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Coulped neutronics/thermal-hydraulics calculation of VVER-1000 fuel assembly

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Abstract: This paper presents a computational scheme using MCNP5 and COBRA-EN for coupling neutronics/thermal hydraulics calculation of a VVER-1000 fuel assembly. A master program was written using the PERL script language to build the corresponding inputs for the MCNP5 and COBRA-EN calculations and to manage the coupling scheme. The hexagonal coolant channels have been used in the thermal hydraulics model using CORBRA-EN to simplify the coupling scheme. The results of two successive iterations were compared with an assigned convergence criterion and the loop calculation can be broken when the convergence criterion is satisfied. Numerical calculation has been performed based on a UO_2fuel assembly of the VVER-1000 reactor.

Keywords: *MCNP, COBRA-EN, coupling scheme, power distribution.*

I. INTRODUCTION.

The nuclear reactor core is a complicated multi-physics system, in which neutronics, thermal-hydraulics and fluid dynamics are coupled together. To assess nuclear safety analysis, neutronics and thermal-hydraulics characteristics need to be considered, and power distribution is one of the most important characteristics. Core physics codes such as SRAC or MCNP can be used for calculating the power distribution in the reactor core. However, these codes cannot handle the coupling effect of the multi-physics phenomena such as the temperature feedbacks. The temperature feedback effect from the fuel which can make a change in the coolant density should be considered. This phenomenon affects the neutron moderation ability, neutron flux and tends to make a change of the power distribution in the reactor. Inversely, the change in the power distribution leads to the change in the fuel temperature and coolant density.

Several coupling models have been developed to investigate the neutronics and thermal-hydraulics characteristics of the fuel assembly. A coupling model using MCNP/COBRA-TF [1] was developed to predict the pin power of a fresh PWR fuel assembly. In that research, the fuel and coolant temperature are taking into account using interpolation methods for the temperature dependent of nuclear cross-section. Another coupling model, which used PARCS and COBRA-TF [2] has been done to investigate the steady state and transient state of PWR fuel assembly. In this paper, a neutronic/thermal-hydraulic coupling calculation scheme has been developed using the MCNP5 and COBRA-EN codes and applied for analyzing the VVER-1000 nuclear fuel assembly. To simplify the coupling scheme, the hexagonal

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coolant channel has been used instead of the commonly used triangular one. A master program to manage the coupling calculation was written using PERL language. The master program consists of some specific programs to create the data inputs for the calculation scheme and to compare the results of the power distribution between successive iteration steps for checking the convergence criterion. Application has been performed based on calculation of a UO_2 fuel assembly of the VVER-1000 reactor.

II. CALCULATION OF THE VVER-1000 FUEL ASSEMBLY BENCHMARK

In this part, the comparison between our calculations and the benchmark results for the VVER-1000 fuel assembly [3] was presented in order to verify the neutronic calculation using MCNP5, which will be used in the coupling scheme. The parameters of the VVER-1000 fuel assembly of the benchmark problem are taken from Ref. [3]. The *k-inf* value of the fuel assembly at state S2 calculated using MCNP5 were compared with the benchmark results obtained using six other codes MCU, TVS, WIMS8A, HELIOS, MCNP4B and MULTICELL as shown in Table I. It can be seen that the *k-inf* obtained from MCNP5 calculation has a good agreement with the benchmark results.

Table I. Results of k-inf at state S2.

MCNP5	MCU	TVS	WIMS8A	HELIOS	MCNP4B	MULTICELL
1.17858	1.1779	1.1768	1.1695	1.175	1.18	1.1776
Error (pcm)	68	178	908	358	142	98

