology by the Fuel Cycle Analysis group of the Department of Nuclear Engineering.

The results are shown in Fig. 8. The assembly criticality difference does not exceed 1% ΔK showing good agreement between the codes.

Table 7. Material composition: Gd IFBA

Isotope	Fraction of isotope, weight %	Number density, # / (barn · cm)
Gd154	1.90	5.04E-04
Gd155	12.7	3.42E-03
Gd156	17.6	4.74E-03
Gd157	13.6	3.62E-03
Gd158	21.7	5.75E-03
Gd160	19.3	5.06E-03
O	13.3	3.47E-02

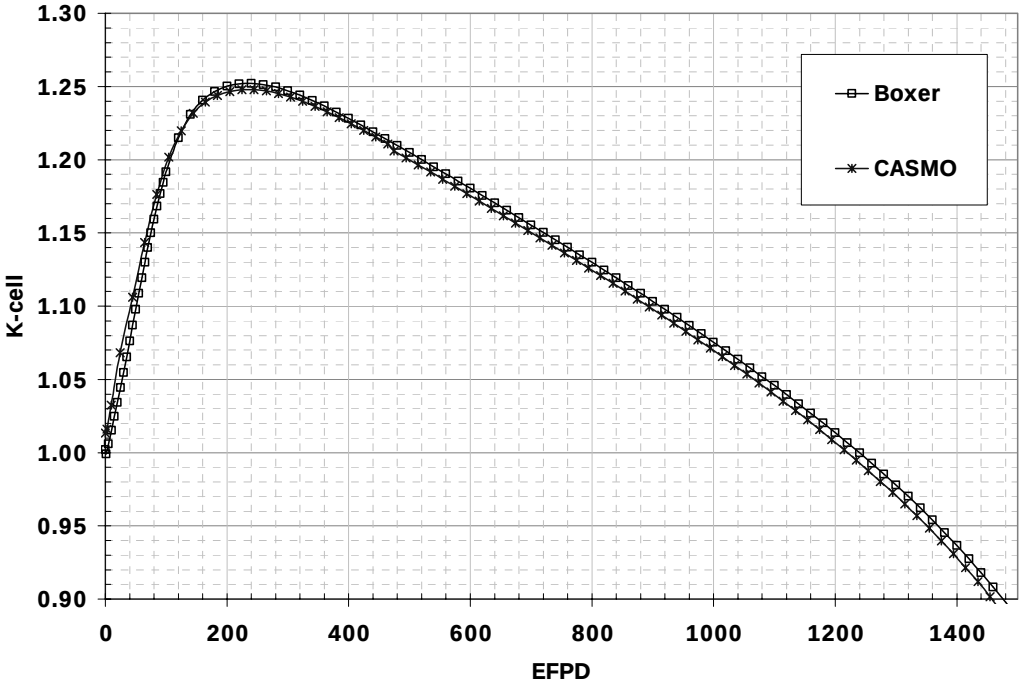


Fig. 8: Criticality of Gd IFBA fuel pin cell: BOXER vs. CASMO comparison

III.5 Non-linear reactivity model for estimation of core critical boron concentration

One of the well known and most significant design challenges of the Pu containing lattices is the reduced worth of neutron poison materials used for the core reactivity control. In PWRs, typically, burnable poisons are used in combination with boron dissolved in the reactor coolant. The concentration of soluble boron (SB) is relatively easy to adjust. However, its maximum concentration is limited to about 2000 ppm primarily by the coolant chemistry considerations [3] and coolant temperature reactivity coefficient. As a result, much smaller amount of excess reactivity can be controlled by SB in Pu containing lattices than in conventional UO_2 lattices, which also implies more extensive use of burnable poisons and the requirement for the higher BP loadings.

In light of the considerations stated above, an evaluation of the core critical boron concentration (CBC) as a function of burnup must be performed in order to estimate the BP loading such that the maximum CBC does not exceed the limit of 2000 ppm.

Discharge fuel burnup and cycle length can be estimated to a reasonable degree of accuracy based on assembly level burnup calculations through the use of the Linear Reactivity Model [4]. Somewhat more complex procedure can be used for the fuel cycle analysis if the reactivity dependence on burnup is evidently non-linear. Such technique, known as Non-Linear Reactivity Model (NLRM), was used for the analysis reported in Task 2 of the current project.

In work on Task 3, we developed a calculational methodology based on NLRM, which allows estimation of the core critical boron concentration based on assembly level calculations data.

Methodology

The developed methodology can be applied to various burnable poison design options e.g. BP homogenously mixed with the fuel, BP coating of the fuel pellet (IFBA-type), or BP containing rods inserted into guide tubes (WABA).

In the case of homogeneous poison or IFBA rods, the core was assumed to consist of fresh, once-burned and twice-burned fuel assemblies of the same type. In the case of WABA, the poison rods are located in the fresh fuel and removed after first refueling.

The following additional assumptions were made in the methodology development:

- The core is managed in 3-batch scheme, although this model can be easily extended for the general n-batch core case.
- The core is operated at steady state (equilibrium core).
- Equal power share between different fuel batches within the core is assumed.

The single-batch corrected for leakage core reactivity, ρ_{EFF}, is given by:

$$\rho_{EFF}(BU) = \rho_{assembly}(BU) - \rho_{laekage} \tag{1}$$

The assumption of equal power sharing between all fuel batches in the core results in the following relation between reactivity of the core and reactivities of individual fuel batches:

$$\rho_{core}(BU) = \frac{\rho^1_{EFF}(BU) + \rho^2_{EFF}(BU) + \rho^3_{EFF}(BU)}{3} \tag{2}$$

where $\rho^i_{EFF}(BU)$ is reactivity of i'th batch.

Since only one fuel type is assumed, the batches differ only in their accumulated burnup. In addition, the average core reactivity becomes zero at the end of each cycle (EOC). Then, assuming the same assembly type for all batches, the burnup accumulated by each batch in one cycle (BU_C) can be found from the following relation:

$$\begin{aligned} \rho_{core}(EOC) &= \frac{\rho^1_{EFF}(EOC) + \rho^2_{EFF}(EOC) + \rho^3_{EFF}(EOC)}{3} = \\ &= \frac{\rho_{EFF}(BU_C) + \rho_{EFF}(2\times BU_C) + \rho_{EFF}(3\times BU_C)}{3} = 0 \end{aligned} \tag{3}$$

After that, we can determine the core reactivity as a function of burnup using the single assembly reactivity and cycle burnup (BU_C),

$$\rho_{core}(BU) = \frac{\rho_{EFF}(BU) + \rho_{EFF}(BU + BU_{CYCLE}) + \rho_{EFF}(BU + 2 \times BU_{CYCLE})}{3} \tag{4}$$

Since we know the core reactivity at every burnup point (Eq. (4)), we can derive an expression for the core critical boron concentration (CBC) as function of burnup. Here, CBC is a soluble boron concentration required to keep the core reactivity equal to zero during the fuel cycle. First, we define the soluble boron reactivity worth (BW) as the change in reactivity per one ppm change in the soluble boron concentration:

$$BW_{Batch} = \frac{\Delta \rho}{\Delta ppm} = \frac{\rho_{EFF}(ppm_2) - \rho_{EFF}(ppm_1)}{ppm_2 - ppm_1} \quad \left[\frac{1}{ppm}\right] \tag{5}$$

where ppm_1 and ppm_2 are the two boron concentrations, $\rho_{EFF}(ppm_1)$ and $\rho_{EFF}(ppm_2)$ are the two corresponding reactivity values. Since BW varies with burnup, fuel batches will have different BW at each burnup point. From Eq. (5), we can find that the batch reactivity expressed through the soluble boron concentration and worth is:

$$\rho_{EFF} = BW_{Batch} \times ppm \tag{6}$$

Thus, the core CBC can be found from applying Eq. (6) to Eq. (4):

$$\begin{aligned}
&\rho_{core}(BU) = \\
&\frac{BW_1(BU) \times ppm_{core}(BU) + BW_2(BU) \times ppm_{core}(BU) + BW_3(BU) \times ppm_{core}(BU)}{3} = \\
&= \frac{(BW_1(BU) + BW_2(BU) + BW_3(BU)) \times ppm_{core}(BU)}{3} = \\
&= \frac{(BW(BU) + BW(BU + BU_C) + BW(BU + 2 \times BU_C)) \times ppm_{core}(BU)}{3} = \\
&= BW_{AVE} \times ppm_{core}
\end{aligned} \tag{7}$$

where,

$$BW_{AVE} = \frac{BW(BU) + BW(BU + BU_C) + BW(BU + 2 \times BU_C)}{3} \tag{8}$$

Finally, solving (7) for the core CBC, we obtain:

$$ppm_{core}(BU) = \frac{\rho_{core}(BU)}{BW_{AVE}(BU)} \tag{9}$$

Description of Calculation Procedure

In order to estimate core reactivity and CBC using NLRM, we performed three fuel assembly burnup calculations with the BOXER code. In the first calculation, we found fuel assembly reactivity, $\rho_{assembly}$, as function of burnup. In this calculation, soluble boron concentration is equal to zero. Then, we fit the calculated fuel assembly reactivity versus burnup data to 5th order polynomial function using Least Square Fit algorithm:

$$\rho_{assembly}(BU) = A_0 + A_1 \times BU + A_2 \times BU^2 + A_3 \times BU^3 + A_4 \times BU^4 + A_5 \times BU^5 \tag{10}$$

In the next two BOXER runs, we calculate single assembly CBC using BOXER built-in option for critical poison concentration search instead of *k-inf* eigenvalue search. In these two calculations, the *k-inf* values are forced to be equal to 1.03 and 1.04 respectively. Here, we assume $3\%\Delta\rho$ leakage reactivity and $1\%\Delta\rho$ perturbation for the estimation of BW at each burnup point. From the results of these two calculations, we derive $\Delta\rho$ and Δppm. Then, using Eq.(5) we obtained assembly BW at each time-step and fit the derived assembly BW versus burnup data to 5th order polynomial function using Least Square Fit algorithm:

$$BW_{Batch}(BU) = C_0 + C_1 \times BU + C_2 \times BU^2 + C_3 \times BU^3 + C_4 \times BU^4 + C_5 \times BU^5 \tag{11}$$

Finally, the core CBC is calculated from Eq. (9), in which the core reactivity is calculated using Eq. (4) and the core average BW is calculated using Eq. (8).

As mentioned earlier, for the WABA type burnable poison absorber analysis, the non-poisoned batch reactivity and BW data was used for the simulation of once- and twice-burnt fuel batches.

IV. Scope of calculations

This section presents a list of all cases investigated in this work. Table 8 presents a matrix of possible geometry-BP material arrangements

Table 8: 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. Reminder: the defined scope of calculations was 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. For all cases, the comparisons are performed for core critical Boron concentrations, by implementing the non-linear reactivity model.

