Studies of mixed HEU-LEU-MTR cores using 3D models

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ABSTRACT

Several different core loadings were assembled at the SAPHIR research reactor in Switzerland combining the available types of MTR-type fuel elements, consisting mainly of both HEU and LEU fuel. Bearing in mind the well known problems which can occur in such configurations (especially power peaking), investigations have been carried out for each new loading with a 2D neutron transport code (BOXER). The axial effects were approximated by a global buckling value and therefore the radial effects could be studied in considerably detail. Some of the results were reported at earlier RERTR meetings and were compared to those obtained by other methods [1] and with experimental values.
For the explicit study of the third dimension of the core, another code (SILWER), which has been developed in PSI for LWR power plant cores, has been selected. With the help of an adapted model for the MTR-core of SAPHIR, several important questions have been adressed.
Amoung other aspects, the estimation of the axial contribution to the hot channel factors, the influence of the control rod position and of the Xe-poisoning on the power distribution were studied.
Special attention was given to a core position where a new element was assumed placed near a empty, water filled position. The comparison of elements of low and high enrichments at this position was made in terms of the induced power peaks, with explicit consideration of axial effects.
The program SILWER has proven to be applicable to MTR-cores for the investigation of axial effects. For routine use as for the support of reactor operation, this 3D code is a good supplement to the standard 2D model.

1. Introduction

The MTR type swimming pool reactor SAPHIR was in operation since 1957. Starting on a power level of 1 MW it was upgraded up to 10 MW_{th} in 1984. The reactor was intensively used for beam tube experiments with neutron scattering, isotope production, irradiation tests of reactor materials, silicon doping, neutron activation analysis, neutron radiography and last but not least for the education of nuclear power plant operators.

Within the RERTR program the EIR (now PSI) played an active role over many years (see e.g. [1,2]). The new fuel was used starting with medium enriched uranium (45%). LEU fuel elements were in use since 1986. Because of the satisfactory performance of mixed cores and a relatively large stock of unirradiated HEU elements the full conversion to pure LEU cores was never been completed.
On the other hand critical loadings containing different types of MTR fuel had to be assembled very carefully. This was especially important because the relatively high amount of fissible material inside the SAPHIR elements (410 g U235 per element) could cause problems with power peaking effects.

Beside a prescribed but more or less empiric procedure for the assembling of the loadings, core calculations were performed for each new loading since 1990. In this manner hot core positions could be avoided and a better feeling of the properties in the core could be achieved. These calculations were done by means of a twodimensional transport code (BOXER) [3] in orthogonal coordinates. Whereas the radial effects could be analysed in good detail axial effects were taken into account by a global buckling value only

Because of the relatively small cores size of research reactors the control rods can cause large local perturbations. This might significantly influence the power distribution over the core. Such axial effects can be studied among others by three-dimensional calculations with the nodal program (SILWER) [4] developed in PSI. In this paper results are described for a standard mixed core configuration as well as a special LEU core containing a fresh element near a water hole.

Although the research reactor SAPHIR was shut down at the end of 1993 and prepared for decommisioning since May 1994, the investigations reported here should be of general interest for all other operators of MTR reactors.

2. A typical composition of the SAPHIR core

The SAPHIR reactor was operated at the maximal power level of about 10 MW during 3 to 4 weeks, followed by a low power period of one week which was used for reloading, maintenance and training activities.