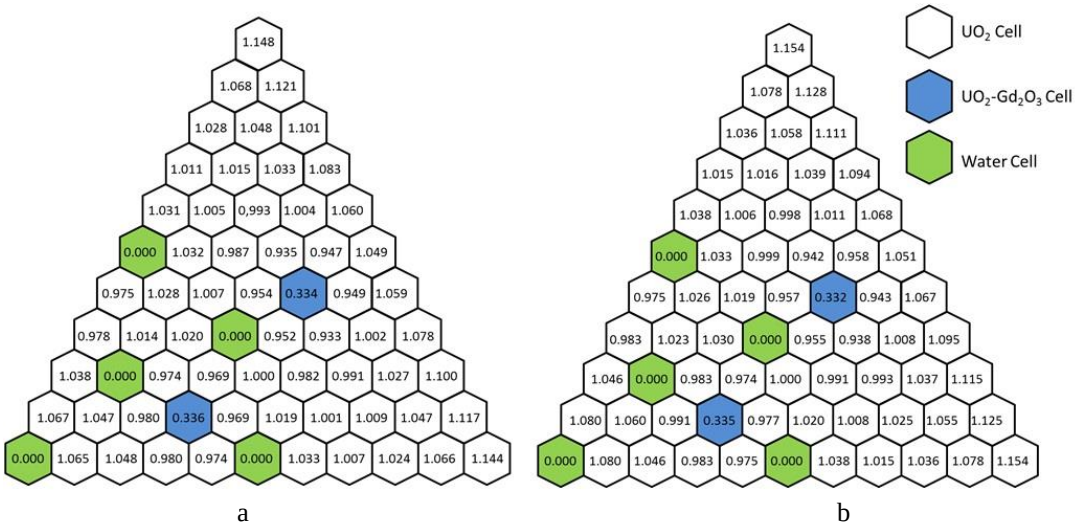

Fig.1. Power distribution in VVER-1000 fuel assembly at state S2.
(a: MCNP5 result; b: MCNP4B result [1])

The pin-wise power distribution for one sixth of the VVER-1000 fuel assembly calculated using MCNP5 was compared with that obtained from MCNP4B calculation [3] as shown in Fig. 1.The deviation of the power distribution between the two codes is within 1.70%. Thus, our calculation model and the results are reliable, and can be used for the coupling scheme.

III. COUPLING SCHEME

According to the coupling model between MCNP and COBRA-TF [1], we developed a coupling scheme of MCNP5 and

COBRA-EN to investigate the neutronics/thermal hydraulics coupling effect. The flow chart is shown in Fig. 2. The master program written by PERL language consists of specific programs as follows:

- *MCNP run*: The lunch-script for running MCNP5;
- *mc2cobra*: Collecting the result of the power distribution from MCNP5 output to make new input for COBRA-EN;
- *COBRA-EN run*: The lunch-script for running COBRA-EN;
- *cobra2mc*: Collecting the result of the coolant density from COBRA-EN output to make new input for MCNP5;
- *compare unit*: Checking for convergence criterion considering the difference on the power distributions between two successive iteration steps. If the difference is larger than the convergence criterion, a new iteration is performed. If the difference satisfies the convergence criterion, the calculation is stopped and the power distribution is accepted and printed out in *result printout*;
- *Result printout*: Printing the final result of the power distribution.

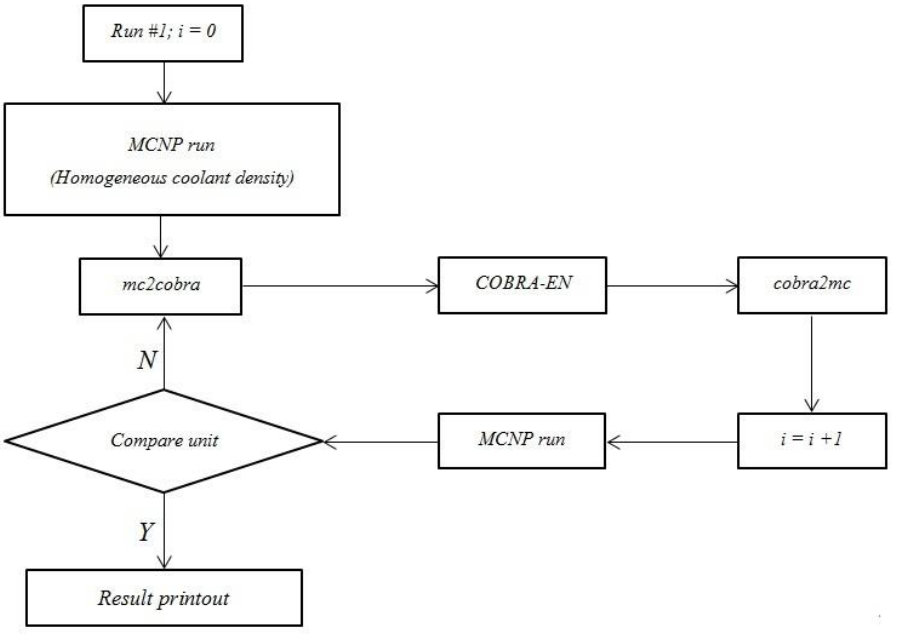

Fig.2. Coupling calculation scheme

In this paper, to investigate the interaction between power distribution and coolant density, we used reciprocal calculations of MCNP5 and COBRA-EN until the power distribution results are converged.

