INVESTIGATION OF VOID REACTIVITY BEHAVIOUR IN RBMK REACTORS

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ABSTRACT

The fuel of RBMK together with graphite as moderator has a high positive void reactivity coefficient, which is reduced by control rod absorbers and fixed additional absorbers to values below 1 ß. Different non-fuel core components have different and partly opposite influences on the void reactivity. In the heterogeneous RBMK core all these influences contribute to the resultant void reactivity feedback.
The void reactivity behaviour as a function of coolant density was calculated for different RBMK NPPs, using the 3D core model QUABOX/CUBBOX. It was found that this reactivity function can have a significant non-linear dependence on density.

1. INTRODUCTION

A high positive void reactivity effect played a decisive role in the Chernobyl accident. Therefore this positive effect was reduced significantly by reconstruction measures in all RBMK's. Due to the importance of the void reactivity behaviour for RBMK reactors, the effect and the parameters influencing it were analysed in more detail.

2. CHARACTERISTICS OF RBMK CORES

The RBMK core consists of pressure tubes inside a large stack of graphite blocks. It is a thermal reactor moderated by graphite. The fuel elements within the pressure tubes are cooled by light water which is heated up to boiling conditions. Due to the graphite the light water coolant affects the neutronics only by a slight contribution to moderation, but the absorption effect cannot be neglected. Thus, a loss of water or an increase in void fraction reducing the neutron absorption, causes a power rise according to the positive void reactivity coefficient.

This coefficient is defined as

$$\alpha_\varphi = \Delta\rho/\Delta\varphi$$

while $\Delta\rho$ is the change of reactivity due to the corresponding change of void fraction $\Delta\varphi$. The total void reactivity effect is obtained, comparing coolant states without void (water phase) and completely voided conditions.
To reduce the void reactivity effect the reconstruction measures for RBMK reactor cores generally consist of the insertion of additional absorbers (80 – 100 for RBMK –1000 and about 52 - 53 for RBMK –1500), changes in the construction of control rods and more restrictive operation procedures using control rods to keep the operational reactivity margin (ORM) sufficiently high. This parameter describes the sum of control rod insertion depths by an equivalent number of fully inserted rods.

3. THE 3D CORE MODEL QUABOX/CUBBOX

The 3D core model QUABOX/CUBBOX /1/, which was developed for Light Water Reactors with quadratic fuel assemblies, was applied for the investigations. The code solves the neutron diffusion equation in Cartesian geometry with two energy groups. The used flux expansion method, based on the spatial approximation of neutron flux by local polynomials of the 2^{nd} , 3^{rd} or up to the 6^{th} order, results in a high accuracy of spatial flux distribution even for a coarse mesh in x-y plane. Additional to the neutronics a thermalhydraulic feedback model is implemented. It consists of a fuel rod model with radial zones, describing the radial heat transfer from the fuel to the coolant, a coolant channel model describing the one dimensional two-phase flow in parallel channels. If a more detailed thermohydraulic model is necessary with a closed loop representation of the coolant circuit to describe the coolant flow and the thermalydraulic feedback a coupled version of the neutronics code with the system code ATHLET /2, 3, 4/ is available. An application for the ATWS – transient 'Total Loss of Feedwater' in RBMK was presented in /5/.

In order to study RBMK problems, the code was adapted to the special features of this type of reactor within a co-operation with RDIPE /6/. For this purpose the following models were implemented:

- Control rod model, to describe the heterogeneous construction of different types of control rods, including the different directions of insertion from the top as well as from the bottom of the core.
- A model simulating the automatic local power regulation (LAC/LEP)
- A model for the graphite temperature behaviour
- An interface to a data base, describing the operational state of the reactor core with core loading, control rod positions, burnup distribution and coolant flow distribution at core inlet.

The neutron kinetics calculations are based on two group cross sections, which have been calculated by the transport code WIMSD. The cross sections are provided as tables within a cross section library, which contains the dependencies on fuel temperature, coolant density, burnup and other parameters determining the neutron balance. These feedback parameters are provided by the 3D core model and the corresponding set of cross sections are obtained by interpolation of the table values.

