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Calculation of the local power peaking near VVER-440 control assemblies with Hf plates

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ABSTRACT

The original coupler design of the VVER-440 assemblies had the following well known deficiency: The relatively large amount of water in the coupler between the absorber and fuel part of the control assembly can cause undesirably sharp power peaking in the fuel rods next to the coupler. The power peaking can be especially high after control rod withdrawal when the coupler reached low burnup level region of the adjacent assembly. The modernized coupler design overcomes the original problem by applying a thin Hf plate in the critical region. The very complicated structure of the coupler requires the verification of the core design methods by high precision 3D Monte Carlo calculations. The paper presents an MCNP reference calculation on the control rod coupler benchmark with Hf absorber plates. The benchmark solution with the KARATE-440 code system is also presented. The need for treating the Hf burnout in the reflector region is investigated.

DESCRIPTION OF THE BENCHMARK

In the 9th Symposium a benchmark problem was formulated to study the power distribution of VVER-440 fuel assemblies near to a control assembly [1]. The investigated system of the benchmark is an infinite core made up from VVER-440 assemblies with enrichment zoning. The geometry of the benchmark consists of a central control assembly and the surrounding fuel assemblies. The geometry has 60-degree symmetry; a 60-degree sector can be seen in Figure 1. This sector is the basic unit in the MCNP [2] calculations. The control assemblies in the positions corresponding to the 6th group (of the standard VVER-440 loading scheme) are partially inserted. The control assemblies are inserted such a way that the 244 cm high core contains 49.7 cm of the boron steel part of the assembly. On the top, bottom and radial boundaries mirror boundary conditions are applied. The spacer grids are neglected. The average enrichment of the fuel assemblies is 3.82%. In the active height the follower assemblies are considered as identical with the "regular" assemblies. The boron steel part of the follower is unburnt. The distributions of the assembly-wise burnup, fuel and moderator temperatures are homogeneous. The boron concentration is 0., the fuel and moderator temperature is 260 Celsius degree. The relatively large amount of water in the coupler between the absorber and fuel part of the control assembly can cause undesirably sharp power peaking in the fuel rods next to the old coupler [1]. The modernized coupler design overcomes the original problem by applying a thin Hf plate in the critical region (see Figure 2).

According to the new design to study the effect of the modernized coupler the original benchmark was modified in the following way:

- From the upper grid towards the steel rods in the fuel elements 0.06 cm thick and 15.04 cm long Hf plates were fitted to the inner surface of the assembly shroud.
- The lattice pitch of the fuel rods was increased from 1.22 cm to 1.23 cm.
- The radially averaged burnup of the fuel assemblies and the fuel part of the follower was set to 21296 MWd/tU.

To study the influence of the material changes in the control assembly along the axial direction the following calculations are proposed:

- k_k pin-wise 2-D peaking factor averaged over rows of fuel pins in the assembly next to the control assembly.
- k_v assembly-wise 3-D peaking factor for the 7 assemblies involved in the basic unit.

The isotope concentrations for the MCNP were determined by MULTICELL [3] calculations using reflective boundary conditions. In the calculations 18 actinides and 35 fission products were taken into account. The cross sections of actinides for 260 C temperature were determined by the NJOY code [4]. The missing fission products were replaced with their boron equivalents The MCNP calculations were performed dividing the pins into 40 parts with equal heights. The in-going and out-going currents on the boundary of the different coupler regions were determined during MCNP runs.

In the KARATE [5] nodal and fine-mesh benchmark calculations the number of the axial mesh points were 40. The coupler part in the diffusion calculations of the KARATE code system is excluded by using precalculated albedo matrices.

$$J^-_g = \sum_{g'=1}^{2} \alpha_{gg'} \cdot J^+_{g'}$$

1D multigroup COLA transport calculations of the different coupler regions and neighbo[u]r assemblies were carried out and subsequently the two-group albedo matrices were determined and parametrized in the form

$$\alpha_{gg'} = \alpha_{gg'}(C_B, \rho_m)$$

for regions not containing either boron steel or Hf

$$\alpha_{gg'} = \alpha_{gg'}(C_{Bsteel}, C_B, \rho_m)$$

for regions containing boron steel

$$\alpha_{gg'} = \alpha_{gg'}(F_{Hf}, C_B, \rho_m)$$

for regions containing Hf.

