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Gadolinium Credit Application for Transport and Storage Casks loaded with BWR UO_2 Spent Fuel Assemblies

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ABSTRACT

Transport and storage casks for BWR UO_2 spent fuel assemblies are usually designed taking into consideration the criticality safety analysis with the assumption of fresh fuel and with an isotopic composition corresponding to the most penalizing fresh fuel without gadolinium. The effects of the burnup and the presence of burnable neutron poison fuel rods in the BWR fuel design, which can lead to an important gain in reactivity, were consequently not considered.

In the last few years, AREVA TN has studied a conservative method by taking into account the gadolinium (Gd_2O_3) contained in the burnable poison fuel rods in order to increase the performance of the casks or to limit the amount of neutron absorbers (boron content or thickness of the absorber plates in new basket designs). This method is based on the definition of the operating conditions of the core and the fuel assembly parameters ensuring the conservatism of the calculations (spent fuel inventory and criticality assessments). Therefore, several calculations were performed to evaluate the sensitivity of different parameters. Indeed, current BWR UO_2 fuel designs are highly heterogeneous both radially and axially, with the presence of partial-length fuel rods and positions of these rods in the fuel assemblies, each assembly with its specific initial fissile enrichment distribution and gadolinium fuel rod configuration. Moreover, depletion calculations of BWR UO_2 fuel assemblies depend on the local core conditions: mainly the coolant void fraction, the presence of control rods during the operating cycle, the distribution of fissile content in the fuel assemblies, the number of burnable neutron poison fuel rods per fuel assembly, and positions of these rods in the fuel assemblies.

This paper presents the results of the sensitivity calculations, the conservatism of the method developed for both depletion and criticality calculations, and the reactivity gained compared to the fresh fuel assumption.

1 INTRODUCTION

From criticality-safety analysis point of view, transport and storage casks for BWR UO_2 spent fuel assemblies were designed at AREAVA TN under the fresh fuel assumption and by considering the isotopic composition corresponding to the most penalizing fresh fuel.

As long as the fuel enrichment of the BWR UO_2 fuel assemblies is sufficiently low, the simplified method based on the modeling of the un-irradiated fuel assembly with all fuel pins using the highest lattice maximum (or maximum average) initial ^{235}U enrichment is adequate to cover the needs. Nevertheless, the ever-increasing enrichment of modern BWR UO_2 fuel assemblies over the last decade has prompted AREVA TN to investigate new methods in order to limit both the increase of the neutron poison content in the new basket designs and to increase the performance of the casks with the existing baskets.

AREVA TN's strategy consists of taking credit for the presence of Integral Burnable Absorbers (IBA) in the BWR UO_2 fuel assembly designs. Typically, BWR fuel assemblies make heavy use of gadolinium poisoning (Gd_2O_3) in some fuel rods such as IBA to control the reactivity excess at the beginning of life of the fuel in the core. The approach of taking credit from the presence of gadolinium in some fuel rods of the assembly in the criticality safety analysis is commonly referred to as the “gadolinium credit.”

Taking credit from the presence of gadolinium in the fuel assembly design is very often not considered as burnup credit. However, the gadolinium depletion reactivity peak, which corresponds to the consumption of nearly all of the gadolinium content, is determined as a function of burnup. Therefore, taking credit from burnable gadolinium in some fuel rods is primarily a burnup credit approach. This entails the necessity of defining a method to ensure conservative assumptions of the spent fuel inventory and criticality calculations.

Due to the complexity of modeling BWR UO_2 spent fuel assemblies, the evaluation of potential gains from the use of gadolinium credit needs furthers physical understanding of BWR fuel assembly design parameters and the core operating conditions. This understanding will help establish a simple and practical method which can be used in the spent fuel inventory calculations and the safety-criticality analysis for the transport and storage casks of BWR UO_2 spent fuel assemblies.

In this study, sensitivity calculations were first performed to define a conservative approach for depletion calculations on BWR UO_2 fuel assemblies with the presence of burnable neutron poison (gadolinia Gd_2O_3). The results of these sensitivity calculations were then used in the criticality analysis of AREVA TN’s representative transport and storage cask for BWR UO_2 spent fuel assemblies in order to evaluate the reactivity gain in comparison to the fresh fuel assumption. Also, a simplified model was compared to the results obtained with a existing model of the BWR UO_2 assembly to confirm that the simplified model to be used for the criticality safety analysis of transport and storage casks using gadolinium credit method was conservative.

2 FUEL DEPLETION CALCULATION ANALYSIS

Modern BWR UO_2 fuel assembly designs are highly heterogeneous in fuel rod enrichment mapping both radially and axially when considering the combination with the presence of partial-length fuel rods, the positions of these rods in the fuel assemblies, and the different geometrical shapes of water channels. Each assembly has its specific initial enrichment and gadolinium content distribution. Moreover, depletion calculations of BWR UO_2 fuel assemblies depend on the local core conditions: the important axial moderator density variation (linked to the coolant void fraction) from the bottom end to the top end of the fuel assembly due to a melting of two-phase flow (water and steam); the presence of control blades during the operating cycle; the distribution of fissile content in the fuel assemblies; the number of gadolinium fuel rods per fuel assembly; and the positions of these rods in the fuel assemblies. This thus necessitates a careful analysis of the assembly design and the reactor operating conditions in order to define a conservative methodology for the depletion calculation.

The purpose of this part of the study focused first on the physical understanding of the different phases of irradiation of a modern BWR UO_2 fuel assembly design. Sensitivity analyses were then performed on the relevant assembly design and operating parameters of the core to ensure conservative calculations of spent fuel inventory.

2.1 BWR UO_2 fuel bundle analyzed

Depletion calculations were performed using the Westinghouse SVEA-96 Optima 2 assembly [1] which consists of a 10×10 lattice. The design of the SVEA-96 Optima 2 fuel assembly is highly heterogeneous and is comprised of 96 fuel rods of varying ^{235}U enrichment (from ~3% up to ~5%) with 80 rods of pure UO_2 and 16 with an amount of 5 wt. % of gadolinium added as burnable poison. The rods are arranged in four separate sub-bundles, each containing 24 rods on a square pitch. The sub-bundles are set inside zircaloy sub-channels. Four water wings and a central diamond-shaped central canal, together with the inter-assembly (outer) gaps, ensure better neutron moderation over the fuel assembly length (see Figure 1).

Axially, three different lattices (main axial zones) have been considered so as to take into account "vanished" regions of the assembly resulting from the presence of partial-length rods. Those zones have been identified as dominant lattice (DOM), vanished 1 and vanished 2 lattices (VAN1 and VAN2), and are given in Figure 2.