Initially, the calculation scheme starts with MCNP5 calculation for an initial input with an assumption of uniform coolant density and coolant temperature in the VVER-1000 fuel assembly. The power distribution is obtained, and then is transferred to "*mc2cobra"* module to generate input file for COBRA-EN. The "*COBRA-EN run*" subroutine is executed to calculate the thermal hydraulics properties of the fuel assembly. Once the temperature distribution is obtained, the distribution of the coolant density along the assembly is updated and transferred to "*cobra2mc"* module for further iteration with MCNP5.The calculation procedure is repeated until the power distribution satisfies the convergence criterion.

IV. CALCULATION MODEL

Numerical calculations were performed based on the VVER-1000 fuel assembly. The detailed parameters of the fuel assembly are taken from the benchmark problem [3]. The assembly consists of 312 fuel pins, 18 guide tubes and 1 central tube. The guide tubes and central tube are filled by water. The effective length of the fuel assembly is 354 cm and is divided into 10 axial nodes. The MCNP5 model of the VVER-1000 fuel assembly is shown in Fig. 3, where only one sixth configuration of the assembly is used for calculation due to its symmetry. Table I shows the thermal hydraulic parameters used in the COBRA-EN calculations.

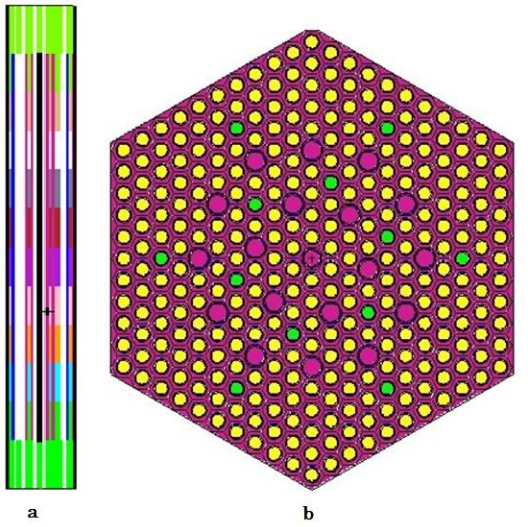

Fig.3. VVER-1000 fuel assembly modeled by MCNP5.
(a: vertical cross-section; b: horizontal cross-section)

Table II. Parametersof coolant used in COBRA-EN calculation

Parameters	Value
Pressure (MPa)	15.7
Average mass flux (kg/m^2/s)	3771
Channel length (m)	3.54
Number of axial nodes	10
Inlet temperature (K)	564

The dependence of coolant density on temperature and pressure can be described as:

$$\rho_1 = \rho_0 / (1 + \beta (t_1 - t_0)) / (1 - (p_1 - p_0) / E)$$

Where: ρ_1 = *final density (kg/m^3)*

ρ_0 = *initial density (kg/m^3)*

β = *volumetric temperature expansion coefficient (m^3/m^3 ^{o}C)*

t_1 = *final temperature (^{o}C)*

t_0 = *initial temperature (^{o}C)*

E = *bulk modulus fluid elasticity (N/m^2)*

p_1 = *final pressure (N/m^2)*

p_0 = *initial pressure (N/m^2)*

In this coupling model, this dependence is calculated automatically by COBRA-EN while the dependence of fuel and cladding thermal conductivity on temperature is not considered. We have carried out the COBRA-EN calculations for two assumed configurations of the coolant channel in the VVER-1000 fuel assembly: hexagonal and triangular channels as showed in Fig. 4. The difference in the coolant channel temperatures obtained from these two configurations is lower than 1 K. To simplify the model, the hexagonal configuration for the coolant channel was used in the coupling calculation scheme.