4. ANALYSIS OF VOID REACTIVITY

The analysis showed that the void reactivity behaviour of RBMK depends strongly on the heterogeneous structure of the core and of changes of core conditions by modifying the core loading or burnup conditions. The reactivity behaviour was studied for different RBMK power plants and reactor core conditions. Also, new loading strategies, using fuel with the burnable poison Erbium to reduce the number of additional absorbers, were taken into account.
The different core components have different influences on the void reactivity behaviour. The fuel itself has a high positive void reactivity, which becomes larger with increasing burnup. Absorbing materials have a negative influence on the reactivity effect. The construction of control rods consisting of an absorber, a graphite displacer connected to the absorber element and a water column between both parts increases the number of non-fuel components in the core. The graphite displacer is inserted into the core, if the control rod is withdrawn. These displacers in the core have an increasing effect on the positive void reactivity coefficient.
The influence of different parameters and core components on the void reactivity behaviour can be demonstrated by studies of simplified macro-cell arrangements, representing selected core regions. In the full reactor core the void reactivity is determined by an interaction of influences from different components and different neutronics parameters as burnup, graphite temperature and xenon poisoning. The corresponding effects are evaluated in the following chapters.

4.1 INFLUENCES OF CORE COMPONENTS AND PHYSICAL PARAMETERS FOR A MACRO-CELL

To study the influence of different core components on the void reactivity behaviour, macro-cells consisting of an arrangement of 4x4 channels were used. In these macro-cells single fuel channels can be replaced by non-fuel components.
Figure 1 shows the results of a macro-cell consisting only of fuel channels. The fuel has an enrichment of 2.0 % U235. The void reactivity behaviour was determined as a function of coolant density for three burnup states 5, 10 and 15 MWd/kg. All other parameters as e.g. fuel temperature or graphite temperature were assumed to be constant. For an average burnup of 10 MWd/kg the total void reactivity effect (difference of reactivity for states with and without water in the fuel channels) is 1875 pcm or 3.2 ß, assuming an effective fraction of delayed neutrons of ß = 580 pcm. For pure fuel the void reactivity as function of coolant density shows only a small deviation from a linear dependence. In Figure 2 the same case is presented for fuel with a higher enrichment of 2.4 %. The increase of enrichment reduces the positive void reactivity effect and for an average burnup of 10 MWd/kg a value of about 1200 pcm (2.0 ß) is obtained. If two channels of the macro-cell are replaced by other core components the void reactivity behaviour can be influenced strongly. The results are presented in Figure 3 for an average burnup of 10 MWd/kg and 2 % - fuel, showing besides the effect of fixed additional absorbers, the effect of different control rod components as graphite displacers, water columns and absorber rods.

The results show the enhancing effect of graphite displacers on the positive reactivity effect, whereas the insertion of absorbing elements are reducing the void reactivity values. This effect is more significant for control rod absorbers than for additional absorbers.

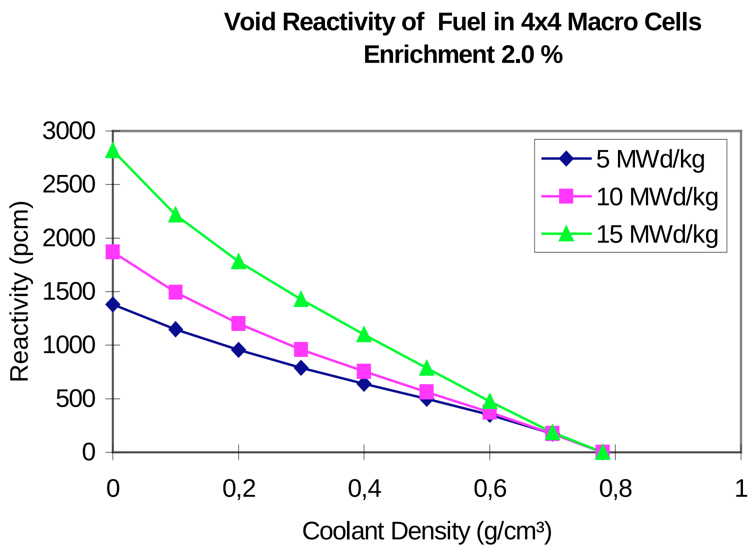

Figure 1: Void reactivity as function of coolant density for a macro-cell consisting of 4x4 fuel channels with an enrichment of 2.0% and different burnup states.