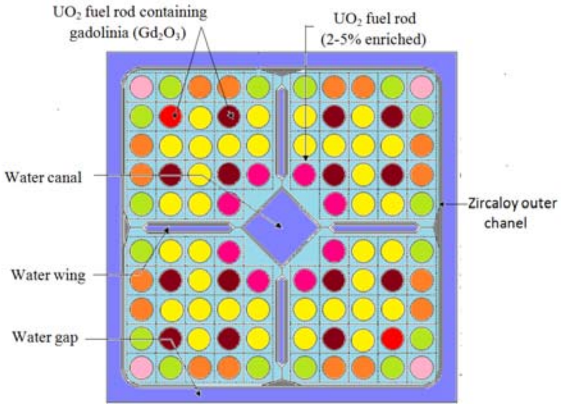


***Figure 1**: SVEA-96 Optima 2 fuel assembly cross-section view*

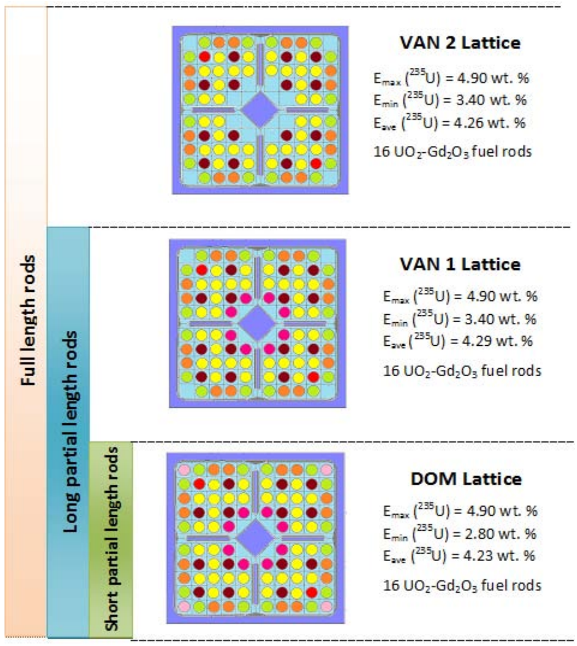


***Figure 2**: SVEA-96 Optima 2 fuel assembly lattice axial zones modeled*

2.2 Depletion codes and nuclear data

Depletion calculations were carried out by using the two dimensional (2-D) T-DEPL lattice depletion sequence of the TRITON module from the SCALE 6.0 computer code system [2] that has been developed at the Oak Ridge National Laboratory (ORNL), and by using the ENDF/B-V 44 neutron energy group library and the continuous energy solver CENTRM for resolved resonance processing for the SVEA-96 Optima 2 assembly. Numerical comparisons of the fuel inventory between the ENDF/B-V 44 and 238 libraries were done for different levels of burnup and the results obtained were quite similar.

Depletion calculations were performed on each axial zone (DOM, VAN1 and VAN2 lattices) of the SVEA-96 Optima 2 assembly.

2.3 Irradiation phases of the BWR assembly

Depletion calculations of the BWR UO_2 fuel assembly with the presence of gadolinium fuel rods resulted in two opposing effects. On the one hand, the burn-out of gadolinium, which leads to a reactivity gain; on the other, the simultaneous change in the fuel composition due to depletion of the fuel and buildup of plutonium and fission products, which globally leads to a reactivity loss, forming a maximum value of reactivity referred to as "the gadolinium depletion reactivity peak" or simply "reactivity peak" obtained for a burnup of about 15 GWd/t_{HM}. Calculated k_∞ values as a function of burnup for the BWR UO_2 studied with and without gadolinium are shown in Figure 3.

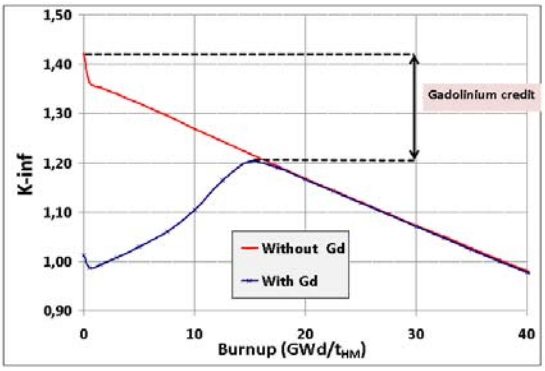


Figure 3: BWR UO_2 assembly irradiation phases

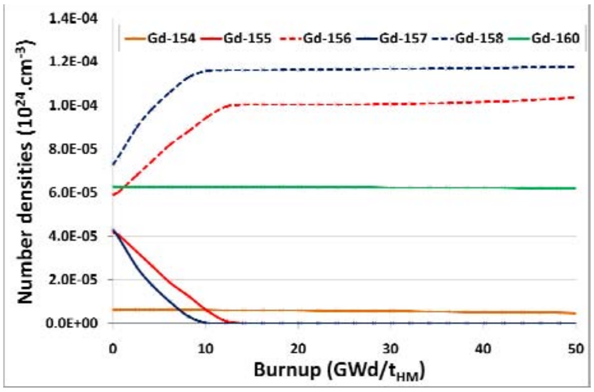


***Figure 4**: Depletion of main gadolinium isotopes*

The predominant phenomenon of the reactivity increase observed during the first few burnups (generally first cycle) is due to the depletion of the main neutron absorbing gadolinium isotopes, ^{155}Gd and ^{157}Gd. These isotopes have huge absorption cross sections in the thermal neutron energy range and they have almost disappeared at the reactivity peak under irradiation by (n, γ) reaction to ^{156}Gd and ^{158}Gd as shown in Figure 4. The ^{157}Gd disappears faster than the ^{155}Gd due to its higher absorption cross sections.

2.4 Sensitivity calculations

The potential impact of the assembly design and core operating parameters on the k_∞ values at the reactivity peak are outlined in the following sections.

a. Influence of the void fraction

Due to the two-phase flow present in BWR core, the water density around BWR fuel pins changes from about 0.7 g/cm^3 to values approaching 0.1 g/cm^3 as the water moves from the bottom to the top of the core. The void fraction (VF), which is the average density of the moderator, including consideration of both the density of the saturated or sub-cooled water and the steam voids introduced by the boiling of the water flowing through the core, can be defined as the following ratio:

$$VF = \frac{V_{steam}}{V_{steam} + V_{liquid}} \quad [\%]$$

Depletion calculations were performed considering the DOM axial zone lattice of the BWR UO_2 assembly studied. The bypass region was fixed as having single-phase water, i.e. a pure liquid with a density of 0.737 g/cm^3 was considered in the central water canal, the water wings and the inter-assembly (outer) gaps. The water in the four sub-channels had a homogenous VF, ranging from VF = 0 % (pure liquid) to a VF = 80% (steam with density of 0.147 g/cm^3) in a step of 20%.

The results obtained for the k_∞ values versus burnup are given in Figure 5. It can be noticed that an increase in the void fraction (decrease in the average moderator density) leads to a lower thermalization of the neutrons (less ^{235}U fissions) and an increase of the amount of neutrons captured by the fuel. Therefore, the k_∞ value at the reactivity peak is lower for higher void fractions and the fuel depletion is slightly retarded compared to 0% void fraction.

