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Originally published:

September 2019

Annals of Nuclear Energy 136(2020), 107005

DOI: https://doi.org/10.1016/j.anucene.2019.107005

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Study of the influence of water gaps between fuel assemblies on the activation of an aeroball measurement system (AMS)

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ABSTRACT

The aeroball measuring system (AMS) at Siemens/KWU built pressurized water reactors (PWR) is an important part of the in-core instrumentation to determine in detail the local power distribution. Simulations were carried out with the help of the MCNP6 Monte Carlo program to determine the possible impact of an additional the water gap between the fuel assemblies with regard to the $^{51}V(n,\gamma)^{52}V$ reaction rate in the AMS. A simplified geometric model in a 3x3 matrix of identical fuel assemblies was used and four AMS lances were simulated in the central fuel assembly. By shifting the outer 8 fuel assemblies, different water gaps were created and the effects on the reaction rate of the AMS were calculated for different burn-up values and boron contents in the cooling water. It was found that the change of reaction rates can reach up to 10% for an assumed gap maximum of 1cm. The changes are largest for burn-up values at 30 and 45 GWd/t and slowly increase with decreasing boron concentration. The results are an important piece of information to assess the possibility of detecting non-nominal water gaps during reactor operation.

INTRODUCTION

The Siemens/KWU built Vor-Konvoi and Konvoi PWRs [1] are equipped as part of their in-core instrumentation with an aeroball measuring system (AMS). It is used to determine the core power density periodically in great detail and calibrate with this information the continuously measuring n-β in-core detectors. The AMS determines the power density on the basis of the reaction rates of $^{51}V(n,g)^{52}V$. Small steel spheres containing vanadium (vanadium content 1.5%) are briefly irradiated at predetermined positions in the reactor core and the resulting ^{52}V activities are measured. The spheres have a diameter of 0.17 cm and are in a double tube with an outside diameter of 0.6 cm. The balls are transported pneumatically. The relatively short half-life of ^{52}V of 3.7 minutes allows the sphere to be used again for the next measurement. Practically, the AMS measurement can be repeated every 15 minutes. The AMS lances in which the spheres are irradiated are located in the outer guide tubes for the control rods of the fuel assemblies. Figure 1

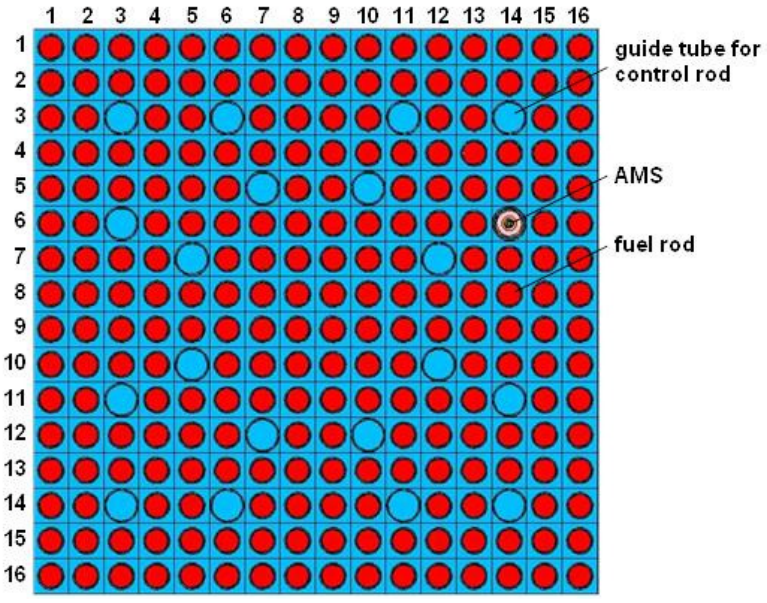

Fig. 1: Fuel assembly with AMS lance at position 14/6.

shows a fuel assembly with an AMS lance at position 14/6. The symmetric positions 6/3, 14/6 and 11/14 are also instrumented in other fuel assemblies. In total 28 AMS lances are distributed inside the reactor core. In [2, 3] a detailed description of the AMS can be found. In [4] the influence of a position shift of the AMS lances inside the guide tubes was discussed. In another study [5] it was shown that additional gaps between the fuel assemblies can trigger an increase in power in the outer fuel rods. In this paper it is investigated to which degree the reaction rates of the AMS are influenced by water gaps between the fuel assemblies.

METHODOLOGY

The investigations were carried out using the Monte Carlo program MCNP6 [6]. In a 3x3 fuel assembly lattice, eight fuel assemblies were grouped around a central fuel assembly with four AMS lances. The eight outer fuel assemblies were shifted outwards in four steps with an increment of 0.25 cm. Cooling water was placed in the resulting additional gaps. In addition, the burn-up state of the fuel assemblies and the boron content in the cooling water were varied. Several criticality calculations were carried out for each gap width. In these calculations, the boron concentration and the burn-up were modified on the basis of a given matrix and the effect on the reaction rates for the $^{51}V(n,\gamma)^{52}V$ reaction was studied. Due to the short irradiation times in the actual AMS measurements compared to the ^{52}V lifetime, these reaction rates can be considered proportional to the activation of the AMS. Since the source term distribution changes due to the changes in geometry, the calculations were normalized to the source density of two inner fuel rods of the central fuel assembly. It is assumed that the gap width changes have no or insignificant effects on these central rods.