Table 9, shown below, summarizes all 54 BP design options considered, which are divided into the following series of cases:

Table 9: List and Description of all calculated cases

Cases 2 – 4:	WABA/Boron, different B densities;	
Cases 5 – 10:	WABA/Gd, Variable BP volume, ring geometry, Gd density, assembly comparisons only;	
Cases 11 – 13:	WABA/Gd	For each material: constant BP densities; variable ring geometry $\Rightarrow$ different BP volume;
Cases 14 – 16:	WABA/Hf	
Cases 17 – 19:	WABA/Er	
Cases 20 – 27:	IFBA/B, IFBA/Gd, IFBA/Hf, IFBA/Er, variable BP material, coating thickness;	
Cases 28 – 36:	Homo/Gd, variable Gd volume, and number of rods/assembly;	
Cases 37 – 45:	Homo/Hf, variable Hf volume, and number of rods/assembly;	
Cases 46 – 54:	Homo/Er; variable Er volume, and number of rods/assembly.	

Table 9.A. WABA Cases

Case #	Case designation	Inner / outer radii of the BP ring (cm)	BP material in BP region (vol/o)	Number of BP rods per assembly	Total weight of BP (kg/assembly)
1	No BP	-	-	0	0.00
2	WABA-B-1	0.35306 / 0.40386	20.4	24	0.39
3	WABA-B-2	0.35306 / 0.40386	N/A	24	0.44
4	WABA-B-3	0.35306 / 0.40386	N/A	24	0.55
5	WABA-Gd-1	0.35306 / 0.40386	50.0	24	3.74
6	WABA-Gd-2	0.29360 / 0.40386	50.0	24	3.74
7	WABA-Gd-3	0.37931 / 0.40386	50.0	24	3.74
8	WABA-Gd-4	0.35306 / 0.44895	50.0	24	3.74
9	WABA-Gd-5	0.35306 / 0.46895	50.0	24	3.74
10	WABA-Gd-6	0.35306 / 0.40386	100.0	24	7.47
11	WABA-Gd-7	0.40137 / 0.46895	100.0	24	11.43
12	WABA-Gd-8	0.36758 / 0.46895	100.0	24	16.48
13	WABA-Gd-9	0.33379 / 0.46895	100.0	24	21.08
14	WABA-Hf-1	0.40137 / 0.46895	100.0	24	14.77
15	WABA-Hf-2	0.36758 / 0.46895	100.0	24	21.29
16	WABA-Hf-3	0.33379 / 0.46895	100.0	24	27.24
17	WABA-Er-1	0.40137 / 0.46895	100.0	24	13.18
18	WABA-Er-2	0.36758 / 0.46895	100.0	24	19.01
19	WABA-Er-3	0.33379 / 0.46895	100.0	24	24.32

Table 9.B. IFBA Cases

Case #	Case designation	IFBA coating thickness (mm)	BP material in BP region (vol./o)	Number of BP rods per assembly	Total weight of BP (kg/assembly)
20	IFBA-B-1	0.0115	100.0	116	0.72
21	IFBA-B-2	0.0115	100.0	264	1.64
22	IFBA-Gd-1	0.0115	100.0	116	0.88
23	IFBA-Gd-2	0.0115	100.0	264	1.99
24	IFBA-Gd-3	0.0160	100.0	156	1.64
25	IFBA-Gd-4	0.0160	100.0	264	2.78
26	IFBA-Hf-1	0.0160	100.0	264	3.24
27	IFBA-Er-1	0.0160	100.0	264	3.63

Table 9.C. Homogeneous Cases

Case #	Case designation	BP material in BP region (vol/o)	Number of BP rods per assembly	Total weight of BP (kg/assembly)
28	HOMO-Gd-1	0.5	264	1.79
29	HOMO-Gd-2	1.0	264	3.58
30	HOMO-Gd-3	2.0	264	7.17
31	HOMO-Gd-4	0.5	132	0.90
32	HOMO-Gd-5	1.0	132	1.79
33	HOMO-Gd-6	2.0	132	3.58
34	HOMO-Gd-7	0.5	64	0.43
35	HOMO-Gd-8	1.0	64	0.87
36	HOMO-Gd-9	2.0	64	1.74
37	HOMO-Hf-1	1.0	264	9.26
38	HOMO-Hf-2	2.0	264	18.53
39	HOMO-Hf-3	3.0	264	27.79
40	HOMO-Hf-4	1.0	132	4.63
41	HOMO-Hf-5	2.0	132	9.26
42	HOMO-Hf-6	3.0	132	13.90
43	HOMO-Hf-7	1.0	64	2.25
44	HOMO-Hf-8	2.0	64	4.49
45	HOMO-Hf-9	3.0	64	6.74
46	HOMO-Er-1	2.0	264	4.13
47	HOMO-Er-2	4.0	264	8.27
48	HOMO-Er-3	6.0	264	12.40
49	HOMO-Er-4	2.0	132	2.07
50	HOMO-Er-5	4.0	132	4.13
51	HOMO-Er-6	6.0	132	6.20
52	HOMO-Er-7	2.0	64	1.00
53	HOMO-Er-8	4.0	64	2.00
54	HOMO-Er-9	6.0	64	3.01

V. Results of calculations

This section presents summary of the calculational results, starting with a reference, No BP case, and continuing with all possible BP design options and variable parameters. Results are grouped into sub-sections and presented in the order following the list of cases summarized in Tables 2.A through 2.C.

V.1 WABA-type BP designs

Cases 2 – 4: WABA/Boron, different B densities

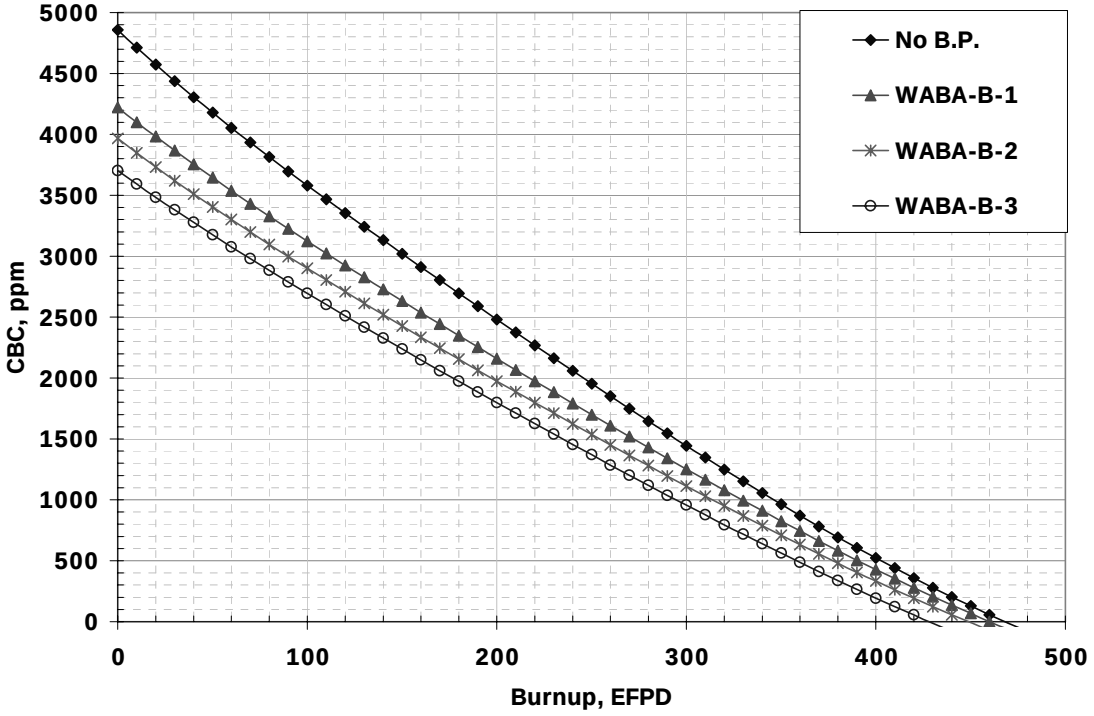


Fig. 9: CBC for WABA-Boron cases with variable poison density

Fig. 9 shows a limited potential of reducing the maximum CBC by utilization of possible WABA-B BP designs. Maximum loading of WABA-B in all available core positions may reduce CBC from ~ 5,000 ppm to about 3,800 ppm. Thus, utilization of the WABA-B BP in Pu-based

FFF core does not provide an adequate solution for the design problems considered in this report. This conclusion supports results of numerous analyses performed and reported in the past.

Cases 5 – 10: WABA/Gd, Variable BP volume, ring geometry, and Gd density

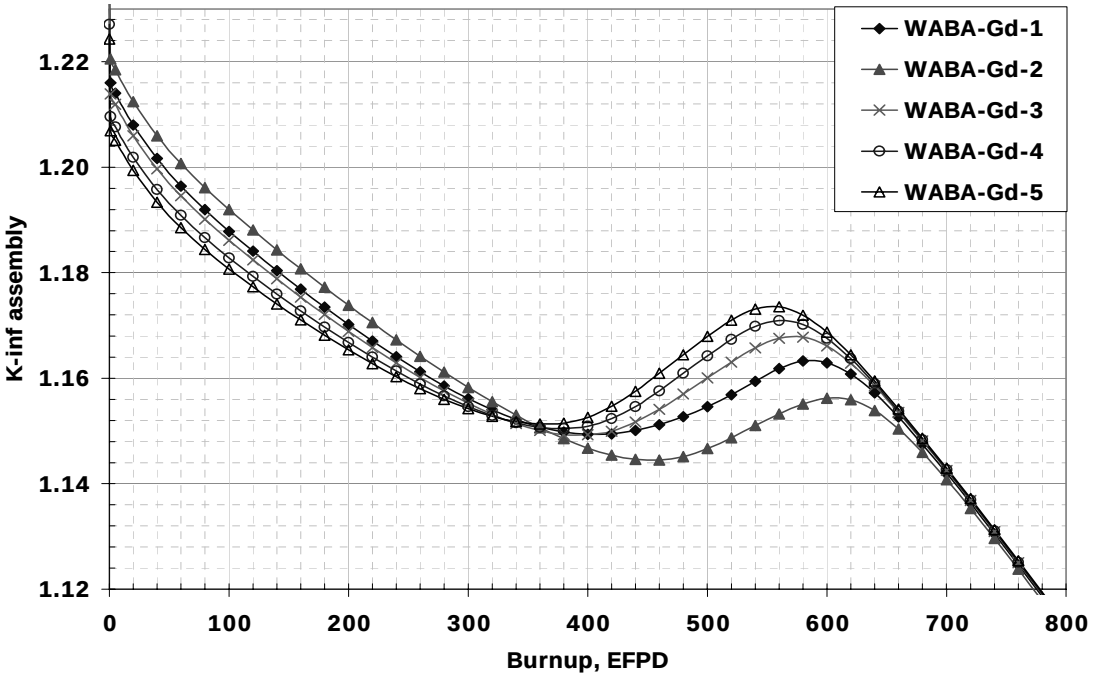


Fig. 10: K-ass for WABA-Gd cases with variable BP ring dimensions

Assembly criticality curves shown in Fig. 10 summarize potential of WABA-Gd BP design for different BP ring dimensions, i.e. volume fraction. Number of Gd rods is 24 for all cases and Gd density is varied accordingly to conserve total poison weight per assembly.

