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# Effectiveness of Different Burnable Poisons in a Long Cycle BWR

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BWR fuel assemblies for very long cycle operation are investigated with three different types of burnable absorbers; gadolinium, erbium, and the $B_4C$ in alumina annular burnable absorber. Their nuclear characteristics such as reactivity and power distributions are compared. Two-dimensional assembly calculations were done by CASMO-4 and three-dimensional core Haling calculations were done by SIMULATE-3. The results show that the enriched Gd-157 gadolinium case has the lowest reactivity swing until end-of-life (EOL). However, the local peaking factor (LPF) in the assembly calculation and the nodal peaking in the core calculation at beginning-of-life (BOL) were quite high. The erbium case showed more reactivity swing than the gadolinium case but the LPF and nodal peaking were the lowest of all three cases. The $B_4C$ case had the highest reactivity at BOL which must be suppressed by control rods. The most important advantage of $B_4C$ over gadolinium or erbium was the saving of uranium inventory needed to achieve the equivalent target exposure of 15 EFPY. Further analysis for transient conditions must be performed to ensure meeting all transient limits.

***KEYWORDS: BWR, Very long cycle operation, burnable poison***

## 1. Introduction

Besides reducing the cost of electricity by increasing the reactor capacity factor, long cycle reactor core operation offers some other distinct advantages. First, the simplification and automation of a long cycle core will significantly reduce the dependence on the local industrial infrastructures (both hardware and software), thus widening the appeal of nuclear plants around the world. Second, typically the long cycle core has a small- or medium-size power rating, i.e., several hundred MWe. The financial risk associated with each core would then be smaller. Also, the long cycle operation reduces the need for storage of spent fuel. Lastly, from a proliferation point of view, the need for safeguard barriers against diversion of fuel during handling is reduced since refueling is avoided (no access to spent fuel). However, a major drawback of a long cycle core is a more expensive fuel cycle since a larger fraction of the fissile part in the fuel remains unburned.

Control of the reactivity that must be loaded into the core to achieve a cycle on the order of 15 years presents a significant challenge. Toshiba Corporation has utilized enriched gadolinium in its design of fuel for a BWR with a very long operating cycle.[1,7] The present paper describes the results of a study to evaluate the use of enriched erbia or natural $B_4C$ in alumina as alternative burnable poisons. A primary objective in all such designs has been to maintain k infinity at average void close to 1.05 over the entire 15 year life of the core in order to minimize control rod

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insertion while providing sufficient reactivity to allow for plant maneuvering and calculational uncertainties. Also important are the local peaking factor, the void reactivity and the uranium enrichment required to attain the desired core life.

## 2. Methods and Benchmarking

Individual fuel bundle calculations were performed with Studsvik of America's CASMO-4 lattice physics code.[2,3] Because this commonly used code employs the method of characteristics to determine the flux distribution within the bundle, it is well suited to analysis of highly heterogeneous bundles such as those investigated here, which include both uranium enrichments (up to 19 w/o) and burnable poison loadings (up to 14 w/o gadolinia) that are higher than used in typical light water reactor fuel designs.

For whole core calculations, SIMULATE-3 was used to perform core-wise burnup calculations[4,5] based on the generated library. Haling depletion was adopted to compare the core performance using various burnable poisons in order to circumvent detailed control rod pattern designs. The actual Haling calculation was carried out as follows: (1) a target core burnup was first chosen; (2) assuming a constant power distribution (say flat power distribution), the end-of-cycle (EOC) core conditions (i.e., the burnup distribution) was determined; (3) an updated EOC power distribution based on the EOC core conditions was obtained; (4) the newly-obtained power distribution was substituted back to step (2); (5) repetition of (2) to (4) lead eventually to a consistent cycle-average power distribution (Haling power shape) and the EOC core conditions. If one assumes that

- all control rods are fully withdrawn at the end of cycle
- the reactivity of fuel is a decreasing function of exposure at the end of cycle,

it can be proven that the Haling power shape provides minimum power peaking during the cycle among all possible operations (also known as Haling principle [6]). This provides a reference power shape for BWR operations, so that manipulation of control rods during the cycle should match the reference Haling power shape as close as possible. One should also note that although the Haling power shape is the best available power shape the Haling principle itself does not offer an explicit method of designing the core to achieve this power distribution. Hence, the Haling method is an ideal, non-constructive concept. Nevertheless, all the core calculations shown here are based on the Haling method providing a consistent comparison.