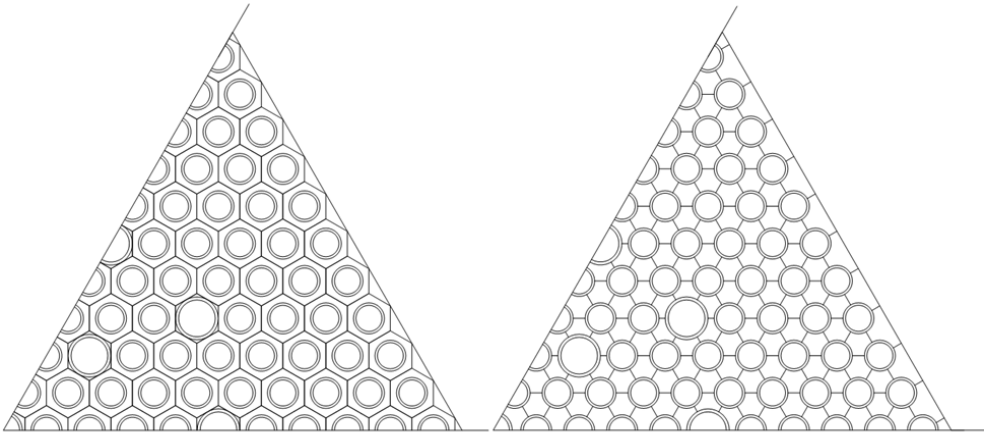

Fig.4. The 1/6th model of the VVER-1000 fuel assembly in COBRA-EN.
(a: Hexagonal coolant channel; b: Triangular coolant channel)

V. RESULTS AND DISCUSSIONS

The power distribution in the one sixth configuration of the VVER-1000 fuel assembly was calculated using MCNP5 with 50 million histories divided into 2000 cycles. The results are shown in Fig. 5. Because the coolant channels around the higher power pins have higher temperature, the coolant density is lower than the average in the fuel assembly. Taking into account the coolant density effect, the power of these higher power pins are decrease due to the lower moderation ability and the thermal neutron flux of these respective coolant channels. Therefore, when the coolant density effect is considered by using the coupling scheme, the radial power distribution becomes flatter and consequently, the power peaking factor is decreased from 1.115 to 1.111 as shown in Fig. 5.

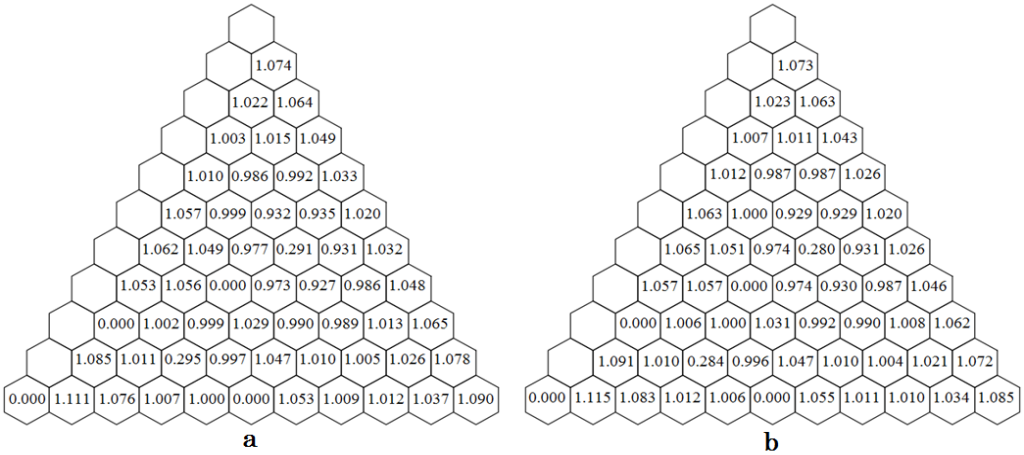

Fig.5. Radial power distribution for two cases: with (a) and without (b) the use of the coupling calculations

The axial power distributions in two cases: with and without the use of the coupling calculation scheme are shown in Fig. 6. One can see that the axial peaking factor obtained is increased by 13.61% from 1.47 to 1.67. The power peak moves from the central position down to the position of the 4th node of the assembly when the coupling scheme is applied. The average power density in the lower half of the fuel assembly increases about 35% taking the coolant density feedback into account. Because the coolant comes from the bottom with the inlet coolant temperature of 564 K to the upper part of the fuel assembly with the outlet temperature of about 600 K, this makes the coolant density at the bottom part higher than that at the upper part of the fuel assembly and as a result, the thermal neutron flux in the bottom part is also higher. These results show similar trends to those for axial power density of PWR fuel assembly calculated by MCNP4/COBRA-TF [1]. Consequently, an increase in the coolant temperature at the bottom part of the fuel assembly was found as shown in Fig. 7. It can be seen that the axial power distribution and coolant temperature distribution are quickly converged due to only the coolant density effect is considered in this coupling scheme.