It may be concluded that increasing Gd region of the WABA-type geometry, available within the guide tube (all 24 positions), may result in a modest reduction of the required control reactivity.

A potential for the excess reactivity reduction of WABA-Gd BP is demonstrated in Fig. 11, where WABA-Gd-1 represents a standard design (dimensions), and WABA-Gd-6 represents a case with maximum poison load achievable in standard WABA-type geometry of a PWR of current generation and Gd poison material. A reduction of ~4% ΔK in BOC reactivity may be achieved. Though, this reduction is not negligible, clearly stand-alone utilization of WABA-Gd BP design can not address adequately the problem of excess CBC in FFF lattices.

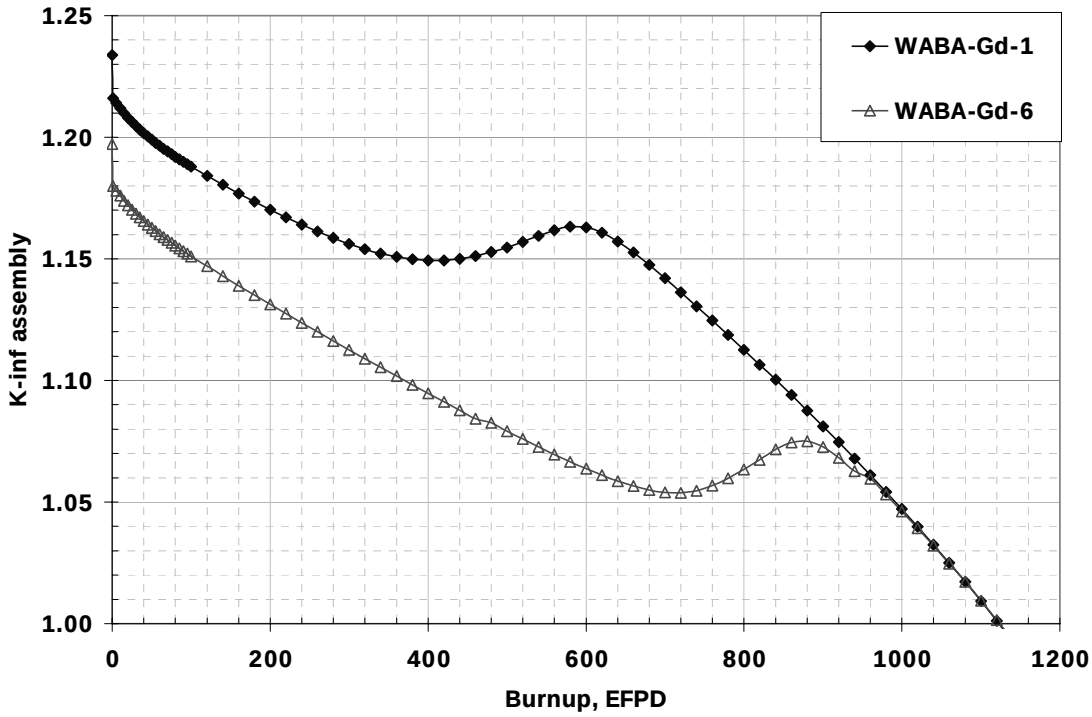


Fig. 11: K-ass for WABA-Gd cases with variable BP content

Cases 11 – 13: WABA/Gd

Assuming constant (maximum attainable) poison density in a single BP rod and 24 rods/assembly, these cases show potential to reduce CBC for different BP ring dimensions (inner and outer diameter). Contrary to cases 5-10, total weight of Gd/assembly is varied proportionally to variation of Gd volume/rod. Fig. 12 shows the comparison which leads to conclusion that the CBC is reduced from 4,100 ppm to 3,500 ppm for a maximum poison weight. Thus, the summary conclusion is that utilization of Gd poison in WABA-type geometry has a potential to compensate excess criticality equivalent to reduction of CBC of about 600 ppm.

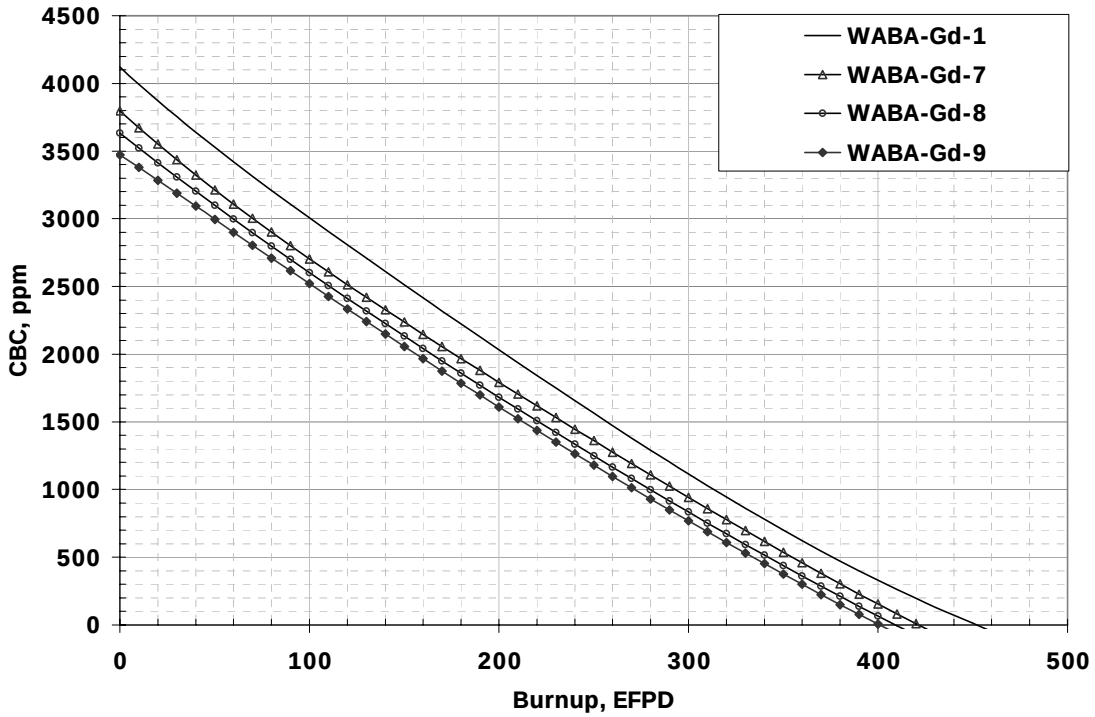


Fig. 12: CBC WABA-Gd cases with variable BP content and BP ring dimensions

Cases 14 – 16: WABA/Hf

This sub-section presents the results of WABA-type geometry with Hf BP material. Poison ring was varied resulting in different poison volume and total weight, while poison density was kept constant for all cases. Results are shown in Fig. 13 and indicate that utilization of Hf burnable absorber in WABA-type geometry has no potential for a significant reduction of CBC requirements.

Cases 17 – 19: WABA/Er

This sub-section presents the results of WABA-type geometry with Er BP material. Poison ring was varied resulting in different poison volume and total weight, while poison density was kept constant for all cases. Results are shown in Fig. 14 and indicate, as in Hf cases, that utilization of Er burnable absorber in WABA-type geometry has no potential for a significant reduction of CBC requirements.