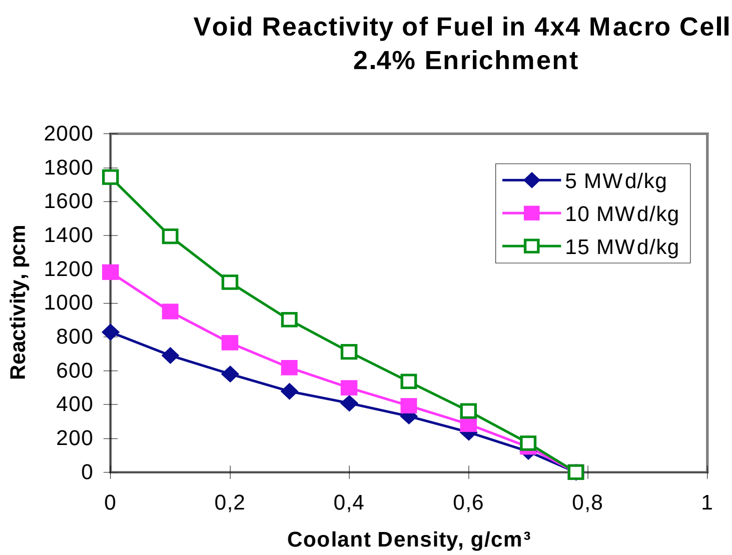

Figure 2: Void reactivity as function of coolant density for a macro-cell consisting of 4x4 fuel channels with an enrichment of 2.4% and different burnup states.

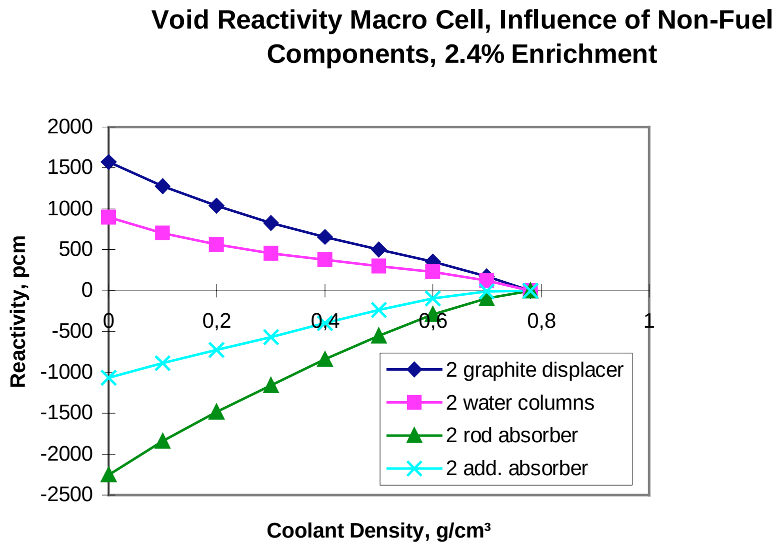

Figure 3: Macro-cell studies of void reactivity. Two fuel channels are replaced by non-fuel components

