Optimal Hydride Fueled BWR Assembly Designs

Massimiliano Fratoni and Ehud Greenspan
Nuclear Engineering Department - University of California at Berkeley
Berkeley CA 94720-1730 USA
maxfratoni@nuc.berkeley.edu, gehud@nuc.berkeley.edu

Abstract

The feasibility of improving the performance of BWR's by using hydride fuel instead of oxide fuel is assessed. Performance improvements looked for including enhanced power density, simplified fuel bundle and core design and less negative void coefficient of reactivity. A 3-D neutronic analysis is performed to determine attainable discharge burn-up, pin-by-pin power distribution, axial power distribution, reactivity coefficients, reactivity worth of control elements and burnable absorber effects. It is found that hydride fuel bundle design can be greatly simplified by eliminating water rods and partial length fuel rods and by shrinking the water gaps surrounding the bundle box. As a result the hydride fuel bundle contains 96 full length fuel rods of a uniform composition versus 71 effective full length fuel rods of 8 different compositions of the reference oxide fuel bundle. The cruciform control elements are replaced by a cluster of control rods without increasing the number of control drive mechanisms. IFBA is identified as the preferred burnable poison. A companion study of the thermal-hydraulic and vibration characteristics of BWR cores predicts that the increase in the number of fuel rods per given core volume combined with the low peak-to-average pin-wise power distribution of hydride fuel designs enables increasing the BWR power density by up to 40% relative to the oxide fuel design. The net outcome is expected to be improved BWR economics even though hydride fuel requires higher uranium enrichment. Use of hydride fuel may also improve the stability of BWR's against power oscillations as the void coefficient of reactivity of hydride fuelled designs is less negative than that of oxide fuelled designs.

KEYWORDS: hydride fuel, oxide fuel, LWR, BWR, burn-up, control blades, control rods

1. Introduction

The objective of this study is to investigate the neutronic feasibility of designing BWR's fuel bundles to have better performance than currently used oxide fuel bundles [1-4]. This study follows a preliminary one-dimensional parametric analysis [5] that identified the geometries that promise to attain high burn-up levels while meeting all the constraints on reactivity coefficients. The main focus of the present work is to perform an in-depth 3-D analysis on a limited number of the promising bundle geometries. The neutronic design methodology used for analyzing chosen hydride fuel bundles is also applied to the analysis of the reference oxide fuel bundles in order to have a reference against which the hydride fuel bundle designs could be consistently compared.

2. Models and methodology

2.1 Reference oxide fuel bundle

The oxide fuel bundle selected for the reference design is the GE11 BWR/5 design. Although contemporary BWR's use oxide fuel bundles of improved design, the GE11 was the most advanced design we were able to get consistent and reliable set of data for. The comparison of

hydride versus oxide fuel bundle design was done in a way that is expected to arrive at reliable conclusions that are generic to the fuel type and not sensitive to the level of sophistication in the oxide fuel bundle design.

The reference GE11 oxide fuel bundle is made of a 9x9 lattice enclosed in a SS bundle box. The water in the box is in a two phase liquid-vapor state, with an average void volume fraction of about 40%. Because of boiling, the coolant does not provide sufficient moderation at the upper part of the fuel bundle. Additional moderation is provided as follows: (1) two large rods filled with liquid water, so called "water rods", are placed at the center of the bundle in place of 7 fuel rods; (2) 8 fuel rods are "partial length fuel rods"; they contain fuel in the lower 2/3 of the active core length and liquid water in the upper 1/3; (3) a large liquid water gap is provided between the fuel bundles. This water gap provides also space for the insertion into the core of cruciform shaped control elements. As a result, the effective number of effective full length fuel rods per bundle is about 71.