SIMULATION MODEL

The investigations were carried out in a 3x3 fuel assembly lattice, corresponding to figure 2. The figure shows the lattice with and without gaps between the fuel assemblies. The standard fuel assemblies of Vor-Konvoi reactors with a 16x16 matrix were used in the lattice. In each fuel assembly, 236 fuel rods and 20 control rod guide tubes are modeled. The fuel rods in the geometry were accurately implemented with cladding, helium gap and fuel pellet. The total height of the model was 430 cm. The fuel part of the reactor core with 390 cm takes up the main share of the height. Above and below 20 cm thick layers with a homogenized steel/water mixture as neutron reflectors were modeled (see figure 2).

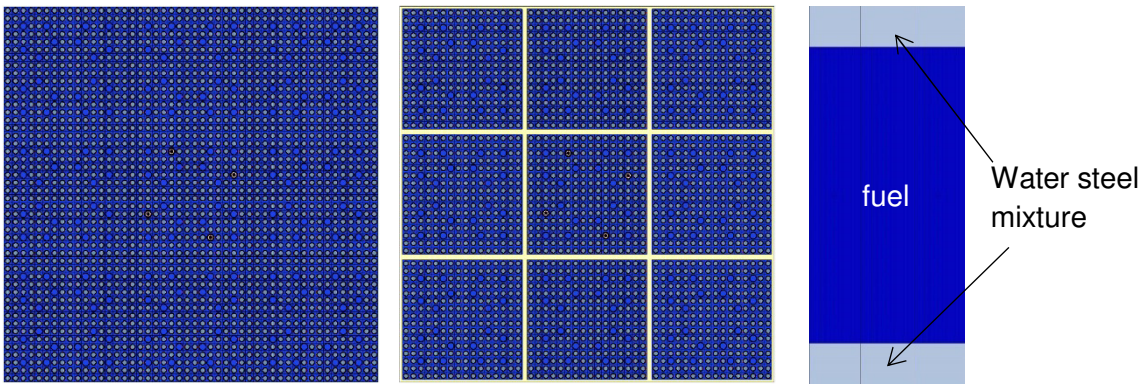

Fig. 2: Horizontal and vertical section through the geometry model of the 3x3 fuel assembly lattice with and without gap and with the 4 AMS lances in the central fuel assembly.

The AMS lances were present only in the central fuel assembly at their respective pin positions. To improve the statistics, all four possible AMS pin positions (3/11, 6/3, 14/6 and 11/14) were averaged. This is possible because both the model geometry and the AMS positions have a 90° symmetry. The AMS lances were accurately modeled except for the steel balls, which were replaced by a cylinder with the diameter of the balls and filled with a homogeneous iron/air mixture. The AMS lances were aligned centrally in the guide tube. The vertical boundary surfaces of the 3x3 matrix were defined as periodic surfaces so that an infinite lattice is created. Vacuum has been assumed at the horizontal boundary surfaces. In addition, a moderator region of half a gap size had been included at the periodic boundary surfaces in order to guarantee perfect periodicity.

In order to move the eight outer fuel assemblies away from the central fuel assembly, a FORTRAN program was used to create the coordinate transformation instructions in MCNP6 format. From burn-up calculations, corresponding nuclide data was available for the material compositions of the fuel elements in steps of 5 GWdays/ton (GWd/t). The combustion calculations were carried out with CASMO5 [7] using a standard fuel element with 4.4% enrichment and an average boron concentration in the cooling water of 500ppm.

SOURCE TERM DETERMINATION AND SCALING

The source neutrons were determined by means of critical calculations with the program MCNP6 and simulated separately for the different configurations in geometry, burn-up values and boron content. The start coordinates for neutrons were predefined using the pin centers of each fuel pin in the nine assemblies. Also, a predetermined energy distribution (watt spectrum with a = 0.965 MeV and b = 2.29 MeV^{-1}) was used [8]. Source distributions and spectrums are then determined iteratively in MCNP6 until convergence is reached. Only after this the actual gap sensitivity studies can be carried out.

Fig. 3 shows the distributions of the normalized source neutrons on a mesh for the geometries with and without gap. The right picture with the water gap indicates a slight decrease of source strength at the inner fuel rods. The cause is the better moderation by the water gap and thereby the increase of the source neutrons and the power at the edges of the fuel assemblies relative to the power in the center. Due to the internal normalization of MCNP6, this leads to an artificial decrease of the sources in the center of the central fuel assembly (see table 1). For purposes of conservativeness the source strength of selected

