ALLEGRO Core Neutron Physics Studies

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Abstract

The status of neutron-physical analysis of ALLEGRO - demonstrator of the gas cooled reactor is presented at this article.

A benchmarking of existing neutronic codes used for PWR analyses mainly was initiated as a first task, solved at running projects. As there are available no neutronic experiments with He coolant at fast spectrum, code to code comparison was selected as first stage of validation process.

ALLEGRO oriented neutronic benchmark at EU H2020 project VINCO was split into two phases. Definition, solution and conclusions of first phase concentrated on pin calculation - The First VINCO Neutronic Methodological Benchmark - is described in this paper. Definition of second phase - VINCO Neutronic Assembly Oriented Benchmark - and its first evaluation are treated as well.

Evolution of ALLEGRO core is driven by two factors - the DHR issue related to power density and the potential use of UOX fuel for first cycles (instead of MOX). The first round of calculations oriented on UOX fuel feasibility including resulting directions for core modifications is presented in the paper.

Key Words: ALLEGRO, neutronic benchmark, feasibility study, GFR

1. INTRODUCTION

Gas cooled fast reactor demonstrator ALLEGRO was originally proposed and developed at CEA France. Resulting status is called CEA concept 2009. Consequently development activity was delegated to V4G4 countries - Czech Republic, Slovakia, Hungary and Poland. Status of development activities in the field of reactor physics is characterised at this paper.

2. THE FIRST VINCO NEUTRONIC METHODOLOGICAL BENCHMARK

3D reactor physics common calculation exercises ("benchmarks") were performed in earlier studies. The whole core calculation including reflectors and detailed description of the structural elements, which are based on the 2009 CEA concept of the ALLEGRO core [1], was aim of this activity. Fixed nominal technological data at nominal reactor state (geometry, composition) were prescribed. It had to be modified in specified calculation branches according to different types of the thermal expansion and control rod positions. The parameters of the point kinetic model to be applied in a system thermal hydraulic code had to be determined this way. Static mechanical models of the expansion processes were specified by the benchmark. The obtained deviations among the participants are characterizing the user effects, the modelling uncertainties and the influence of the nuclear data differences all. There is no possibility to separate them because of the complexity of the benchmark problem. A conclusion could be drawn that a step by step procedure starting from simple problems (homogenous material, Wigner-Seitz cell or SA in asymptotic approach) is necessary if we wish to identify the reasons of the deviations. This approach of the simplicity is followed in the "First VINCO Neutronic Methodological Benchmark" [2]. Additionally, the simple benchmark was extended with burnup calculations and with inclusion of leakage in asymptotic approximation by neglecting the complicated processes necessary in the reflector regions.

In the usual deterministic reactor physics calculations the following two level approach is applied:

1. Group constant generation for the second level by using a spectral code. Only a limited part of the reactor, namely a pin cell with its environment or assembly, is modelled in the asymptotic region.
2. Parameterization according to the temperatures and the isotopic composition.
3. Nodal code modelling of the entire core using the parameterized group constants.

The presented benchmark is aiming at the first phase of the above procedure. Additionally – to avoid or minimize the user effects - the simplest heterogeneous unit of the reactor, a pin surrounded by the hexagonal cell is to be calculated. (Calculation of the assembly would raise very similar modelling problems.)

Taking into account the capabilities of the different computer codes concerning the leakage calculations and the buckling iterations in the calculation routes, two options are defined. In the case of Option A, the buckling is to be iterated to reach the criticality, while in the case of Option B, the buckling is always fixed.