In the burnup calculations the ^{174}Hf, ^{176}Hf, ^{177}Hf, ^{178}Hf, ^{179}Hf and ^{180}Hf isotopes are treated The burnout of the Hf isotopes is characterized by the time integral of the incoming partial current at the proper surface of the control assembly.

On the basis of MCNP 3D results correction factors were determined:

$$J^{-}_{MCNP} = D\alpha_C(p_o)J^{+}_{MCNP}$$

Where J^{+}_{MCNP} is the partial current calculated by MCNP with given p_0 parameters
$\alpha_c(p_o)$ is the albedo matrix with given p_0 parameters calculated with the COLA code
D is the diagonal correction matrix for each albedo type.

The benchmark problem of the new coupler design has been solved by the KARATE code system and the results were compared to those of the MCNP. The two k_v peaking factor curves of fuel assembly next to the absorber calculated by MCNP with and without Hf show minor difference near the critical axial position (see Figure 3). The results of the GLOBUS module of the KARATE code system are fairly close to the reference solution (see Figure 4). Figures 5-7 show the k_k curves averaged over the 1st, 2nd and 3rd rows calculated by MCNP with and without Hf. The Hf plate applied in the new design effectively removes the power peak. The SADR fine mesh calculations of KARATE give quite similar row averaged peaking factors to the reference MCNP solution (See Figures 8-10).

METHODICAL INVESTIGATIONS OF HF BURNOUT

The applied Hf plates of the follower assemblies that belong to not the regulating group stay mainly in the top reflector region near the core, which has relatively high thermal neutron flux. To assess the need to take into account the Hf burnout outside the core the original benchmark problem with reflective boundary conditions was modified. The top and bottom boundary conditions at the core were replaced by explicit material compositions of the reflector regions. Two MCNP calculations were carried out. In the first case the control assemblies were inserted into the core, the position was the same as in the benchmark. In the second case the control assemblies were fully removed. Figure 11 shows the position of the Hf plate in case of withdrawn rods. The total absorption rate in the Hf plate in case 1 was five times higher than in case 2. The power flattening effect during burnup changes this ratio considerably. The top reflector was modeled in a COLA 1D transport calculation. Figure 12 shows the flux distribution in the top reflector at nominal moderator conditions. The active part of working fuel assemblies ends at Z=0. The Hf plate was inserted into the reflector region and burnup calculations were made for 3 and 4-year irradiation. In the EOC (CB=0.) conditions the 2-group albedos were evaluated for the unburnt, for the 3 and 4-year irradiated Hf and for the original coupler section without Hf. Using the calculated albedos and applying a representative partial current into the coupler section, the partial thermal neutron current back to the fuel assemblies was evaluated to demonstrate the effect of Hf composition. Table 1 shows the arbitrarily normalized thermal current for the different cases.

Case	Fresh Hf	3 cycle burnt Hf	4 cycle burnt Hf	Without Hf
J^{-}_{th}	1.00	1.15	1.19	1.77

Table 1
The arbitrarily normalized thermal neutron partial current to the fuel region
for the different cases.

The above neutron current, which is responsible for the power peaking near the coupler, shows not negligible change from cycle to cycle, so the treatment of Hf burnout in the reflector is recommended.

SUMMARY AND CONCLUSIONS

The very complicated structure of the VVER-440 coupler requires the verification of the core design methods by high precision 3D Monte Carlo calculations. The paper presents an MCNP reference calculation for the control rod coupler benchmark with Hf absorber plates. The calculation methods of the KARATE-440 code system were verified by solving the benchmark problem. The treatment of the Hf burnout in the reflector region is recommended.