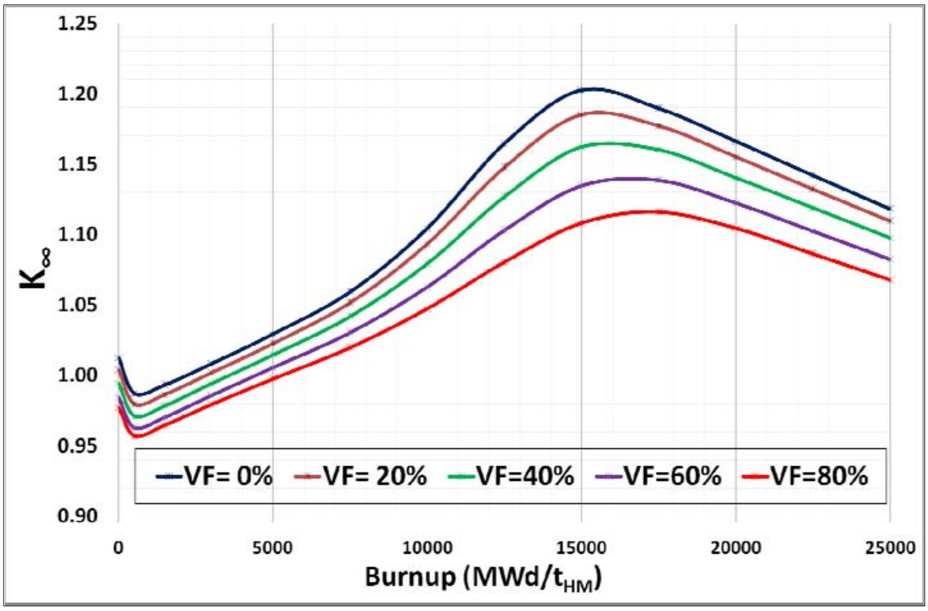
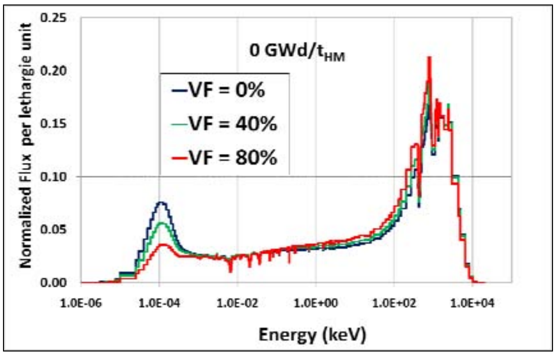


***Figure 5**: Effect of the void fraction on the reactivity*

A variation of the void fraction leads to a change in the neutron energy spectrum and, therefore, the fuel composition. Indeed, a higher void fraction combined with the presence of gadolinium content in some fuel rods induces a harder neutron spectrum, which depresses the ^{235}U fission and produces more ^{239}Pu by neutron absorption of ^{238}U. This hardening of the neutron spectrum leads to a significant decrease in the efficiency of the burnable absorber and, therefore, to a delay in the consumption of the gadolinium which tends towards a decrease in reactivity. Figure 6 shows such spectrum hardening at 0%, 40% and 80% void fractions for fresh fuel and for a burnup of 15 GWd/t_{HM} (burnup corresponding to the reactivity peak at VF = 0%).



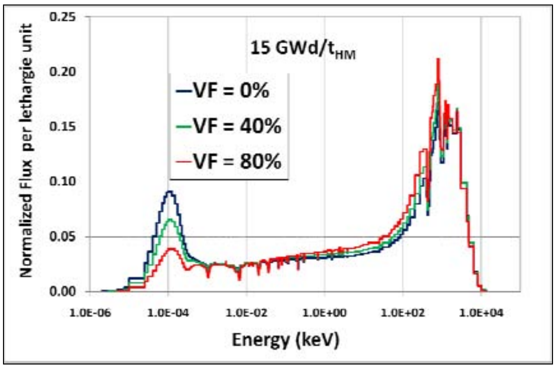


***Figure 6**: Effect of the void fraction on the neutron spectrum*

b. Gadolinium fuel rod effects

In this part of the study, the number of gadolinium fuel rods in the assembly, the gadolinium content and the gadolinium rod placement in the SVEA-96 Optima 2 assembly were studied to establish their effects on the k_∞ value at the reactivity peak. Calculations were carried out for the DOM axial zone lattice considering the maximum average enrichment (4.29 wt. %) at 0% and 80% void fractions.

- *Number of gadolinium fuel rods*

The influence of the number of gadolinium fuel rods on the reactivity was studied through a variation of the number of gadolinium fuel rods in the assembly from 0 (without gadolinium) up to 16 UO_2-Gd_2O_3 fuel rods. The position of the gadolinium fuel rods and the gadolinium content in the assembly were assumed to be unchanged. Figure 7 illustrates the effects of the number of gadolinium fuel rods on the reactivity as a function of the burnup.

Decreasing the number of gadolinium fuel rods does not change the k_∞ value at the reactivity peak for a given void fraction value. This is due to the fact that gadolinium fuel rods are distributed uniformly over the fuel assembly and gadolinium consumption is homogeneous in all gadolinium fuel rods. Therefore, gadolinium disappears with the burnup whatever the number of gadolinium fuel rod in the fuel assembly. Nevertheless, a decrease in the number of gadolinium fuel rods increases the k_∞ value below the reactivity peak. Indeed, for a given value of void fraction, the thermal-to-fast flux ratio increases when the number of gadolinium fuel rods decreases which leads to a less hard spectrum.

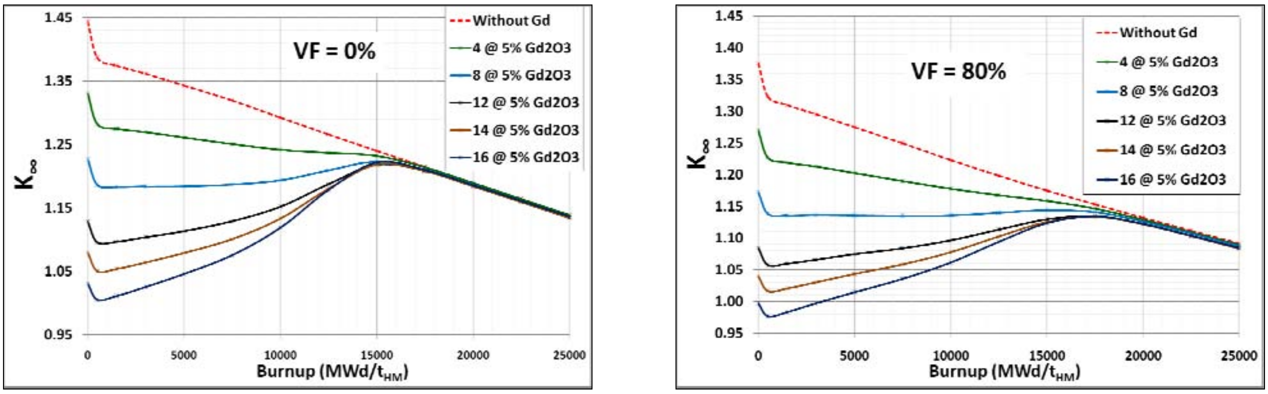


***Figure 7**: Effect of number of gadolinium fuel rods on reactivity at 0% and 80% void fraction*

- *<u>Effect of the gadolinium content</u>*

The main advantage of gadolinium is its very high thermal neutron capture cross section making it a very efficient neutron absorber. This efficiency is not only due to the distribution of the absorber in the assembly that defines the k_∞ value at the reactivity peak but also to the amount of gadolinium in some fuel rods of the assembly. The aim here is to study the effect of the variation of the gadolinium amount (2 to 5% of the fuel pellet mass) on the reactivity versus the burnup level. The number of the gadolinium fuel rods and their location in the assembly are considered unchanged. Figure 8 shows the effects of the amount of gadolinium in the assembly on the reactivity as a function of the burnup.

