COMPARISON OF UOX AND MOX FOR SUPER CRITICAL LWR

W. Bernnat

University of Stuttgart, Germany

Abstract

For the present design variant of fuel assemblies of the High Performance LWR, assembly and assembly cluster burnup calculations were performed to get information about k-infinity vs. burnup and power distributions for different moderator and coolant states. The analysis was performed for UOX and MOX fuel by the Monte Carlo code MCNP5 coupled with a burnup code. The moderator and coolant state parameters were varied according to typical values in evaporator, super heater I and super heater II. Single assemblies were moved inside a cluster to simulate bending effects due to temperature gradients etc. to get information about the influence on the power distribution.

1. Introduction

The High Performance Light Water Reactor (HPLWR) works with super critical H_2O at 25 MPa. A detailed description of a three pass core with evaporator, superheater I and super heater II is given by Schulenberg (2007, 2010). The core consists of clusters of 3x3 assemblies with 40 fuel pins, an inner moderator box, coolant between inner box and assembly box and moderator water between the assembly boxes of the clusters.

The power distributions in HPLWR assemblies depend essentially from moderator and coolant density, temperature and burnup dependent content of fissionable material. Especially, the coolant density decreases strongly from evaporator bottom to top and in the super heaters. Depending from location in core quite different reactivity effects can be observed. To get information about the power distribution and reactivity during irradiation in different core locations, 2D assembly or assembly cluster burnup calculations were performed with a coupled Monte Carlo burnup method. The different locations in core were characterized by moderator state in the moderator box and outer gap and by the coolant state.

As fuel Uranium oxide with up to 6 wt% U-235 and MOX up to 8 wt% Pu-fiss was used. Additionally, for the outer edge pins of each assembly, burnable poisons (up to 3 wt% Gd_2O_3) were partly used to reduce the pin power at the higher moderated edges and the initial reactivity. For the case of Gd free edge pins, the corresponding enrichment was reduced. The Gd poisoned pins in MOX assemblies contained UOX fuel. Clusters with pure UOX and MOX fuel and a mixture of Uranium and MOX fuel were analysed. The MOX fuel composition was a typical LWR Plutonium (first reprocessing) in natural Uranium.

For many moderator and coolant states 2D burnup calculations were performed. The results are detailed power distributions, k-infinity vs. burnup, number densities for all explicitly regarded nuclides of the burnup model and conversion rates. Due to a very detailed geometrical model of the assemblies also power gradients inside the pins were determined. Furthermore, for different core locations also reactivity and power distribution effects for controlled clusters and clusters with displaced assemblies were calculated.

2. Model for assembly analysis

The assembly burnup analysis gives information about detailed power and burnup distribution inside an infinite lattice of assembly clusters. To simulate the moderator and coolant states in the different zones of the three pass core the calculations were performed for typical combinations of moderator densities in the inner box and the outer gap and the coolant density. The typical values for the moderator/coolant states were taken from Maraczy (2008).

2.1 Geometrical model

For the present design of the HPLWR fuel assembly (Fig. 1) 2D burnup calculations for different states of the moderator inside the moderator box, outside of the assembly box (gap) and of the coolant were performed. Each assembly contains 40 fuel rods with steel cladding and a wire as spacer (Fig. 2). The main data of the assembly and the fuel are taken from HPLWR core data sheet (Schulenberg et. al, 2007). For the reference fuel 6 wt% U-235 was assumed for all pins except the outer edge pins. For these pins either 5 wt% U-235 were assumed or 6 wt% U-235 and 2-3 wt% Gd_2O_3 burnable poison. The isotopic composition of plutonium of MOX fuel is listed in Tab. 1.

For the three main core zones of the present HPLWR design (Schulenberg et. al. 2007) with evaporator, super heater I and super heater II (see Fig. 3) representative moderator and coolant temperatures were taken for the bottom part, the centre part and top part of the core (see Fig. 4). The corresponding average temperature values chosen are from these figures for the bottom, centre and top regions, marked by vertical lines. Additionally, based on the burnup distributions of these cell burnup calculations, the power distribution and reactivity values for different average burnups were calculated for the case of inserted control elements and displacements of assemblies inside a 3 x 3 assembly cluster. The displacements may be caused due to bowing and tolerances or defects of spacers between the assemblies in a cluster or between clusters. The results of these calculations show the principal power distributions for clusters in regular and perturbed lattices