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FIGURES

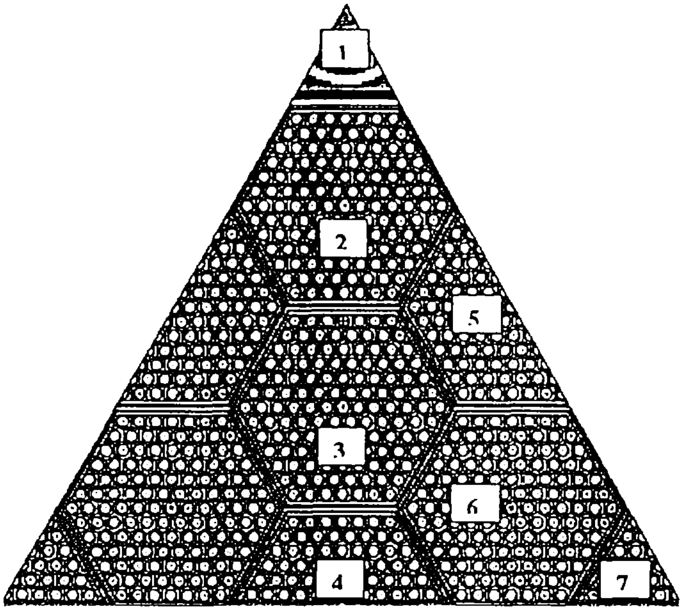

Figure 1
The seven assembly positions in the benchmark

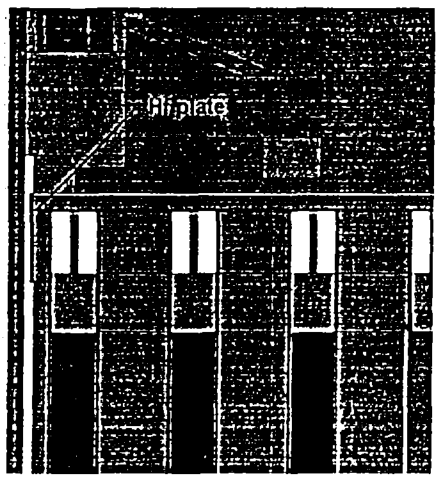

Figure 2
Location of the Hf plate in the modernized coupler

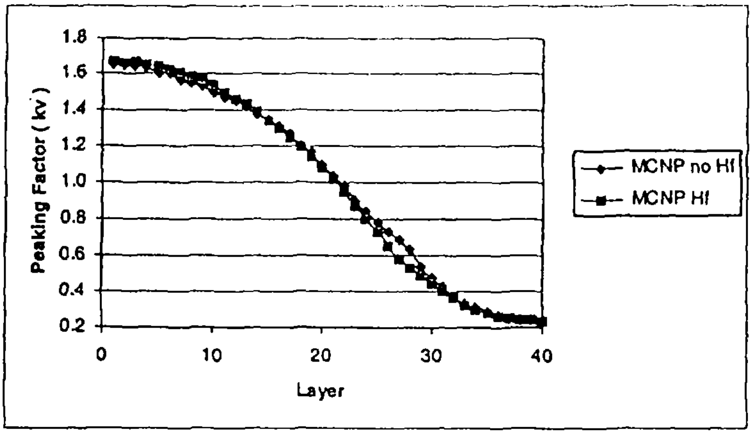

Figure 3
k_v peaking factor of fuel assembly next to the absorber calculated by MCNP with and without Hf.

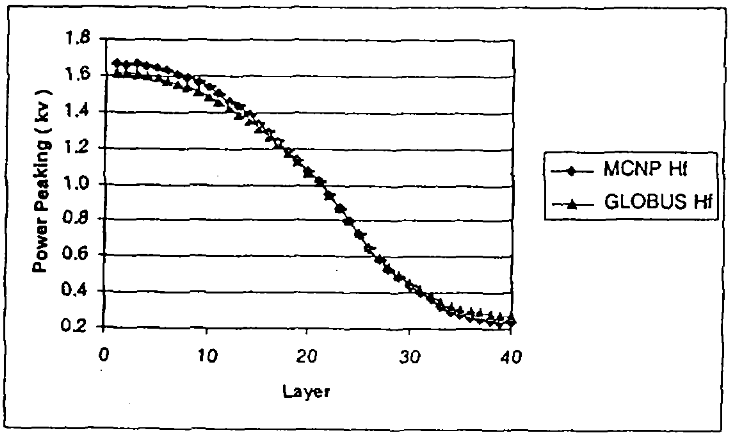

Figure 4
k_v peaking factor of fuel assembly next to the absorber calculated by MCNP and GLOBUS

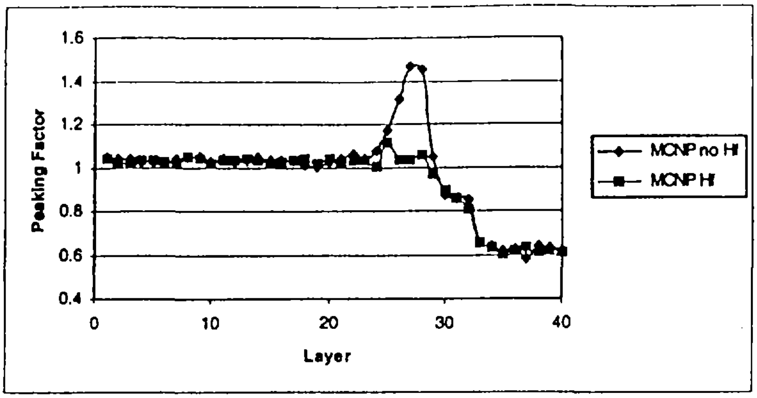

Figure 5
k_k averaged over the 1st row calculated by MCNP with and without Hf.