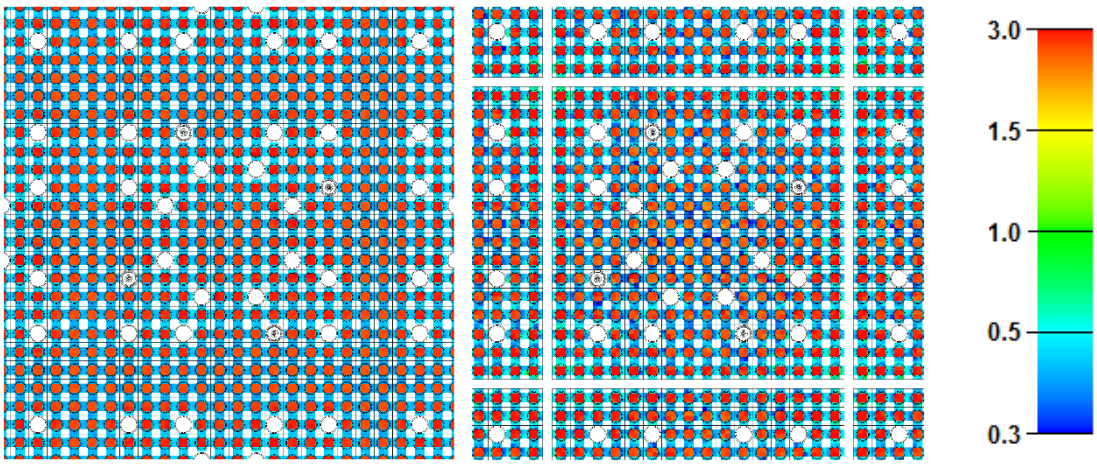

Fig. 3: Distribution of normalized source neutrons (determined with a Mesh Tally and therefore not completely fixed on the fuel pins) for a system without (left) and with (right) a 1 cm gap. The boron concentration in the cooling water was 100 ppm each and fresh fuel assemblies.

central fuel rods was held constant in the later analyses. To perform the renormalization of the MCNP6 results the fission energy depositions at two centrally located

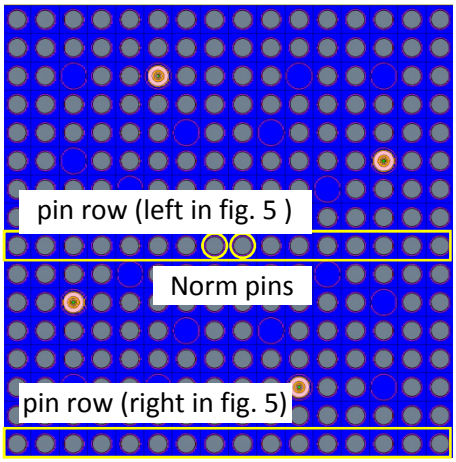

Fig. 4: Fuel assembly with the pin rows for the scale investigation and the two pins for the normalization.

fuel pins of the central fuel assembly were used as reference. Due to their rather large distance to the edge, these should only very slightly be affected by the effect of the water gaps. Particularly, the fission energy deposition of one row located directly at the gap and one row at the fuel assembly center (see Fig. 4) was plotted. Fig. 5 shows the resulting effect for both pin rows. Without additional gap (delta-gap width 0 cm, red) the central pin row shows two maxima at pin positions -4 and 3 (left). The reason is the closeness of the guide tubes filled with cooling water, which enhance the moderation. The pins at the edge of the fuel assembly have the smallest value. With a gap between the fuel assemblies, the maxima are shifted to the edge of the fuel assembly at positions 1 and 16.

Because of the internal normalization carried out by MCNP6, a slight decrease of the values in the central pins is created – which is eliminated by our renormalization. The effect of gap size on average fuel assembly power cannot be answered in the context of this study because it depends on the particular fuel assembly neighborhood and gap configuration for a particular reactor loading.

It can be also noted that the values of the pins from the edge row show less pronounced maxima. The influence of the water filled guide tubes is smaller in this case since they are further away (Fig. 5, left). Regardless of this, one can still see the influence on the AMS (decrease of the peak), which is at position 11. With an increase of the gap, the fission energy deposition increases rapidly for all pins in this row, especially those at the corner. From a gap width of 0.5 cm all pin values are above those of the central row.

In this study the renormalization was carried out by obtaining the reaction rate differences of the mean value of the fission energy deposition for the two fuel pins designated as "norm

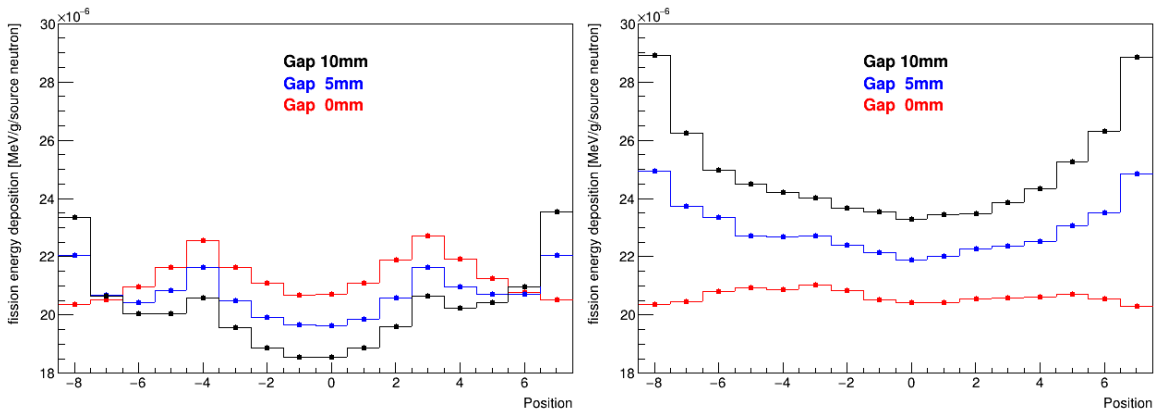

Fig. 5: Fission energy deposition in MeV/g (normalized to one source neutron) of the fuel pins in a central row (left) and in the row directly at the gap (right) at different gap widths. The boron content in the water was 100 ppm and fresh fuel assemblies.

pins" in Fig. 4 for each simulation. Scaling factors were determined accordingly. Table 1 shows averaged values of the fission energy deposition of the two normalization pins for different gap widths and burn-up values using the example of a boron concentration of 100 ppm.