## 3. BWR Model Description

The reference core design used in this study is a BWR rated at 900 MWth with 956 fuel assemblies. Each assembly has a 7x7 fuel rod array with 2.0m active length, and the bundle pitch is 0.7-times the size compared with current BWR bundle. The area of the fuel bundle cell is about half that of a typical BWR and the water to fuel volume ratio is about three, which is about 10% more than a typical 8x8 BWR fuel. Detailed base design parameters of the core and fuel have been established by Toshiba in Refs. [1,7].

For the fuel management, the reference LSBWR core uses single-batch fuel management with a target cycle length not less than 15 years, whereas typical BWRs use 3- to 4-batch fuel management with 18 or 24 month cycles. Using the linear reactivity model [8], one finds the discharge burnup, $B_d$, for a steady-state core having $n$-batch fuel management (1/$n$-th of the core refueled each cycle):

$$B_d = nB_c = \frac{2n}{n+1} B_1 \tag{1}$$

where $B_c$ is the cycle burnup and $B_1$ is the single-batch burnup. The cycle length is proportional to the burnup by a constant factor of 1/(specific-power). Hence, Eq. (1) shows that for a given fuel type the maximum cycle length (i.e., maximizing $B_c$ with respect to $n$) occurs at $n$=1. This explains why a single-batch fuel management is usually preferred for the long cycle core. On the other hand, Eq. (1) shows that in order to maximize the discharge burnup (fuel utilization) for a given fuel type, the number of fuel batches should be as large as possible. A limiting case is that of the continuous refueling where $n\to\infty$. The single-batch fuel management gives the lowest fuel utilization. Therefore, one should recognize that there is a fundamental tradeoff between achieving a longer fuel cycle (more energy delivery per cycle) and promoting more efficient fuel utilization (high burnup).

## 4. Criteria for Evaluating Fuel Assembly Designs

In this study, the criteria related to the burnable poison loading in fuel assemblies are set as follows; First, the combination of fuel enrichment and burnable poison loading must provide adequate reactivity to reach the design life of 15 years. For fuel design scoping purposes, this is initially evaluated by requiring that the reactivity at a void fraction of 40% be positive out to an exposure corresponding to the full power life of the core. The void level of 40% is estimated to be the core average void during most of the cycle. Haling calculations were performed to the exposure corresponding to the 15 year life of the core for those assembly designs which were deemed worth pursuing.

Second, the combination of fuel enrichment and burnable poison loading must provide adequate reactivity to allow plant maneuvering during the cycle and to allow for possible inaccuracies in calculating reactivity at the exposure levels achieved during operation, which are significantly beyond current experience. Following Toshiba's lead, we have assumed that this requires an unrodded $k_\infty$ of about 1.05 during the cycle, excluding the very end.

Third, the combination of burnable poison and fuel enrichment distribution must provide adequate control of local peaking, measured by the local peaking factor (LPF).

Fourth, the reactivity parameters of the assembly must be sufficient to allow stable operation of the reactor over the whole cycle. The reactivity parameters to which we refer include the void and doppler coefficients of reactivity, the control rod worth, the delayed neutron fraction and the prompt lifetime. For this work we have evaluated only the void coefficient. The doppler coefficient and the delayed fraction are usually not significantly influenced by the burnable poison loading. CASMO will be utilized to provide these estimated values.

## 5. Performance of Designs

The designs using erbia and $B_4C$ in alumina burnable poisons have been evaluated in comparison to the base gadolinia design. All assembly designs utilize a 7x7 array of rods. The gadolinia and erbia designs employ 3 water rods and 46 fuel rods per assembly; the $B_4C$ design employs 39 fuel rods and 10 rods containing $B_4C$ in alumina.