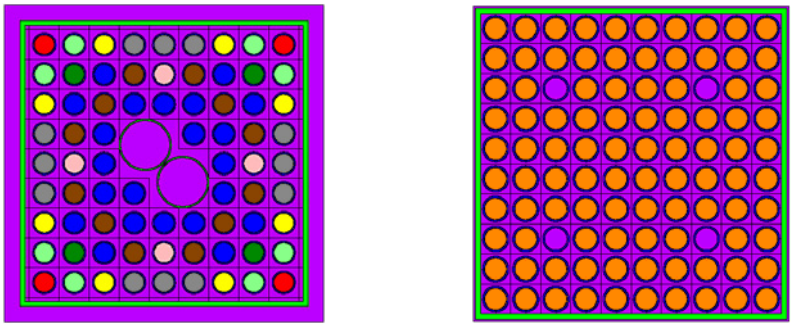
The reference fuel bundle is very heterogeneous. The extra moderation provided is not uniform and must be balanced by using fuel rod location dependent enrichment levels to avoid excessive peak-to-average pin-wise power distribution. Thus, each bundle has 8 different fuel rod compositions; they are distinguished by their enrichment axial distribution. Fuel enrichment varies from 2.4% to 4.9%; the bundle average being 3.9%. The enrichment is distributed in the bundle so as to balance the water density distribution. Thus, a lower enrichment is used at the lower part of the fuel rod where the moderator-to-fuel atomic ratio is the highest. Likewise, the corner rods have a smaller enrichment and the enrichment increases going toward the bundle radial center. Gadolinia (Gd_2O_3) burnable poison is loaded into 12 of the fuel rods. All the fuel rods have caps of natural uranium at the bottom and at the top.

2.2 Hydride fuel 10x10 bundle

The main advantage of using hydride fuel in BWR's is the possibility to provide adequate moderation without the need for special liquid water volumes that, otherwise, could have been used for insertion of additional fuel rods; the extra moderation is provided by the hydrogen in the fuel matrix. Thus, the fuel bundle using hydride fuel is designed without water rods, partial length fuel rods and wide water gaps. Only 2 *mm* gap is left from bundle to bundle so no space remains for control blades insertion; the reactivity control is to be provided using control rods dispersed between fuel rods as in PWR cores. The total dimensions of the fuel bundle, including the external water gap, are kept the same as of the reference design but the inner dimensions of the fuel box are enlarged. The fuel rods pitch is kept about the same as for the reference oxide fuel and this allows incorporating in the bundle a 10x10 array of rods. Of these, 96 are used for full length fuel rods and 4 are used for control rods; they are filled with liquid water when the control rods are fully withdrawn. The hydride fuel considered for this model is $U(45w/o)ZrH_{1.6}$ [7]. The uranium enrichment is uniform over the entire fuel bundle; the reference enrichment chosen is 5%. The pitch-to-diameter ratio (P/D) is obtained from the 1-D analysis [5] in order to maximize the achievable burn-up in the range of feasible geometries. Clad thickness and pellet-clad gap thickness are determined using correlations developed in the NERI project [1]. Different options for burnable poison have been considered; they are described below.

Figure 1 compares the new bundle design for hydride fuel versus the reference oxide fuel bundle designs. The hydride fuel bundle is much simpler and more uniform than the reference oxide fuel bundle; it has only one type of rods and a single enrichment against 8 different rod types and 9 different enrichment levels in the reference bundle.

Figure 1: Comparison between the reference oxide (left) and hydride fuel bundle (right) designs; each color represents a different rod type.



2.3 Methodology for analysis

The 3-D fuel bundles were modeled in detail using MCNP5 while the depletion analysis was done using the utility MOCUP that couples MCNP5 for calculating one group effective cross sections and ORIGEN2 for the actual fuel depletion [8-10]. This analysis is performed for a single bundle and the results are projected into the entire core according to the chosen fuel management scheme. Each fuel rod, water body and control element is accounted for discretely in the MCNP model, as represented in Figure 1. Axially, the fuel bundle is divided into 24 equal length regions. Axial water density distribution that is typical to BWR/5 core designs is assumed; it varies from subcooled water at the inlet to about 60% void fraction at the outlet. The water density distribution is assumed to be unchanged during the reactor operation. Top and bottom reflectors are modeled as two homogeneous zones: the bottom one made of 50 vol% water at inlet conditions and 50 vol% structural material, 40 cm thick; the top one with 75 vol% of water at outlet conditions and 25 vol% structural material, 80 cm thick.