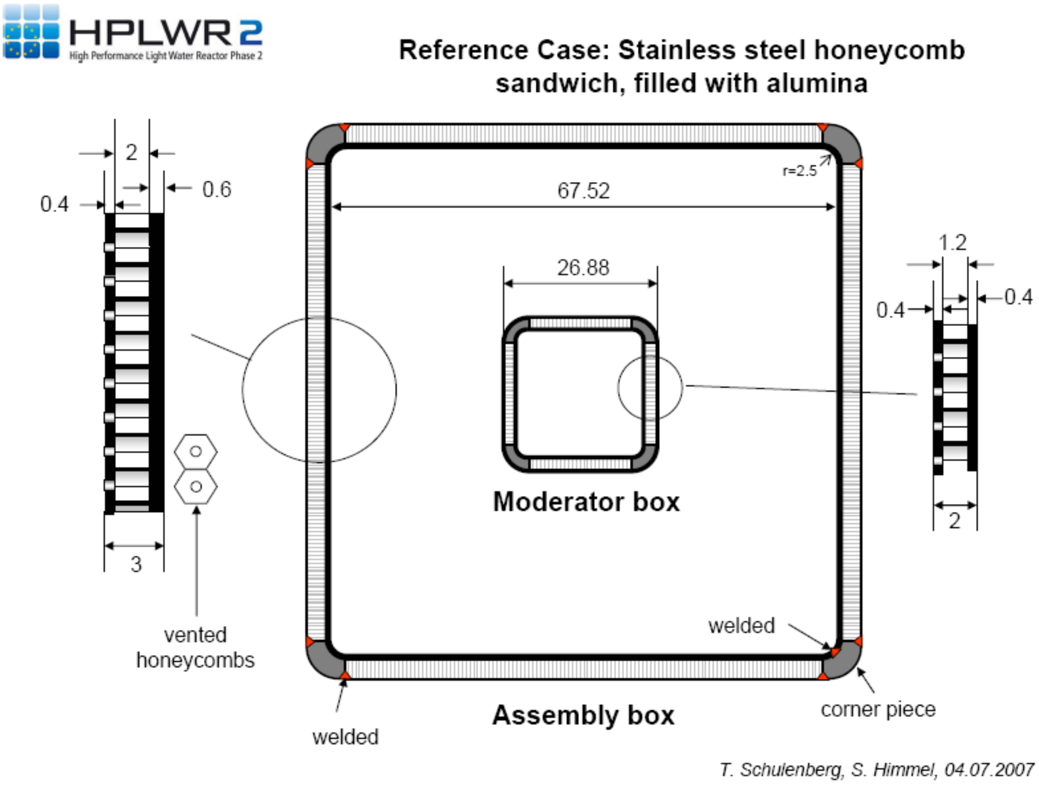


Figure 1: Design of HPLWR fuel assembly boxes

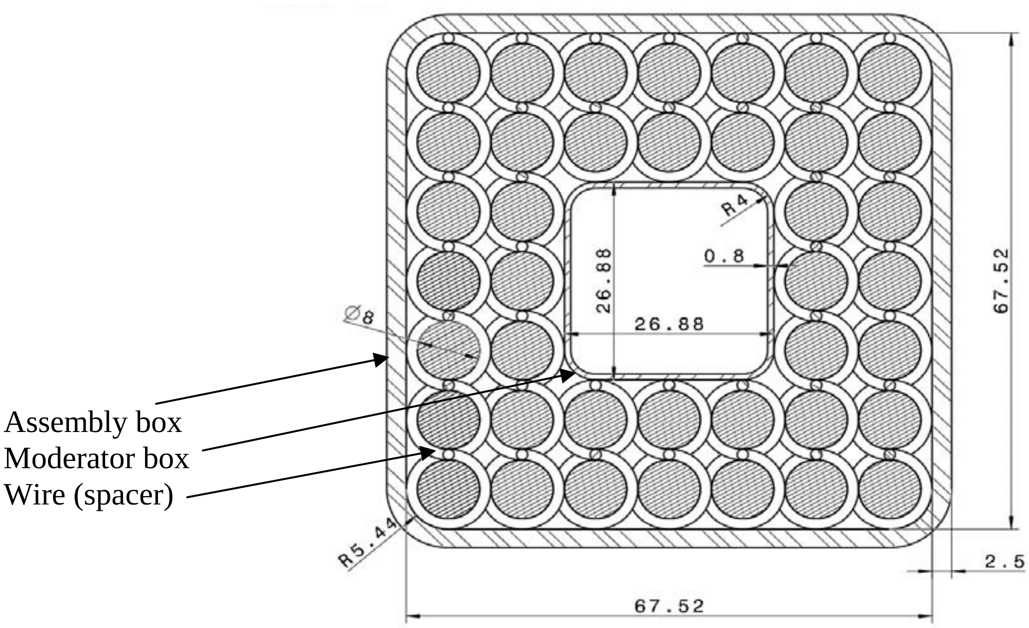


Figure 2: Fuel pin arrangement in the HPLWR assembly (Schulenberg, Himmel 2007)