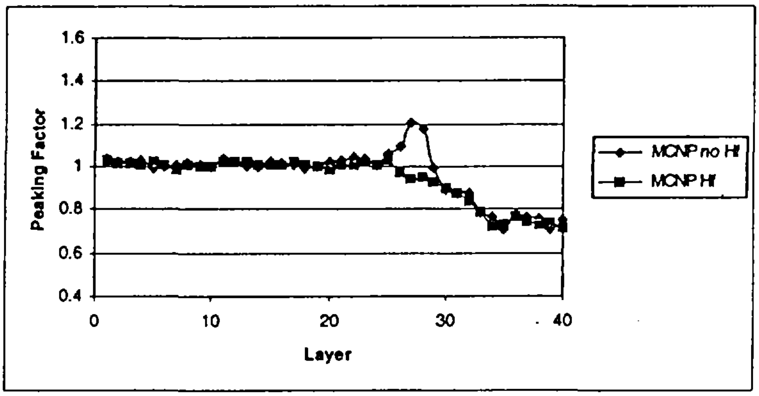

Figure 6
k_k averaged over the 2nd row calculated by MCNP with and without Hf.

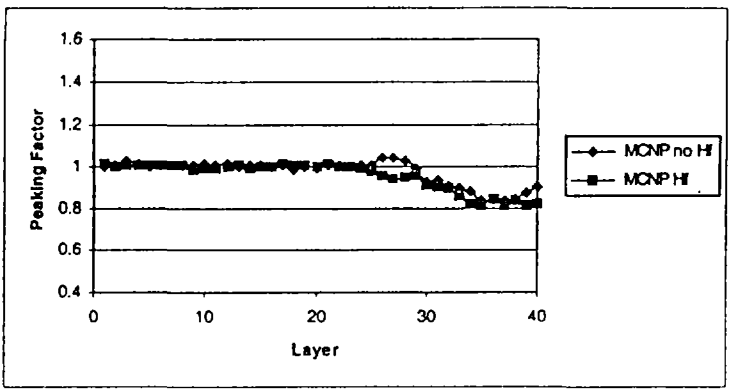

Figure 7
k_k averaged over the 3rd row calculated by MCNP with and without Hf.

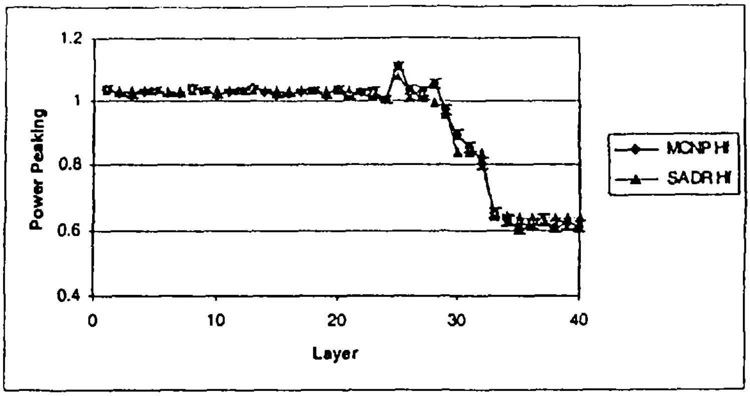

Figure 8
Comparison of k_k averaged over the 1st row calculated by MCNP and SADR.

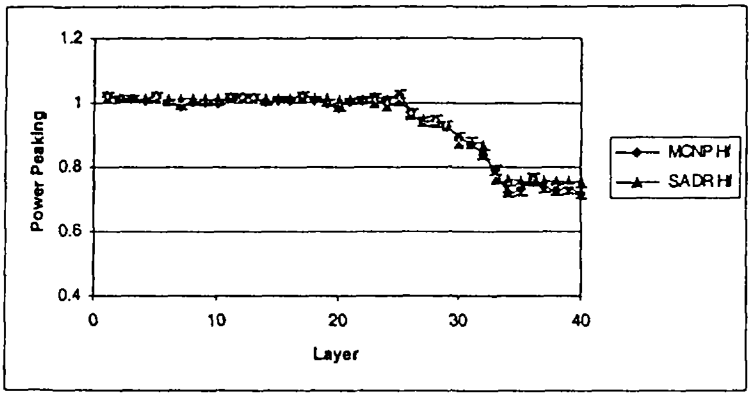

Figure 9
Comparison of k_k averaged over the 2nd row calculated by MCNP and SADR.

