INVESTIGATION OF THE MOX PIN TYPE ALLEGRO REACTOR CORE

Štefan Čerba, Ján Haščík, Vladimír Nečas, Vladimír Slugeň

Institute of Nuclear and Physical Engineering, Slovak University of Technology in Bratislava, Ilkovičova 3, 812 19 Bratislava, Slovakia, EU

E-mail: stefan.cerba@stuba.sk

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1. Introduction

The Gas-cooled Fast Reactor (hereinafter the GFR) is one of the six most promising reactor concepts selected by the Generation IV International Forum (GIF)[1].The GFR is a helium cooled system operated at high temperatures in the fast neutron spectrum. The Sustainable Nuclear Energy Technology Platform(SNETP) has selected the GFR as one of the most suitable reactor designs to deal with the issues of uranium utilization and waste minimization. The design of this reactor may partially benefit from a number of previously proposed but not realized conceptions as well as from the research of related technologies of the Sodium-cooled Fast Reactor (SFR) and the Very High Temperature Reactor (VHTR). Among the numerous research activities done into this technology no one led to the final built of any gas cooled fast reactor, therefore the research of the ALLEGRO GFR demonstrator is one of the most necessary steps in the development of the GEN IV GFR. This process has already been started under the umbrella of the European Commission and the GoFastR project. Although Slovakia is not the main contributor to the development of this reactor but Slovakia has been given a privilege to participate in the research since ALLEGRO is assumed to be sited in the central European region.

2. Description of the ALLEGRO MOX reactor core

ALLEGRO is a small 75 MW_{th} reactor, aimed to be the demonstrator of the GEN IV GFR technology. Although there are numerous conceptual designs investigated in the EU, the presented study was performed on the basis of the ESNII+ ALLEGRO MOX core design [2]. The cross sections of the ALLEGRO reactor core models are shown in Fig.1 and the main reactor parameters can be found in Tab.1.

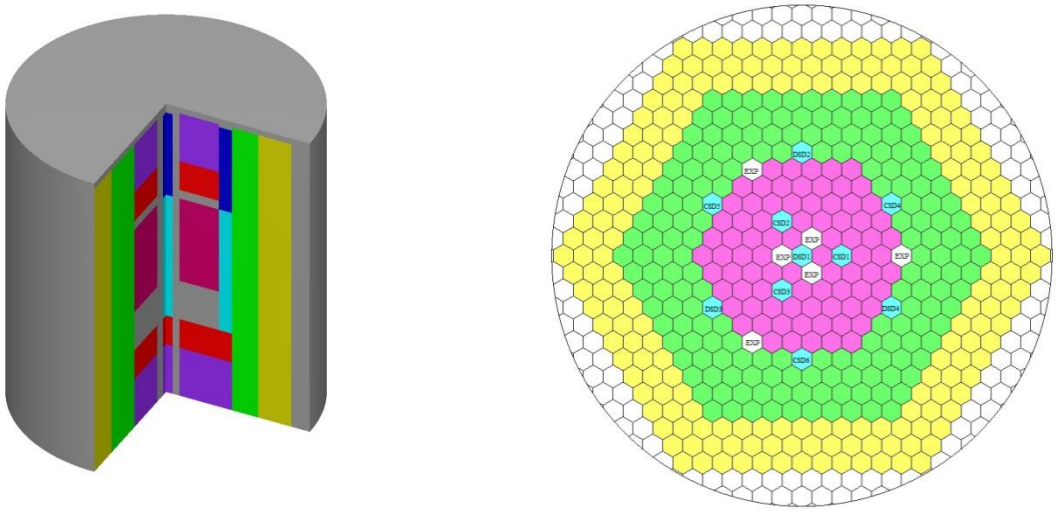

Fig.1:*Cross section of the ALLEGRO reactor core.*

Tab.1. *Basic core parameters [6]*.

Identification	value
Reactor thermal power [MW_{th}]	75
Primary coolant	He
Coolant pressure [bar]	70
Coolant input/output temperature [°C]	260/535
Average fuel temperature [°C]	867
Fuel type and geometry	MOX pin
Average Pu content inHM [$\%_V$]	26
Number of fuel S/As	81
Number of control (CSD/DSD) S/As	6/4
Number of reflector/shield S/As	174/198
Core height (hot) [cm]	86.58
Total reactor height (hot)[cm]	296.99

3. Calculation tools and methods

To ensure diversity of results, 2 stochastic and 1 deterministic computational codes were used for this study. As reference the MCNP5 [3] code was selected, which is ageneral-purpose Monte Carlo N–Particle code. This code treats an arbitrary three-dimensional configuration of materials in geometric cells and is very versatile in source definition and tally structures. One of the main advantages of MCNP is its flexibility to use various pointwise cross section libraries. On the other hand, the user must pay a "heavy" computation price for the continuous energy (CE) calculations and therefore it is not advantageous to use MCNP5 for routinely repeating calculations.