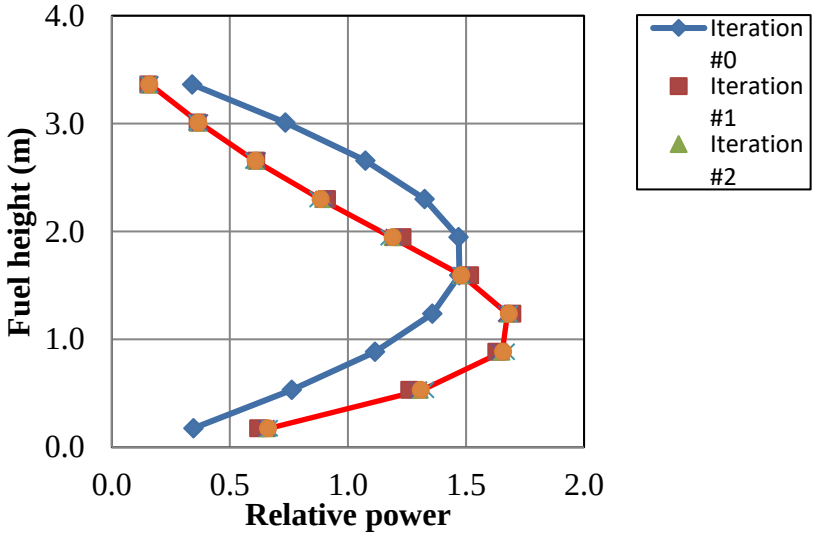

Fig.6. Axial power distribution for two cases: with (Iteration #1-#6) and without (Run #1) the use the coupling calculations

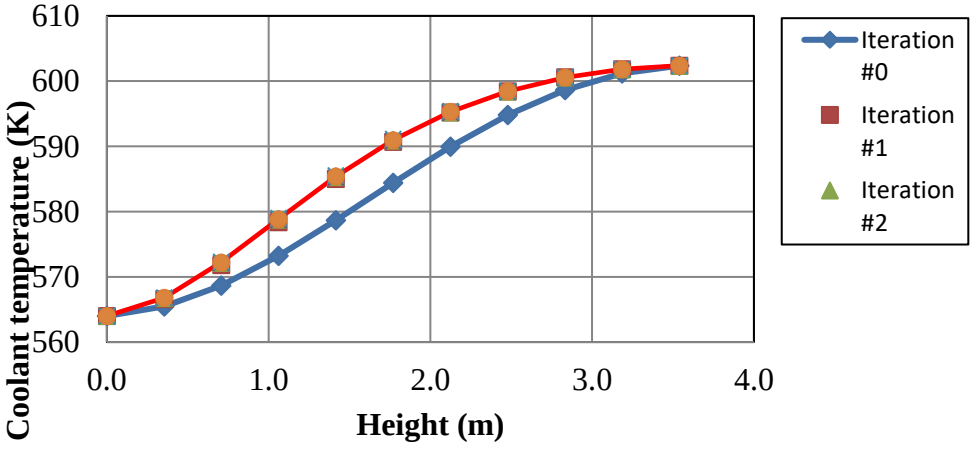

Fig.7. Axial coolant temperature distribution for two cases: with (Iteration #1-#6) and without (Iteration #0) the use the coupling calculations

In addition, the results of *k-inf* at iteration steps are shown in Fig 8. The *k-inf* decreases when the coupling scheme is applied and is converged after few iteration steps. The decrease of *k-inf* is caused by higher temperature of coolant, as shown in Fig 7. Variation in the power distribution is defined as the maximum deviation between the calculation results of the two successive iteration steps from all the fuel pins, and shown in Fig. 9. It can be seen that the variation decreases quickly from about 2.8% in the first iteration step to a stable value of around 0.5% after the third iteration. This stable value depends on the statistics deviation of Monte-Carlo calculation in MCNP5.