Decreasing the gadolinium concentration will increase the k_∞ value at the reactivity peak. Indeed, an increase in the amount of gadolinium engenders a harder neutron spectrum which depresses fission of ^{235}U therefore delaying the consumption of the gadolinium which tends towards a decrease in reactivity (shifting of the reactivity peak).

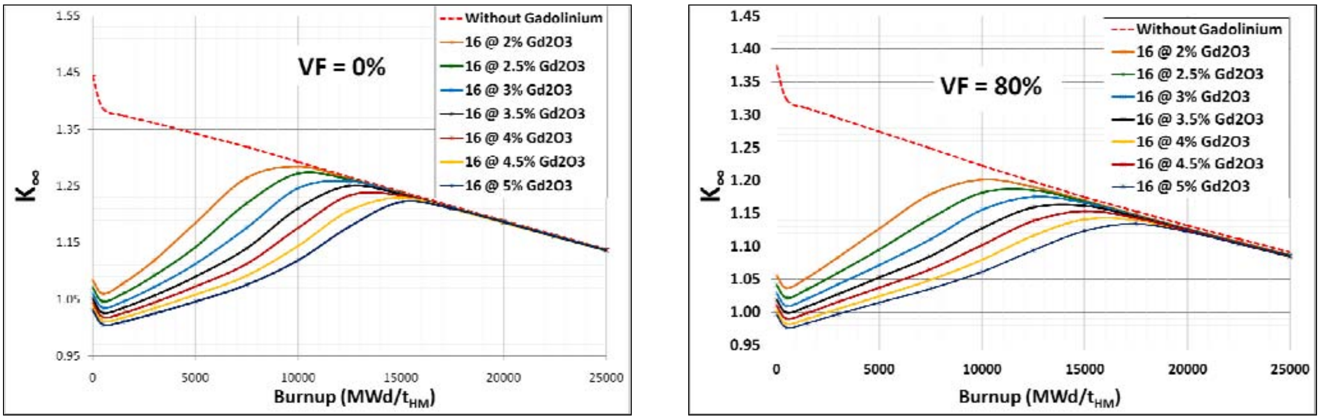


***Figure 8**: Effect of gadolinium content on reactivity at 0% and 80% void fraction*

- <u>*Gadolinium fuel rod location in the assembly*</u>

The influence of the gadolinium fuel rod position in the assembly was studied through eight configurations including the reference case (see Figure 9). The number of the gadolinium fuel rods and the gadolinium content in the assembly were considered unchanged in each examined configuration.

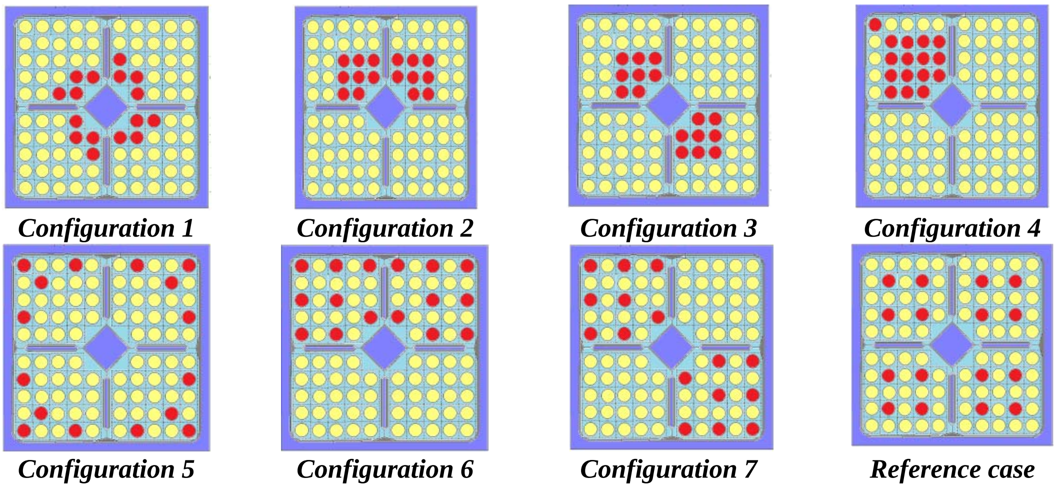


Figure 9: *Gadolinium fuel rod locations*

Figure 10 presents the effect of the gadolinium fuel rod locations in the assembly on the reactivity as a function of the burnup. The k_∞ value at the reactivity peak is maximum when the gadolinium fuel rods are placed at the edges of the assembly close to the inter-assembly (outer) gaps and are spaced apart. Indeed, gadolinium is worth more in these areas of increased moderation capability due to the increased amount of thermal neutrons available for absorption. However, the inter-assembly area is reserved for control blade insertion and when the gadolinium fuel rods are placed close to the control blades, the gadolinium and the control blades self-shield each other spatially and, therefore, the effective worth of both poisons is decreased. Moreover, the effectiveness of the gadolinium location in the assembly is a function of the power distribution. Therefore, gadolinium fuel rods cannot be placed in a BWR fuel assembly design at its edges.

Spacing out gadolinium fuel rods in the assembly and placing them away from the control blades areas (inter-assembly outer gaps) led to the highest k_∞ value at the reactivity peak among realistic configurations. In this respect, the optimum gadolinium fuel rod location in the assembly for any given number of gadolinium fuel rods is the actual design of the assembly (reference case).

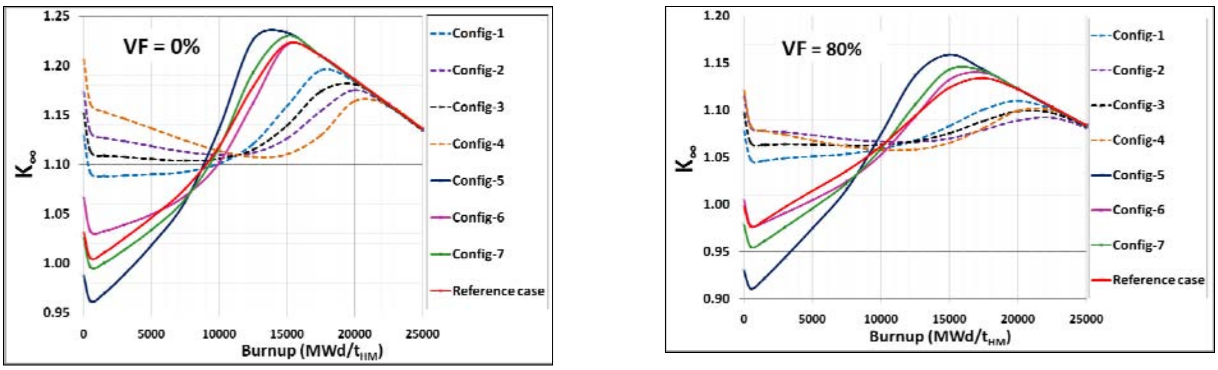


Figure 10: *Effect of the gadolinium fuel rod positions on reactivity at 0% and 80% void fraction*

c. Effects of fuel irradiation parameters

The impact of the main spectral irradiation parameters is examined in this section as a function of the burnup so as to define conservative parameters for depletion calculations of the BWR UO_2

- *Control blade insertion*

BWR reactors operations can involve periods of partial control blades (CBs) insertion between BWR assemblies in the core. In order to maximize the reactivity effect due to this insertion, the effect of a full axial control rod insertion (B_4C) during the entire burnup was analyzed. Depletion calculations were performed with and without the presence of control blades at 0 % and 80% void fractions and considering the DOM axial zone lattice with the real enrichment distribution of the BWR UO_2 assembly studied. The CBs were inserted during the entire depletion calculations (see Figure 11).