The SCALE6 [4] system solves this issue by introducing a multi-group (MG) approach, in addition to the thorough CE treatment. The SCALE system interconnects several deterministic and stochastic codes for criticality calculations, dose estimation or shielding and uncertainty analyses, but for this study only the Monte Carlo KENO6 module was used. Although the use of MG treatment can speed up the Monte Carlo calculation several times, however, by collapsing the CE energy structure to a finite number of energy groups, the resonance self-shielding of the system may be influenced or even omitted. In such cases the physics of the investigated system may be significantly altered. In addition to the Monte Carlo uncertainty, this may bring another portion of discrepancies into the calculations.

As a counterweight to these "brute force" stochastic techniques there are several sophisticated deterministic methods available. Instead of random sampling, these methods solve the Ludwig Boltzmann transport equation directly, by means of numerical methods. Due to the complicity of solution methods, the majority of deterministic codes is often burdened with limitations. This is reflected on the simplicity of geometry models, or for more complex systems, the transport solution is replaced by diffusion approaches. In either case, the physics of the system should be well understood and therefore these codes are appropriate for experienced users only. DIF3D [5] is a deterministic diffusion code which is capable of solving various geometry structures, including hexagonal 3D problems using the nodal method. It works with region wise multi group cross-section libraries in ISOTXS format. For this study 2 sets of cross section libraries were used, both prepared using the TRANSX [6] code. The first one was the ZZ_KAFAX_E70 [7], which is a Korean 150 group neutron cross section library for fast reactors in MATXS format based on ENDF/B-VII.0 [8] evaluated data. The second set SBJ_620G_E71 [9] is a 620 group neutron cross section library. It was prepared by the authors of this paper for the purpose of GFR reactor core calculations. For both cross section libraries also the collapsed 25 group versions were used.

4. Calculation results

In terms of the most basic calculation of excess reactivity (ρ_e) there were 11 cases investigated, all are listed in Tab 2. For MCNP5 and SCALE6 heterogeneous but for DIF3D homogenous core models were used. In both cases all control rods were placed at the upper position, marked as "all-up" (AU). The influence of the used cross section libraries was estimated by the relative deviation ($\Delta\rho_{MCNP}$) from the MCNP5 CE calculation.

Tab. 2.*Comparison of various XS libraries and group structures.*

Computer code	XS data file	Energy groups	ρ_e [pcm]	$\Delta\rho_{MCNP}$[pcm]
MCNP5	ENDF/B VII.0	CE	1126.8 ± 7.9	
KENO6	ENDF/B VII.0	CE	1292.5 ± 4.7	165.7
KENO6	ENDF/B VII.0	CE HOMO	974.4 ± 19.6	-152.4
KENO6	ENDF/B VII.0	27 G	6263.5 ± 8.8	5136.7
KENO6	ENDF/B VII.0	200 G	2713.3 ± 8.4	1586.5
KENO6	ENDF/B VII.0	238 G	2870.2 ± 9.4	1743.4
KENO6	ENDF/B VII.0	238 G + cell	2539.1 ± 8.9	1412.3
DIF3D	SBJ_620G_E71	620 G	1089.7	-37.1
DIF3D	ZZ_KAFAX_E70	150 G	512.0	-614.8
DIF3D	SBJ_620G_E71	25 G	1605.5	478.7
DIF3D	ZZ_KAFAX_E70	25 G	1112.8	-14.0

The results clearly show that the 27 group cross section libraries of KENO6 are not suitable and even the 200 and 238 group structures are significantly overestimating the excess reactivity of the system. The 238 group libraries can be used only if cell calculations are performed, but even in this case the deviation exceeds 1400 pcm. This could be explained by the changes of the neutron spectrum at the boundary of fuel and reflector. There was a very good agreement found between the CE MCNP5 and fine group DIF3D calculations, where for the 620 group case, the deviations was only -37.1 pcm. After transport corrections and group collapsing the deviation from MCNP5 was still lover than 500 pcm, while the single processor calculation time was decreased to 8.8 seconds (24 hours for MCNP5 on a parallel 12 processor system). After considering all pros and cons, the DIF3D code with both XS libraries and the SCALE6 system with 238 group XS libraries were selected for next calculations.