Table 1: Averaged values of the Fission energy deposition in MeV/g (normalized to a source neutron) of the two normalization pins for different gap widths and burn-up values using the example of a boron concentration of 100 ppm. The burn-up values are given as "Effective Full Power Days" (EFPD).

EFPD [GWd/t]	gap widths [cm] 0.0	0.25	0.5	0.75	1.0
	Fission energy deposition in MeV/g (normalized to a source neutron) $x10^{-5}$				
0	2.07 ±0.24%	2.02 ±0.25%	1.97 ±0.25%	1.92 ±0.25%	1.85 ±0.26%
15	1.58 ±0.36%	1.53 ±0.36%	1.49 ±0.36%	1.45 ±0.36%	1.42 ±0.36%
30	1.40 ±0.37%	1.35 ±0.37%	1.32 ±0.37%	1.29 ±0.37%	1.24 ±0.37%
45	1.26 ±0.37%	1.22 ±0.37%	1.19 ±0.38%	1.17 ±0.38%	1.13 ±0.38%
60	1.14 ±0.37%	1.10 ±0.38%	1.09 ±0.38%	1.05 ±0.39%	1.03 ±0.40%

A maximum reduction of 13% could be determined for fuel assemblies with 30 GWd/t. To compare the reaction rates of the AMS between different calculations, the results for the calculations with gaps were scaled based on the assumption that the fission energy deposition does not change at the “norm pins”. Thus, the scaling effect of the sources can be compensated. It is further assumed that a general increase of the power due to feedback effects in the modeled system should have negligible influence, and no correction was performed for this effect.

SIMULATION

Calculations were carried out for the gap widths 0.0 cm, 0.25 cm, 0.5 cm, 0.75 cm and 1.0 cm. The burn-up values of the fuel assemblies were 0, 15, 30, 45 and 60 GWd/t and boron concentrations in the cooling water 100, 500 and 1000 ppm. The calculations were performed on 64 CPU cores in parallel using MCNP6’s parallel processing capabilities.

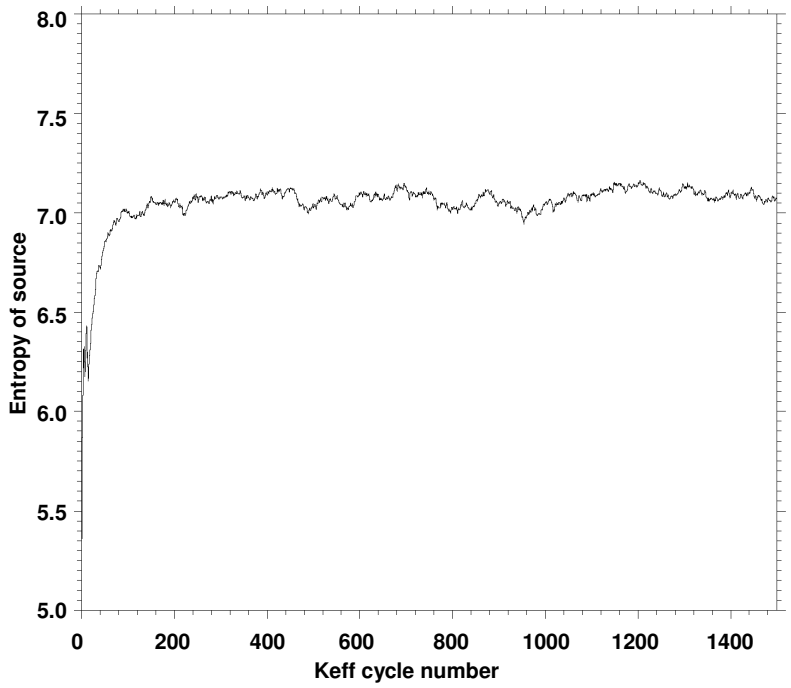

Fig. 6: Convergence of the Shannon entropy of a neutron source term over the cycles (gap width of 0.5 cm, boron concentration of 500ppm and fresh fuel assemblies)

Depending on the configuration, between 5000 and 10000 cycles with 10000 source neutrons were run, whereby the first 300 cycles were used for the iterative calculation of the source neutron distribution. For one calculation, the computing time on the Rossendorf Cluster was around 2.5 hours. Fig. 6 shows as an example of the convergence of the Shannon entropy [8] of a neutron source term as a function of the calculated cycles. Above 300 cycles, the Shannon entropy oscillates around a fixed value, which guarantees the convergence.

RESULTS

The simulations were performed as described and the number of neutron capture reactions in the vanadium region of the AMS was determined. The final results were averaged over the four symmetrically arranged AMS lances of the central fuel assembly and were corrected according to the described scaling in the source section. Based on these results linear regression was used to determine the change of rates of the $^{51}V(n,\gamma)^{52}V$ reactions as a function of the gap width. The slope of the linear regression (parameter p1) represents the change of the reaction rate with increasing of the water gap and the parameter p0 the reaction rate without gap. The calculated values refer to a start neutron weighted with the corresponding normalization factor (see section “source term”). The results are shown in Figures 6, 7 and 8 for different boron concentrations. In the following, the results for different boron concentrations are discussed.