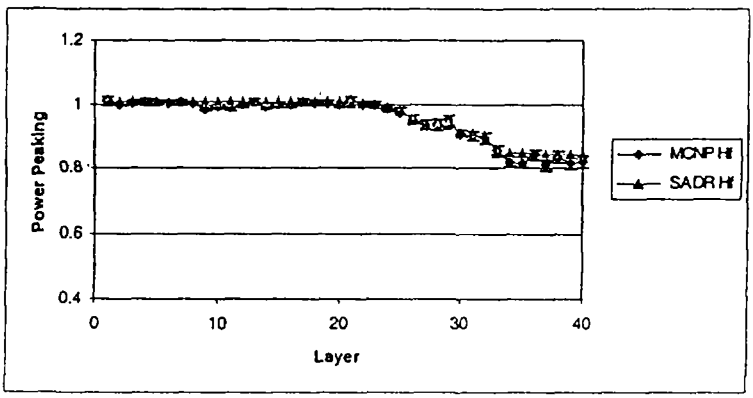

Figure 10
Comparison of k_k averaged over the 3rd row calculated by MCNP and SADR.

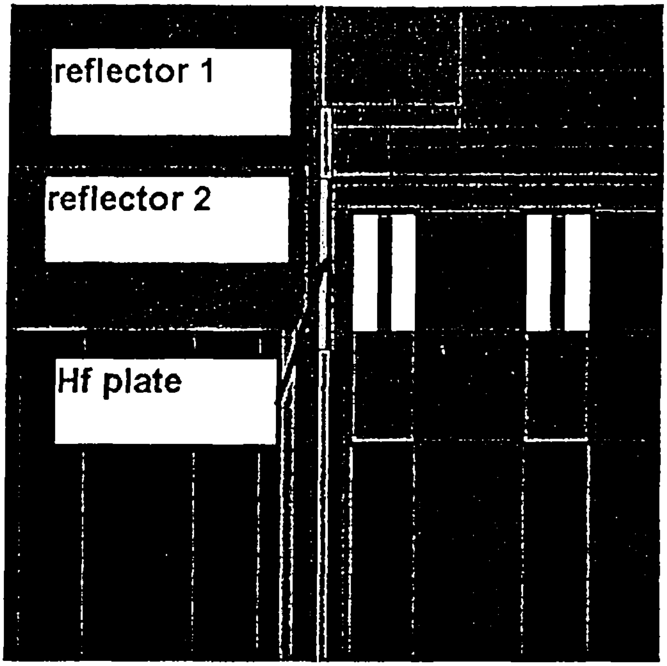

Figure 11
The location of the Hf plate in the top reflector in case of withdrawn absorbers.
MCNP 3D calculation.

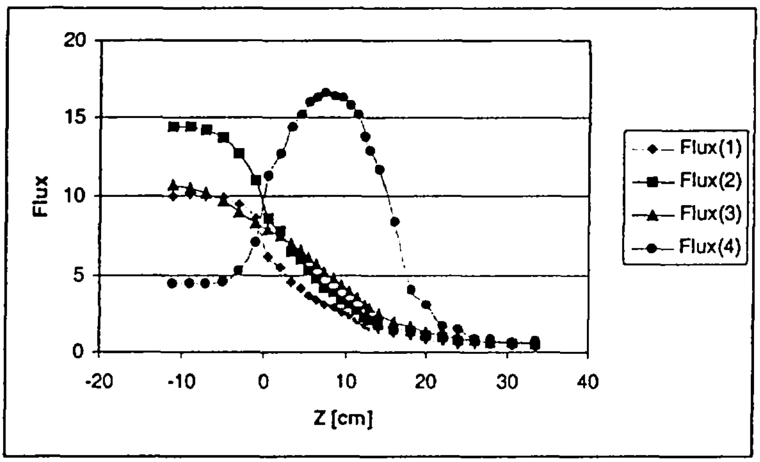

Figure 12
Flux distribution in the top reflector from COLA 1D calculation.
The active part of working fuel assemblies ends at Z=0.