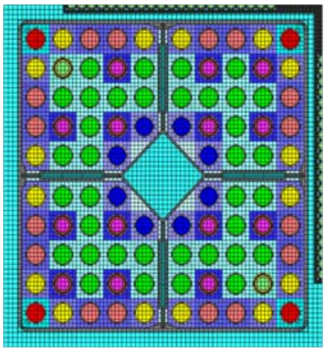


***Figure 11**: DOM models with the presence of control blade*

The results obtained for the k_∞ values as a function of burnup are illustrated in Figure 12. It can be noticed that the insertion of the control blades induces a harder neutron energy spectrum. Moreover, this hardening of the spectrum is increased by the gadolinium content in some fuel rods and the effect of the void fraction. The hardening of the neutron spectrum leads to a significant decrease in the efficiency of the burnable absorber with the increasing burnup and, therefore, to a delay in the consumption of the burnable absorber which tends towards a decrease in reactivity. Therefore, the k_∞ value at the reactivity peak is smaller and the fuel depletion is slightly retarded compared to the scenario without control blade insertion.

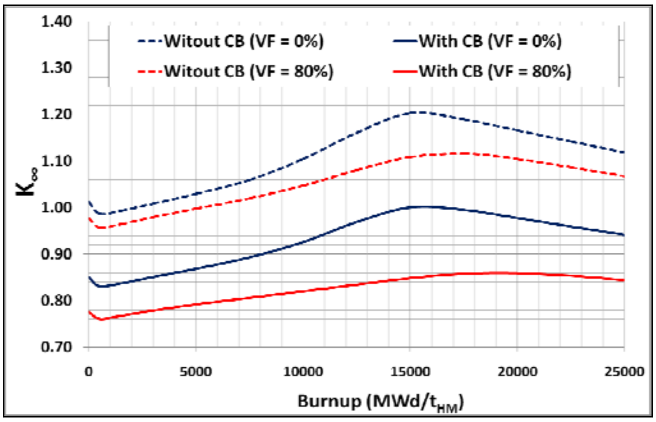


***Figure 12**: Effect of control blade insertion on the reactivity at 0% and 80% void fraction*

Spectrum hardening due to control blade insertion affects the fuel composition by absorbing thermal neutrons. Figures 13 and 14 illustrate the variation of the ^{235}U and the ^{155}Gd as a function of the burnup and at 0% and 80% void fractions. It can be observed that the depletion of these two isotopes during burnup is reduced when the void fraction increases and with the presence of control blades.

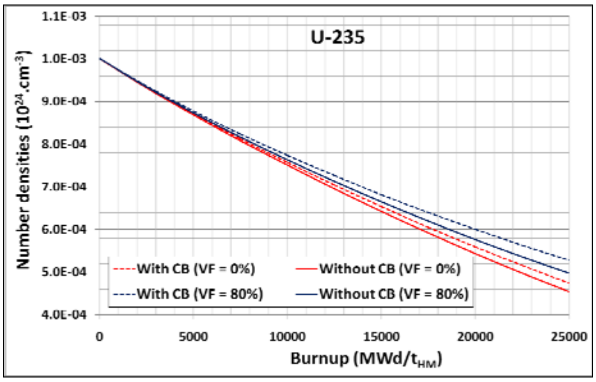


Figure 13: Effect of control blade insertion on ^{235}U

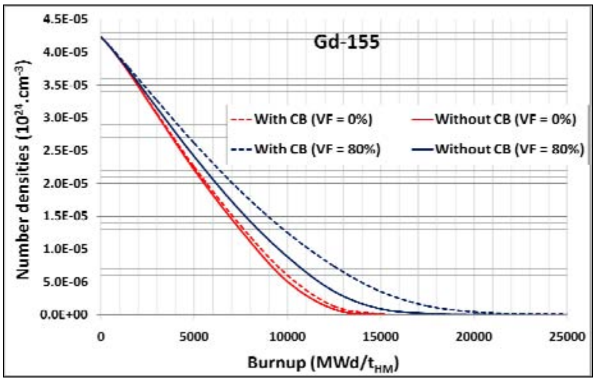


Figure 14: Effect of control blade insertion on ^{155}Gd

- *Fuel specific power*

Recent studies performed in [3] for a transport and storage cask have shown that the specific power used in the depletion calculations had a small effect on the reactivity in the range 10-20 GWd/t_{HM} BWR which corresponds to a range of burnups where the value of the reactivity peak is reached in BWR UO_2 fuel assembly types. However, the impact of a BWR operating history should be studied depending on the isotopes of interest in the gadolinium credit application (typically some thermal isotope products such as ^{155}Gd depend mainly on the irradiation history of the fuel).

- *Fuel temperature*

The maximum effective mean fuel temperature in the core should be considered as it induces neutron spectrum hardening. Indeed, it is conservative to consider a high value for the fuel temperature as it leads to more resonant captures on ^{238}U, and subsequently to further production of ^{239}Pu. However, it should be noticed that the fuel temperature used in the depletion calculation has a slight effect on the criticality calculation [3] for transport and storage casks loaded with BWR UO_2 assemblies between 10 and 20 GWd/t_{HM}.

- *Cooling time*

For transport and storage cask applications, it should be acceptable to consider the minimum cooling time that can be justified by the operators in the criticality studies. However, it is conservative to perform depletion calculations without inter-cycle downtime in order to minimize ^{241}Pu decay.

3 APPLICATION AND GAIN ESTIMATION

The gadolinium credit reactivity versus burnup has been evaluated for a representative AREVA TN transport and storage cask (see Figure 18) loaded with 69 SVEA-96 Optima 2 type spent fuel assemblies. Criticality calculations were performed using the three dimensional continuous energy particle transport calculation code TRIPOLI-4 [4] based on the Monte-Carlo method.

Note that these calculations were carried out to identify the conditions at which the reactivity in transport and storage configurations are maximized (reactivity peak), i.e. the burnup point where the combination of the presence of integral burnable poison (Gd_2O_3) and the operating conditions of the core yield the highest k_{eff} value at the reactivity peak. They do not examine the variation of the reactivity of the cask as a function of the burnup.