The fuel cycle strategy considered assumes 4 equal size batches. This means that at the end of each cycle a quarter of the bundles are unloaded and replaced by fresh fuel bundles while the rest of the bundles are shuffled inside the core according to their exposure level. The time-dependent burn-up level of the fuel bundle is assumed to be a non-linear funtion; it rapidly decreases with time. Table 1 gives the batch-dependent burn-up and corresponding power density assumed for the reference BWR.

Table 1: Fractional burn-up achieved after each cycle and average power level per cycle.

Batch	Fractional *BU* per Cycle	Power [*MW*]
Fresh	31.32%	5.40
1st Cycle	27.41%	4.73
2nd Cycle	24.16%	4.17
3rd Cycle	17.11%	2.95

To account for this time dependent behavior, the following methodology was developed, so to predict the average core characteristics based on data obtained by the simulation of a single bundle. The multiplication factor of the core is expressed as:

$$k = \frac{P_{NL}\nu\int_V \Sigma_f \phi dV}{\int_V \Sigma_a \phi dV} \quad (1)$$

where V, P_{NL}, ν, ϕ, Σ_f and Σ_a are, respectively, the volume, non-leakage probability, number of

neutrons generated per fission, total neutron flux, effective one group fission and absorption macroscopic cross sections of the core. Considering the core as a cluster of *n* bundles, *k* can also be expressed as:

$$k = \frac{\sum_{i=1}^{n} P_{NL,i} \nu_i \int_{V_i} \Sigma_{f,i} \phi_i dV}{\sum_{i=1}^{n} \int_{V_i} \Sigma_{a,i} \phi_i dV} \tag{2}$$

where the subscript *i* refers to the i^{th} bundle. As the power generated in bundle *i* is:

$$P_i = E_f \int_{V_i} \Sigma_{f,i} \phi_i dV \,, \tag{3}$$

where E_f is the recoverable energy per fission, (2) can be rewritten as follows:

$$k = \frac{\sum_{i=1}^{n} P_{NL,i} \nu_i \int_{V_i} \Sigma_{f,i} \phi_i dV}{\sum_{i=1}^{n} \int_{V_i} \Sigma_{a,i} \phi_i dV} = \frac{\sum_{i=1}^{n} P_{NL,i} \nu_i P_i}{\sum_{i=1}^{n} \frac{\int_{V_i} \Sigma_{a,i} \phi_i dV}{\int_{V_i} \Sigma_{f,i} \phi_i dV} P_i} = \frac{\sum_{i=1}^{n} P_{NL,i} \nu_i P_i}{\sum_{i=1}^{n} \frac{P_{NL,i} \nu_i P_i}{k_i}} \quad . \tag{4}$$

Assuming that P_{NL} and ν are the about the same for all bundles, (4) can be simplified as follows:

$$\frac{1}{k} = \sum_{i=1}^{n} \frac{f_i}{k_i} \quad \text{or in terms of reactivity} \quad \rho = \sum_{i=1}^{n} \rho_i f_i \tag{5}$$