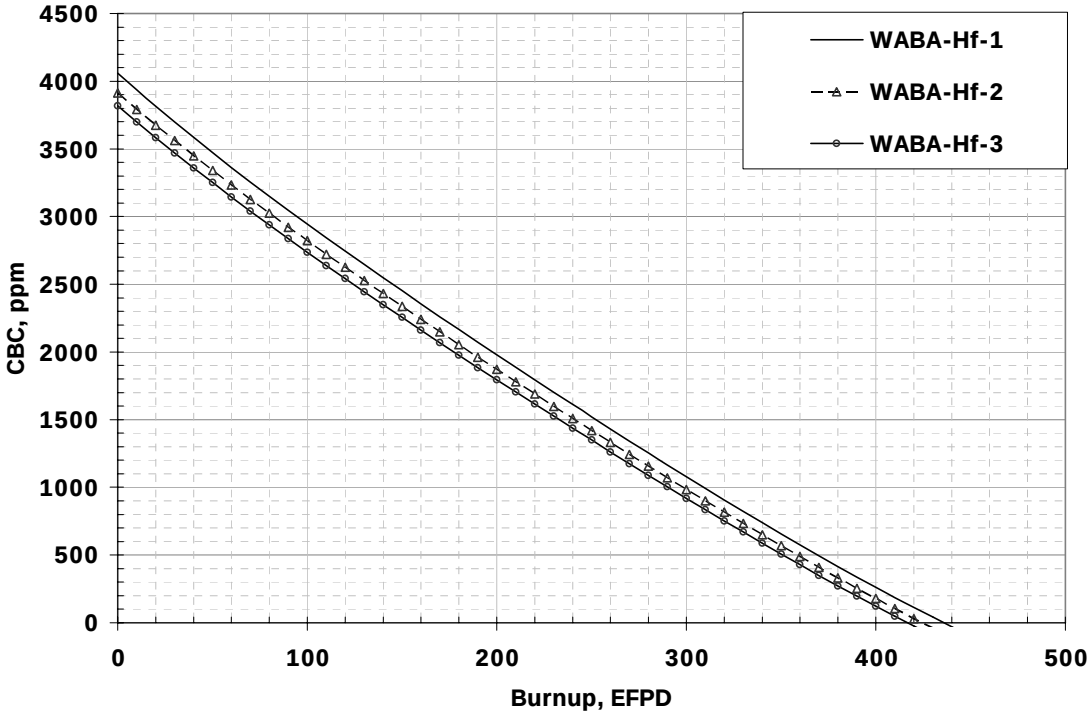


Fig. 13: CBC for WABA-Hf cases with variable BP ring dimensions

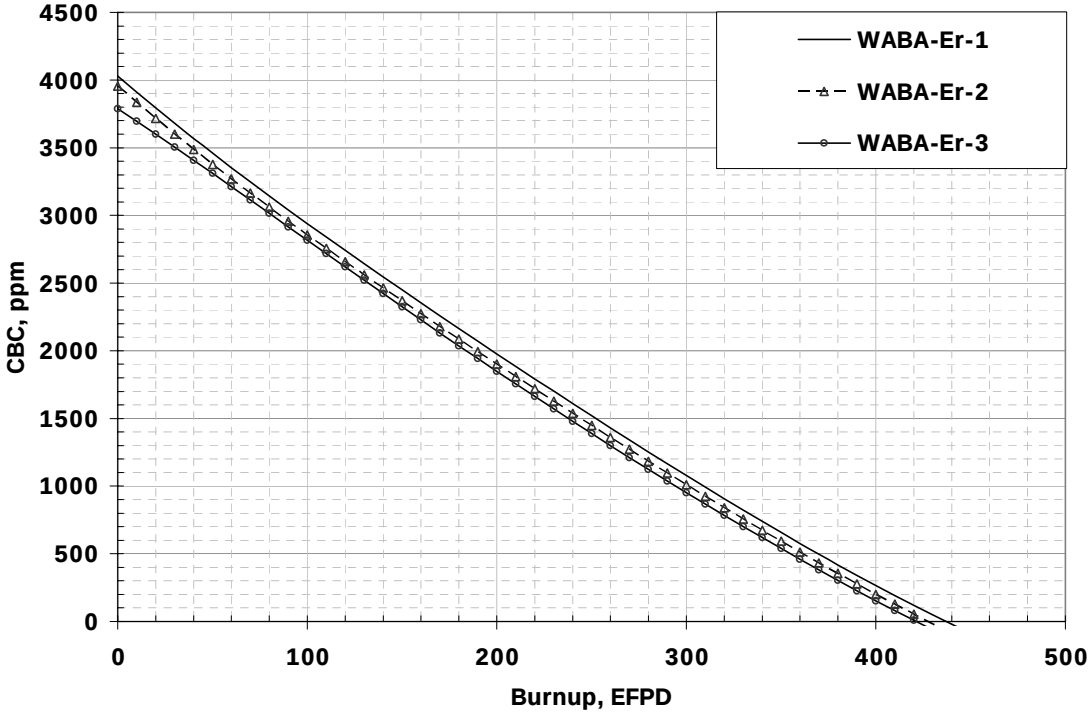


Fig. 14: CBC for WABA-Er cases with variable BP ring dimensions

The results of the WABA-type designs calculations (cases 11 – 19) are summarized in Table 10, showing maximum required CBC and residual poison penalty in effective full power days per cycle. An overall conclusion from all cases considered shows clearly that utilization of BP designs of WABA-type geometry with all possible BP materials does not present a viable solution for design challenges of Pu-based FFF cores.

Table 10: Results Summary: WABA cases (11-19)

Case #	BP Material	Maximum CBC (ppm)	Residual poison penalty (EFPD/cycle)
11	Gd_2O_3	3797	47
12		3632	59
13		3473	67
14	Er_2O_3	4029	31
15		3956	40
16		3787	47
17	HfO_2	4060	32
18		3912	44
19		3818	51

V.2 IFBA-type BP designs

Cases 20 – 27: IFBA-type geometry with B, Gd, Hf, and Er BP materials

This sub-section presents the results of calculations for IFBA-type BP geometries with all BP materials. The results are summarized in Table 11 and Fig. 15. Variable design parameters were poison coating thickness and number of BP pins/assembly.

Main conclusions from the presented results may be summarized as follows:

- IFBA-type BP designs with Hf and Er are not capable to reduce maximum CBC below 3,000 ppm.
- IFBA-type BP design with 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 BP design alone is not capable of reducing the maximum core CBC below 2,000 ppm even if all fuel pins in the assembly have BP (IFBA) coating.

Table 11: Results Summary: IFBA cases

Case #	Case designation	BP material	pins per assembly	coating thickness (mm)	CBC (ppm)	Residual penalty (EFPD)	Max. Pin power peak
21	IFBA-B-1	ZrB_2	116	0.0115	4314	3.6	1.085
22	IFBA-B-2		264	0.0115	3587	9.7	1.112
23	IFBA-Gd-1	Gd_2O_3	116	0.0115	3364	1.4	1.156
24	IFBA-Gd-2		264	0.0115	2886	4.3	1.113
25	IFBA-Gd-3		156	0.0160	2695	2.6	1.220
26	IFBA-Gd-4		264	0.0160	2397	6.0	1.113
27	IFBA-Hf-1	HfO_2	264	0.0160	3486	42.4	1.118
28	IFBA-Er-1	Er_2O_3	264	0.0160	3789	15.7	1.119

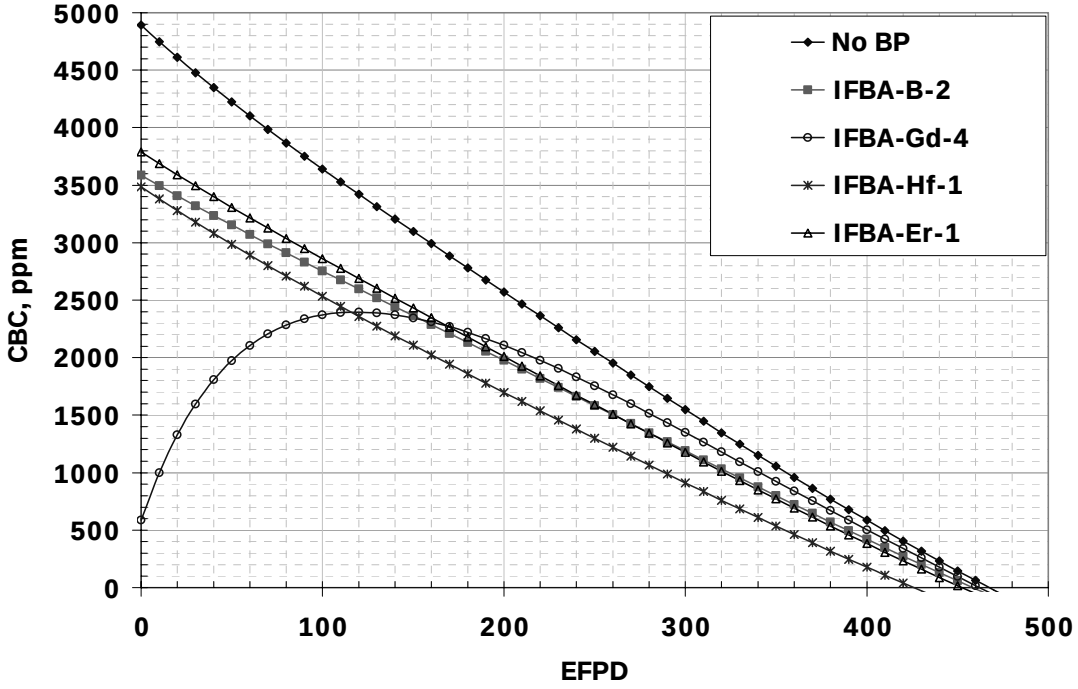


Fig. 15: CBC for IFBA-type geometry

V.3 BP designs based on homogeneous mixture of fuel and poison material.

Cases 28 – 36: Homo/Gd

Homogeneous fuel/Gd BP designs are summarized in this sub-section. Two design parameters were varied:

- Gd volume content – 0.5, 1.0, and 2.0 volume percent, and
- Number of rods/assembly – 64, 132, and 264.

Main results are summarized in Table 12 and Figures 16 through 21.

Table 12: Results Summary: Homo-Gd cases

Case #	Case Id	Pins per assembly	v/o BP	max CBC (ppm)	Residual penalty (EFPD)	assembly Pin power peak
28	HOMO-Gd-1	264	0.5	2943	5	1.113
29	HOMO-Gd-2		1.0	2161	8	1.164
30	HOMO-Gd-3		2	1117	16	1.136
31	HOMO-Gd-4	132	0.5	3430	3	1.112
32	HOMO-Gd-5		1.0	2779	4	1.197
33	HOMO-Gd-6		2	2114	8	1.145
34	HOMO-Gd-7	64	0.5	4059	1	1.111
35	HOMO-Gd-8		1.0	3680	2	1.233
36	HOMO-Gd-9		2	3433	4	1.156

Figures 16 to 18 show CBC curves for different number of rods per assembly with different Gd volume content, and Fig. 19 shows CBC curves for identical Gd content distributed in different number of rods/assembly. Results presented in this section indicate that homogeneous Gd/fuel BP designs offer real potential to reduce maximum critical boron concentration to an acceptable level of 2,000 ppm or less. From the neutronic perspective a preferable solution is to distribute a given amount of Gd poison among all fuel rods within assembly (see Fig. 19).

Additional consideration is the residual penalty associated with incomplete burnup of poison at EOC.

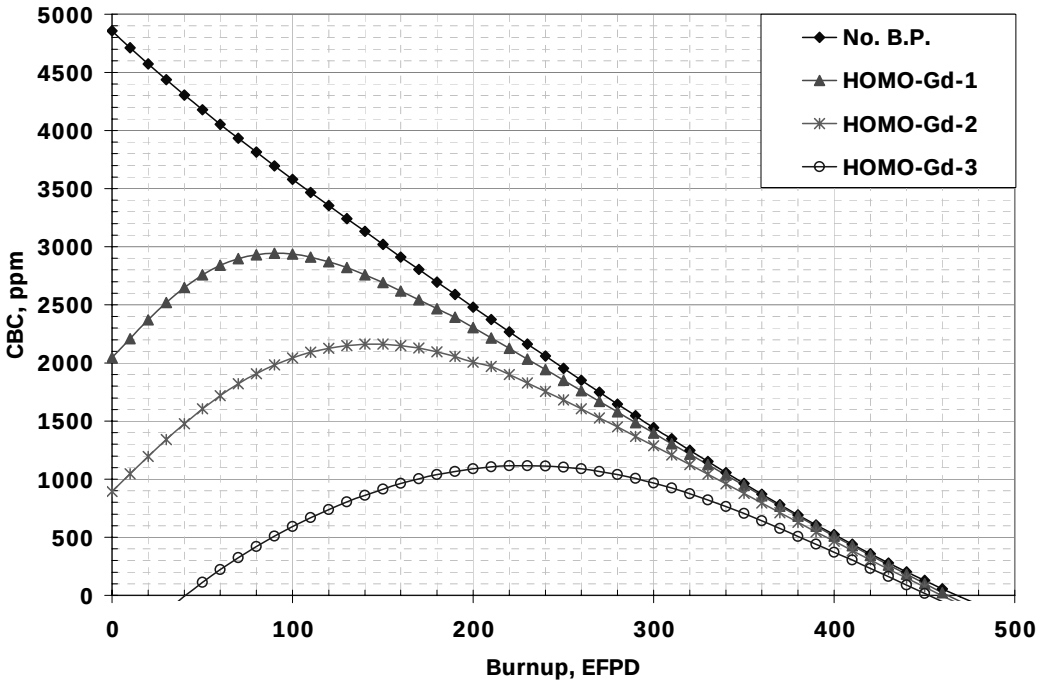


Fig. 16: CBC for 0.5, 1.0, 2.0 v/o poison (264 BP rods/assembly)