To evaluate, whether the system of control rods(CR) disposes enough negative reactivity to bring the reactor to a sufficient level of subcriticality, the worth of each control rod should be of a high interest. The worth of i-th CR ($\Delta\rho_i$) can be calculated by Eq. (1) where $\rho_e$is the excess reactivity of the system and ρ_i the reactivity, when the i-th CR is fully inserted. The results can be found in Tab.3.

$$\Delta\rho_i = \rho_i - \rho_e \tag{1}$$

In the reference MCNP5 case the worth of all CR was calculated to 12599.2 ± 7.2 pcm and the worth of the CSD and DSD systems to 8871.1 ± 4.2 and 4111.8 ± 4.2 pcm respectively. Due to the distribution of neutron flux in the core the worth of single devices in various positions differ in a significant manner. While the worth of the central DSD1 device was 2599.1 ± 5.5 pcm, the peripheral CSD4 unit disposes only 452.6 ± 5 pcm. Although there were appreciable discrepancies in the calculation of excess reactivity between codes and XS libraries, but these tendencies were consistent also for cases with inserted CR and therefore the deviations in the CR worth were not that significant. For the case with allCR inserted in the core, marked as "all-down" (AD),there was a -135 pcm deviation between

MCNP5 and KENO6 and 800 pcm deviation between MCNP5 and DIF3D. For single CRs this discrepancy did not exceed 2 %. This accuracy is sufficient, since in MCNP5 the heterogeneous CR design was investigated, while in DIF3D homogeneous compositions were used. The discrepancy between the two DIF3D calculations can be considered as negligible.

Tab. 3.*Results of control rod worth.*

Control rod ID	SCALE6 E70 235G	MCNP5 E70 CE	DIFF3D	
			KAFAX_E70	SBJ_E71
AD	12599.2 ± 7.2	12734.6 ± 11.2	11565.4	11800.6
CSD1	2286.7 ± 5.4	2310.0± 11.3	2172.4	2199.6
CSD4	452.6 ± 5.4	442.9 ± 11.1	436.5	451.5
DSD1	2599.1 ± 5.5	2643.9 ± 11.4	2342.3	2397.1
DSD2	451.6 ± 5.4	447.8 ±11.1	451.5	451.5
CSD	8871.1 ± 4.2	8952.2 ± 11.1	8278.7	8424.3
DSD	4111.8 ± 4.2	4130.8 ± 11.2	3754.3	3863.3
CSD1R	7239.8 ± 5.6	7361.1 ± 11.1	6785.5	6873.0
CSD2R	1453.3 ± 5.5	1396.9 ± 11.2	1353.5	1402.7
DSD1R	2599.1 ± 5.5	2643.9 ± 11.4	2342.3	2397.1
DSD2R	1415.1 ± 5.7	1397.9 ± 11.2	1353.6	1402.7

If one summed up the worth of singe CRs, one would find out this sum not to be equal to the worth of all CRs. The explanation is: there exists interference between control rods, and under the certain action of certain CRs, the worth of a single one can be amplified or attenuated. The mathematical expression can be found in Eq. (2), where $\rho_{1,2..N}$ is the worth of all CRs, ρ_i the worth of the investigated one and $\rho_{(1,2..N)-i}$ the worth of all CRs except the investigated one.

$$A_i = \frac{\rho_{1,2..N} - \rho_{(1,2..N)-i}}{\rho_i} \tag{1}$$

If A_i<1 the worth of the given CR is attenuated and shadowing effects occur, otherwise if A_i>1 there are anti-shadowing effects and the worth of the given CR is amplified. The results of performed calculations can be found in Tab.4.

Tab. 4.*Results of control rod amplification factors.*

Control rod ID	SCALE6 E70 235G	MCNP5 E70 CE	DIFF3D	
			KAFAX_E70	SBJ_E71
CSD1	1.093 ± 0.005	1.097 ± 0.009	1.039	1.039
CSD4	1.383 ± 0.025	1.348 ± 0.050	1.232	1.247
DSD1	0.816 ± 0.008	0.810 ± 0.007	0.768	0.761
DSD2	1.401 ± 0.025	1.306 ± 0.049	1.232	1.247
CSD	0.963 ± 0.001	0.961 ± 0.002	0.944	0.942
DSD	0.921 ± 0.002	0.916 ± 0.005	0.875	0.874
CSD1R	0.969 ± 0.001	0.963 ± 0.003	0.944	0.942
CSD2R	1.252 ± 0.008	1.220 ± 0.015	1.136	1.143
DSD1R	0.816± 0.008	0.810 ± 0.007	0.768	0.761
DSD2R	0.921 ± 0.002	1.218 ± 0.005	1.136	1.143

Although the range of CR worth is relatively wide, the observed interference between CRs is not significant. The CSD and DSD systems are influenced only marginally. The 1st rings of the CSD and DSD systems are slightly attenuated and there is a small, but noticeable anti shadowing effect in case of the second ring of both CSD and DSD systems. The strongest shadowing effect was observed for the central DSD1 assembly, which was caused by the presence of high worth CSD1-3 devices in the central region. The strongest anti shadowing effect was found for CSD4, which is located in the region in which the neutron flux is pushed out from the centre, due to the operation of DSD1 and CSD1-3 devices.