The physical effects of the modelling to be verified by solving the benchmark are as follows:

1. Nuclear data uncertainties
2. Satisfactorily detailed energy discretization
3. Resonance self-shielding in the energy region of the resolved resonances
4. Resonance self-shielding in the unresolved region by using statistical approach
5. Representing anisotropy of the scattering in the leakage calculation
6. Representing anisotropy of the flux in the leakage calculation

The results of the following codes are presented:
UJV Řež: ECCO module of ERANOS2.2 with JEF3.1 library [3]
VUJE: HELIOS 2.1.1 [4] with ENDF/B-VII.0 cross section library
VUJE: SERPENT2.1.25 [5] with ENDF/B-VII cross section library
NCBJ: SCALE 6.2 [6] with ENDF/B-VII.0 (not confirmed by NCBJ)
NCBJ: SCALE 6.1.3 with ENDF/B-VII.0 (not confirmed by NCBJ)
MTA EK: ECCO module of ERANOS2.2 with JEF3.1 nuclear data.

Some results obtained for the MOX and UOX fuel case are presented in the following Figures 1 - 6. Significant numerical instability can be seen at pellet expansion coefficient values calculated by HELIOS code - see Fig.4.

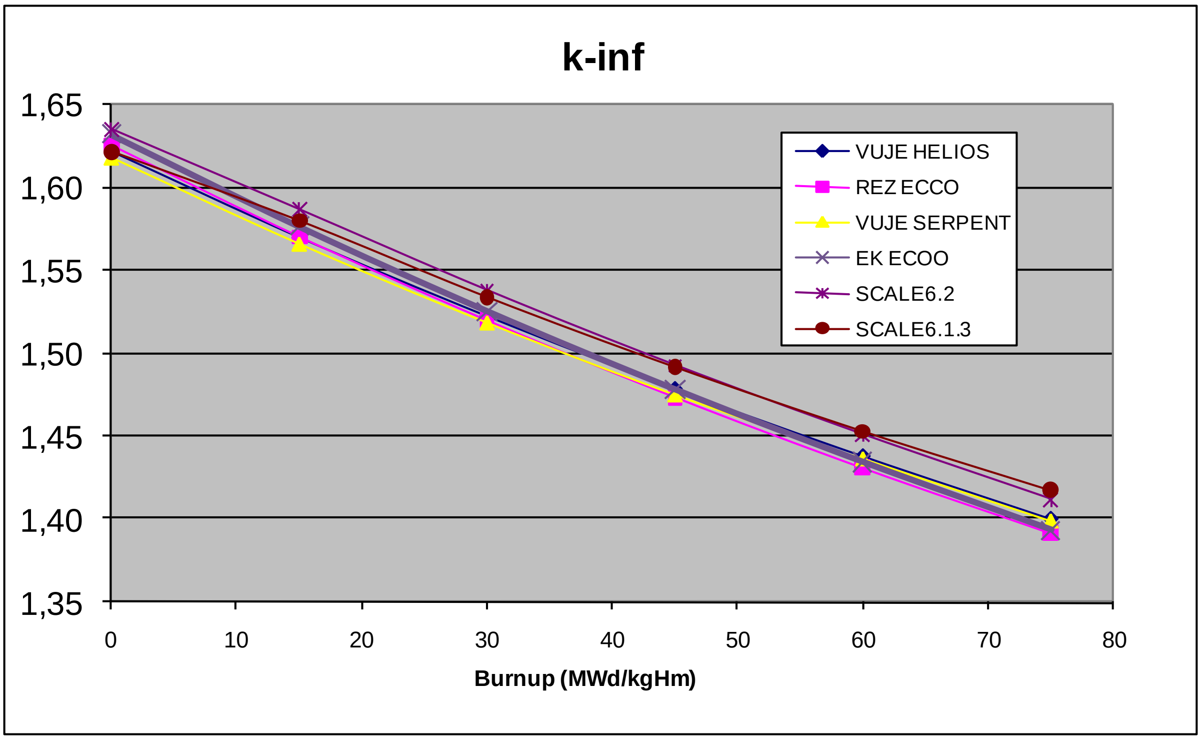

Fig.1 Comparison of the effective infinite multiplication factor ("k-inf") at Methodical benchmark