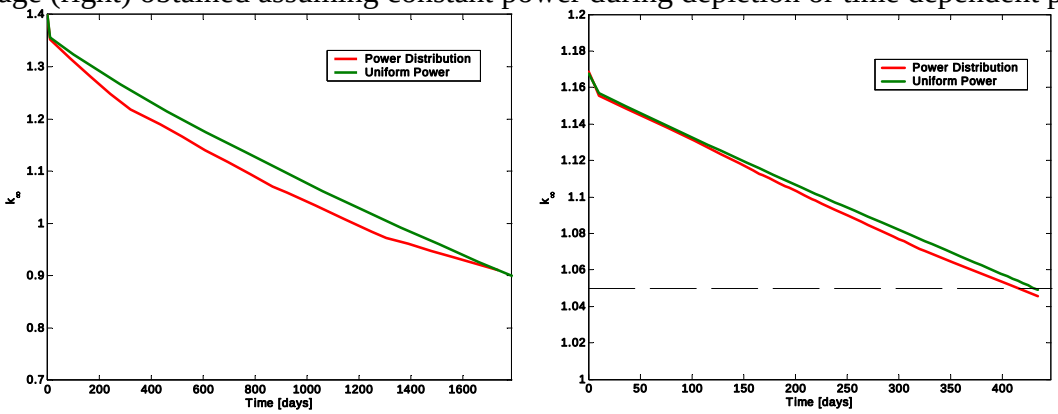
where f_i is the fraction of the total power generated in bundle *i*. In order to account for the effect of the power variation as a function of burn-up, the power density was varied in a step function manner as prescribed by Table 1; the power level of a bundle is kept constant during each cycle but changed when moving to the next one. The average power level is set equal to the reference average power per bundle that is assumed 4.31 MW_{th}. An iterative procedure was developed to predict the achievable burn-up while properly modeling the variation in the bundle power level. First, a discharge burn-up value is guessed and then the cycle length can be calculated, since:

$$\overline{P} = \frac{\sum_{i=1}^{n} P_i}{n} = \frac{1}{n} \sum_{i=1}^{n} \frac{m_{HM}}{T} \alpha_i BU = \frac{m_{HM} BU}{nT} \tag{6}$$

where $\overline{P}$ is the average power per bundle, m_{HM} the initial mass of heavy metal per bundle, α_i the fraction of the total burn-up achieved during the i^{th} cycle, *BU* the discharge burn-up, *n* number of batch and *T* cycle length. Once the cycle length has been obtained, depletion can be done for a single bundle and core average k_∞ can be determined as in (5). The EOL average core multiplication factor is required to be about 1.05, conservatively assuming a margin of 5% to account for radial neutron leakage probability that is not accounted for in the single bundle analysis. If the thus obtained k_∞ does not meet the 1.05 constraint, the analysis is repeated assuming a new value for the final burn-up that will be smaller or larger than the previous one if the EOL k_∞ is respectively <1.05 or >1.05.

Figure 2 shows the time-dependent k_∞ obtained using the above methodology as compared with simpler procedures; significant differences are observed. The simpler procedures tend to over-predict the achievable burn-up.

Figure 2: Comparison of time dependent multiplication factor for a single bundle (left) and core average (right) obtained assuming constant power during depletion or time dependent power.



Once the cycle length has been determined, the average core k_∞ can also be calculated at any time t during depletion knowing that:

$$\frac{\sum_{i=1}^{4} P_i}{k_\infty(t)} = \sum_{i=1}^{4} \frac{P_i}{k_b[t+(i-1)T]} \tag{7}$$

where k_b is the multiplication factor calculated for a single bundle.

2.4 Burnable poisons

The analysis of the effect of burnable poisons requires an additional iteration procedure. This is due to the fact that the amount of burnable poison to be initially loaded into the bundle is a design variable. It is assumed that this amount should be that for which the average core k_∞ at beginning of cycle (BOC) is equal to that of the reference oxide fuel with burnable poison. As a result, a double constraint is imposed on the core average k_∞ – both at BOC and at the EOC (1.05). The imposition of the two constraints is obtained using a double iteration procedure. First an initial amount of burnable poison is assumed for which a depletion analysis is performed using the iterative procedure described in the previous section. Using the results of this depletion analysis, the average core BOC k_∞ is calculated for a cycle length that gives EOC k_∞ of 1.05. If this BOC k_∞ value does not match the constraint, a new initial amount of burnable poison is assumed and another iteration is performed.

2.5 Reactivity control system

Rather than cruciform-shaped control blades inserted into the water gap in-between fuel bundles used in contemporary BWR's, the approach adopted for the control system of hydride fuelled BWR cores is similar to that used in PWR's – control rods dispersed throughout the fuel bundle. The cluster of control rods in four adjacent fuel bundles can be actuated by a single drive mechanism, making the total number of control drives equal to that of contemporary BWR's. As no water gaps are required for the hydride fuelled cores, it makes sense to combine four fuel bundles of traditional BWR dimensions into a single fuel assembly, thus also simplifying the fuel handling and, possibly, reducing the fuel fabrication cost.