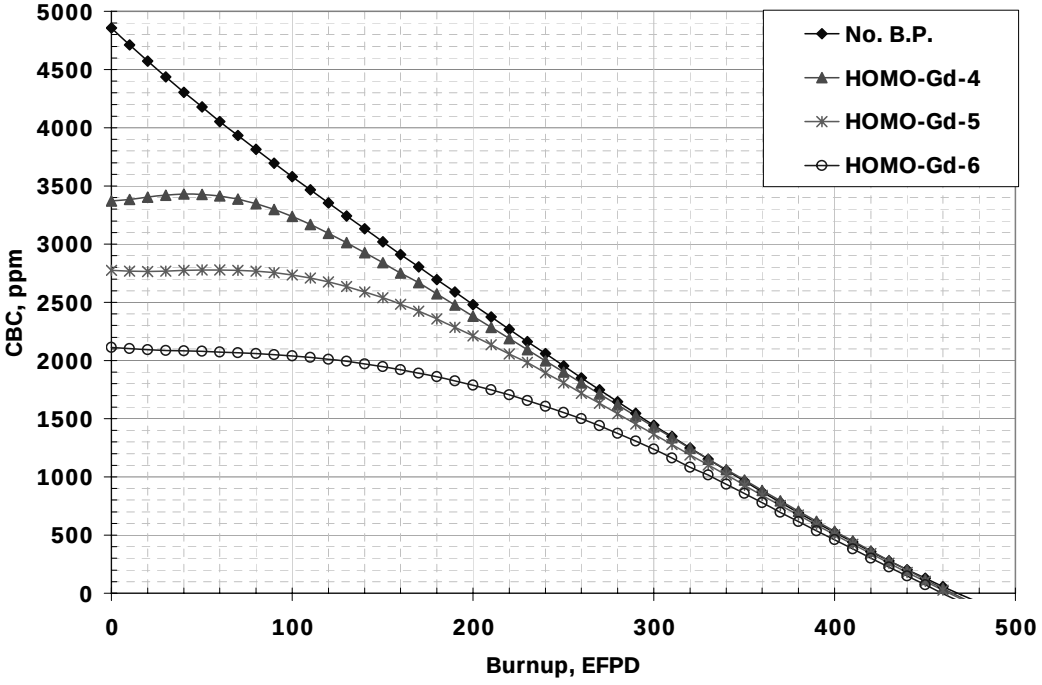


Fig. 17: CBC for 0.5, 1.0, 2.0 v/o poison (132 BP rods/assembly)

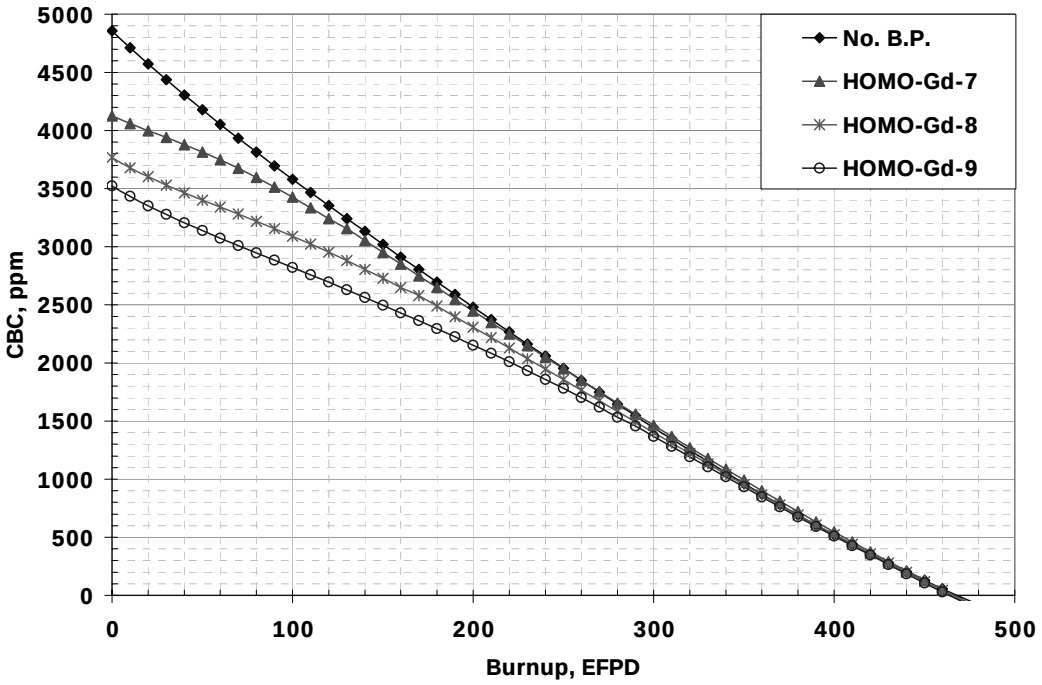


Fig. 18: CBC for 0.5, 1.0, 2.0 v/o poison (64 BP rods/assembly)

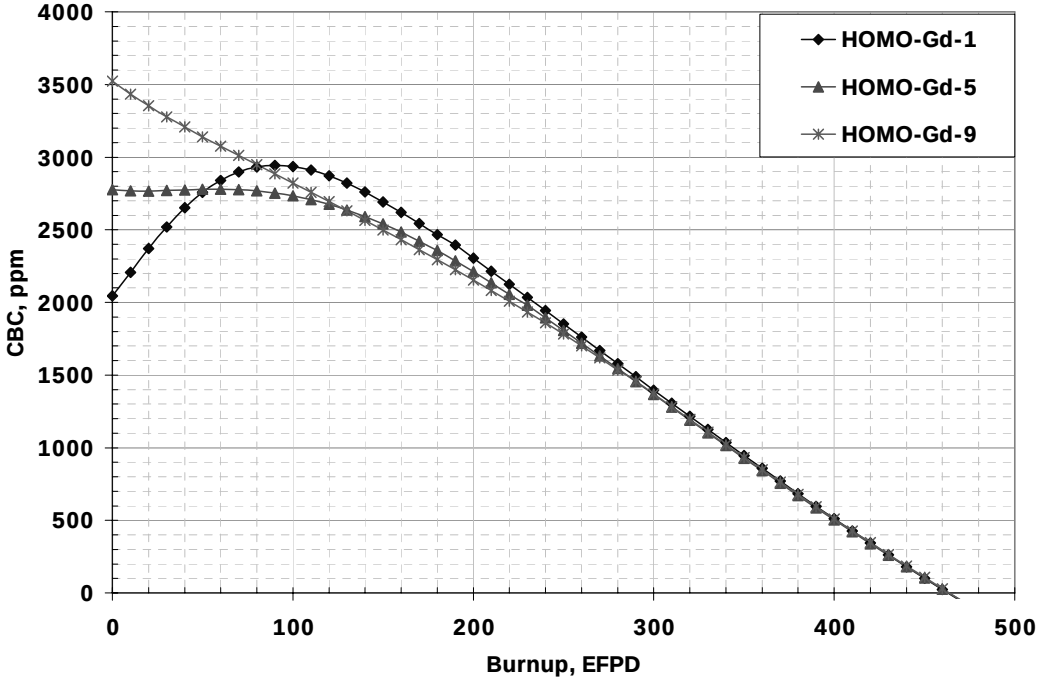


Fig. 19: CBC, 264, 132, 64 rods/assembly, Gd weight = 1.79 kg/assembly

An alternative presentation of the maximum core CBC and residual penalty effect is given in Figures 20 and 21.