Table 1: Isotopic composition of MOX fuel

Isotope	wt%
238Pu	2.59
239Pu	53.85
240Pu	23.65
241Pu	13.13
242Pu	6.78

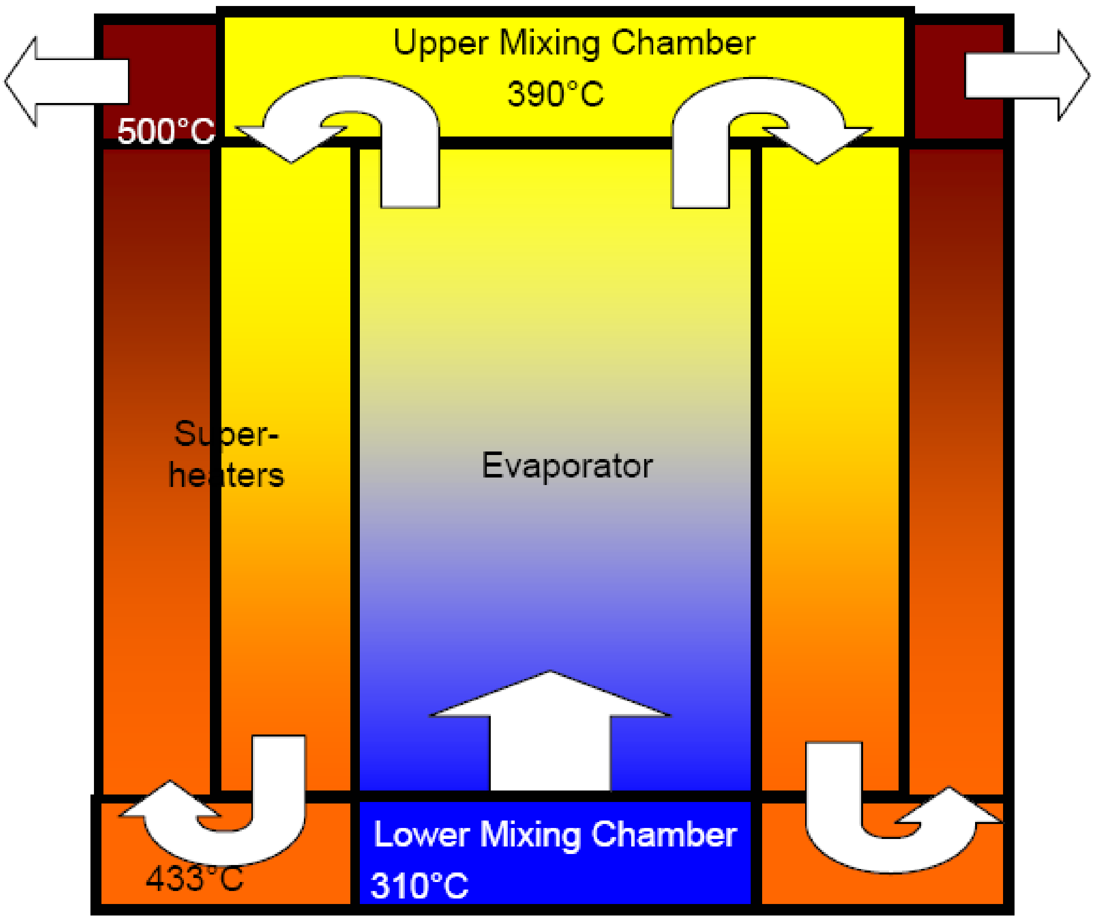


Figure 3: HPLWR coolant flow path in three pass core

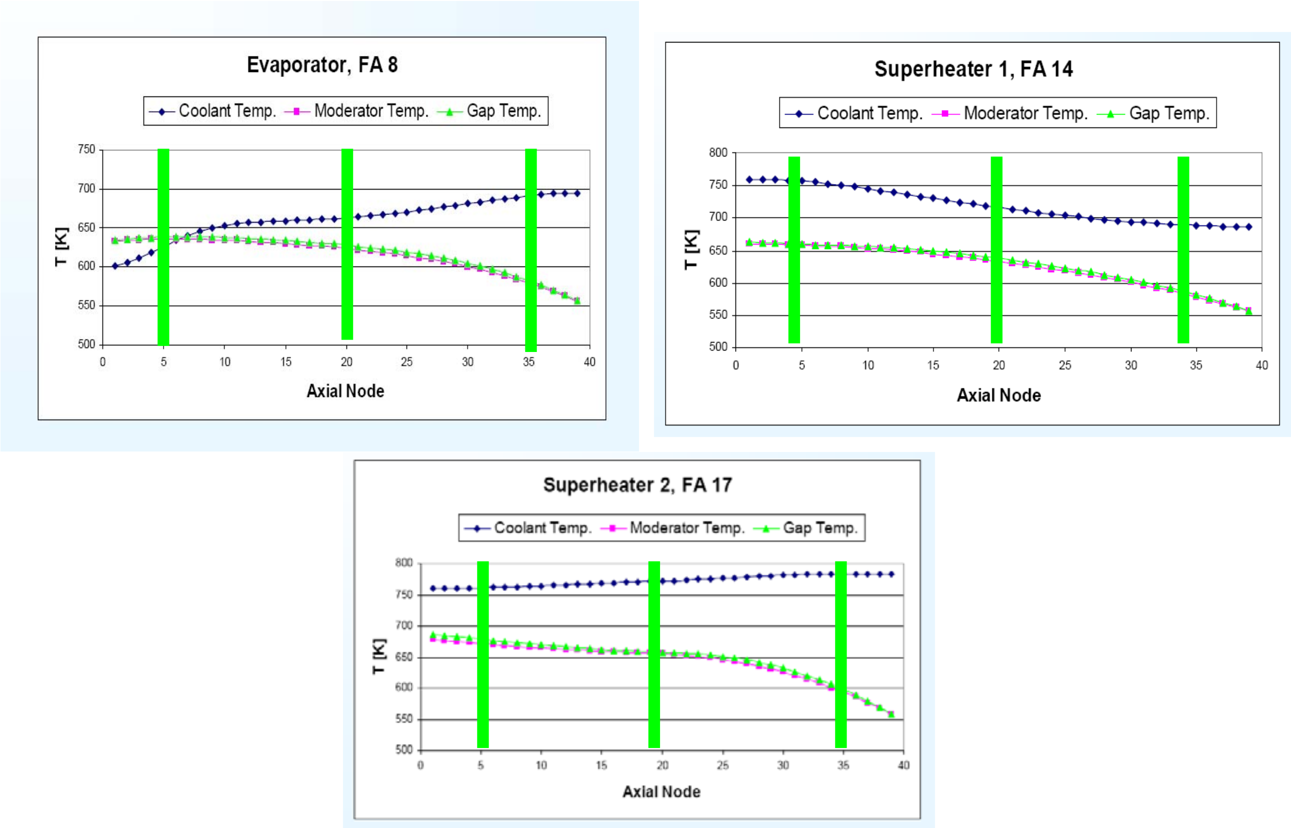


Figure 4: Representative coolant moderator and gap temperatures in evaporator, and super heaters

2.2 Coupled Monte Carlo burnup program

The burnup analysis was performed by a coupled Monte Carlo transport and burnup calculation. For the solution of the transport equation the Monte Carlo program MCNP5 (MCNP5, 2003) was used. The burnup calculations were performed by an efficient model which was used for LWR and research reactors (Nabbi, Bernnat, 2005). In this model 20 actinides and 85 fission products were regarded explicitly. Comparisons with burnup codes regarding much more nuclides such as ORIGEN showed sufficient agreement in respect to reactivity and main reaction rates. The corresponding spectrum dependent average cross sections (mainly capture and fission) were calculated by MCNP for every burnup step. The densities and temperatures of moderator and coolant, the fuel temperature and the assembly power were kept constant during burnup. This model was used for several applications, e. g. for a BWR assembly burnup benchmark organized by OECD/NEA (OECD/NEA 2000, 2003).

2.3 2D Calculation model for assembly burnup calculations

The 2D model of the assembly realized by the Monte Carlo program MCNP is shown in Fig. 5. The moderator and assembly boxes were simulated by a realistic model; the Honeycomb structures together with the isolating material and water were homogenized, however. The same was done for the perforated box walls. The fuel pins were modelled by a cylinder for the UO_2 or MOX and a surrounding homogenized zone which represents the gap, the cladding and the spacer wire. To get information about power gradients the pins were azimuthally subdivided into 4 quarters. The UOX with Gd_2O_3 as burnable poison were additionally radial subdivided into 10 zones to account for the thermal flux profile inside the fuel rod. The model shown in Fig. 6 represents a cluster with regular structure for a wide gap. In the assemblies in the centre and at the main axes control rods can be inserted. The gap width between the assemblies can be varied.