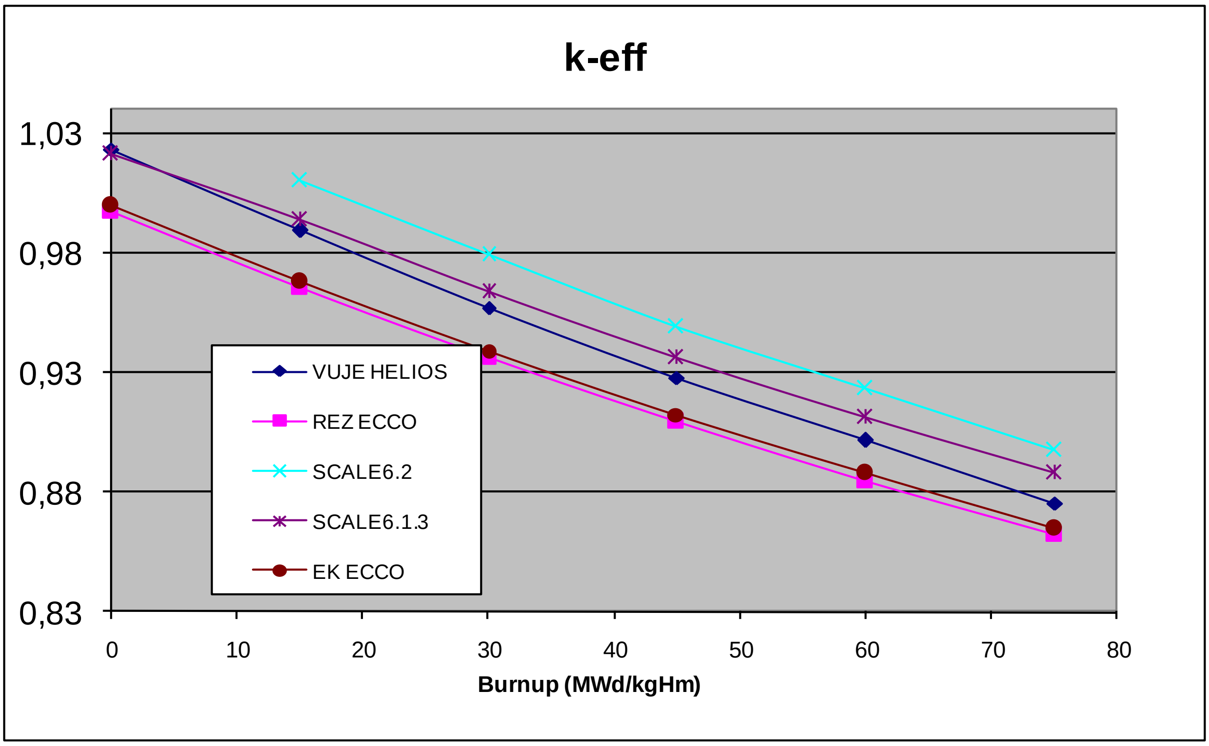

Fig.2 Comparison of the effective multiplication factor taking into account the leakage effect with the prescribed buckling at Methodical benchmark