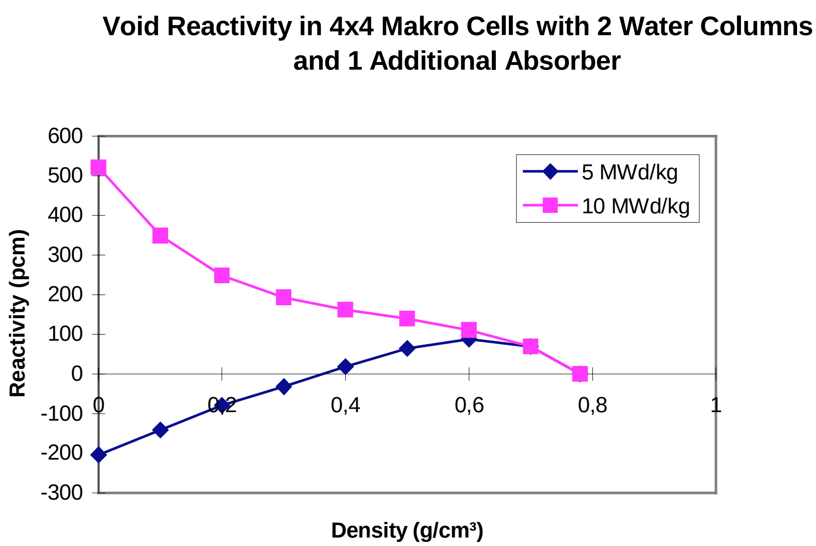

Figure 4: Void reactivity of a macro-cell, replacing three fuel channels by two water columns and one additional absorber.

An interaction of different components can change the shape of the void reactivity curve for the macro-cell drastically. If two water channels and one additional absorber are loaded the reactivity behaviour of Figure 4 is obtained. (Burnup: 5 and 10 MWd/kg), showing a significant non-linear reactivity dependence as a function of coolant density.

4.3 FULL CORE BEHAVIOUR OF VOID REACTIVITY

The void reactivity behaviour of a RBMK reactor core is determined by its heterogeneous structure and the influences of the different core components, this affects also the non-linearity of the reactivity function.
An example presents Figure 5 showing the void reactivity function for an operational state of Ignalina 1 from March 94. The reactivity curves have a pronounced “S – shape” and the largest reactivity changes are correlated with coolant density changes in the low and high density range.

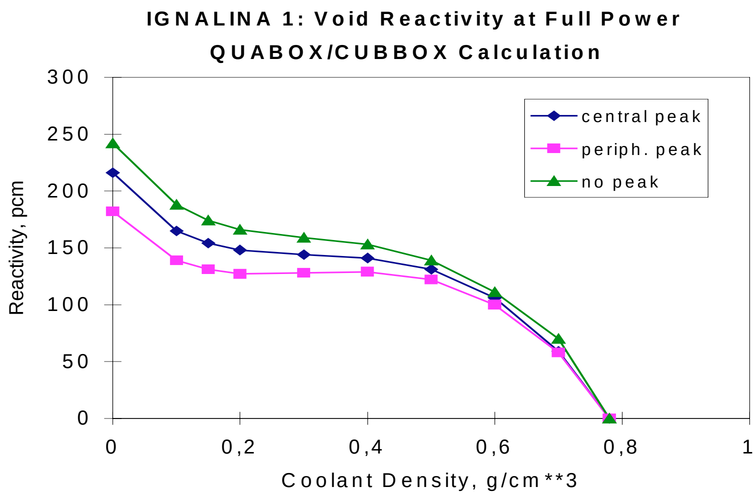

Figure 5: Void reactivity behaviour of Ignalina 1, March 94, depending on coolant density for an operational condition and two conditions with disturbed peaking power distributions.

Additionally to the operational state two disturbed states with a central power peak and a peripheral peak have been analysed, studying how local changes in the flux distribution can change the void reactivity effect. The results show that the disturbances of power are reducing the void reactivity effect.

If different plants or different core conditions are looked at, the void reactivity curve can vary significantly. Figure 6 shows two operational conditions of the NPP of Smolensk 3 from May 93 and October 96 and one from Leningrad 4. For the Smolensk 3 core of May 93 the total void effect is even negative, while a decrease of coolant density above 0.6 g/cm³ still provides a positive reactivity effect. For Leningrad 4 the total void effect is positive but there is a coolant density region between 0.2 and 0.5 g/cm³, where a density decrease also causes a reactivity decrease. The difference between the two core states of Smolensk 3 is caused by different core loadings and different burnup conditions. In May 1993 a number of 97 additional absorbers was loaded, which was reduced to 85 in October 1996. Additionally, the first core state consists of about 38 % of fuel elements with low enrichment of 2.0 %. In October 1996 this fuel, besides a small fraction of 3 %, was replaced by fuel elements with a higher enrichment of 2.4 %.