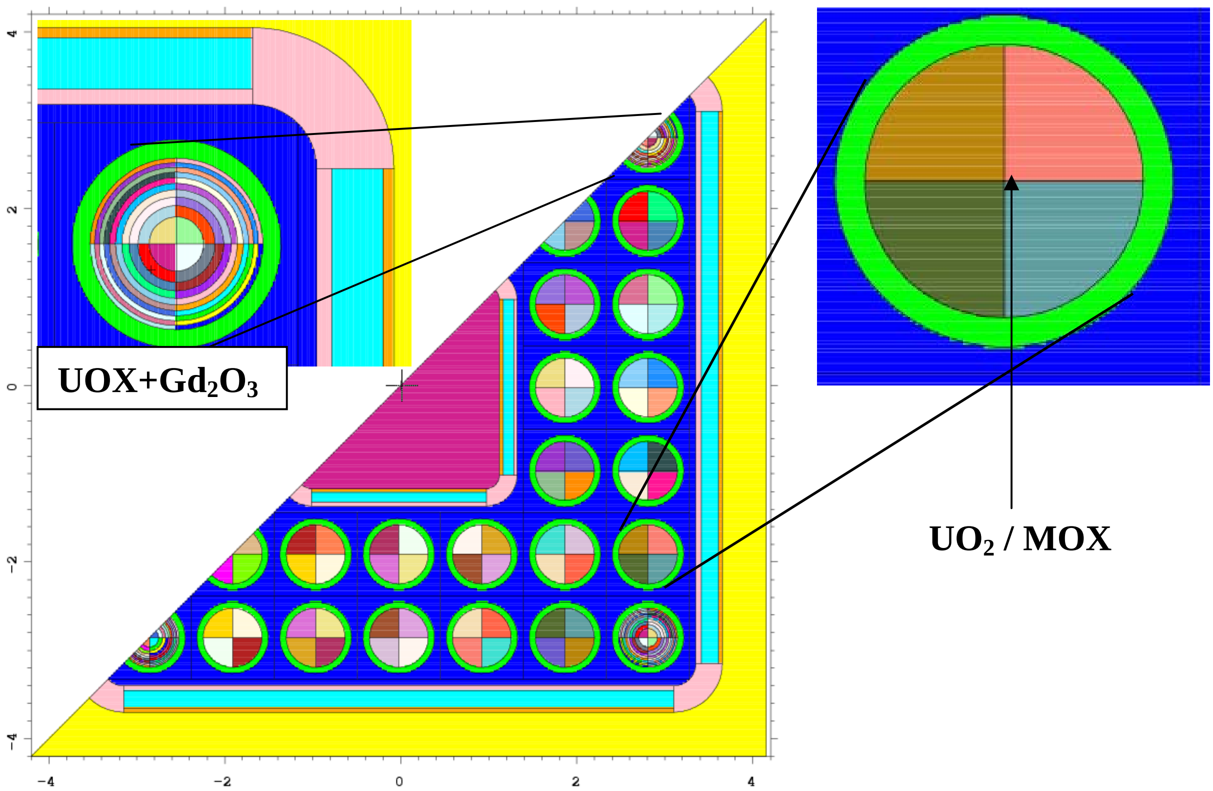


Figure 5: MCNP model of fuel assembly (containing Gd_2O_3) in edge pins

The cluster burnup calculations were performed for a mixture of UOX and MOX in the cluster. The UOX assemblies were assumed in the centre and at the four edge positions of the cluster. The model shown in Fig. 6 assumes symmetry. An additional model was generated for a full cluster without symmetry to calculate power distributions for displaced assemblies in the cluster.

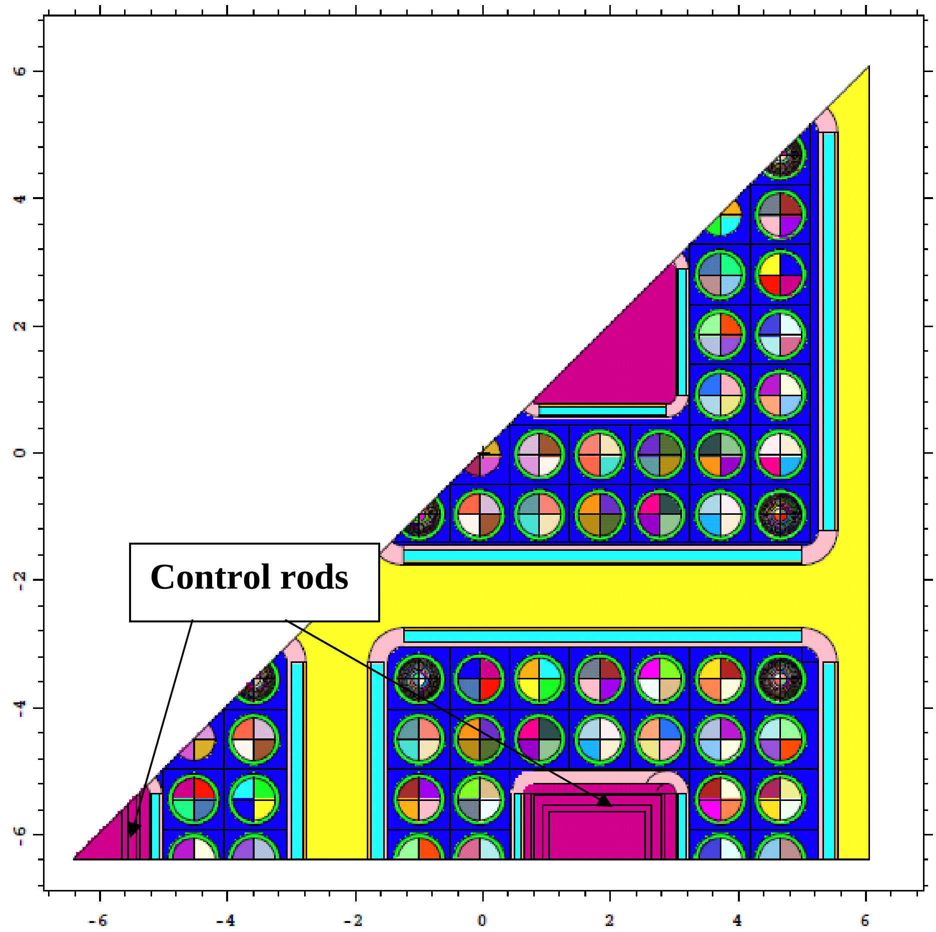


Figure 6: Geometrical model for cluster burnup calculations (wide gap)