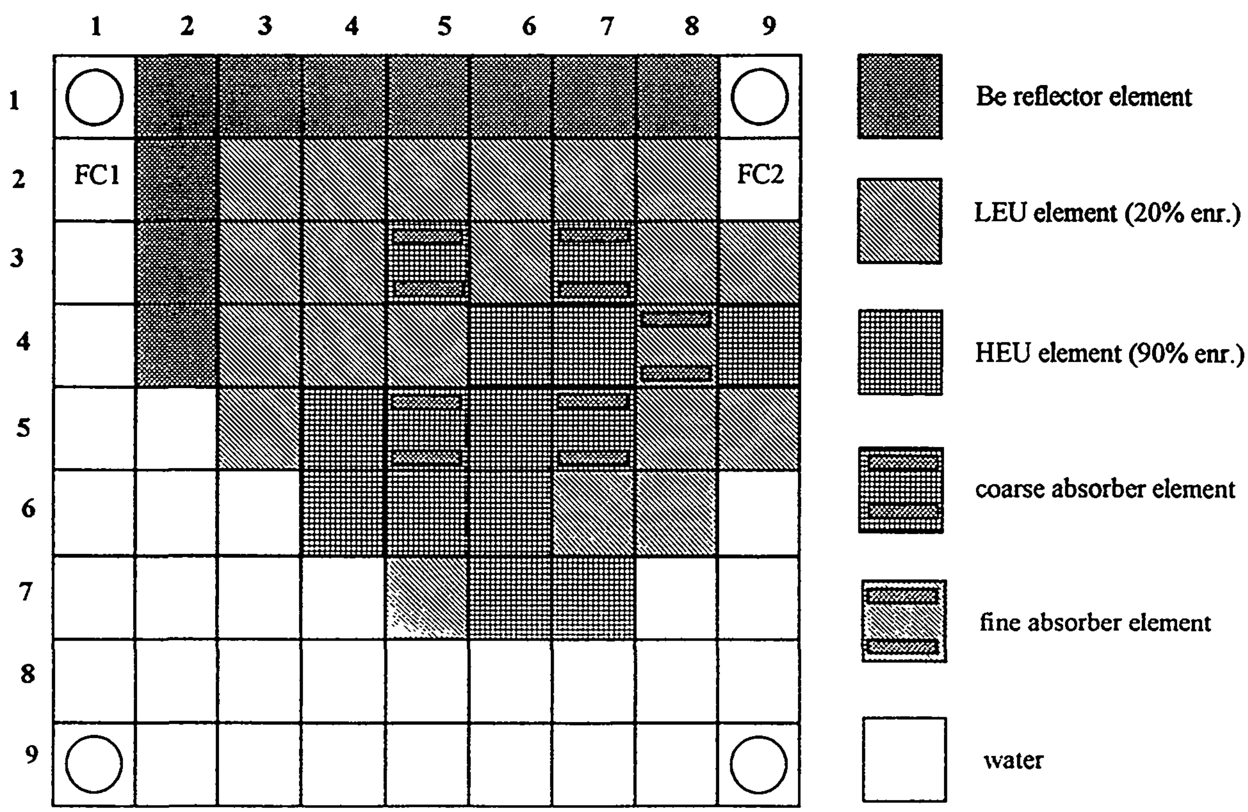

Fig.1: Core composition of loading 622 (the last one of SAPHIR)

The standard core loading has to guarantee an excess reactivity for the envisisaged operation period, the required worthes of the control rods, sufficient distance to boiling limits for each core position and best neutronic conditions for all users of the facility.

A typical core composition as result of the optimisation of the conditions as described above is shown in figure 1. The 10 beryllium reflector elements are aranged between the fuel elements and the beam tube heads in direction of the upper part of figure 1. The nonreflected core positions were used for irradiation experiments (isotope production, silicon doping, irradiations for activation analysis, material tests).

The averaged burnup of a core loading was between 30 and 35%. New elements were inserted at first in a peripheral position. After some runs they were moved step by step towards the core centre and reached a final burnup of about 65 %. The more or less empirical loading strategy devided up the core into 3 concentric areas which should not contain more than a prescribed amount of U-235. A visual inspection of the emmited light at full power was used as indicator of the power distribution. Shadows were interpreted as distortions or signs of starting boiling effects.

Since 1990 systematic investigations of the core behaviour of mixed loadings were performed. For each new loading a two-dimensional calculation with the transport option QP1 of the code BOXER [3] (part of the code system ELCOS) was done before fuel elements were shuffled.

As a consequence of these investigations empty incore positions filled with water were avoided, because in the vicinity of such places very high power peaks can occur (see section 3.3). Furthermore, reactor operation with nonsymmetric control rod positions was forbidden, as this can cause the power density to rise locally above a secure level.

A value of 200 $W \cdot cm^{-3}$, corresponding to a heat current of 43.2 $W \cdot cm^{-2}$ was fixed as the permitted upper limit of the local power density (axial mean). This was in good agreement with the results of thermohydraulic studies which were performed in parallel [5].

3. Three-dimensional investigations

The two-dimensional core calculations could be performed with a good geometric resolution (1 cm in the standard case down to 0.2 cm for special purposes). In some cases the maximum achievable power density value could only be determinated with the best resolution.

The disadvantages of an only two-dimensional core description are the neglection and simplification of axial effects which are caused by the control rods and the different boundary conditions. With the help of a three-dimensional program the following questions should be answered:

- How is the power peaking influenced by the control rod position ? What are the maximal achievable hot channel values ?

- What is the influence of the axial distribution of the burnup ?

- How large is the effect of the Xe-poisonning on the properties of the core ?

- Are the calculated reactivity values of the control rods in agreement with the experiments ?

Most of the answers will be presented in the next parts of this paper.

3.1. The program SILWER for three-dimensional core calculation

As shown in figure 2 the program SILWER is a part of the code system ELCOS which was developed for steady state calculation of light water reactors as well as for the production of input parameters for dynamic simulation of nuclear power plants. ELCOS consists of the following components (see fig. 2):

1 **ETOBOX** for the generation of group cross sections from data libraries in the ENDF/B-format

2. **BOXER** for cell calculations and two-dimensional diffusion or transport description of the core

3. **CORCOD** for the derivation of interpolation coefficients of group constants suited for the three-dimensional calculations