To understand the behaviour of the ALLEGRO core from local point of view, a special feature of the SCALE6 system, the calculation of local multiplication values (LMV)[10] can be used. These LMV factors may paint out, how a given fuel assembly is behaving in a given position of the reactor core. These LMV factors can reveal existence of locally decoupled neutronic zones. In our case, these factors were calculated for both ”all up” and ”all down” cases. The results can be found in Fig.2.To graphically plot the LMV results a special C++ utility was developed.

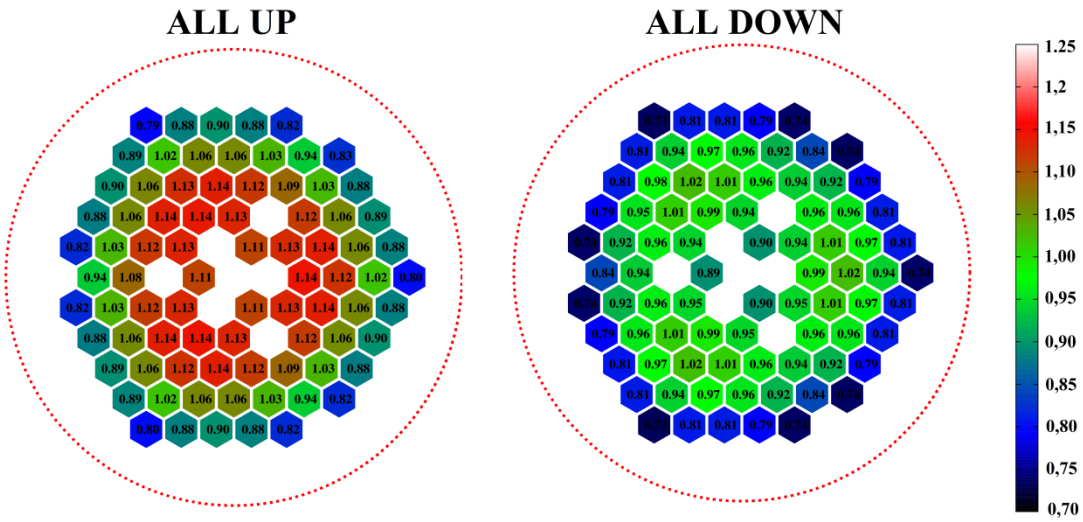

Fig.2: *Results of LMV factors for the ALL UP and ALL DOWN cases*

It is obvious, that under normal operation conditions, the LMV factors exceed the value of unity, but the thing we should be concerned about, is the existence of such zones in a case where all CRs are fully inserted. From Fig.2 we can see 12 S/As with LMV>1 and another 4 with LMV are close to 1. This phenomenon may have been caused by the low worth of CRs in the peripheral region. This question should be addressed in future analyses.

5. Conclusions

In this study the neutronic performance of the ESNII+ ALLEGRO MOX core was investigated. The stochastic MCNP and SCALE and the deterministic DIF3D codes were used with various cross section libraries. In case of SCALE6 multi group treatment was used and it was found out that, the lowest discrepancy to the MCNP CE calculation can be found for 238 group cross section libraries with cell calculations. In case of DIF3D both ZZ_KAFAX_E70 and SBJ_620G_E71 MATXS cross section libraries showed good performance. The total worth of CR was calculated to 12599.2 ± 7.2 pcmby MCNP5 and 11800.6pcm by DIF3D. It was found out, that although the cross section libraries differed in terms of excess reactivity, but the deviation for CR worth calculation was not significant. The results of CR interference showed that there exist some shadowing and anti-shadowing

effects between the CRs, but they are not significant. The calculation of LMV factors identified an existence of local neutronic zones. This phenomenon should be studied in the future. By way of conclusion it can be said, that it is advantageous to perform the ALLEGRO core calculations by DIF3D, since the precision is comparable with Monte Carlo ones and it is not burdened with statistical uncertainties. Another advantage of DIF3D is the 10 second calculation time, while to obtain MCNP5 results of similar precision it takes several days to run.

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