100 ppm boron concentration

Table 2 presents the results of the linear regressions for a boron concentration of 100 ppm in the coolant water, which are shown graphically in Figure 6. The reaction rate increases

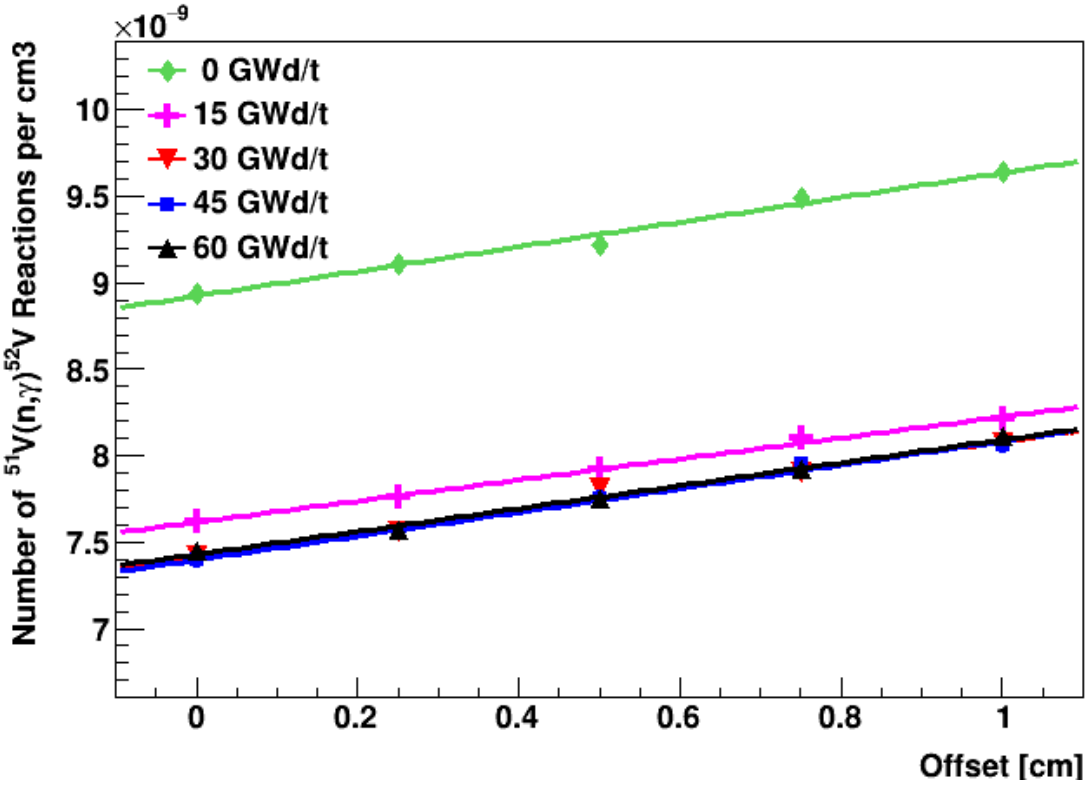

Fig. 6: Number of $^{51}V(n,\gamma)^{52}V$ reactions per cm^3 normalized to one source neutron and multiplied by the corresponding scaling factor as function of the gap width and for different burn-up values. The boron content in the cooling water is 100 ppm.

between 8 and 9.3 % in the calculation with a 1 cm gap width compared to those without gap. The calculated statistical errors are between 0.4 and 0.6 %. A small increase of the reaction rate change with higher burn-up values could be observed. The calculated probabilities for the χ^2/ndf (ndf: number of degrees of freedom) show a good agreement of the simulated data points with the used linear approach.

Table 2: Results of linear regression for a boron concentration of 100 ppm. The unit of the parameters p0 and p1 are "number of $^{51}V(n,\gamma)^{52}V$ reactions per cm^3" and "(number of $^{51}V(n,\gamma)^{52}V$ reactions per cm^3)/(per additional gap in cm)" normalized to one source neutron and multiplied by the corresponding scaling factor.

EFPD [GWd/t]	p0	p1	p1/p0 [%/cm]	χ^2/ndf	Prob.
0	$8.93 \cdot 10^{-9}$ ±0.23%	$7.12 \cdot 10^{-10}$ ±4.96%	7.98±0.40%	5.483/3	0.1397
15	$7.62 \cdot 10^{-9}$ ±0.33%	$6.10 \cdot 10^{-10}$ ±6.52%	8.01±0.52%	1.231/3	0.7455
30	$7.42 \cdot 10^{-9}$ ±0.35%	$6.62 \cdot 10^{-10}$ ±6.55%	8.92±0.59%	3.405/3	0.3333
45	$7.40 \cdot 10^{-9}$ ±0.35%	$6.87 \cdot 10^{-10}$ ±6.29%	9.29±0.58%	1.628/3	0.6531
60	$7.43 \cdot 10^{-9}$ ±0.36%	$6.64 \cdot 10^{-10}$ ±6.63%	8.93±0.59%	1.485/3	0.6858