The number and location of the control rods and, possibly, the outer diameter of these rods need to be determined for each hydride core design. The design requirement adopted is that the control system must have a reactivity worth that is at least equal that of the control blades in the

reference oxide fuelled core at both hot full power condition and cold shutdown condition.

Four B_4C control rods per fuel bundle, located as shown in Figure 1 (right figure), are found sufficient to provide the required reactivity worth, as shown in Table 2. The control rod diameter is slightly larger than that of the fuel rods diameter. The reactivity worth at full power is calculated for the time of maximum core excess reactivity – corresponding to BOC in the absence of burnable poisons.

Table 2: Control systems reactivity worth comparison

System	Oxide 9x9	Hydride 10x10
Reactivity control system	Control blades	Control rods
Control system reactivity worth at hot full power [*$*]	38.30	38.27
Control system reactivity worth at cold shut-down [*$*]	25.75	26.26

3. Results

The purpose of the neutronic analysis is to determine the achievable BU as well as the burn-up-dependent parameters of interest including pin-by-pin power distribution across the fuel bundle, axial power distribution, reactivity coefficients and reactivity worth of control elements.

Considering the complexity and heterogeneity of the systems under investigation, a multi-zone approach is used for the depletion analysis. Twenty four depletion zones are used for the oxide fuel bundles: a zone for each enrichment level in each of the 8 fuel rod types. Only 9 zones are used for the hydride fuel bundles since they are significantly less heterogeneous; 3 radial zones and 3 equal length axial zones.

A total of 102 nuclides are tracked by MOCUP, 34 actinides and 68 fission products. All the cross sections used correspond to the actual material operating temperature and they have been generated from ENDF/B-VI Release 3 and VMCCS libraries. Bound scattering kernel is used for the zirconium-hydrogen in the fuel in addition to the water outside the fuel (SAB2002 library). The power distribution in the depletion zones is automatically calculated adding ad hoc tallies in the MCNP5 input. The statistical uncertainty for the MCNP5 calculation of the multiplication factor is set to $<5\cdot10^{-4}$ so that, after propagation through the *k* averaging procedure, the uncertainty in the core average *k* is $<2\cdot10^{-3}$.

3.1 Achievable burn-up

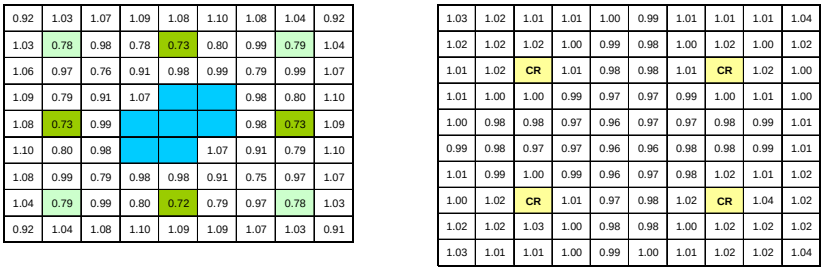
3.1.1 Oxide fuel

When not accounting for burnable poison, the reference oxide fuelled core reaches a burn-up level of 43.5 *GWD/MTHM* during a total fuel residence time of 1740 days – about 15 months per cycle. The pin-by-pin power distribution at BOC is shown in Figure 3 (left); the power peaks on the external pins having the highest enrichment that are close to the water channels. The BOC pin power peaking factor is 1.10; it progressively decreases with burn-up. The axial power distribution follows the axial water density distribution; it peaks toward the bottom of the core. The axial peaking factor is 1.6414.