3. Burnup calculations performed

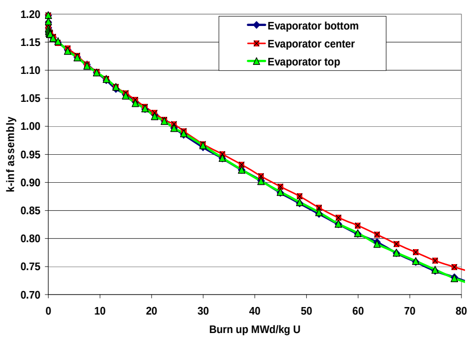
For every core region (evaporator, super heater I and super heater II) the moderator/coolant states were chosen as described. For all combinations assembly burnup calculations were performed. Additionally, a UOX assembly was positioned first in super heater II up to a burnup of 12 MWd/kg HM and then shuffled to the evaporator region. The main results of all calculations are k-infinity as a function of burnup, the pin-wise power distribution and distribution of number densities of the different nuclides, especially of the main actinides. The calculations were performed for UOX, MOX and UOX-MOX clusters.

Based on these burnup calculations, further analysis of assembly clusters were performed to get information about power distributions in case of inserted control rods into a cluster of 3 x 3 assemblies and for the case of displaced assemblies inside a cluster.

3.1 Infinite multiplication factor as a function of burnup

The infinite multiplication factor for the evaporator is shown in Fig. 7 (left) for the representative moderator/coolant states at bottom, centre and top (without burnable poison). There is a slightly lower decrease of k_{inf} for the centre position since the average moderator density was lower than in bottom and top positions. For these calculations it was assumed, that also in the gaps outside the assembly boxes was a down flow. In Fig. 7 (right) the corresponding curves are shown for the super heater 1. The average moderator densities are at lowest in the bottom position. Therefore, the k-infinity is much lower than for the centre and top positions. However, the slope is not as steep as that for the centre and top positions since there is much more Pu buildup due to the harder spectrum. In Fig. 8 (left) k-infinity is shown as a function of burnup for evaporator, super heater 1 and super heater 2 in the axial centre of the core for 3 wt% Gd_2O_3 in the edge pins. The large differences of the infinite multiplication factors at the beginning of irradiation are due to the different moderator/coolant densities at the different locations. For comparison, k-infinity is also shown for the assemblies without burnable poison (however with 5wt% U-235 in the edge pins). The burnout of Gd is completed after about 10-12 MWd/kg HM burnup. After this burnup the Gd-poisoned assemblies show the same k-infinity function as for the non poisoned assemblies. The reactivity of the fresh fuel is remarkably reduced compared to non poisoned fuel. This is very important for the control of power distribution and reactivity during the cycle.

To show the effect of shuffling, in an additional calculation 3 wt% Gd_2O_3 poisoned fuel was irradiated in super heater 2 and then shuffled to the evaporator. The k-infinity as a function of burnup is shown in Fig. 8 (right) for the centre position compared to curves for complete irradiation in evaporator, super heater 1 and super heater 2. The Gd_2O_3 content was 3 wt%. It is clear, that in the evaporator environment k-infinity increases. Compared to the k-infinity for fuel irradiated in evaporator from beginning, the k-infinity of the shuffled assembly is higher in evaporator due to the higher Pu content which was generated in the harder spectrum of super heater 2.



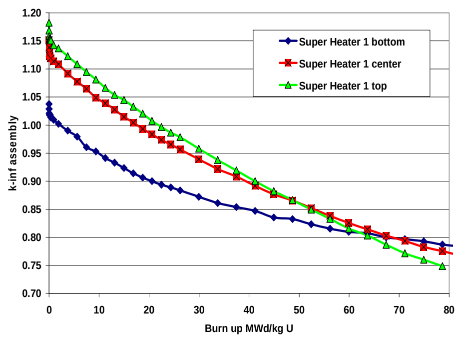


Figure 7: K-infinity vs. burnup in evaporator (left), superheater I (right) for three axial positions (UOX)

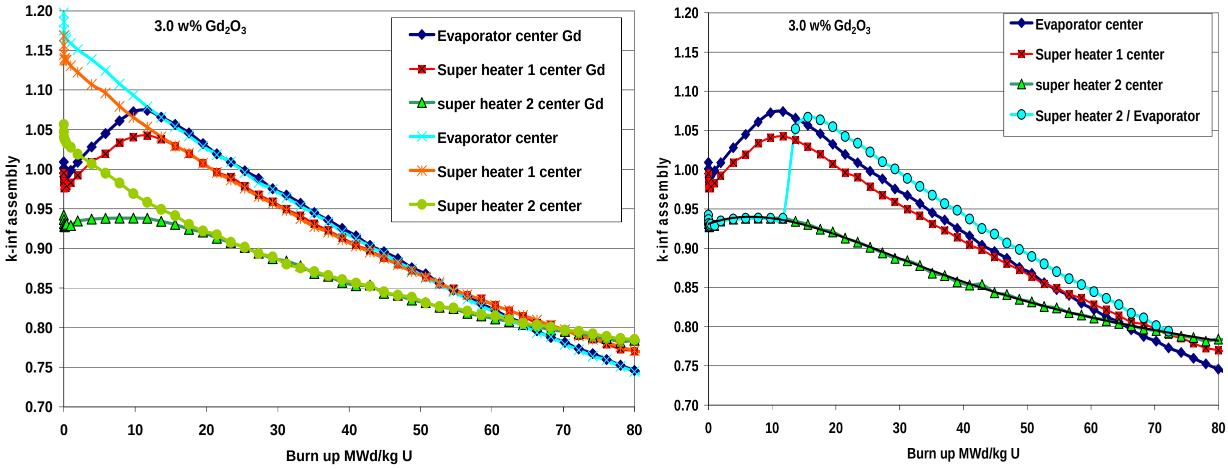


Figure 8: K-infinity vs. burnup for UOX with and without Gd (left), Change of location from super heater 2 to evaporator (right)