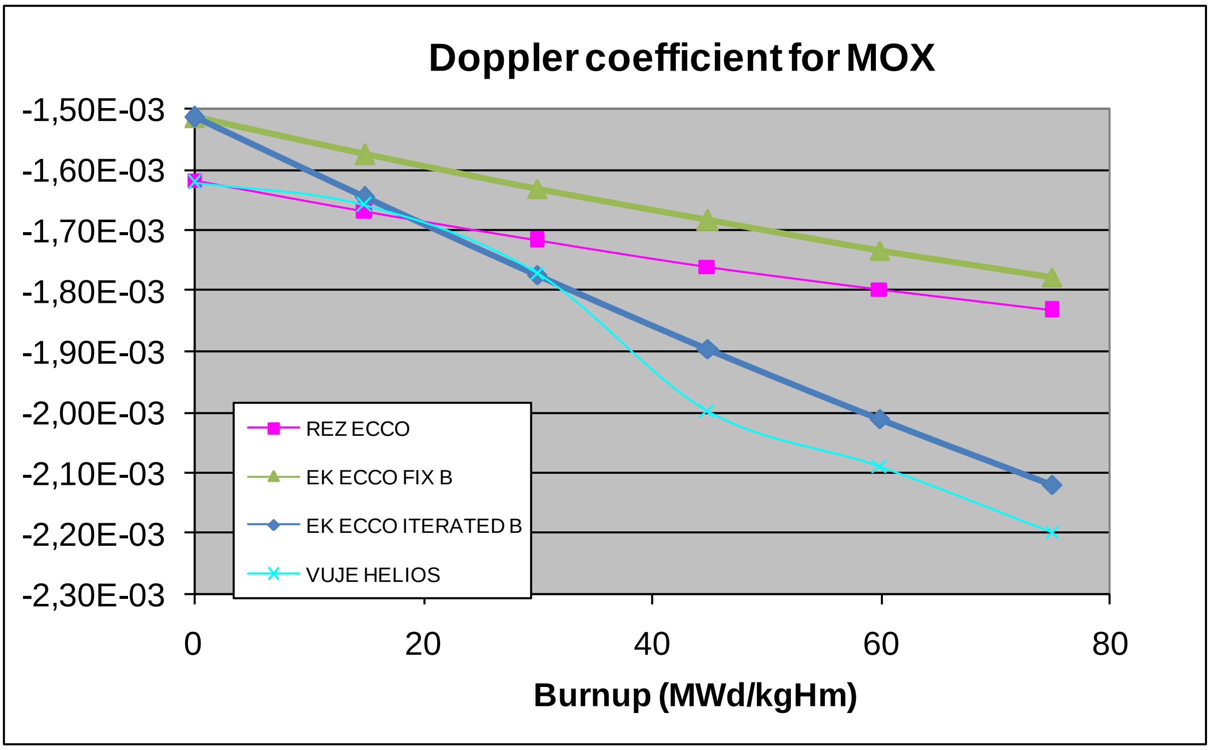

Fig.3 Comparison of the Doppler Coefficients at Methodical benchmark

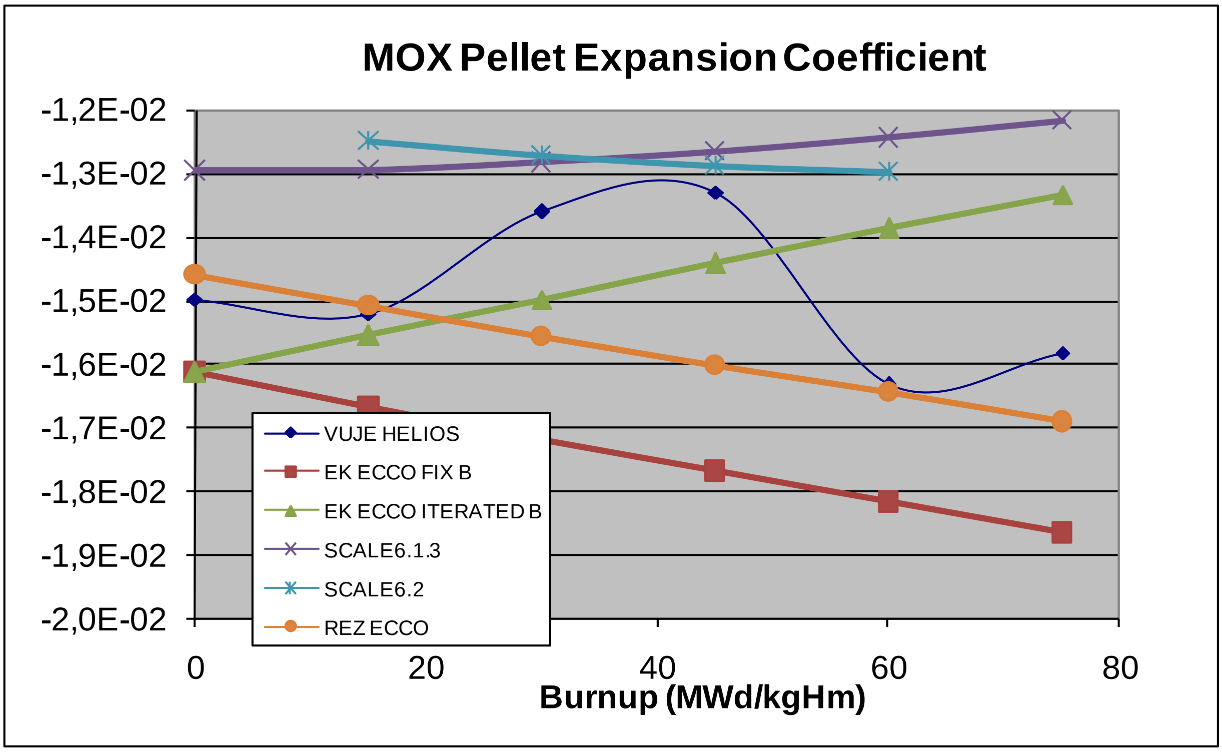

Fig.4 Comparison of the pellet