3.1.2 Hydride fuel

The hydride fuel can reach a burn-up of 52 *MWD/MTHM* during 1412 days of residence time – about 12 months per cycle, when not accounting for burnable poisons. The pin-by-pin power distribution is very flat as illustrated in Figure 3 (right); the BOC peaking factor is only 1.04. On the other hand the axial power distribution shows a large peak at the lower part of the core; the axial power peaking factor is about 2.13.

Figure 3: BOC pin power-to-average power distribution comparison; oxide fuel (left) and hydride fuel (right) without burnable poisons



3.1.3 Discussion

Table 3 compares selected characteristics of the hydride versus reference oxide core designs. Even though the hydride fuel bundle has 96 full length fuel rods versus only 71 effective fuel length oxide fuel rods in identical core volume, the heavy metal (HM) inventory in the hydride fuel bundle is smaller by ~32%. So although the hydride fuel burn-up is 8.5 *GWD/MTHM* higher, its cycle length is shorter than that of the reference oxide fuel design. A longer cycle can be obtained by increasing the initial enrichment; it is estimated that at 7.7% enrichment the hydride fuel cycle will be as long as that of the reference oxide fuel that has an average enrichment of 3.9%. The enhanced fuel cycle cost associated with the higher enrichment is likely to be more than compensated by the remarkable increase in the power density estimated [3] to be on the order of 40% relative to the reference oxide fuel power density.

Table 3: Comparison of system characteristics without burnable poisons

System	Oxide 9x9	Hydride 10x10
Number of fuel rods	~ 71	96
Number of control rods	Control blades	4
P/D	P.I.[(a)]	1.15
Pellet diameter [*cm*]	P.I.[(a)]	1.061
Average enrichment	3.90 %	5 %
Initial HM mass ratio	1.00	0.68
Single batch BOC k_∞	1.4040	1.3701
BU [*GWD/MTHM*]	43.5	52
Fuel residence time [*days*]	1740	1412
Conversion ratio at BOC	0.3772	0.3300

[(a)]Proprietary Information

The relative large peaking in the hydride fuel axial power distribution can be alleviated by axial enrichment split. Two axial enrichment levels will suffice and will not penalize the stated advantages of hydride fuel compared to oxide fuel in BWR's. Another possible approach to flatten the axial power distribution is to use deuterium for the hydride fuel at the lower part of the core, that is likely over-moderated when using hydrogen in the fuel, and to use hydrogen in the fuel at the upper part of the core.

3.2 Reactivity coefficients

Three reactivity feedback mechanisms were considered: (1) increased fuel temperature; (2) small and (3) large void obtained by increasing the moderator void fraction from 40% in standard

conditions to, respectively, 45% and 90%. All of these must be negative as, indeed, is the case as reported in Table 4. The same table also compares the hydride fuel versus reference oxide fuel reactivity coefficients calculated at the beginning and end of the fuel cycle. Whereas the hydride fuel temperature reactivity coefficient is more negative at BOC, it is less negative at EOC. These effects are due to a unique feature of hydride fuel – thermal spectrum hardening due to fuel hydrogen temperature increase the reactivity effects of which are superimposed on the reactivity effect of Doppler broadening of the fuel isotopes resonances. No detailed analysis of the spectrum hardening reactivity effects due to fuel hydrogen temperature increase has been done, as yet, for BWR's. Based on an in-depth analysis done for hydride fuel in PWR's [11] it is anticipated that at BOC the spectrum hardening increases the thermal neutron capture in all the system constituents, per fission neutron generated, because the ^{235}U fission cross-section drops stronger than 1/v around its ~0.3 eV resonance. On the other hand at EOC, when the ^{235}U is depleted and the ^{239}Pu concentration is significant, spectrum hardening enhances the fission (and capture) probability in ^{239}Pu and reduces the thermal neutron capture probability in most of the other system constituents, leading to a net gain in reactivity. By replacing some $ZrH_{1.6}$ by ThH_2 the positive feedback due to ^{239}Pu buildup can be reduced [11]. Large void fractions give similar reactivity effect in both fuels both at beginning and end of cycle, while small void fractions causes a drop in the reactivity that is larger in oxide fuel. The reduced small void reactivity effect for hydride fuelled core is due to the fact that, due to the fuel hydrogen, reducing the water density by 5% corresponds to only ~3% reduction in the hydride fuel hydrogen density. The smaller negative void reactivity feedback of hydride fuel may enhance the stability of BWR's against power oscillations.