500 ppm boron concentration

Table 3 summarizes the results for linear regressions shown in Fig. 7. The boron concentration in the cooling water was 500.00 ppm. The reaction values changed between 6.9 and 9.5 % if a water gap between the fuel assemblies of one cm is assumed. The

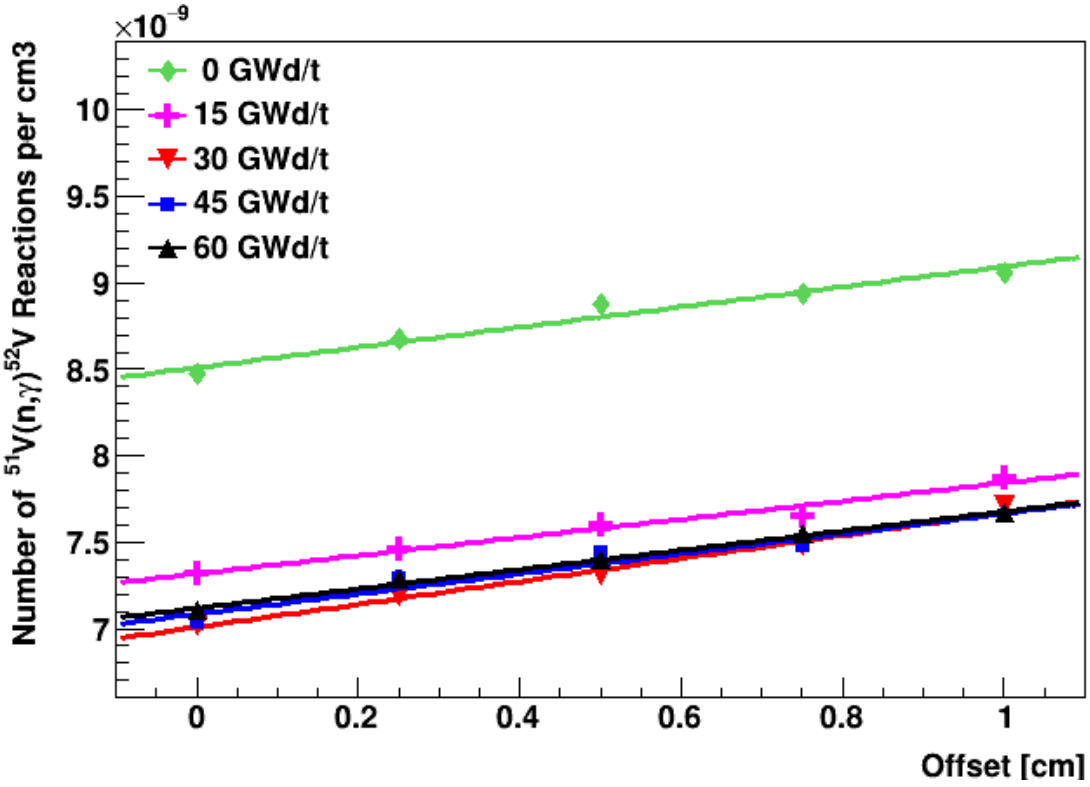

Fig. 7: Number of $^{51}V(n,\gamma)^{52}V$ reactions per cm^3 normalized to one source neutron and multiplied by the corresponding scaling factor as function of the gap width and for different burn-up values. The boron content in the cooling water is 500 ppm.

statistical uncertainties are between 0.4 and 0.6 % per cm. The maximum value of 9.5 % per cm is reached with a burn-up of 30 GWd/t, and then again reduced to 7.7 % per cm at 60 Gwd/t. It must be noted that the calculated probability for the χ^2/ndf values is very low for both the 0 GWd/t and 45 GWd/t burn-up. In order to enable comparison with the other values, linear regression was also retained here. It seems that the relationship between the number of reactions and gap widths becomes non-linear in some configurations.

Table 3: Results of linear regression for a boron concentration of 500 ppm. The unit of the parameters p0 and p1 are "number of $^{51}V(n,\gamma)^{52}V$ reactions per cm^3" and "(number of $^{51}V(n,\gamma)^{52}V$ reactions per cm^3)/cm" normalized to one source neutron and multiplied by the corresponding scaling factor.

EFPD [GWd/t]	p0	p1	p1/p0 [%/cm]	χ^2/ndf	Prob.
0	$8.51 \cdot 10^{-9}$ ±0.24%	$5.85 \cdot 10^{-10}$ ±5.81%	6.87±0.40%	11.19/3	0.0107
15	$7.32 \cdot 10^{-9}$ ±0.34%	$5.25 \cdot 10^{-10}$ ±7.89%	7.18±0.57%	4.282/3	0.2326
30	$7.01 \cdot 10^{-9}$ ±0.35%	$6.63 \cdot 10^{-10}$ ±6.23%	9.46±0.59%	2.839/3	0.4172
45	$7.08 \cdot 10^{-9}$ ±0.35%	$5.82 \cdot 10^{-10}$ ±7.18%	8.21±0.59%	9.963/3	0.0189
60	$7.12 \cdot 10^{-9}$ ±0.35%	$5.58 \cdot 10^{-10}$ ±7.55%	7.84±0.59%	0.972/3	0.8080