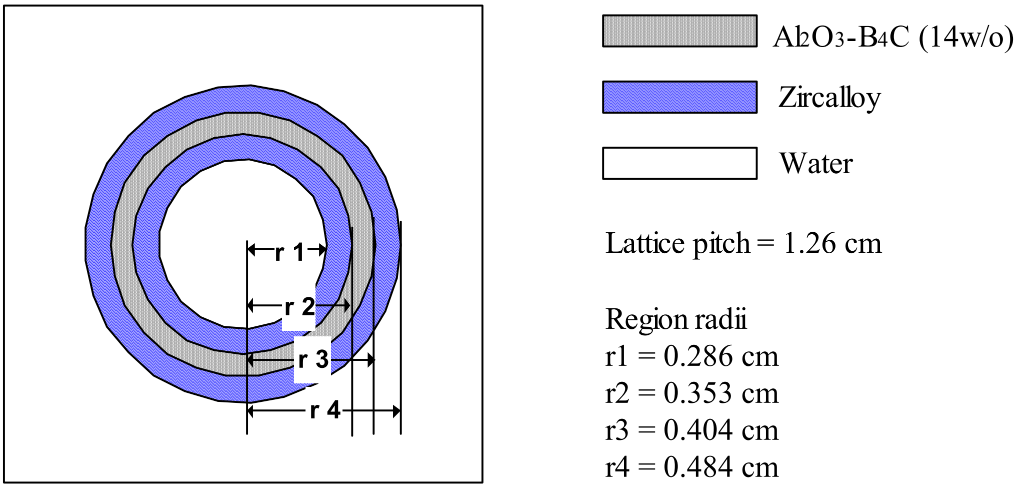


**Fig.1 $B_4C$ in alumina pin cell**

For gadolinia and erbia burnable poisons, Gd-157 and Er-167 were assumed to be enriched to 80 and 100%, respectively. For the $B_4C$ in alumina burnable poison, an annular design is used, with the annulus filled with $B_4C$ in alumina (Fig.1). Fig.2 compares the K infinity at 40% void for the three designs. Fig.3 compares the LPF at 40% void for the three designs. Since the assembly utilizing $B_4C$ in alumina has fewer fuel rods than the other two designs, it has higher average rod power. Therefore, the LPFs are multiplied by the rod power normalizing factor (1.18) so they can be compared based on their actual rod power. The cusps in the LPF curves occur where the location of peak power changes from one fuel rod to another. The reactivity swing is smallest for the gadolinium poisoned assembly to target exposure (15 EFPY), but the LPF for gadolinia is as high as 1.5 at beginning of life (BOL). In actual operation, control rods must be used to suppress these large excess reactivities.

The $B_4C$ poisoned assembly maintains its reactivity as high as other designs despite lower enrichment because of its strategically placed $B_4C$ rods inside the assembly. The asymptotic rate of reactivity loss at high burnup is similar though not identical for all burnable poisons, as one would expect. The $B_4C$ design has a slightly greater rate of reactivity loss than the gad or erbia designs, probably because it has a higher hydrogen to fuel ratio, which decreases the capture in the U-238 resonances and thus generates less plutonium.

As far as the local peaking factor (LPF) is concerned, the erbia design seems superior due to its uniform distribution of poison rods. WABA showed high LPF based on actual rod power since it has fewer fuel rods.