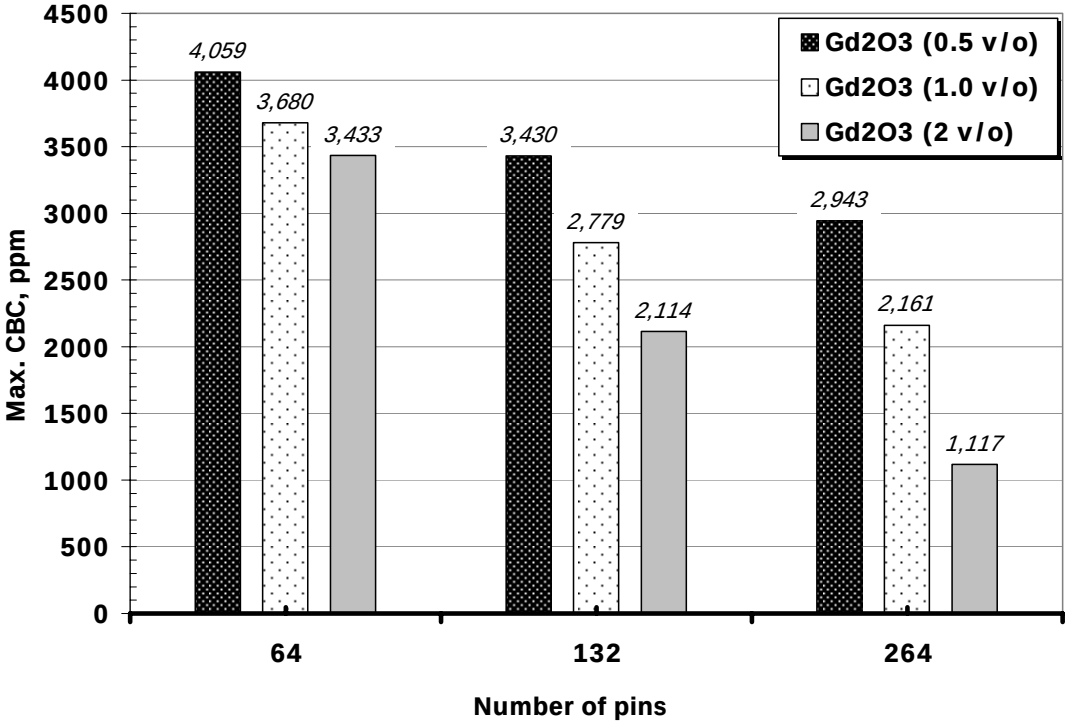


Fig. 20: Maximum CBC for all Homo-Gd Designs

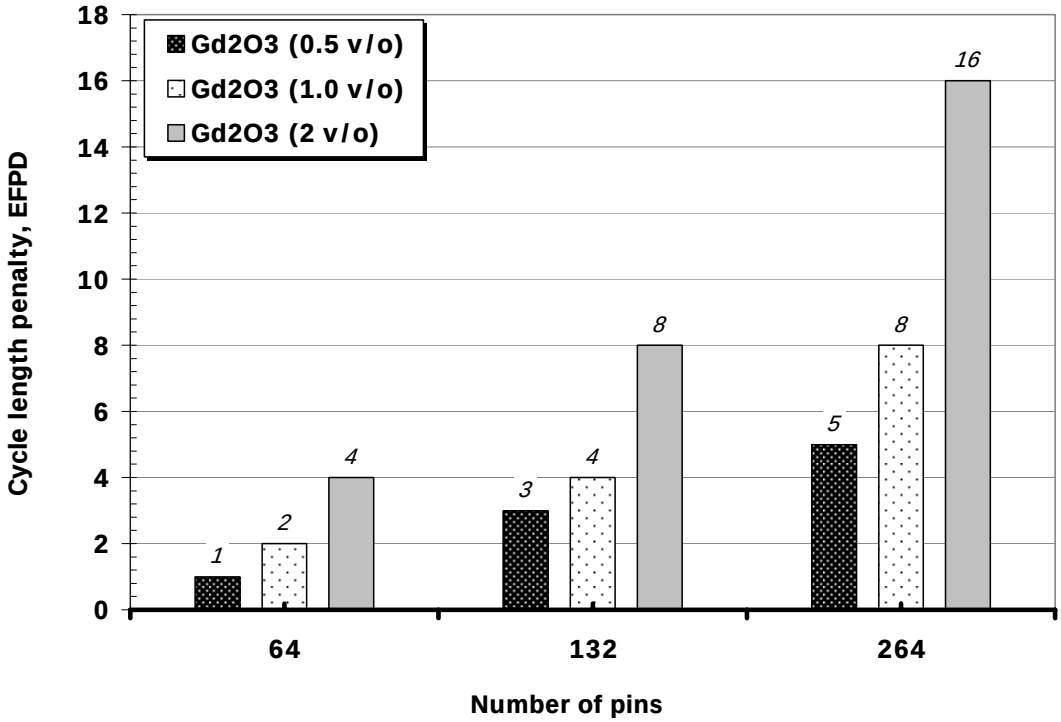


Fig. 21: Residual BP penalty for all Homo-Gd designs

The efficient reduction of the maximum CBC required is inversely proportional to a residual poison penalty. This effect is intuitively consistent with a notion that an increase in a total amount of BP causes a reduction in excess reactivity requirement (CBC) and at the same time an increase in residual amount poison at EOC.

The overall conclusion relevant to developing the Pu-based FFF core is that Homogeneous Gd/fuel BP designs are capable to reduce the maximum CBC to about 2,000 ppm. It is also demonstrated that distributing about 4 kg of Gd among half of the fuel rods in assembly (132) results in a relatively low penalty on fuel cycle length of 2 – 8 full power days.

Cases 37 – 45: Homo/Hf

Following sub-sections presents summary of results for homogeneously distributed Hf and Er BP designs. Similarly to Gd design options, both Hf and Er were distributed homogeneously in 64, 132, and 264 fuel rods. Hf loading was varied for 2, 4, and 6 volume percents, and Er for 1, 2, and 3 volume percents.

The results of the calculations for homogeneous Hf BP designs are summarized in Table 13 and Figures 22 through 26. A potential to reduce maximum CBC by utilizing Hf BP in 264 or 132 fuel rods is demonstrated. Hf volume content of 2 – 3 % seems feasible: pin power peaks are within a reasonable range. The major problem is poor burnup characteristics of Hf depletion chain, resulting in large residual penalty in the range of 100 to 150 full power days per cycle. This penalty may lead to an unacceptably high penalty on a fuel cycle economics.

The possible solution to this problem is utilization of an enriched Hf isotopic composition, and is planned for the next stage of this project.

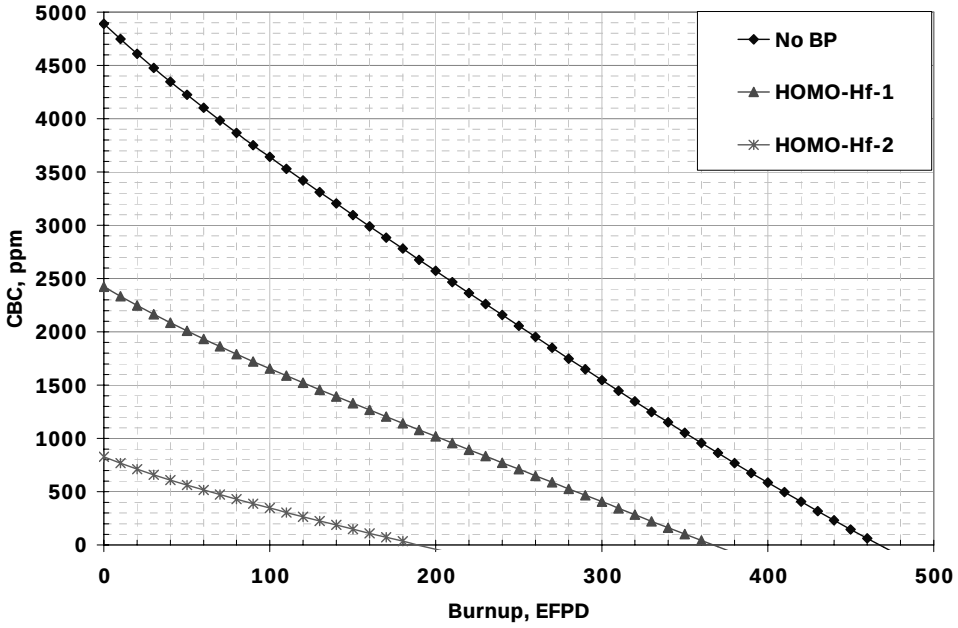


Fig. 22: CBC, Hf, 1 v/o and 2 v/o, (264 pins)

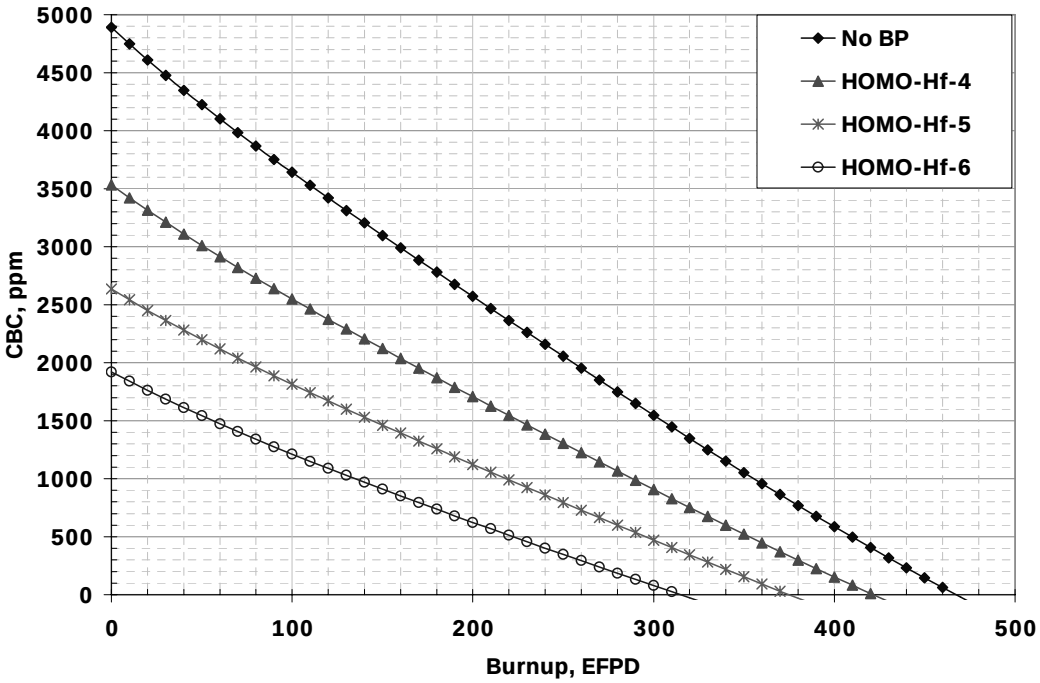


Fig. 23: CBC, Hf, 1 v/o, 2 v/o and 3 v/o, (132 pins)

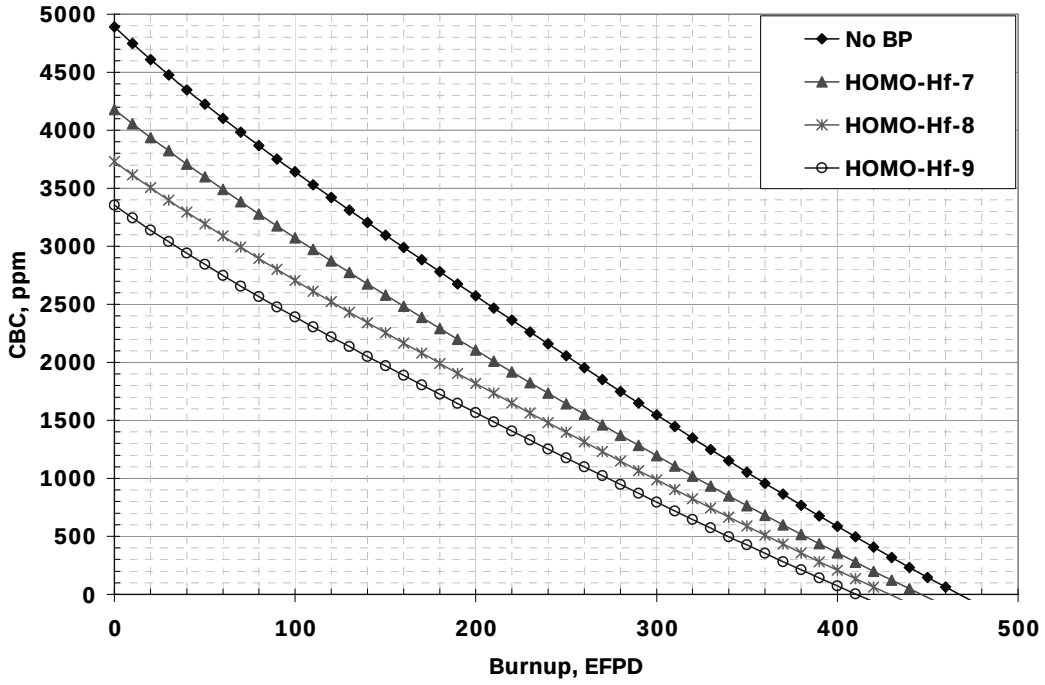


Fig. 24: CBC, Hf, 1 v/o, 2 v/o and 3 v/o, (64 pins)