4. **SILWER** for three-dimensional neutronic and thermohydraulic calculations

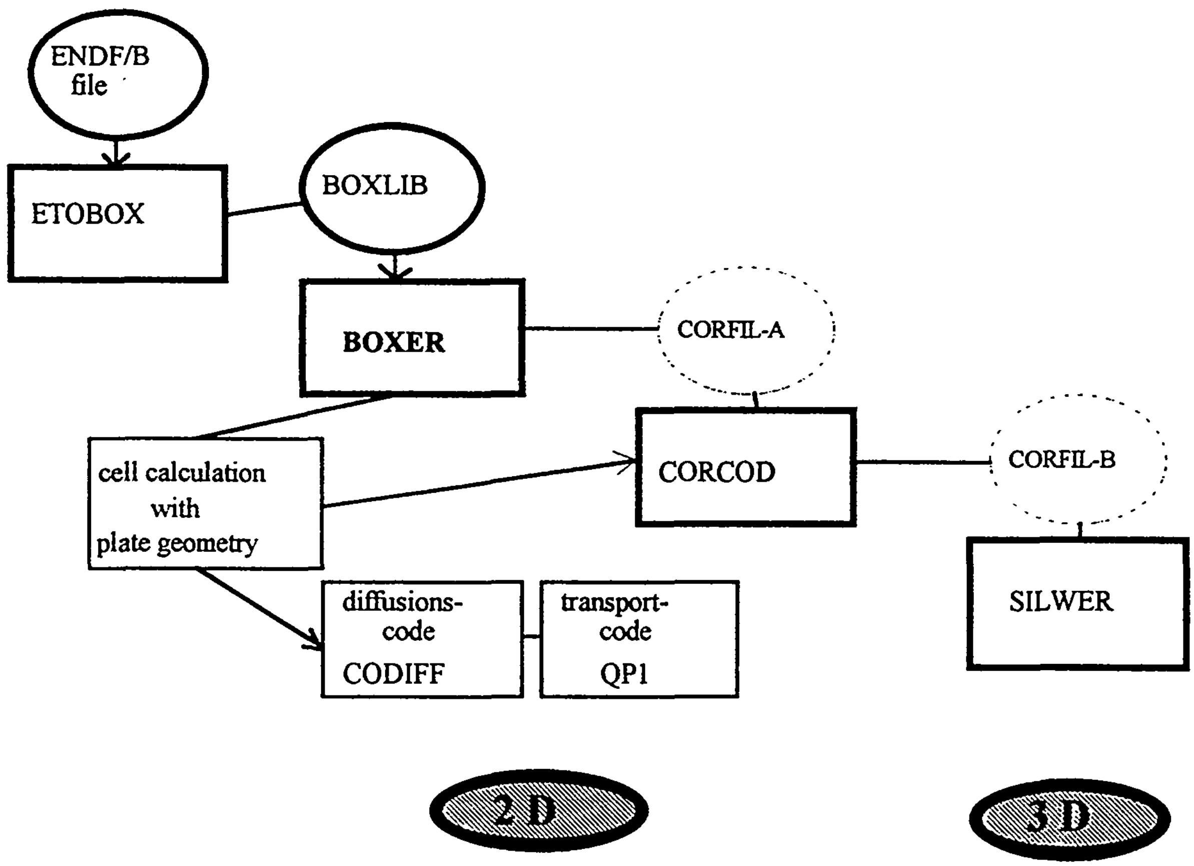

Fig. 2: The components of the code system ELCOS and their connections

Starting with a 70 group cross-section library produced with ETOBOX from ENDF/B formated data, cell calculations were performed in BOXER in real plate geometry with periodic boundary conditions. The number of the resulting flux weighted macroscopic cross sections is usually reduced to 6. Either the full core calculations in 2D or the preparation of cross sections for use in SILWER were done with BOXER. The latter ones were generated in dependency on the burn up of the fuel element type considered. At discret burn up steps the BOXER results were compiled and transfered to a data file CORFIL-A. This data are the reference coordinates for the interpolation which will be done in CORCOD. In this manner the data can be produced for all arbitrary burn up states of the fuel elements in the core. These data are stored in CORFIL-B. The fuel elements containing control rods cannot modellize the absorber plates in detail. Controlled or uncontrolled fuel element zones are distinguished in SILWER to describe the effect of the absorption in the control rods. For the outer zones (Be and water reflectors) in the radial and axial directions special data sets were prepared.

The core configuration to be investigated is described by three-dimensional orthogonal gridmeshes. The spatial resolution can be raised from one mesh point per element (about 8 cm) to 1 cm for calculations of the whole core. The group number was usually 2 or 6 respectively. For the case with the highest resolution in space and energy the cpu-time is in the order of 100.000 seconds on a SUN-workstation. For most of the investigations of SAPHIR cores two groups and a 4 cm grid width turned out to be a good compromise.

The burn up of the fuel elements is known from the operation history for each individual element with an accuracy of 2 to 5% [2]. This information was used in the core model together with an axial distribution derived from gamma spectroscopy investigations. The ^{137}Cs activity distribution of a spent fuel element was taken as measure of the burn up along the fuel element.

3.2. The estimation of the power distribution

As results of a SILWER calculation the eigenvalue of the configuration, the group fluxes and also the power distribution were estimated. The power density P(x,y,z) (usually in W/cm³) represents an array of 100 to 200000 values, depending on the spatial resolution of the used reactor model. This relatively large amount of data is not easy to handle for the description of the core behaviour with regard in relation to possible boiling processes. Therefore, averaging procedures were applied to determine the core positions with the highest heat loading and to evaluate their security against boiling phenomena.

3.2.1. Hot channel factor vs. hot element factor

For the cores of nuclear power plants (NPP) **the hot channel factors (HCF)** are defined. The largest power density values of the pins, the elements and those in the axial direction are independently been connected. To guarantee a sufficient distance to boiling behaviour the HCF values should not exceed a prescribed upper limit.

The definition of the hot channel factor is:

$$HCF = \left(\frac{P^{max}_{plate}}{P^{mean}_{element}}\right)^{max} * \left(\frac{P^{mean}_{element}}{P^{mean}_{core}}\right)^{max} * \left(\frac{P^{max}_{axial}}{P^{mean}_{axial}}\right)^{max} \qquad (1)$$

The cores of the MTR research reactors are small (less than 1 m^3) compared to those of NPP (about 25 m^3). Therefore, local effects like control rod movements or poisonning can have more influence on the HCF value. This overestimation of HCF is mainly caused by the axial contribution.