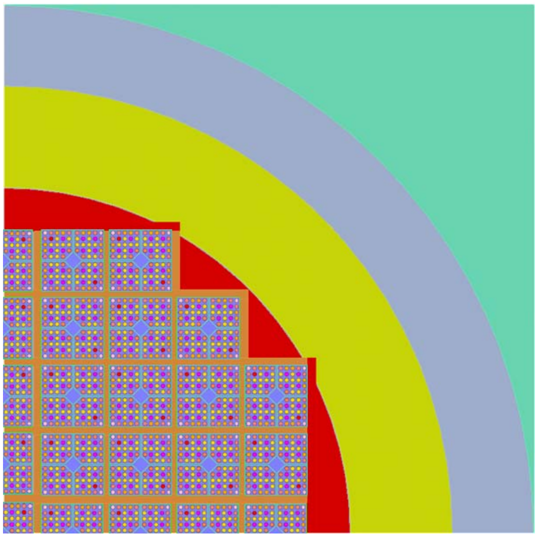


Figure 15: *Sectional view of BWR UO_2 transport and storage cask*

Free spaces in the package were filled with pure water. Criticality calculations were performed with a uniform axial burnup distribution and uniform axial void fraction distribution. The parameters and conditions of irradiation used for the depletion calculations are summarized in the Table hereafter:

Parameter	***Value***
Power density (W/g)	50
Pellet average fuel temperature (K)	900
Cladding temperature (K)	560
Moderator temperature (K)	560
Insertion of control blades (B_4C)	Throughout the irradiation
Moderator density (g/cm^3)	
Water inside central canal	0.737
Water inside wings	0.737
Inter-assembly (outer) gap water	0.737
Water in the four sub-channels (around fuel rods)	0.147 to 0.737
Gadolinium fuel rods	
Number of Gd rods in the assembly	16
Gadolinium (Gd_2O_3) content (wt. %)	5
Gadolinium fuel rod positions in the assembly	design positions

Table 1: *Fuel depletion parameters and conditions*

Criticality calculations for the dual purpose cask were performed with the use of the gadolinium credit method composed of nuclides detailed in the table hereafter:

Gadolinium Credit (10 isotopes)									
^{155}Gd [(a)]	^{235}U	^{236}U	^{238}U	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	^{16}O [(b)]
(a) : from Gd contained in some fuel rods of the assembly									
(b) : Included in the criticality calculations									

Table 2: *Nuclides associated with the method of gadolinium credit*

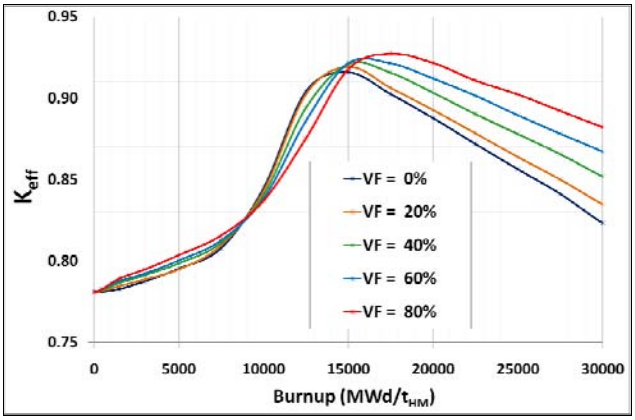
All results of the criticality calculations presented were obtained with a standard deviation of less than 0.1%.

3.1 Impact of the void fraction

Calculations were performed to evaluate the impact of the coolant void fraction (linked to the moderator density used during fuel depletion of the studied fuel assembly) in the cask model. This study was conducted considering the assembly with its real radial enrichment distribution and with the different axial lattice zones (DOM, VAN1 and VAN2). Moreover, no control blade insertion was considered and criticality calculations for the cask were carried out with a single axial uniform spent fuel composition evaluated in the depletion calculations. Figure 16 shows the variation of the reactivity of the cask versus the void fraction and the fuel assembly burnup.

The results show that the increase of the void fraction leads to the highest k_{eff} values at the reactivity peaks which are slightly shifted due to the neutron spectrum hardening. It is also interesting to note the depression values of Δk_{eff} observed between 10 and 15 GWd/t_{HM} in the curves obtained from the comparison to 0% of void fraction. This effect is due to the fact that the reactivity peak at 0% void fraction is obtained earlier compared to the other void fractions.

The Δk_{eff} values at the reactivity peaks obtained from the comparison to 0% void fraction are given in Table 3. The maximum deviation is obtained for 80% void fraction. These results are consistent with studies performed in [5].



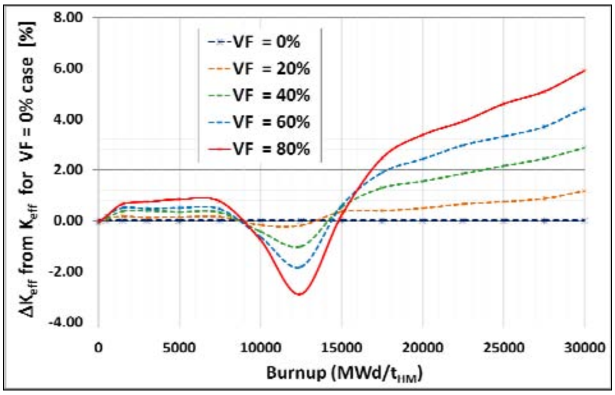


***Figure 16**: Effect of the void fraction on the k_{eff} of the cask*

	Void fraction [%]			
Burnup (GWd/t_{HM}) at reactivity peak	**20**	**40**	**60**	**80**
14 - 18	+0.35%	+0.52%	+0.58%	+1.16%

***Table 3:** Effect of the void fraction (reference 0% void fraction)*

3.2 Impact of the insertion of control blades

Calculations were performed by using the isotopic compositions resulting from depletion calculations with and without the presence of control blades (CBs). Note that the CBs were considered fully inserted axially and that all assemblies, in a conservative way, are assumed to have the same CB exposure in the cask. The k_{eff} and the Δk_{eff} values as a function of the burnup for these two conditions are compared in Figures 17 for 0%, 40% and 80% void fractions.

The presence of CBs in the BWR UO_2 assemblies leads to an important increase in the reactivity at the reactivity peak for low values of the void fraction. Indeed, the hardening of the neutron spectrum in the depletion calculations due to the increase of the void fraction has the effect of decreasing the efficiency of the CBs. The k_{eff} values at the reactivity peak obtained for the three considered void fractions are shifted when the CBs are inserted in comparison to the case without CB insertion. This is due to the neutron spectrum hardening induced by both effects: the increase of the void fraction and the full axial insertion of the CBs throughout the irradiation, therefore inducing a delay in the consumption of the burnable absorber.

The values of the Δk_{eff} obtained at the reactivity peak for the void fraction considered are given in Table 4. The highest Δk_{eff} at the reactivity peak is less than 1.3% when CBs are present throughout the entire depletion with 80 % void fraction.

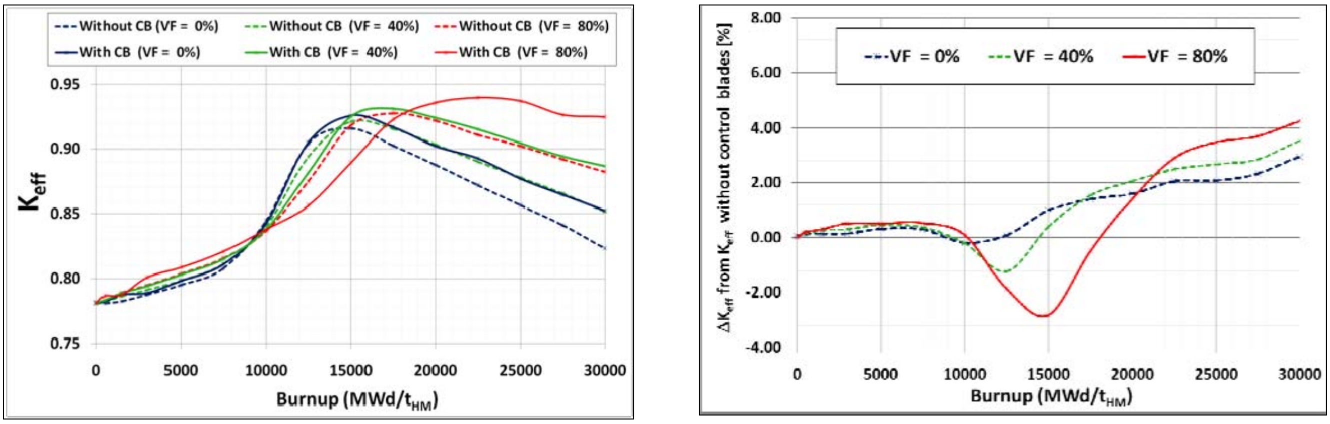


***Figure 17**: Effect of the control blade insertion*

	Void fraction [%]		
Burnup (GWd/t_{HM}) at reactivity peak	**0**	**40**	**80**
15	+0.99%	-	-
17.5	-	+1.01%	-
22.5	-	-	+1.24%