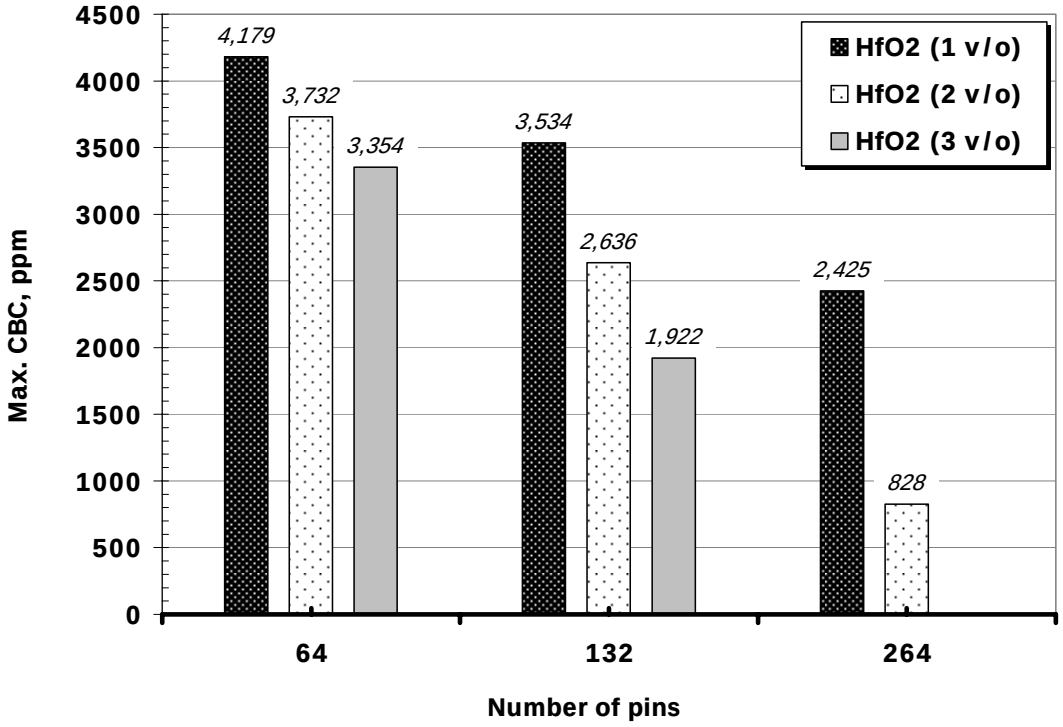


Fig. 25: Max. Core CBC with Hf BP

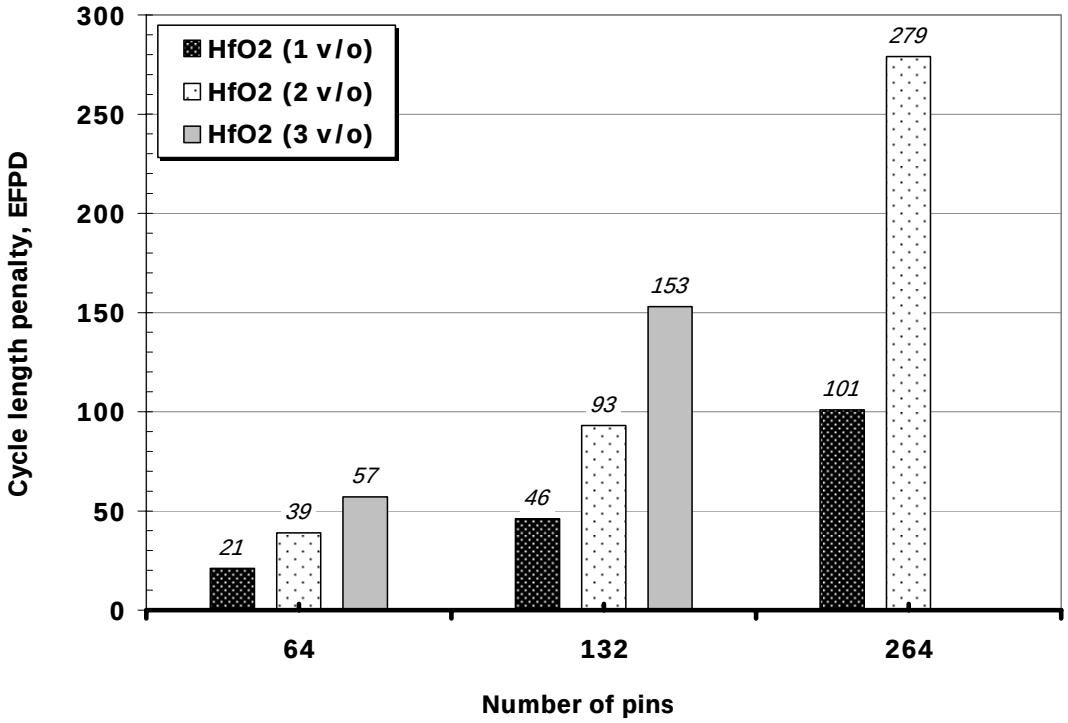


Fig. 26: Cycle length penalty for Hf BP

Table 13: Results Summary: homogeneous Hf designs

Case #	Case designation	BP material	No of pins per assembly	Volume % of BP material	max CBC (ppm)	residual penalty (days)	Pin power peak
37	HOMO-Hf-1	HfO_2	264	1.0	2425	101	1.121
38	HOMO-Hf-2			2.0	828	279	1.124
39	HOMO-Hf-3			3.0	N/A		
40	HOMO-Hf-4		132	1.0	3534	46	1.107
41	HOMO-Hf-5			2.0	2636	93	1.099
42	HOMO-Hf-6			3.0	1922	153	1.096
43	HOMO-Hf-7		64	1.0	4179	21	1.115
44	HOMO-Hf-8			2.0	3732	39	1.113
45	HOMO-Hf-9			3.0	3354	57	1.112

Cases 46 – 54: Homo/Er

The results of calculations for homogeneously mixed Er BP are presented below. Three Er volume fractions were considered – 2 v/o, 4 v/o, and 6 v/o, mixed with 64, 132, and 264 fuel rods. Overall, 9 cases were considered, and results are shown in Table 14 and Figures 27 through 31.

Results indicate that a significant reduction of maximum CBC, below 2,000 ppm, may be achieved by utilizing 4 or 6 v/o of Er mixed in 132 or 264 fuel rods. Similarly to Hf designs, residual Er poison penalty of 40 to 120 full power days seems unacceptably high. Utilization of enriched Er isotopic composition will be considered at the next stage of the project as a possible solution.

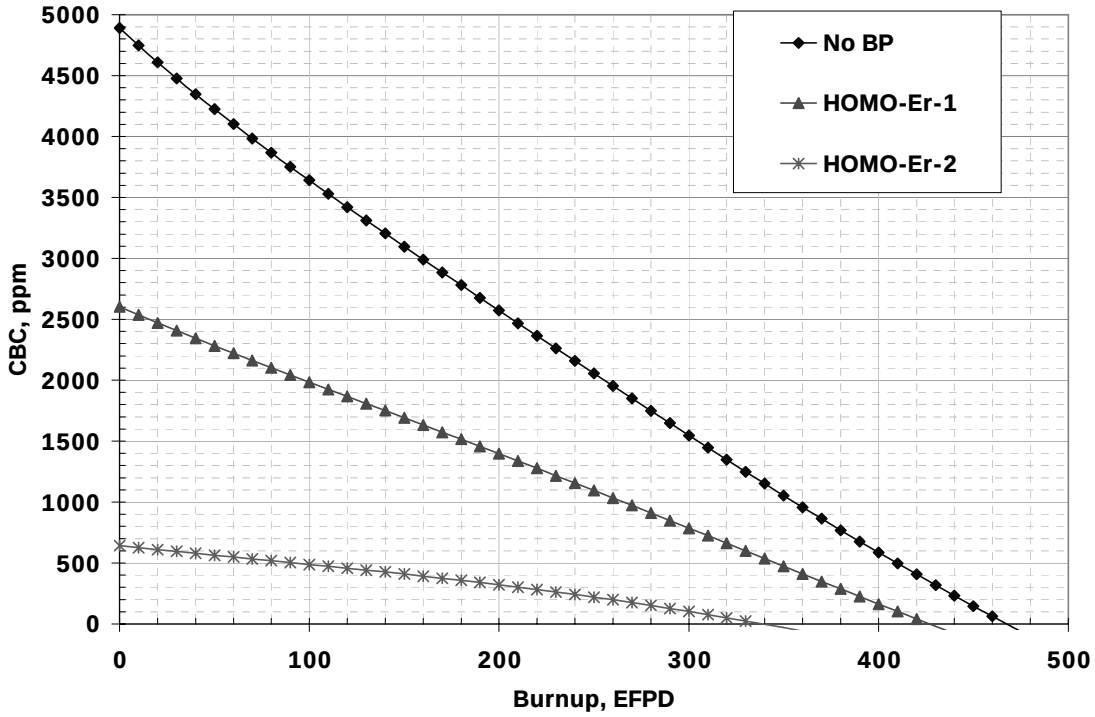


Fig. 27: CBC, Er 2 v/o and 4 v/o, (264 pins)