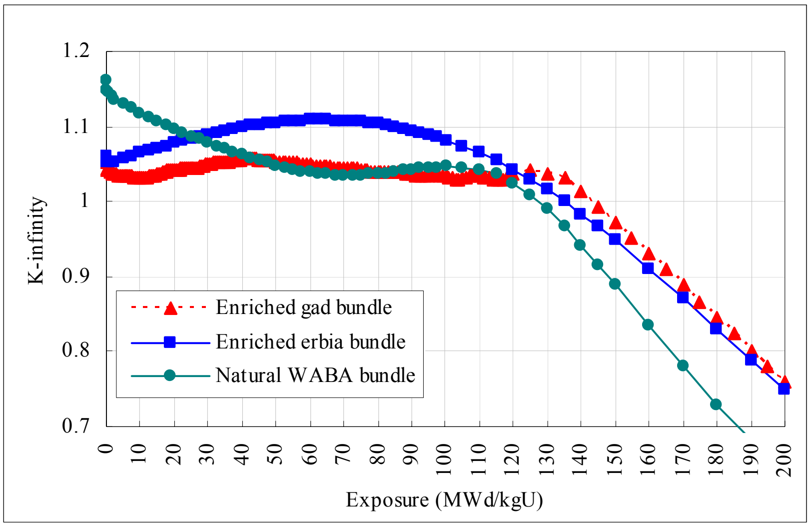


**Fig. 2 Comparison of K-inf at 40% void**

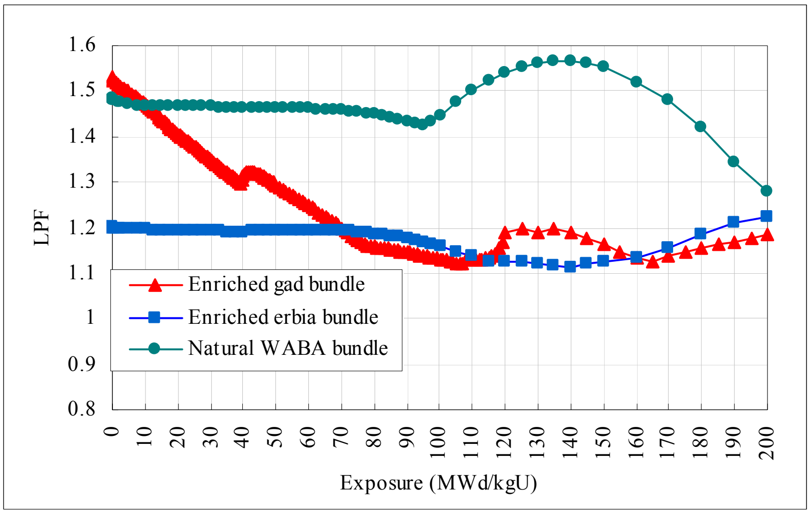


**Fig. 3 Comparison of LPF vs Burnup**

Fig.4 shows the void reactivity curves for the three assembly designs when voids were instantaneously decreased from 40 to 0% void. All cases showed similar trends which gave positive reactivity for 40% to 0%. For the $B_4C$ in alumina loaded assembly, void reactivity is relatively constant throughout the entire exposure range compared to other assemblies, due to the low absorption cross section and location within the assembly of the $B_4C$ in alumina rods. The gadolinium assembly shows the least void reactivity until MOL, due to highest neutron absorption cross section and the location of the gad rods at the edge of the assembly, where higher power is occurring. Erbium comes next and $B_4C$ is most sensitive until MOL. As the burnable poisons burn out toward EOL, the gadolinium and erbium loaded assemblies exhibit slightly more void reactivity than the $B_4C$ loaded assembly.

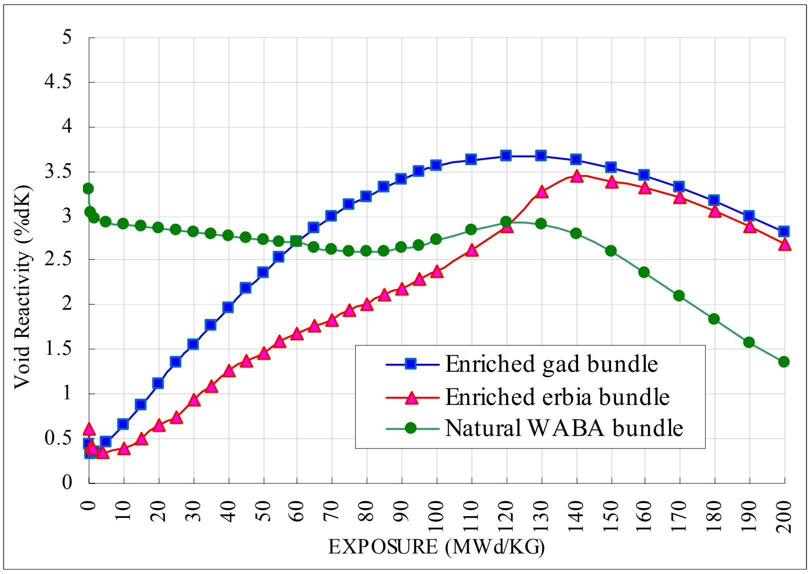


**Fig.4 Comparison of Void Reactivity (40 to 0% void)**

Fig.5 compares the radial core power distribution from the Haling calculation for the three designs and Fig.6 compares the axial core power distribution from the Haling for the three designs. The $B_4C$ design has the lowest nodal peaking in radial or axial peaking whereas the gadolinia case had the highest. Relatively high power is seen for the peripheral assembly area for $B_4C$ loaded core case since the same peripheral assemblies were used as for the gadolinia and erbia cases.