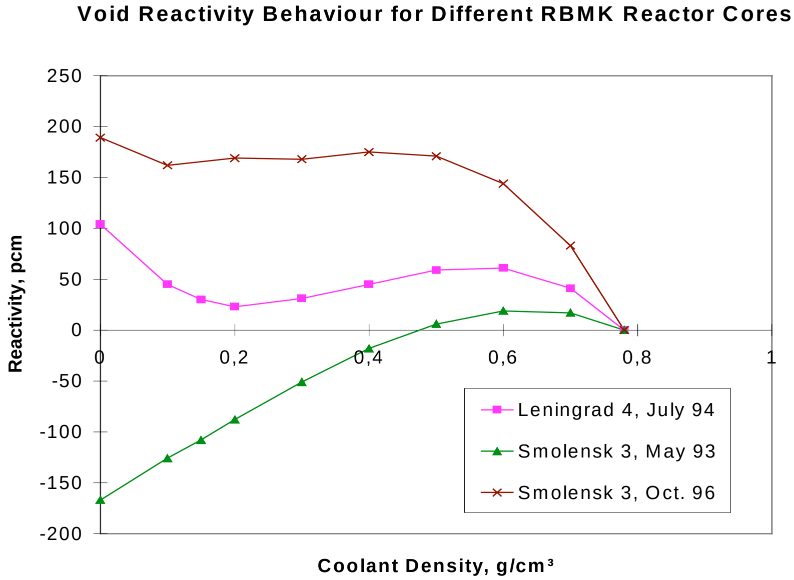

Figure 6: Void reactivity studies of operational states. Two different operational conditions of the plant Smolensk 3 and for comparison a state of Leningrad 4 are shown.

In the RBMK 1500 plants of Ignalina a new loading strategy was introduced to provide the possibility to operate the NPPs without additional absorbers. Therefore the old fuel elements with an enrichment of 2.0 % U235 were replaced step by step by new ones with burnable poison erbium and higher enrichment of 2.4 % to compensate the absorption in the erbium isotopes. The neutronics calculations were performed for an operational state of Ignalina 2 of March 98, which was loaded with about 50 % of the new fuel containing erbium. The number of additional absorbers was reduced to 13.
For this core condition a void coefficient of α_φ = 0.85 ß was determined, in agreement with the measured value of α_φ = 0.7$\pm$2 ß. For the corresponding void reactivity behaviour depending on coolant density a similar shape than in Figure 5 was obtained, however the total void effect was increased by about a factor of two.

4.3 CONSEQUENCES FOR VOID COEFFICIENT MEASUREMENT

The non-linear behaviour of the void reactivity as a function of coolant density has consequences for the interpretation of the void coefficient measurement, since the coolant density distribution at the time of measurement determines the experimental result.
The void coefficient is measured periodically after about 200 effective days according to a standardised procedure. The measurement is performed at a reduced power level of 40 – 90 %. A perturbation of the inlet enthalpy in the core is caused by a change of feedwater flow rate. This perturbation causes a change of void fraction $\Delta\varphi$ in the order of 1 to 3 % and a corresponding reactivity change $\Delta\rho$, which is measured by reactimeters, giving the void coefficient by the relation $\alpha_\varphi = \Delta\varphi/\Delta\rho$. This means that the void coefficient is determined by a reactivity change for

a small density interval around the density distribution in the core during the time point of measurement.
At nominal power the average coolant density is about 0.5 g/cm³. The density increases, if the power is reduced as in the case of measurement, and the reference value of void reactivity measurement is shifted to higher coolant densities. In the case of a non-linear dependency of void reactivity on coolant density the void coefficient is changing if the coolant density distribution changes and a linear extrapolation of the coefficient normally wouldn't represent the total reactivity effect.

SUMMARY

The void reactivity effect of RBMK reactors was studied in detail showing the influence of different core components and parameters determining the neutron flux behaviour. The dependence of void reactivity on coolant density was analysed and the complex interaction of different and partly opposing influences can lead to a non-linear reactivity function depending on coolant density. The void reactivity feedback is depending strongly on coolant density and can even change the sign in different density ranges.

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