Table 4: Reactivity coefficients comparison without burnable poisons

System	Oxide 9x9	Hydride 10x10	Oxide 9x9	Hydride 10x10
Time	BOC	BOC	EOC	EOC
Fuel temperature [*pcm/K*]	-4.6	-6.7	-4.4	-1.0
Void fraction 45% [*Δk%*]	-0.43%	-0.25%	-0.51%	-0.36%
Void fraction 90% [*Δk%*]	-4.65%	-4.75%	-4.82%	-4.87%

3.3 Burnable poison effects

Gadolinia is used as burnable poison in the oxide fuel bundle; it is added in 12 rods at two different weight fractions – 4.5% at the top and 5.5% at the bottom of the core. The use of Gadolinia reduces the attainable burn-up and increases the BOC pin-wise power distribution as illustrated in Figure 4 (left).

Figure 4: Pin power-to-average power distribution when including burnable poison comparison; oxide fuel with gadolinium (left) and hydride fuel with IFBA (right).

1.11	1.22	1.21	1.18	1.17	1.18	1.21	1.22	1.12
1.22	0.94	0.98	0.43	0.73	0.43	0.98	0.95	1.22
1.22	0.98	0.41	0.84	0.97	0.89	0.42	0.99	1.22
1.18	0.43	0.84	1.10			0.90	0.44	1.18
1.17	0.73	0.97				0.96	0.73	1.16
1.19	0.44	0.91			1.08	0.82	0.43	1.17
1.23	0.98	0.42	0.90	0.97	0.84	0.42	0.97	1.20
1.21	0.95	0.98	0.43	0.74	0.43	0.97	0.94	1.22
1.10	1.21	1.21	1.19	1.17	1.18	1.21	1.20	1.11

1.04	1.02	1.02	1.01	1.01	1.00	1.01	1.02	1.02	1.05
1.02	1.02	1.03	1.00	0.98	0.98	1.00	1.03	1.02	1.03
1.01	1.03	CR	1.02	0.97	0.97	1.02	CR	1.03	1.02
1.00	1.00	1.01	0.98	0.96	0.97	0.99	1.01	1.00	1.01
1.00	0.98	0.97	0.96	0.96	0.95	0.97	0.97	0.97	1.01
1.00	0.97	0.97	0.96	0.95	0.96	0.96	0.97	0.98	1.00
1.00	0.99	1.01	0.98	0.96	0.97	0.98	1.02	1.00	1.01
1.01	1.03	CR	1.01	0.97	0.97	1.02	CR	1.04	1.03
1.01	1.00	1.02	0.99	0.98	0.98	1.00	1.03	1.01	1.03
1.04	1.02	1.01	1.00	1.00	0.99	1.01	1.02	1.02	1.05

Different candidates have been considered for burnable poison for hydride fuel. Their performance is compared in Figure 5 and in Table 5. Gadolinium, in metallic form and natural composition, is added in 8 out of the 96 hydride fuel rods. The required amount was found to be 2.87 %. The burn-up penalty is ~6 *GWD/MTHM* as in the oxide fuel (Table 5). Another penalty is a significant increase in the pin-wise power peaking factor. For this reason, boron and erbium, uniformly dispersed in all the fuel rods, were considered. When at natural composition, the needed amount of Erbium in the form of ErH_3 is 0.55 wt%; the resulting burn-up penalty is quite large – 12 *GWD/MTHM*. When using Er that is 100% enriched with ^{167}Er, the burn-up penalty reduces to 9 *GWD/MTHM*. A burn-up penalty similar to that of gadolinium is obtained using IFBA (ZrB_2), a burnable poison that is routinely being used in PWR's. This is our preferred solution. The corresponding BOC pin-wise power distribution is shown in Figure 4 (right).