1000 ppm boron concentration

Table 4 shows the results with a boron concentration in the cooling water from 1000 ppm. The figure 8 displays the corresponding regression lines. The results here are lower than

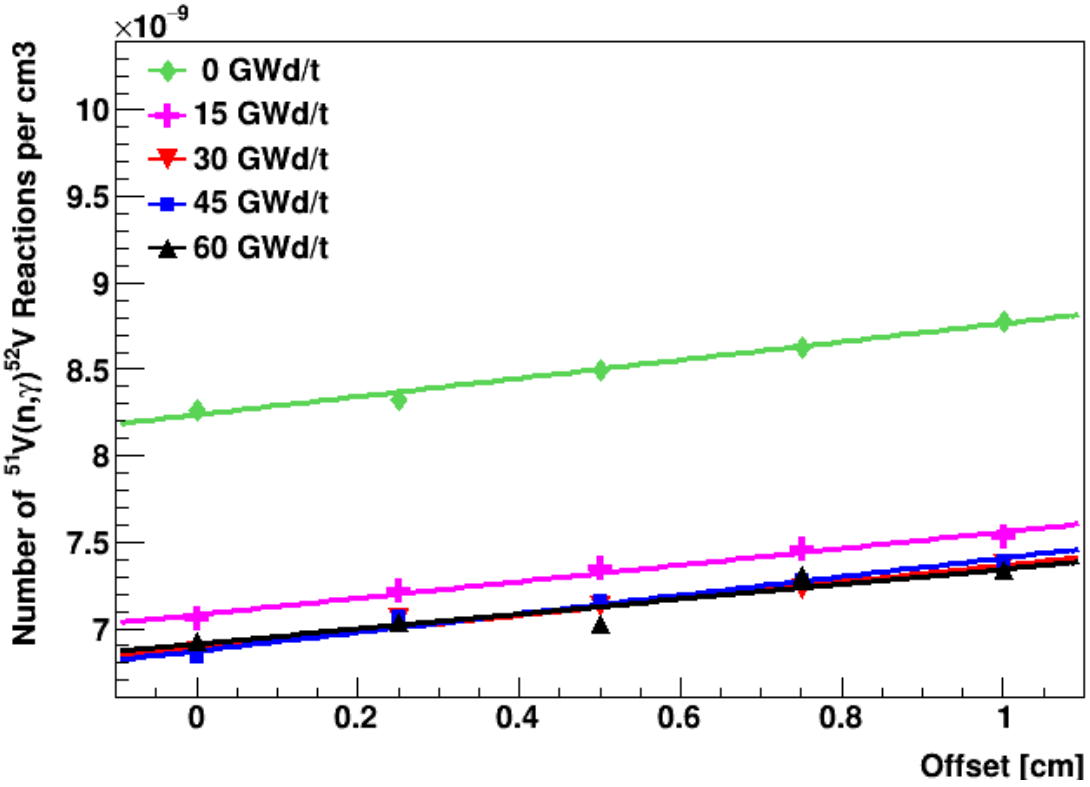

Fig. 8: Number of $^{51}V(n,\gamma)^{52}V$ reactions per cm^3 normalized to one source neutron and multiplied by the corresponding scaling factor as function of the gap width and for different burn-up values. The boron content in the cooling water is 1000 ppm.

with the other boron concentrations and are between 6.2 and 7.8 % per cm. The statistical uncertainties of 0.4 to 0.6 % per cm are comparable with the other simulations. Except for this last value at 60 GWd/t, the reaction rate change shows a continuous increase with higher burn-up. The reason could also be a non-linearity between the points, because the χ^2/ndf probabilities show good compatibility with the assumption of linearity between the change of the reaction rates and the water gap width, with the exception of the value at 60 GWd/t.

Table 4: Results of linear regression for a boron concentration of 1000 ppm. The unit of the parameters p0 and p1 are "number of $^{51}V(n,\gamma)^{52}V$ reactions per cm^3" and "(number of $^{51}V(n,\gamma)^{52}V$ reactions per cm^3)/cm" normalized to one source neutron and multiplied by the scaling factor.

EFPD [GWd/t]	p0	p1	p1/p0 [%/cm]	χ^2/ndf	Prob.
0	$8.24 \cdot 10^{-9}$ ±0.24%	$5.28 \cdot 10^{-10}$ ±6.33%	6.42±0.41%	3.820/3	0.2816
15	$7.08 \cdot 10^{-9}$ ±0.35%	$4.79 \cdot 10^{-10}$ ±8.57%	6.76±0.58%	2.910/3	0.4058
30	$6.89 \cdot 10^{-9}$ ±0.35%	$4.80 \cdot 10^{-10}$ ±8.44%	6.97±0.59%	2.701/3	0.4400
45	$6.87 \cdot 10^{-9}$ ±0.35%	$5.38 \cdot 10^{-10}$ ±7.55%	7.82±0.59%	4.967/3	0.1742
60	$6.91 \cdot 10^{-9}$ ±0.36%	$4.31 \cdot 10^{-10}$ ±9.64%	6.23±0.60%	14.45/3	0.0024

Fig. 9 summarizes the results for the change in the number of reaction rates of the AMS depending on the burn-up and the boron concentration in the cooling water. The values are within a total range of 6 to 9.5% per cm gap distance. The maximum values are at 30 or 45 GWd/t depending on the boron concentration in the cooling water. This result was slightly surprising, because one would expect the maximum change with new fuel assemblies (0 GWD/t). The trend of a decrease of the change in the number of reaction rates with the increase of boron concentration in the cooling water is confirmed for all burn-up values, with