A better possibility to describe the core with regard to safety against boiling is the definition of a **hot element factor (HEF)**. It looks in the data array P(x,y,z) for the absolute hottest position and compares this point with the averaged behaviour of the core.

$$HEF = \left[\left(\frac{P^{max}_{plate}}{P^{mean}_{element}}\right)^{max}_{element} * \left(\frac{P^{mean}_{element}}{P^{mean}_{core}}\right)^{max}_{element} * \left(\frac{P^{max}_{axial}}{P^{mean}_{axial}}\right)^{max}_{element}\right]^{max} \qquad (2)$$

The figure 3 gives a comparison of both factors for a standard core loading when the control rods are moved into the core from the upper to the lower position. The reactor power was held on the same level of 10 MW during the rod insertion.

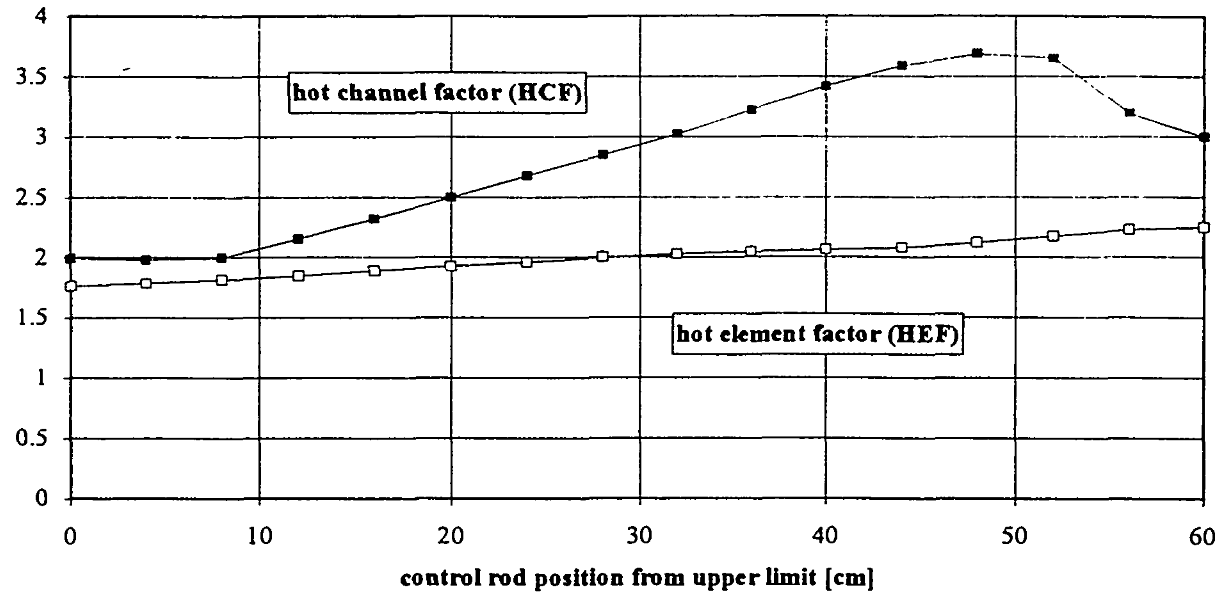

Fig. 3: Hot channel factor and hot element factor respectively for a standard core configuration in dependency on the control rod position (power level constant)

The HEF value is not influenced strongly by the insertion of the control rods while the HEF value does increase substantially. This behaviour is caused mainly by the axial distortion of the flux distribution. In the HCF calculation the axial effects are considered independently and the global reduction of the power density inside the control elements is neglected. The high HCF values represent a strong overestimation of the core behaviour against boiling tendencies. For an adequate description of the operation properties the HEF model is preferable. Nevertheless, the situation with full withdrawn control rods (end of run) is those one with the largest margin against boiling in both models. The "start of cycle" configuration (cold, unpoisoned, small burn up) is the most difficult configuration with regard to boiling.

3.2.2. Influence of the burnup on the power density distribution

In the three dimensional model the axial burn up is described by a distribution based on gamma spectroscopic investigations [7]. Depending on the resolution, 8 to 60 zones with different burn up values are defined. In the radial direction a space independent distribution is assumed. Therefore, the core properties, especially the power distribution, are strongly determined by axial effects. Thus the advantage of the code SILWER is the possibility of investigations under the explicit consideration of unequal burn up over the core height.