Figure 5: Single bundle (left) and core average (right) k_∞ as function of exposure time for Hydride fuel with different burnable poisons

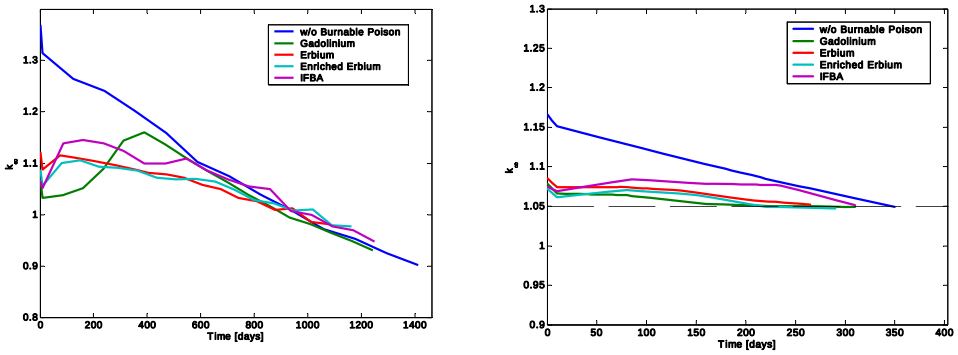


Table 5: Comparison of main effects of burnable poisons

Burnable Poison	Gadolinium	Erbium	^{167}Er	IFBA	Oxide with Gd
BU [*GWD/MTHM*]	46	40	43	46	37.5
Total residence time [*days*]	1242	1078	1162	1248	1482
BU penalty [*GWD/MTHM*]	6	12	9	6	6
Average BOC k_∞	1.0785	1.0856	1.0722	1.0749	1.0728
BOC axial power peaking factor	2.6090	2.9053	3.0028	2.2949	1.8450
BOC pin power peaking factor	1.2459	1.0549	1.0501	1.0524	1.2280

4. Conclusions

Use of hydride fuel makes it possible to design BWR fuel bundles that are significantly less heterogeneous than the oxide fuel bundles in present use. By eliminating the need for dedicated water moderator volumes, the new hydride fuel designs enable to increase the active fuel length in a given core volume by about 35%. Thermo-hydraulics analysis performed in a companion study [3] found that due to this, along with the flatter pin-wise power distribution, it is feasible to increase the hydride fuelled BWR core power density by about 40%. This requires increasing the coolant pressure drop through the core by about 30% and is considered feasible [3]. Alternatively, the hydride core can be designed to deliver the nominal BWR power and have close to the reference BWR pressure drop using fuel bundles that are ~40% shorter than the reference.

The hydride fuel bundles have reduced HM inventory per bundle. Consequently, for the same cycle length the hydride fuel needs to have higher uranium enrichment than the oxide fuel. The

economic benefits of power density increase are likely to overshadow the economic penalty associated with higher enrichment. A potentially promising approach for obtaining long cycles is to use thorium-containing hydride fuels not examined in the present work; the HM contents of thorium-based hydride fuel is more than double that of the U-$ThH_{1.6}$ fuel considered in this work; it is even larger than that of oxide fuel.

The fuel temperature coefficient of reactivity of the hydride fuel bundle designs considered is more negative at BOC but less negative at EOC as compared with that of the reference oxide fuel bundle. The void coefficient of reactivity of the hydride fuel bundle is less negative; this may enhance the stability of hydride fueled BWR's against power oscillations. Adequate shutdown margin can be provided by incorporating four B_4C control rods per 10x10 hydride fuel bundle. It appears desirable to integrate 4 conventional BWR fuel bundles into a single hydride fuel assembly and use a single control drive per assembly.

To withdraw final conclusions the feasibility study need be refined and extended. Future undertakings should include coupled neutronic - thermal hydraulic analysis, transients and accidents analysis, as well as economic analysis. A number of important feasibility issues need to be assessed including the compatibility of hydride fuel with BWR water and clad.

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