The results for UOX show generally a strong decrease of k-infinity with burnup. The consequence is a low average discharge burnup of about 30 MWd/kg HM if not a much higher initial U-235 enrichment is used. Therefore, additionally to the UOX, MOX fuel was used. The corresponding k-infinity vs. burnup is shown in Fig. 9 (left). For comparison in this figure also k-infinity for UOX fuel is shown. The curves are representative for the moderator/coolant state at the top of the evaporator. For both fuel types the use of Gd in edge pins was assumed additionally. The general result is -as expected- that the reactivity of the MOX fuel decreases much slower with burnup compared to UOX fuel. This means that the average discharge burnup increases by about 25% even if the initial reactivity is lower for MOX fuel. Furthermore, during the Gd burnout k-infinity vs. burnup is nearly flat for MOX fuel, at least for the coolant/moderator states of evaporator. In Fig. 9 (right) a comparison of k-infinity vs. burnup is shown for the evaporator at bottom. The mixed clusters show a faster decrease of k-infinity with burnup than pure MOX clusters, but not so strong than pure UOX cluster. In Fig. 10 there is a comparison of k-infinity vs. burnup for mixed UOX and MOX cluster designs with a wide (as for present design) and a narrow gap. The narrow gap increases the conversion rate and reduces partly the strong power gradients in the pins near the moderator gaps, but the initial enrichment must be increased to get sufficient discharge burnup.

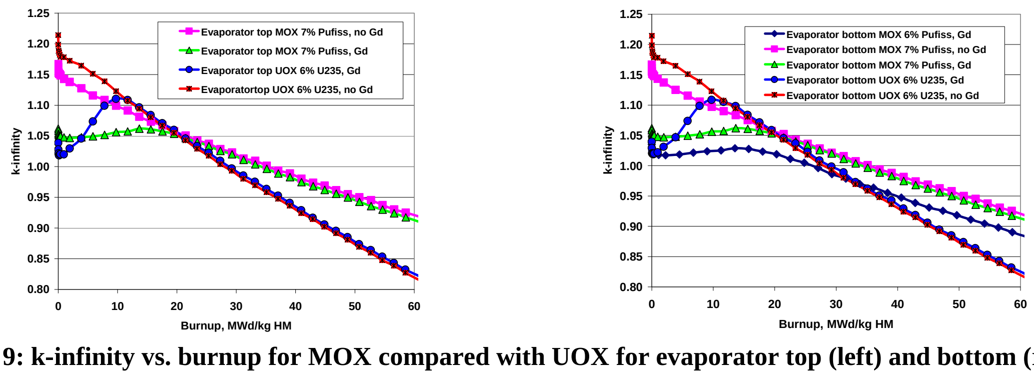


Figure 9: k-infinity vs. burnup for MOX compared with UOX for evaporator top (left) and bottom (right)

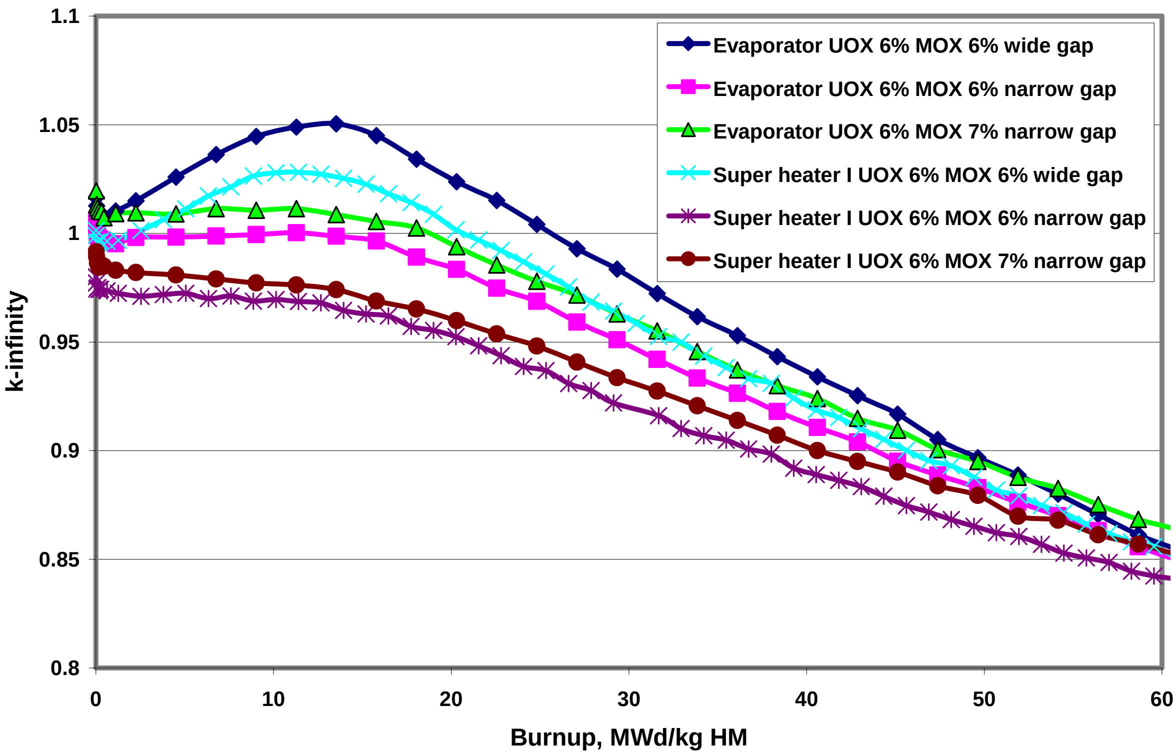


Figure 10: k-infinity vs. burnup for evaporator and super heater 1 for clusters with 5 UOX and 4 MOX assemblies with wide and narrow gap

3.2 Power distribution in UOX assemblies

The influence of control rod insertion and displacements of assemblies inside clusters was analysed based on the burnup distributions performed for the single assemblies. From these calculations, the number densities were taken and used for a 3 x 3 cluster. The geometrical model is identical as for the single assembly, but no symmetry was assumed. At the outer boundary of the 3 x 3 cluster, reflecting boundary conditions were assumed. Control rods were assumed with quadratic form and B_4C material inserted into centre and main axis positions. The model allows arbitrary displacements of all assemblies in a cluster (including rotations). Due to the displacements, the moderator gaps between the assemblies are different with consequences mainly for the power distribution.