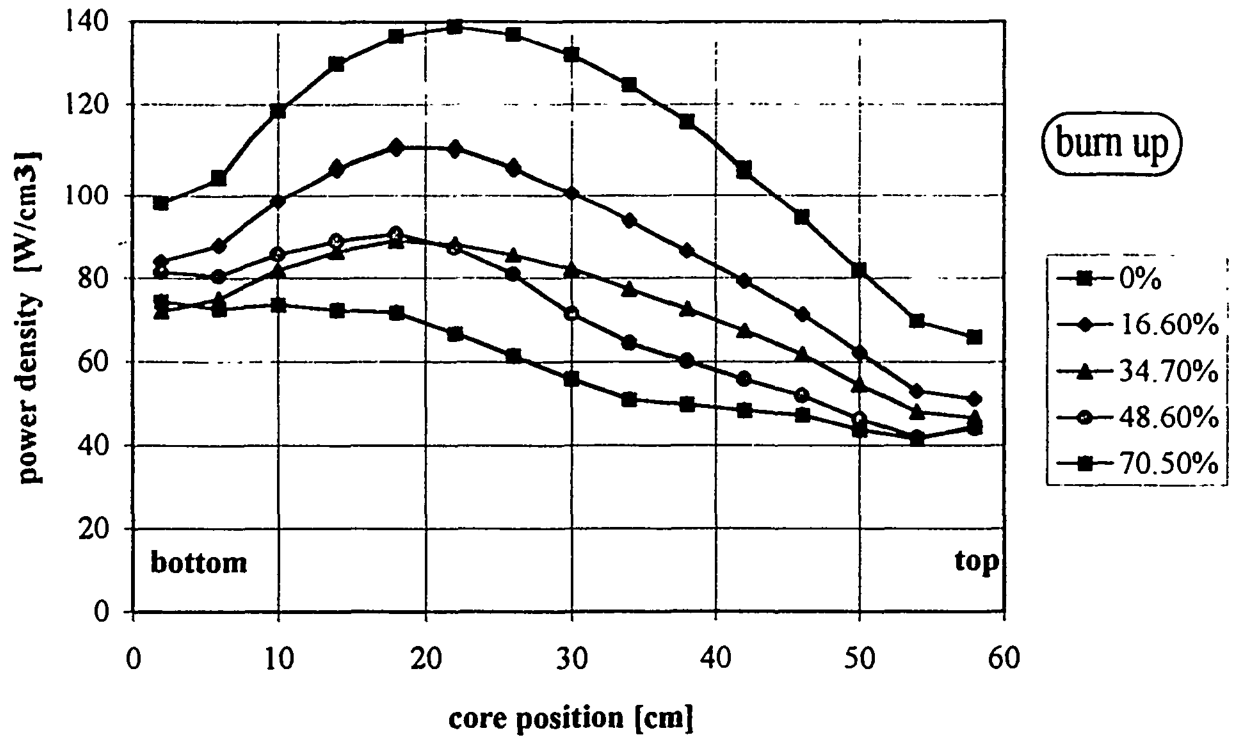

Fig. 4: Axial power distribution in dependency on the burn up of the LEU elements (control rods (plates) half inserted from top)

Figure 4 represents a comparison between the power density distributions over the height of LEU elements with different burn up. The strong rise in direction of the core centre in the case of a fresh LEU element is flattend more and more with growing burn up.

3.2.3. Xe-poisoning of the core

The cross section data for the calculations of the SAPHIR core with SILWER are normally prepared for the state of a saturated poisoning . This standard case can be modified into the Xe-free status by setting the nuclear densities of ^{135}Xe to zero. In this manner the influence of the poisoning on the power distribution can be studied by comparing both of the cases described before.

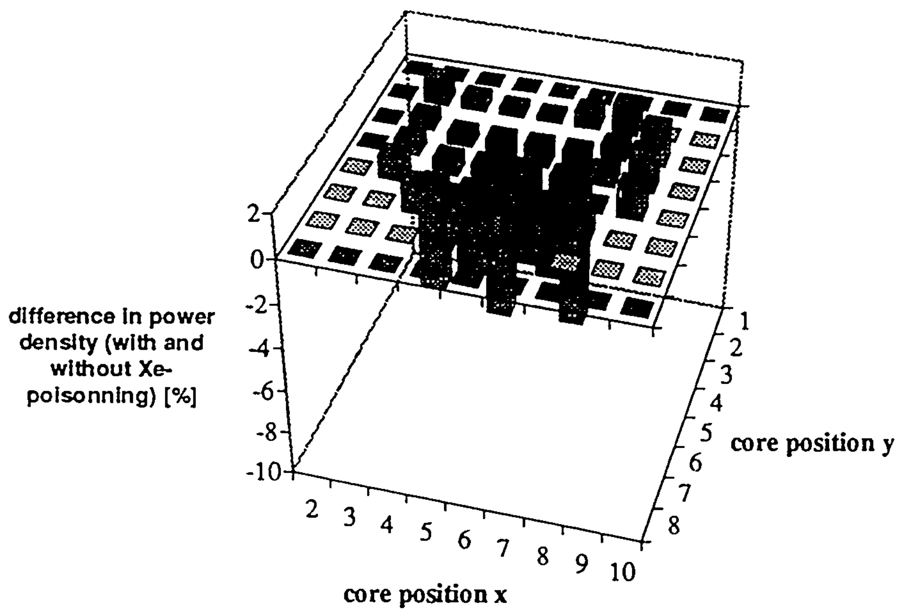

Fig. 5: Effect of the Xe-poisoning on the axial averaged power distribution in a standard core (comparison of the states with and without Xe)

The difference between the two cases concerning the axial averaged power density is in the order of some per cent only. This is a low effect compared to the change in the reactivity which is in the range of 5$. Figure 5 shows that the power density will be reduced in the core centre but increased in the outer elements due to the effect of Xe-poisoning. This means a flattening of the radial power distribution during the reactor operation. The HCF and HEF values became a little smaller in the poisoned case.

Because the compensation of the reactivity loss by poisoning is usually done by removing the control rods, the power distribution is smoothed in axial direction as well.

From this study it can be concluded that the risk of power peaking is lower for the poisoned MTR reactor as the unpoissoned one. But this effect is less important than the influence of the axial burn up described before.

3.4. Special case: a fresh LEU element near an empty core position

Fresh LEU elements contain about one third more fissile uranium than the HEU ones. This is necessarry to obtain a comparable flux level and to reach an reasonable final burn up. The relatively high amount of U-235 can lead to power peak values if the element is driven by high thermal neutron fluxes. This can occur if a new MTR-LEU element is placed in the core centre (56) near an empty, water filled position (66).