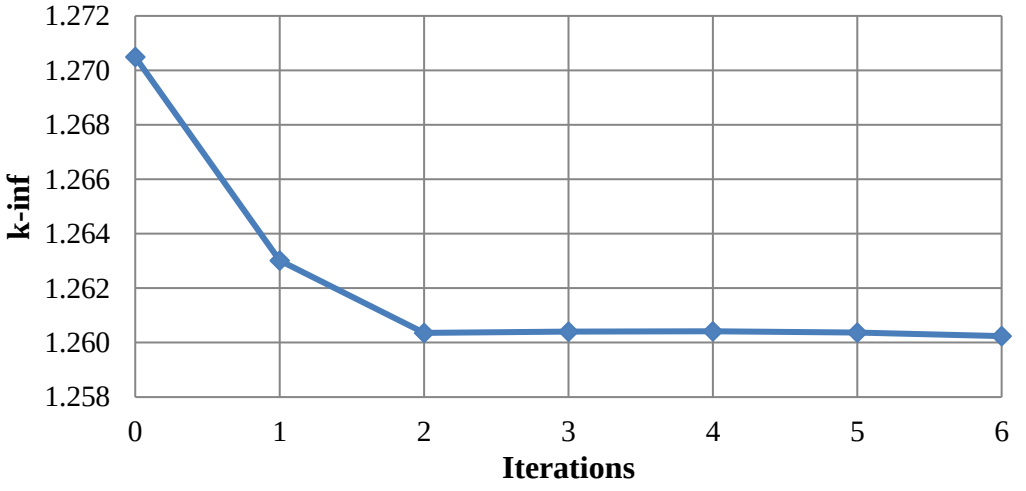

Fig.8. k-inf at iteration steps

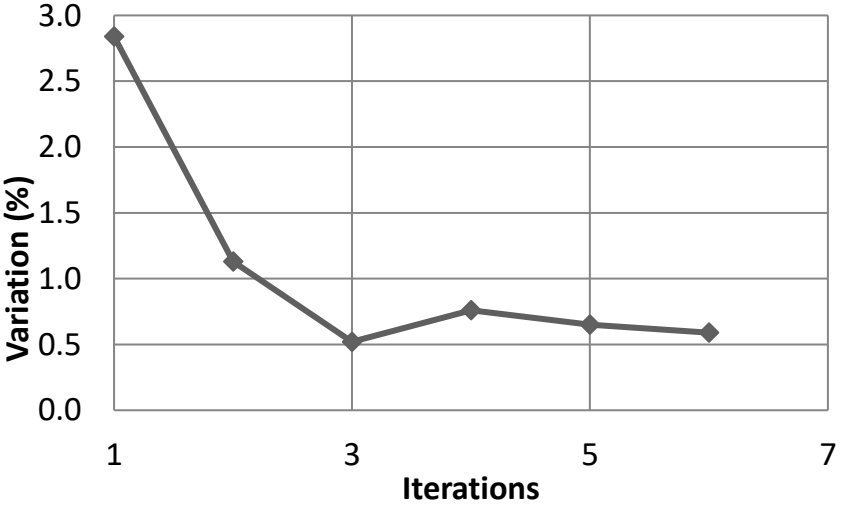

Fig.9. Variation in the power distributions between iteration steps

VI. CONCLUSION

This paper presents the neutronics/thermal hydraulics coupling calculation scheme using the MCNP5 and COBRA-EN to investigate the impact of the coolant density feedback on the power distribution and coolant temperature distribution in the VVER-1000 fuel assembly. The hexagonal coolant channels have been used to simplify the COBRA-EN model. It was found that the coupling scheme has contributed to reduce uncertainties on power peaking factor and coolant temperature distribution

calculations. In future work, this coupling scheme will be improved with consideration of the Doppler effect and Boron concentration to provide better predictions of nuclear reactor core characteristics.

ACKNOWLEDGEMENT

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REFERENCES

[1] V. Sanchez and A. Al-Hamry - Development of a coupling scheme between MCNP and COBRA-TF for the prediction of the pin power of a PWR fuel - International Conference on Mathematics, Computational Methods & Reactor physics, 2009.

[2] A. Abraca, R. Miro, T.Barrachina, G.Verdu – A procedure for coupled thermal-hydraulic subchanel and neutronic codes using COBRA-TF and PARCS – International Nuclear Atlantic Conference, 2011.

[3] Organisation for Economic Co-operation and Development - A VVER-1000 LEU and MOX Assembly Computational Benchmark, 2002.

[4] Björn BECKER - Investigations of COBRA-EN and COBRA-TF for core and assembly simulations and coupling of COBRA-TF and KARBUS – FZKA Technical report, 2005

[5] X-5 Monte Carlo Team - MCNP – A general Monte Carlo N-Particle Transport Code, Version 5, 2003.