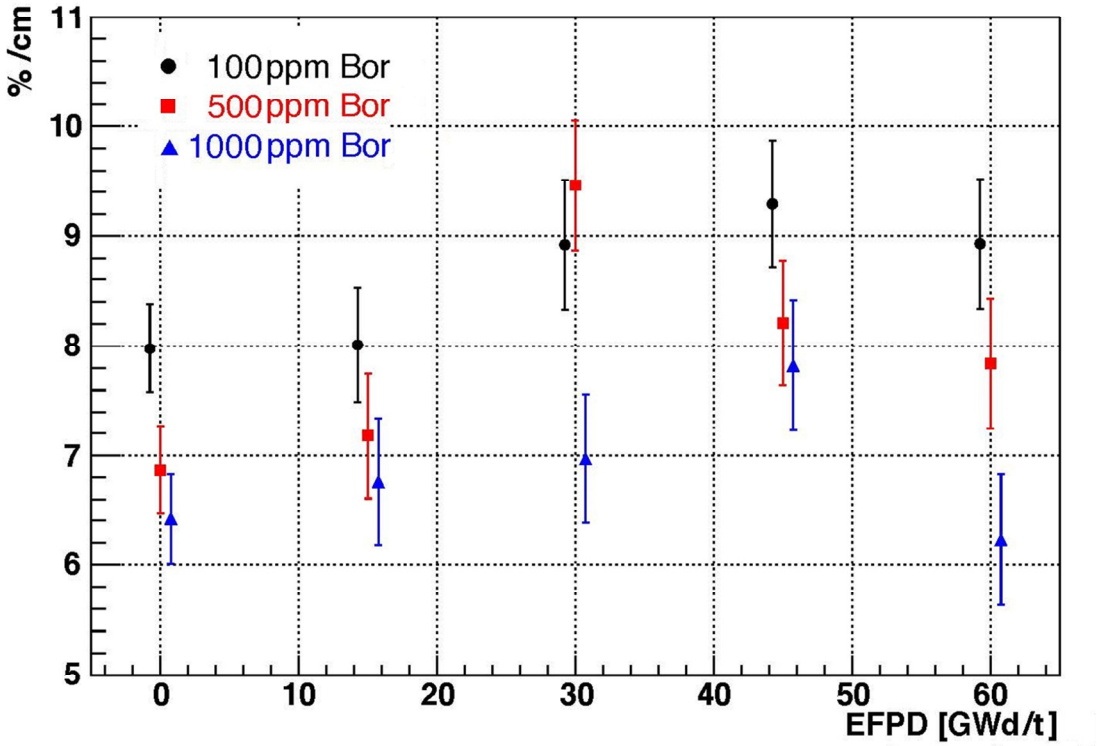

Fig. 9: Summary of the results for the change in the number of reaction rates of the AMS depending on the burn-up and the boron concentration in the cooling water

the only exception the value at 30 GWd/t and 500 ppm boron concentration, which lies above the value at 100 ppm. When considering the error bars, however, this effect can be caused by a statistical fluctuation.

SUMMARY

The Monte Carlo program MCNP6 was used to determine the sensitivity of the AMS activation rate on the variation of the inter-fuel assembly water gap width, i.e. on the change of the fuel assembly pitch. The $^{51}V(n,g)^{52}V$ reaction rates have been calculated directly from analog Monte Carlo simulation of the neutron transport. These investigations are part of an assessment if it is possible to detect gap width changes with the existing in-core instrumentation in PWRs like Vor-Konvoi reactors. A simplified geometric model was used with nine fuel elements in a 3x3 matrix. The reaction rates of four AMS lances were simulated in the central assembly. By displacement of the outer eight fuel assemblies, different water gap widths between the fuel assemblies were generated. The different gap widths were calculated for different burn-up values (0, 15, 30, 45, 60 GWd/t) and boron concentrations in the cooling water (100, 500, 1000 ppm).

In order to take into account the change of the source neutron distribution in the Monte Carlo simulation due to the changes in geometry, the results were normalized to values obtained at the central pins of the central assembly. It is assumed that at this position the changes due to the geometry are negligible. This makes it possible to compare the individual simulations. The values without water gap were used as reference.

Table 5 shows the obtained differences per cm for different boron concentrations and burn-up values. The calculated change per cm water gap width are between 6.2% and 9.5%. The maximum changes are for a boron concentration of 100 ppm in the cooling water and burn-up values at 30 and 45 Gwd/t. The analysis shows that the maximum impact of the largest water gap at 1 cm is between 5 to 10% on the activation rate. Typical water gap variations are of the order of 0.1cm and hence their influence is not detectable in practice because the measurement uncertainty of the AMS system is usually about 3%. Also, in practice, a fuel assembly experiences not a symmetric gap variation at all four faces, which reduces the above calculated maximum values further. Furthermore real reactor core loading pattern are heterogenous and different types of fuel assemblies with different burnup states are neighboring which also decreases the reactivity effect of additional water gaps. This research therefore shows that only in very extreme gap-size cases the AMS is able to detect the anomaly.

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