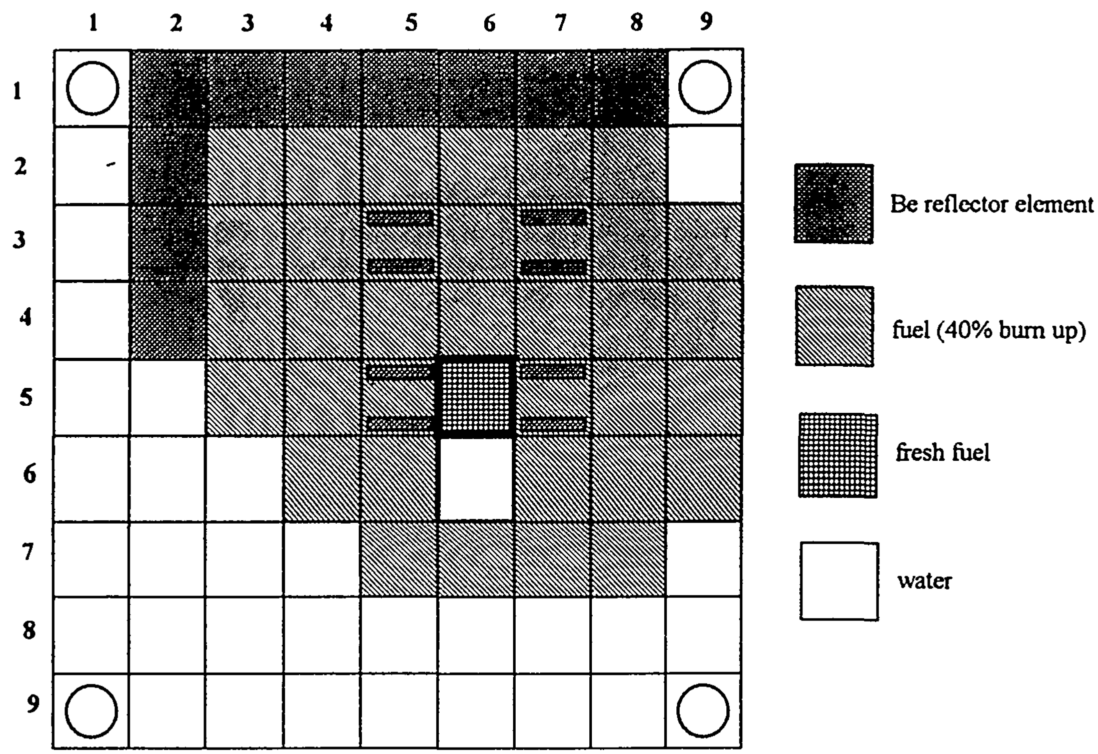

Fig. 6: Core configuration with a fresh fuel element near an empty, water filled position

This behaviour of this special loading was investigated by means of 2D and 3D calculations. An image of the core configuration is given in figure 6. All standard elements were assumed to have a burn up of 40%. The water hole was at the grid position 55. The elements to investigate were placed at position 56.

Using the 2D (x,y) model it was possible to calculate the radial power density distribution very detailed. The resolution was raised from about 1 cm to 0.25 cm. As shown in figure 7 this high resolution have to apply if the real maximum of the peaking should be found.

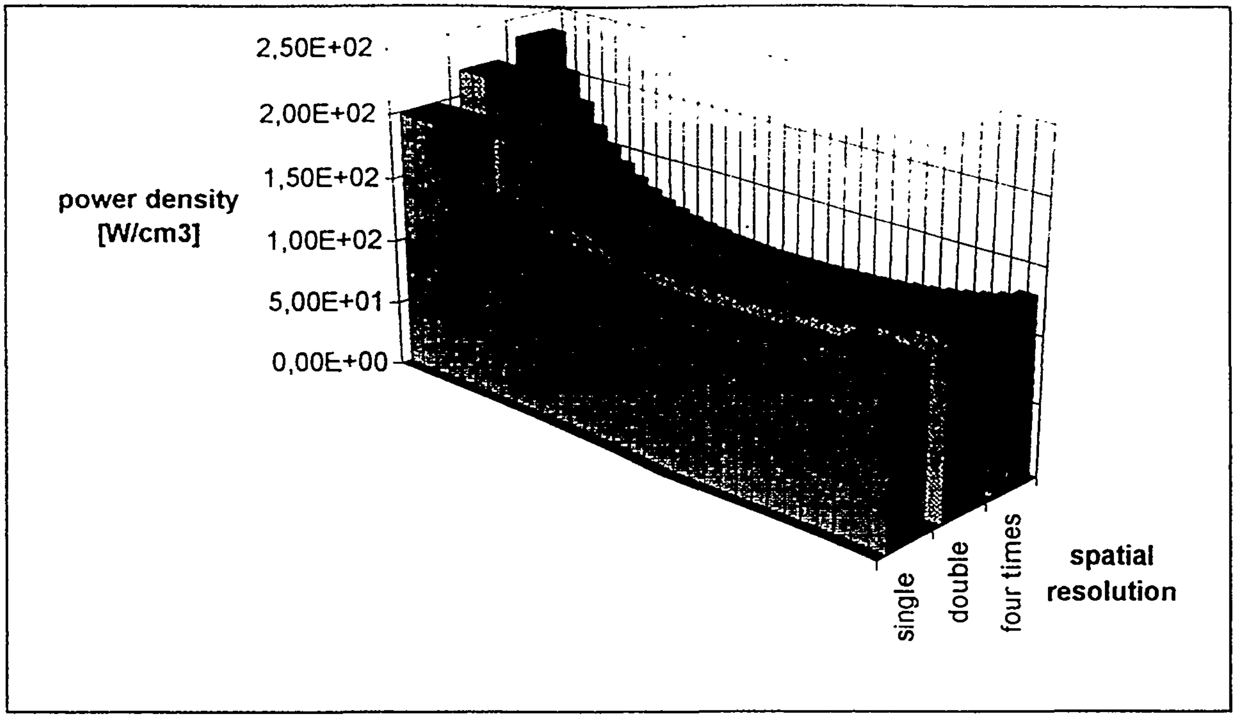

Fig. 7: Power density in a fresh LEU element into the direction to the water hole

The large value of the power density (higher than 200 W/cm^3) at the surface of the fuel element might be difficult for the reactor operation on high power level because the cooling conditions at the outer plate are reduced by the empty grid position.