As an example the power distributions for clusters in evaporator environment for different burnup and displacements of the central assembly are shown in Fig.11 (upper part zero burnup, lower part burnup 20 MWd/kg HM) for the case of inserted control rods. The effect of the displacement can be clearly seen. Furthermore, it can be seen that there is a power gradient inside the fuel pins depending of their positions. Especially, the corner pins of the assemblies show stronger gradients after the Gd burnout. The corresponding results for super heater 1 are shown in Fig. 12. Here, the power gradients for the displaced assembly positions are less different from the regular position as for the evaporator.

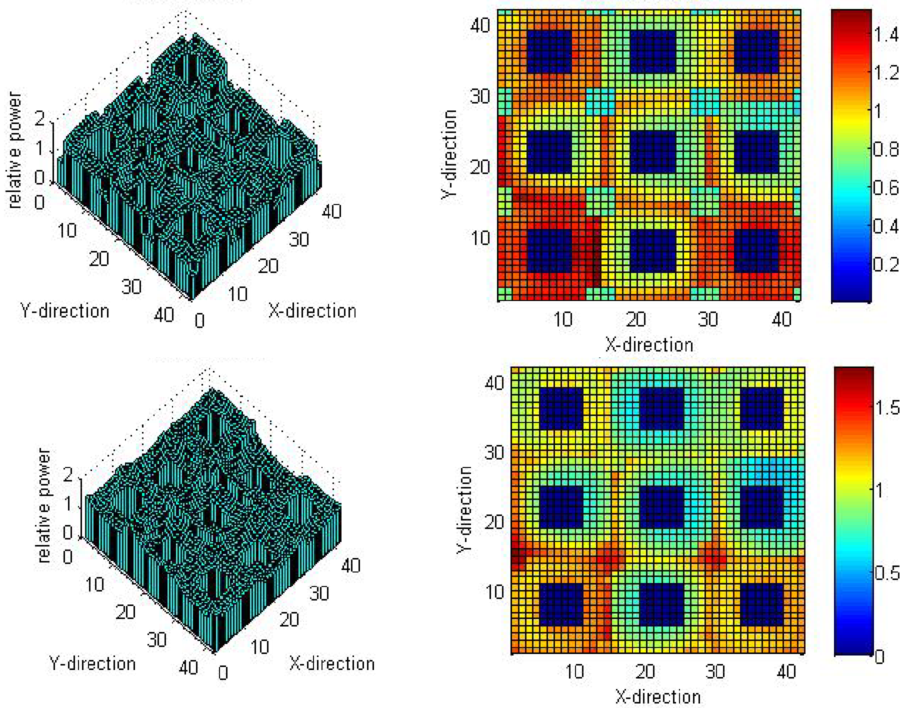


Figure 11: Power distribution for cluster in evaporator centre position with inserted rods and displaced centre assembly. UOX with zero burnup (upper picture) and 20 MWd/kg HM burnup (lower picture)

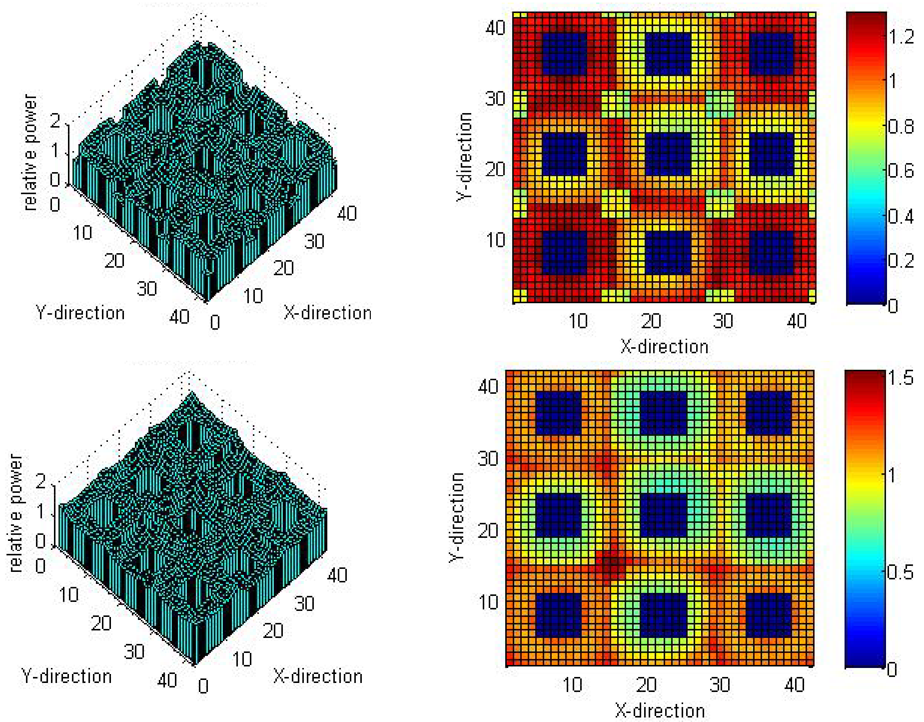


Figure 12: Power distribution for cluster in super heater 1 centre position with inserted rods and displaced centre assembly. UOX with zero burnup (upper picture) and 20 MWd/kg HM burnup (lower picture)

3.3 Power distribution in MOX assemblies

The power density distribution for MOX assembly clusters shows strong gradients in the pins near the gap between the assemblies for fresh fuel. With increasing burnup these gradients reduce to acceptable values. Since the power of the edge pins is very high due to the neighbouring water in the cross of the assembly gaps, the edge pins were composed of UOX with 3% Gd2O3. This reduces the power in this pin at the beginning of life up to comparable high burnup. An improvement of the strong radial gradients could be achieved, if the gap between the assemblies is smaller. This can be seen from Fig.13 narrow gap of 5 mm instead of 10 mm for MOX fuel with 7% Pu-fiss. For comparisons power distributions for MOX assemblies with 10 mm gap is also shown in this Figure. Further calculations were made for a cluster containing 5 UOX assemblies with 6% U-235 enrichment and 4 MOX assemblies with 7% Pu-fiss (see Fig. 14, left: zero burnup, right: 50 MWd/kg HM burnup). The UOX assemblies are located in the centre and in the four edge positions of the cluster. The four MOX assemblies are located at the main axis positions. There are strong differences between MOX and UOX assemblies, also for higher burnup. These differences become smaller if the MOX assemblies have 6% Pu-fiss. This is also true for the super heater I and II positions. For the case of narrow gaps between the assemblies the gradients in pins neighbouring the gaps are smaller than for wider gaps. The strongest gradients in the MOX assemblies appear now at the beginning of life in the pins neighbouring the inner moderator channel, but the gradients reduce with burnup.