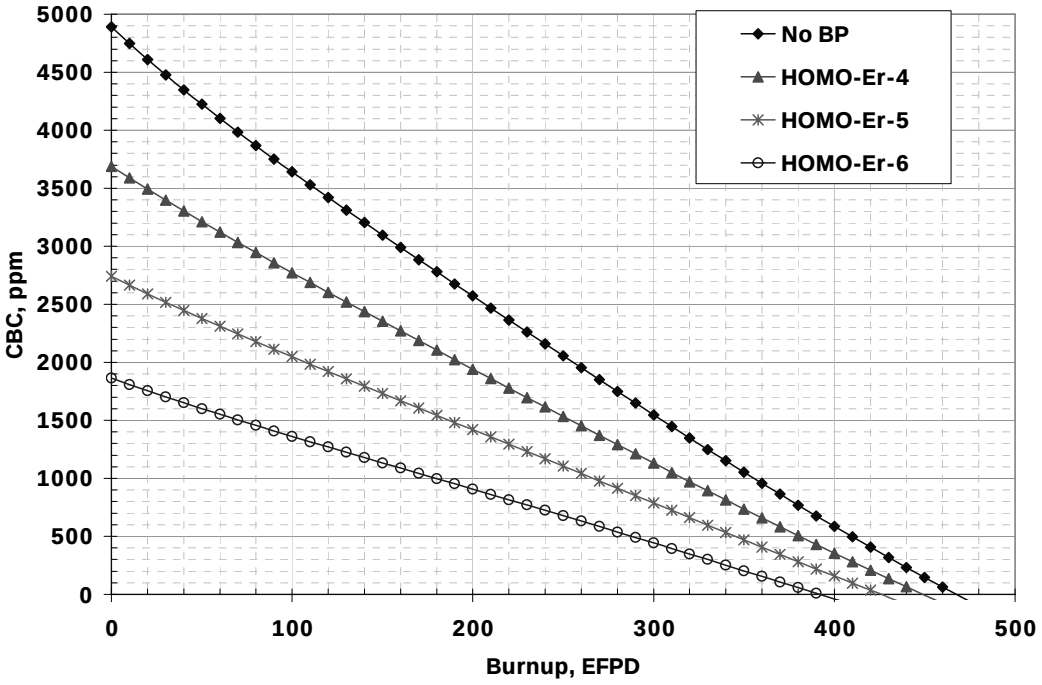


Fig. 28: CBC, Er 2 v/o, 4 v/o and 6 v/o, (132 pins)

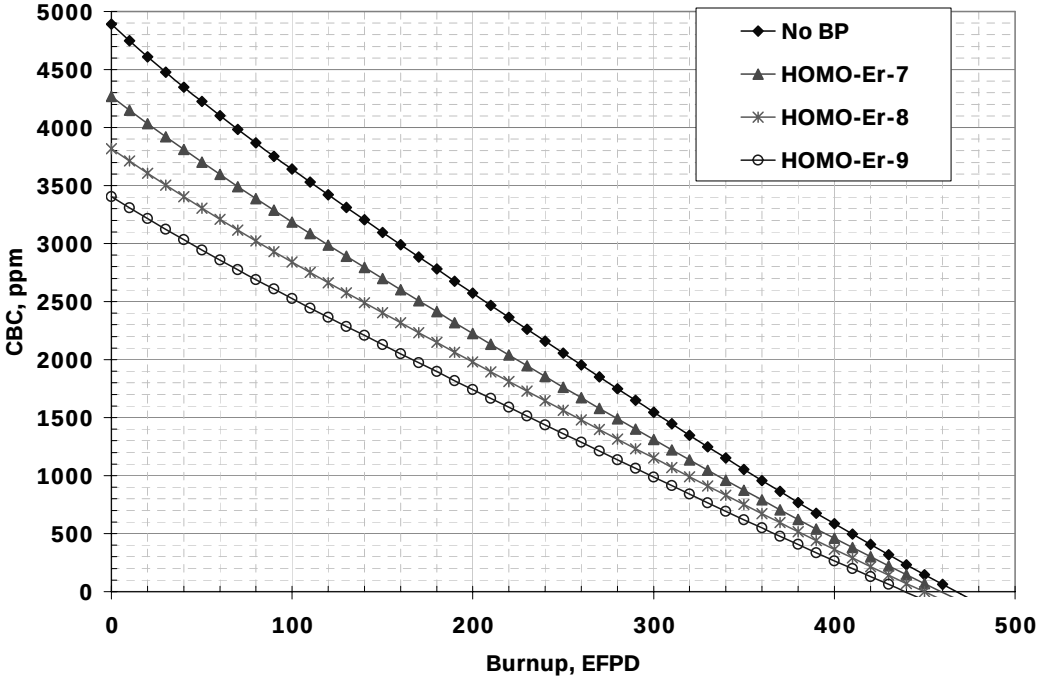


Fig. 29: CBC, Er 2 v/o, 4 v/o and 6 v/o, (64 pins)

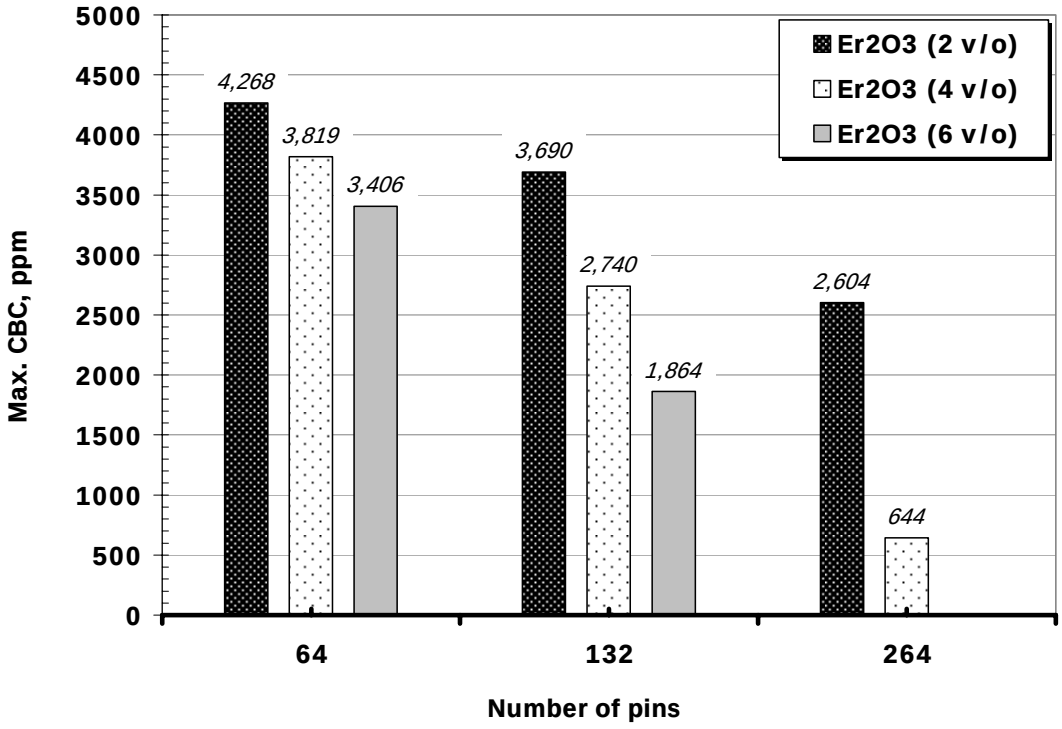


Fig. 30: Max. Core CBC for Er BP

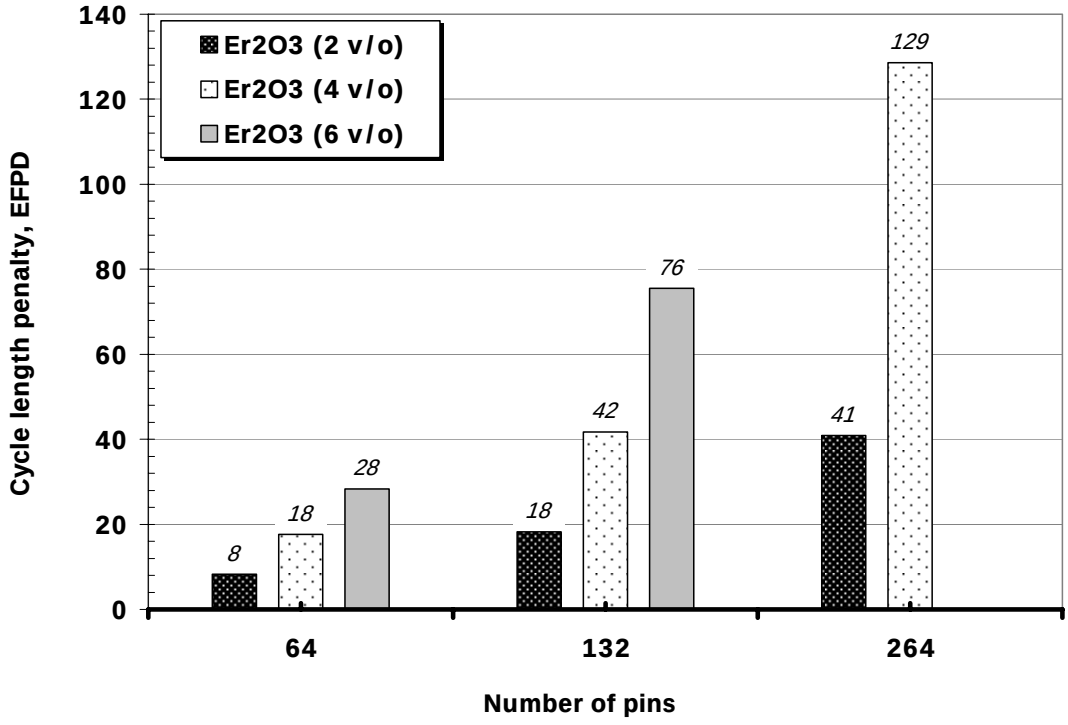


Fig. 31: Cycle length penalty for Er BP

Table 14: Results Summary: Homogeneous cases with Er

Case #	Case designation	BP material	No of pins per assembly	Volume % of BP material	max CBC (ppm)	residual penalty (days)	Pin power peak
46	HOMO-Er-1	Er_2O_3	264	2.0	2604	41	1.122
47	HOMO-Er-2			4.0	644	129	1.125
48	HOMO-Er-3			6.0	N/A		
49	HOMO-Er-4		132	2.0	3690	19	1.094
50	HOMO-Er-5			4.0	2740	42	1.106
51	HOMO-Er-6			6.0	1864	76	1.116
52	HOMO-Er-7		64	2.0	4268	8	1.115
53	HOMO-Er-8			4.0	3819	18	1.114
54	HOMO-Er-9			6.0	3406	28	1.115

VI. Summary and Conclusions

In this task, we assessed the potential of different BP designs and BP materials to reduce the critical boron concentration (CBC) of the Pu-FFF core to below the limit of 2000 ppm. The considered BP materials (B, Gd, Hf, and Er) were utilized in three geometrical arrangements: WABA-type, IFBA-type, and Homogeneous fuel-BP mixture. For each of the BP design options several sub-cases were considered, varied by number of BP rods per assembly, volume and/or BP material density. For each case, three main performance parameters of the BP designs were evaluated:

- CBC required during the cycle,
- Residual reactivity penalty associated with incomplete depletion of the BP material,
- Assembly pin power peaking factors.

In order to evaluate these performance parameters, we developed a calculation methodology based on non-linear reactivity model (NLRM), which allows estimation of the fuel cycle length and the core CBC based on assembly level calculations data.

The results of calculations, performed in this task, can be summarized as follows:

1. 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.
2. IFBA-type
   - IFBA-type BP designs with Hf and Er can reduce maximum CBC up 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.
3. 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 2 - 3 v/o of Hf or 4 - 6 v/o of 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.

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