Taking the third direction into account the calculations with SILWER cannot be performed with the same high spatial resolution as in the case of the 2D model. Nevertheless, a comparison of the behaviour of HEU and LEU elements at this difficult position can be given. Furthermore, the influence of the control rod position on the values of HEF (relevant for thermohydraulic considerations) can be investigated. This data are given in figure 8. For both the types of fresh fuel the largest HEF value can be found at half inserted control rods. This is mainly caused by the two control elements in the direct neighbourhood of the test position 56 (see figure 6).

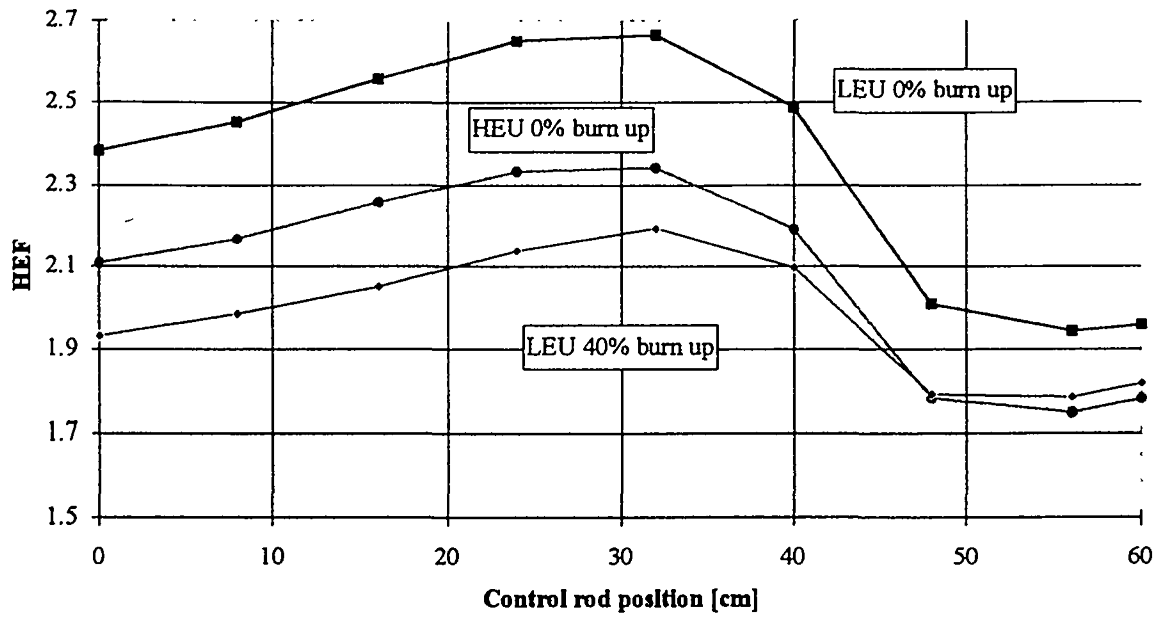

Fig. 8: Hot element factors for the core configurations with different fuel elements (fresh LEU, fresh HEU, burned LEU) at core position 56 near a water hole in dependence on the control rod position

The Hot element factors are in the case of the new LEU higher than for HEU by more than 0.3. Compared with a standard core loading (see 3.2.1. and figure 3) the HEF are higher by 0.7. This indicates an unacceptable high value for a reactor operation on high power level.

3.4 Control rod worthes

By means of the 2D core model regarding the effect of the control rods the two reactor states (full inserted, full withdrawn) can be described only. Therefore it is difficult or unpossible to investigate the operation state with half inserted rods.

	experiments	**calculations**	
beta = 0.0085	rod drop	transport 2D	diffusion 3D
coarse rod 1	1.74 $	1.82 $	1.71 $
coarse rod 2	1.56 $	1.49 $	1.46 $
coarse rod 3	2.35 $	1.67 $	1.95 $
coarse rod 4	1.87 $	1.38 $	1.62 $
all rods together	5.83 $	7.62 $	6.69 $
sum of all single rods	7.67 $	6.36 $	6.90 $
all rods/sum of single	**0.76**	**1.2**	**0.97**

Table: Comparison of measured and calculated reactivity values of the coarse control rods indicating their interaction in the core

The advantage of the 3D calculations is the adequate analysis of axial effects. The partly inserted rods can be simulated by zones which contain the real amount of absorbing material. From the calculated eigenvalues in relation to those of the unperturbed case the reactivity values can be estimated for each rod position. The control rod worth curve for the fine control rod is shown in figure 9 and compared to the experimental data.