***Table 4:** Effect of CB insertion (reference without CB insertion)*

The penalties due to the CB insertion include two conservative assumptions: the duration of CB insertion (throughout the entire irradiation) and the level of axial insertion of the CBs (full axial insertion). Although the probability of an assembly being irradiated with CBs inserted throughout its entire irradiation is low, it is difficult to exclude that possibility. Nevertheless, it is possible to consider a partial axial CB insertion provided that the operator guarantees this limited insertion of the CBs. 3-D calculations were performed with the dual purpose cask to establish the reactivity effect of CB exposure as a function of axial insertion. A series of calculations were performed to determine the effect of various axial CB insertions. The k_{eff} values versus CB insertion are shown in Figure 18.The three void fractions considered and two burnup levels are considered: 22.5 GWd/t_{HM} (burnup at reactivity peak when CBs are present during the entire depletion with 80 % void fraction) and 40 GWd/tHM (burnup beyond the peak reactivity point).

The results show that axial insertions of CBs at above 20 cm induce an increase in the k_{eff} and this increase is stabilized for about 200 cm of axial insertions of the CBs. From these results, it can be also deduced that the CB insertion has a slight effect until the reactivity peak occurs regardless the void fraction. For burnups beyond the peak reactivity point, the CBs insertion has a significant effect on the k_{eff} value.

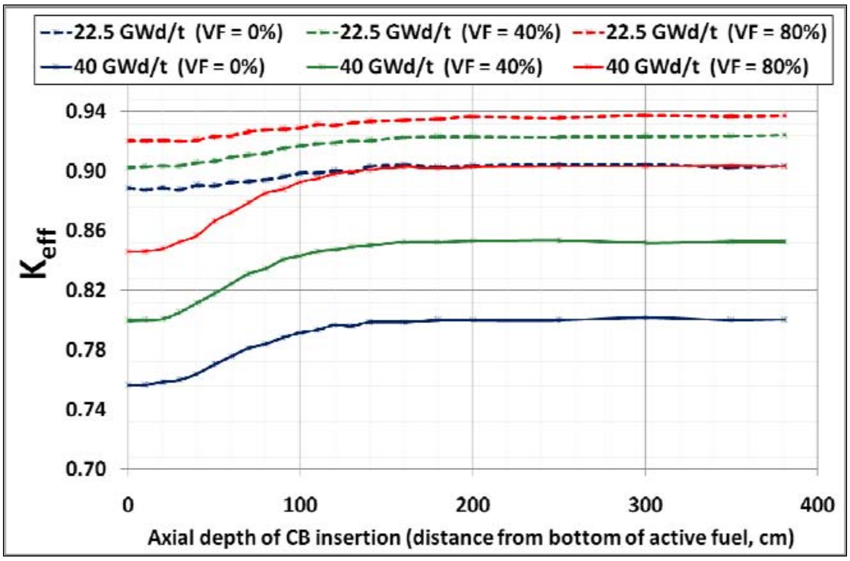


Figure 18*: Effect of the axial depth of CBs insertion*

3.3 Effect of radial enrichment distribution

The results of the assemblies loaded in the transport and storage cask with a heterogeneous radial enrichment distribution in the assemblies (actual model) were compared to a uniform radial enrichment distribution in the assemblies (simplified homogeneous model) by using the maximum average enrichment (4.29 wt. %) of the assemblies in each axial lattice zone (DOM, VAN1 and VAN2). These two models were modeled with the same positioning of the gadolinium fuel rods, the same amount of gadolinium in the assemblies, and the same exposure and full axial insertion of the CBs. Calculations for both models were performed for 0%, 40% and 80% void fractions. The results obtained are illustrated in Figure 19 and the Δk_{eff} values at the reactivity peak for 0%, 40% and 80% void fraction are given in Table 5.

The simplified model with a homogeneous radial enrichment distribution in the assemblies gives higher k_{eff} values than the real heterogeneous actual design of the assemblies in the peak reactivity range considered. The highest Δk_{eff}, obtained at 80% void fraction are approximately 0.5%. These results are consistent with the studies performed in [5].

Thus, the uniform radial enrichment distribution (homogeneous model) is conservative for the criticality analysis of the cask loaded with BWR UO_2 spent fuel assemblies.

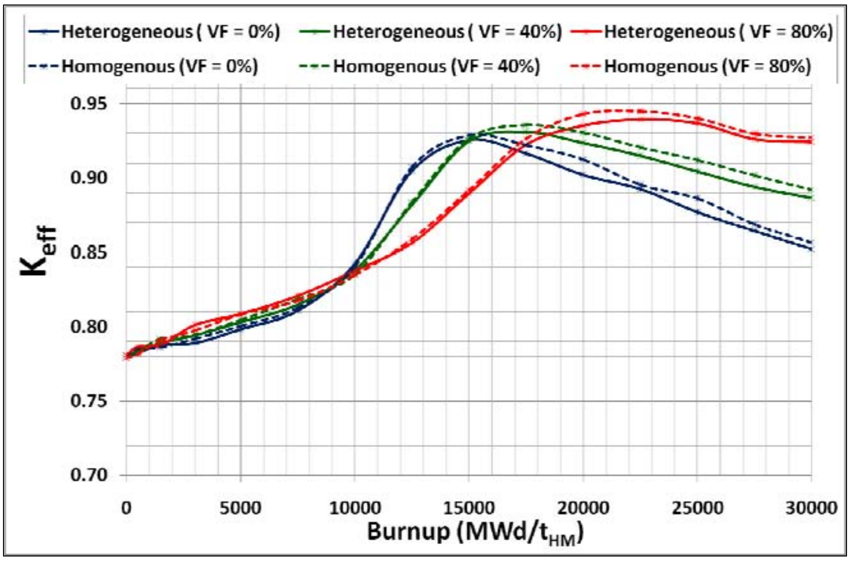


Figure 19*: Comparison between heterogeneous and homogenous radial enrichment distribution*

	Void fraction [%]		
Burnup (GWd/t_{HM}) at reactivity peak	**0**	**40**	**80**
15	+0.32%	-	-
17.5	-	+0.49%	-
22.5	-	-	+0.53%

Table 5: *Effect of the homogenous and heterogeneous radial enrichment distribution*

3.4 Effect of axial zones lattices

Calculations were performed with the DOM axial lattice zone (without vanished regions) over the entire length of the assemblies by using the maximum average enrichment (4.29 wt. %) of the assemblies loaded in the cask. The results were subsequently compared to the results obtained with the assemblies modeled with their different axial lattice zones (DOM, VAN1 and VAN2) and for a uniform enrichment in each zone equal to 4.29 wt. %. The same positioning of the gadolinium fuel rods, the same amount of gadolinium in the assemblies, and the same exposure and full axial insertion of the CBs were considered in the calculations. The results obtained are shown in Figure 20 and the Δk_{eff} values at the reactivity peak corresponding to 0%, 40% and 80% void fraction are given Table 6.