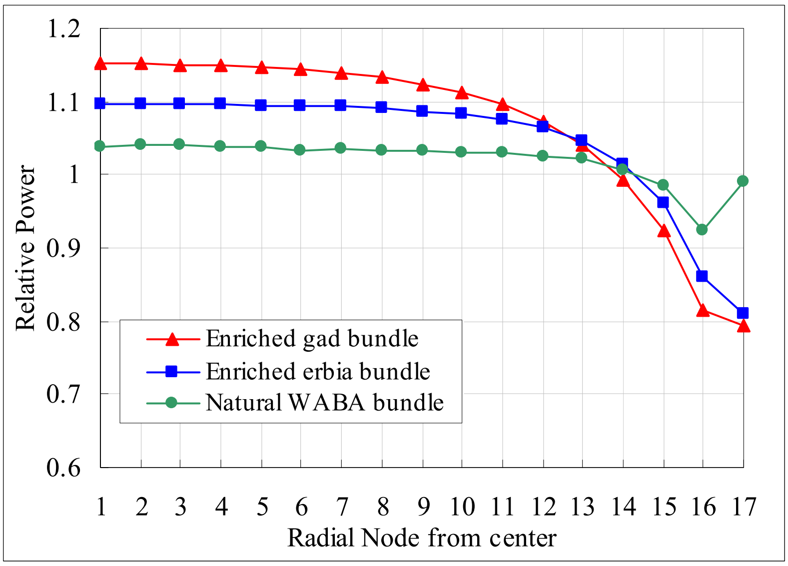


**Fig. 5 Comparison of Haling radial power distributions**

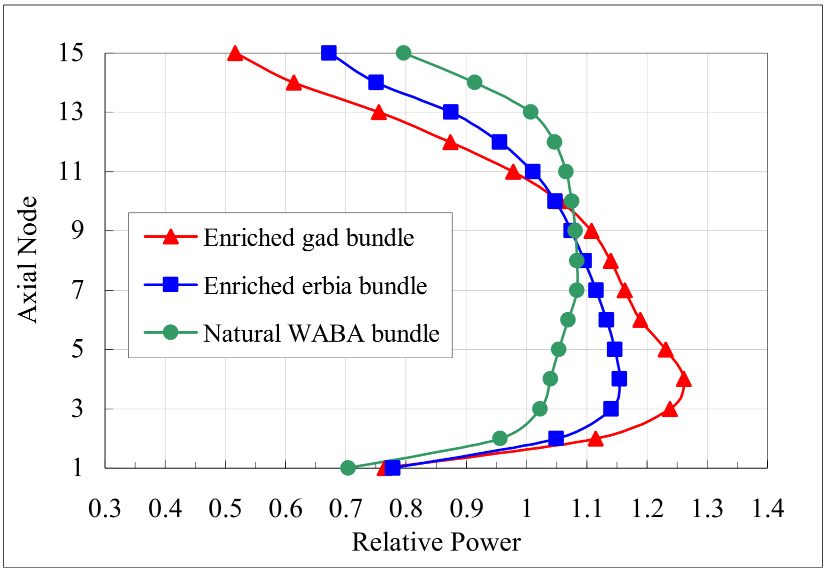


**Fig. 6 Comparison of Haling axial power distributions**

## 6. Conclusions

On the basis of the calculations reported here, no one poison is clearly superior, since each poison is superior in at least one of the several attributes of the design that have been evaluated, as summarized in Table 1:

**Table 1 Design Attributes**

| Attribute | Best design | Worst design |
|---|---|---|
| Reactivity swing (deviation from k=1.05) | Enriched gadolinia | $B_4C$ |
| Reactivity lifetime | Not clear – may be fairly close | Not clear |
| Local peaking | Enriched erbia | Gadolinia or $B_4C$ |
| Nodal peaking | $B_4C$ | Enriched gadolinia |
| Void coefficient | No clear winner | No clear loser |

From the reactivity point of view, gadolinium showed the best result with the lowest reactivity swing using enriched Gd-157. However, the local peaking factor in the assembly calculation was quite high for the initial part of the exposure range, compared with the erbium, with a value above 1.5 at low exposure.

The erbium case showed more reactivity swing than the gadolinium case but the local peaking and nodal peaking were the lowest of all three since erbium was mixed with all 46 fuel pins inside assembly. Both the K-infinity curve and the Haling calculation indicate sufficient reactivity to reach the desired cycle exposure of 113 MWD/kgU.

The $B_4C$ case had the highest reactivity at BOL, which would have to be suppressed by control rods (or by changing the design to include a second burnable absorber). It also showed higher LPF than others when compared with actual rod power since it has fewer fuel rods. However, the nodal peaking for $B_4C$ was lower than gadolinium. Also, $B_4C$ may have a significant advantage over gadolinium or erbium in the saving of uranium inventory. In this study, the U-235 inventory could be lowered few percent (assembly average) to achieve the target exposure.

Void reactivity appeared acceptable for all cases.

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