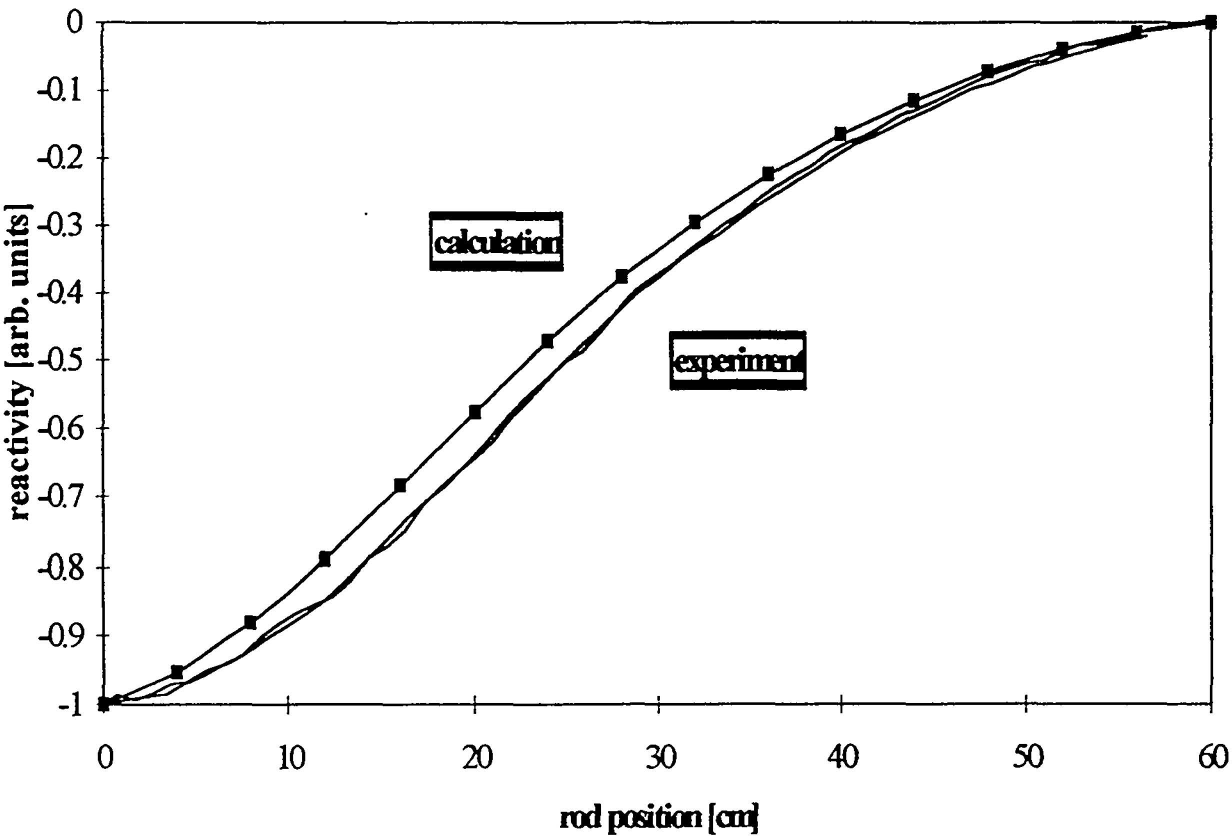

Fig. 9: Comparison of the measured and calculated fine control rod worth in dependence of the rod position

The agreement between the two curves is quite satisfactory. The total reactivity value (in the order of 50 Cents) of this fine control rod can be described with an accuracy of about 10%, depending on the energetic and spatial resolution in the calculations. It should be noted that the measurements have several errors and methodical uncertainties also.

In the case of the four coarse control rods the situation is more difficult. Because of the high worthes (several Dollars) of each rod the total curve as seen in figure 9 could not be measured directly. Usually the rod drop value starting from the critical state was measured for each rod intependently and for all rods simultanuosly. These experimental values could not compared with results from 2D calculations because only the rod positions "full inserted" or "full withdrawn" can be analysed. The estimation of the total rod worth was done by means of a calibration curve.

In the table a comparison is given between the measured and calculated rod worthes. In the experiments the sum of the individual worthes of the four rods is larger than the value of the reactivity when all rods were inserted simultanously The 2D calculations could not support this result. The ratio is here smaller than 1.

The 3D model was able to overcome the methodical error which are mainly caused by the simplification of axial effect. As shown in the table, the 3D reactivity values of all rods together show a shadowing effect as seen in the experiments. The measured reactivity worthes are influenced by the position of the detector position and by the time resolution of the counter. The accuracy of the 3D calculations depends on the number of grid meshes and of energy groups. They are limited by the computer capabilities.

4. Summary

The program SILWER as component of the code system ELCOS has proven to be able to describe axial effects of a MTR core very well. Some limitations regarding the spatial resolution can be overcome by additional detailed calculations with the 2D modul BOXER.

Some interesting conclusions could be drawn from the performed calculations concerning the use of LEU and HEU in mixed cores. It is regarded to do calculations for each new core loading before the operation at power in order to indentify and to avoid hot core positions.

The most dangerous status in respect of the core cooling is the begin of the run when the control rods are half inserted. Effects like poisoning, burn up and rod withdrawal induce a flattening in the power distribution, mainly in axial direction.

Core configurations with water holes surrounded by fuel should be handled with care. The placement of fresh LEU in the vicinity can cause large power peak values.

The code system should be made available on request for other users, especially for the operators of research reactors with MTR fuel.

Acknowledgement

The authors express their thanks to P. Grimm and J.M.Paratte for making available the code system ELCOS and for their numerous hints.

Reference:

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