The homogeneous axial lattice zone without considering the vanished regions (DOM) over the entire length of the assemblies loaded in the cask gives higher k_{eff} values than the real heterogeneous axial lattice zones of the assemblies (actual model) in the peak reactivity range considered. The highest Δk_{eff}, obtained at 80% void fraction, is approximately 1 %.

Finally, the use of a simplified model based on a uniform radial enrichment distribution with the maximum average enrichment of the assemblies including the gadolinium fuel rods and a homogeneous axial lattice zone without vanished regions over the entire length of the assemblies is conservative for criticality analysis of the transport and storage cask loaded with modern BWR UO_2 spent fuel assemblies such as SVEA-96 Optima 2, which are usually over moderated under transportation and storage configurations.

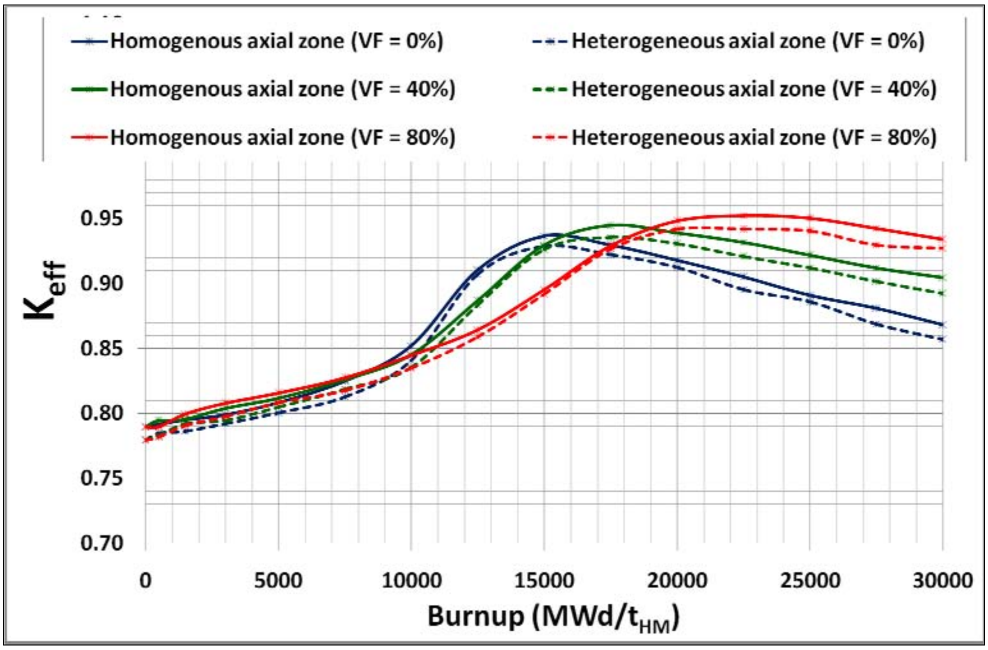


Figure 20:*: Comparison between heterogeneous and homogenous axial zone modeling at the reactivity peaks*

	Void fraction [%]		
Burnup (GWd/t_{HM}) at reactivity peak	**0**	**40**	**80**
15	+0.80 %	-	-
17.5	-	+0.92%	-
22.5	-	-	+1.04%

Table 6: *Effect of heterogeneous and homogeneous axial zones modeling*

3.5 Gain estimation

The results of the fresh-fuel assumption with the maximum average initial ^{235}U enrichment and without gadolinium are compared to the gadolinium credit method for the transport and storage cask loaded with 69 SVEA-96 Optima 2 type spent fuel assemblies considering the simplified model based on the following conservative assumptions:

- a uniform radial enrichment distribution with the maximum average enrichment
- a homogeneous axial lattice zone without vanished regions over the entire length
- CBs fully inserted axially and all assemblies with the same CB exposure in the cask

The comparisons between the k_{eff} value obtained with the fresh fuel assumption and the gadolinium credit method studied could be presented as:

$$\Delta k_{eff} = k_{eff} \text{ (Gadolinium credit method) } - k_{eff} \text{ (Fresh fuel without gadolinium)}$$

The values of Δk_{eff} obtained are given in the table hereafter:

Void fraction [%]	Burnup (GWd/t_{HM}) at reactivity peak	Gadolinium credit method
0	**15**	-6.3%
40	**17.5**	-5.5%
80	**20**	-4.7%

Table 8*: Comparison between fresh-fuel assumption and gadolinium credit methods*

The use of the gadolinium credit method gives a gain of up to Δk_{eff} = 4.7 % for 80% void fraction at the reactivity peak.

4 CONCLUSION

The analyses described in this paper provide a technical basis to support gadolinium credit for transport and storage cask applications loaded with BWR UO_2 spent fuel assemblies. Sensitivity calculations were performed for a modern BWR assembly design in order to define a conservative approach for both depletion and criticality calculations of BWR fuel assemblies with the presence of gadolinium fuel rods. These calculations were mainly based on:

- the reactivity peak characterization as a function of the burnup
- the definition of a simple and practical bounding model that ensures the conservatism of the spent fuel inventory and criticality calculations due to the complexity of the modeling of BWR UO_2 spent fuel assemblies

Sensitivity depletion calculations have shown that the reactivity peak typically occurs for gadolinium poison fuel rods between 10 and 20 GWd/t_{HM} and that the fuel is more reactive when the irradiation conditions lead to a hardened neutron spectrum. The relevant depletion parameters that can affect the neutron spectrum at the reactivity peak are the void fraction and the control blade insertion during the irradiation. Other parameters such as the fuel temperature and the specific power have secondary effects.

The reactivity peak also depends on the fuel design, the amount of gadolinium and the gadolinium fuel rod distribution in the assembly. A simplified modeling approach of the BWR UO_2 based on uniform radial enrichment distribution with the maximum average enrichment of the assemblies including the gadolinium fuel rods and a homogeneous axial lattice zone over the entire length of the assemblies is suitable for criticality analysis.

Criticality calculations performed on a dual purpose cask have shown a gain of between 4-5% in terms of reactivity of the gadolinium credit for transport and storage cask applications compared to the fresh fuel approach without integral burnable absorbers. This gain can be increased to about 8% if main fission products are taken into account. Therefore, considerable interest exists in the use of the gadolinium credit with the potential to greatly reduce cost when it is applied to the design of new baskets for BWR UO_2 spent fuel assemblies in transportation and storage casks.

With the feedback received from this investigation of the gadolinium burnup credit approaches, AREVA TN's current and expected future activities for the transportation and storage of BWR UO_2 spent fuel assemblies are as follows:

- Consideration of axial burnup profile and axial void fraction profile,
- Extension of the gadolinium credit method to other modern BWR UO_2 fuel designs,
- Validation of depletion and criticality calculation tools.

5 REFERENCES

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