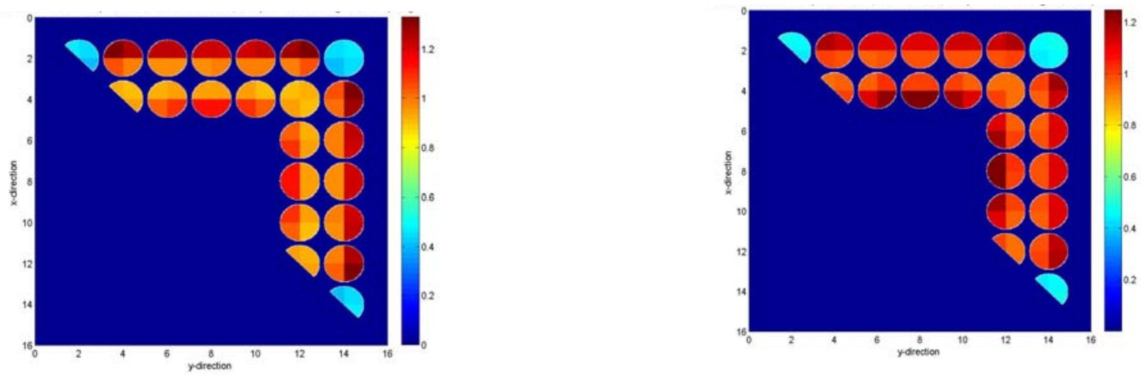


Figure 13: Power distribution in MOX (zero burnup) assemblies with 10 mm gap (left) and 5mm gap (right)

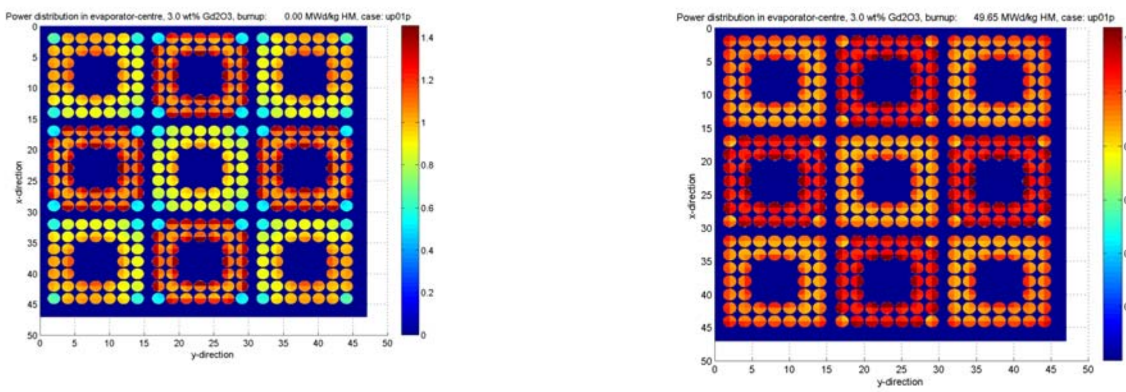


Figure 14: Power distribution in cluster with UOX and MOX assemblies with zero burnup (left), 50 MWD/kg HM (right)

4. Conclusions

The 2D burnup analysis for assemblies and clusters shows the detailed power distribution inside assembles for a number of combinations of moderator and coolant temperature and density and its change with burnup. The calculations performed with a coupled Monte Carlo and burnup code give also information about the nuclide composition as a function of irradiation time and allow additional analysis e. g. for calculation of control rod worth and reactivity coefficients as a function of burnup. These data can also be used for analysis of effects like displacement of assemblies inside clusters.

The analyses were performed for UOX fuel with 6% U-235 with and without Gd_2O_3 as burnable poison in edge positions of the assemblies. Additionally, MOX fuel with 6% Pu-fiss and 7% Pu-fiss was analyzed. The results showed that the use of MOX fuel increases the average discharge burnup since the fuel utilization is remarkably higher for MOX than for UOX. This can be seen regarding the individual conversion rates of the different fuel. The use of MOX possibly together with UOX may be from interest, therefore. Since clusters with MOX showed stronger gradients of power density than it is the case for UOX, it could be necessary to change the moderator and coolant gaps to get optimum conditions.

5. References

[1] MCNP5 (2003) X-5 Monte Carlo Team, Los Alamos. MCNP A General Monte Carlo N-Particle Transport Code, Version 5

[2] T. Schulenberg, J. Starflinger, J. Heinecke, (2006): Three Pass Core Design Proposal for a High Performance Light Water Reactor, Proc. INES-2, Yokohama, Japan, Nov. 26-30, 2006, published in Progress in Nuclear Engineering (2007).

[3] T. Schulenberg, et. al. (2010): Recent Analysis of the HPLWR Three Pass Core. Proc. Of ICAPP' 10, San Diego, CA, USA, June 13-17, 2010

[4] OECD/NEA: Physics of Plutonium Recycling, Volume VII: BWR MOX Benchmark – Specification and Results, ISBN 92-64-19905-5, 2003
OECD/NEA: Benchmark calculations of Power Distribution within Fuel Assemblies, Phase II. NEA/NSC/DOC (2000) 3

[5] R. Nabbi, W. Bernnat: Application of Coupled Monte-Carlo and Burn-up Calculations for Detailed Neutronic Analysis for the FRJ-2 Research Reactor on High Performance Computers. ANS Topical Meeting in Monte Carlo, Chattanooga, TN, 2005

[6] C. Maraczy, G. Hegyi, G. Hordosy, E. Temesvari, C. Hegedos, A. Molnar, "High Performance Light Water Reactor Core Design Studies", *Proc. PBNC 2008*, Paper P16P1221, Aomori, Japan, Oct. 13-18, 2008