expansion coefficients at Methodical benchmark

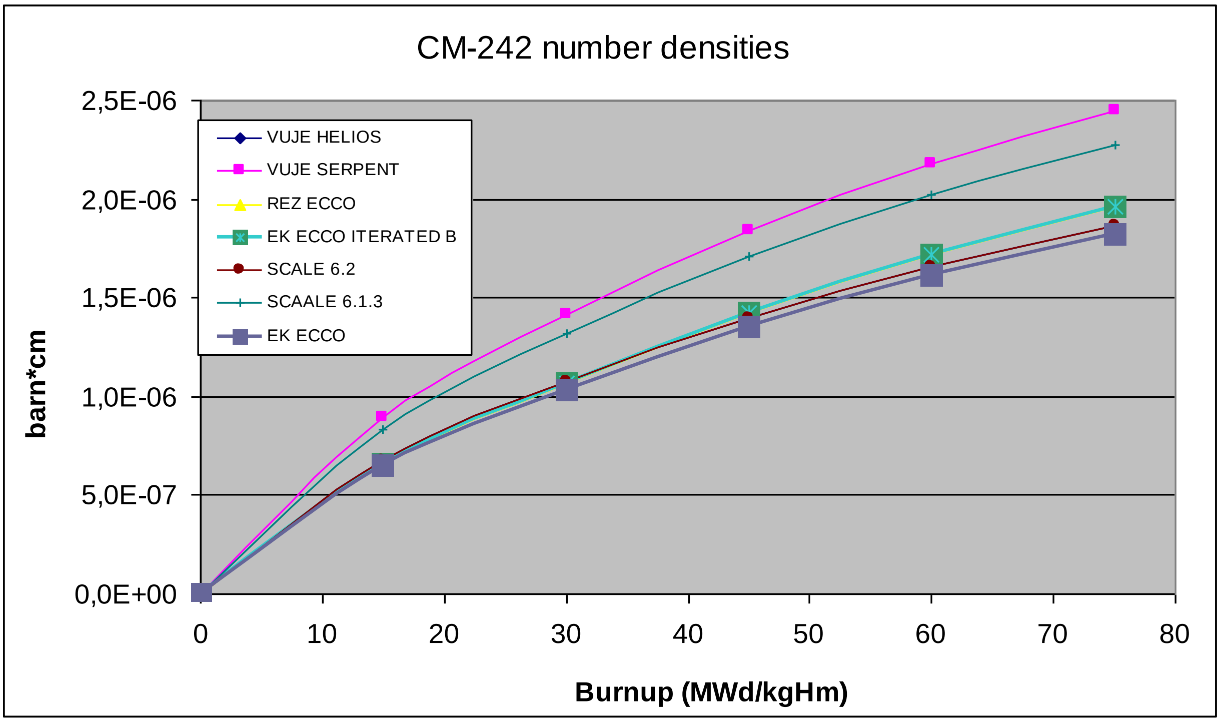

Fig.5 Comparison of the burnup dependent Cm-242 number densities at Methodical benchmark

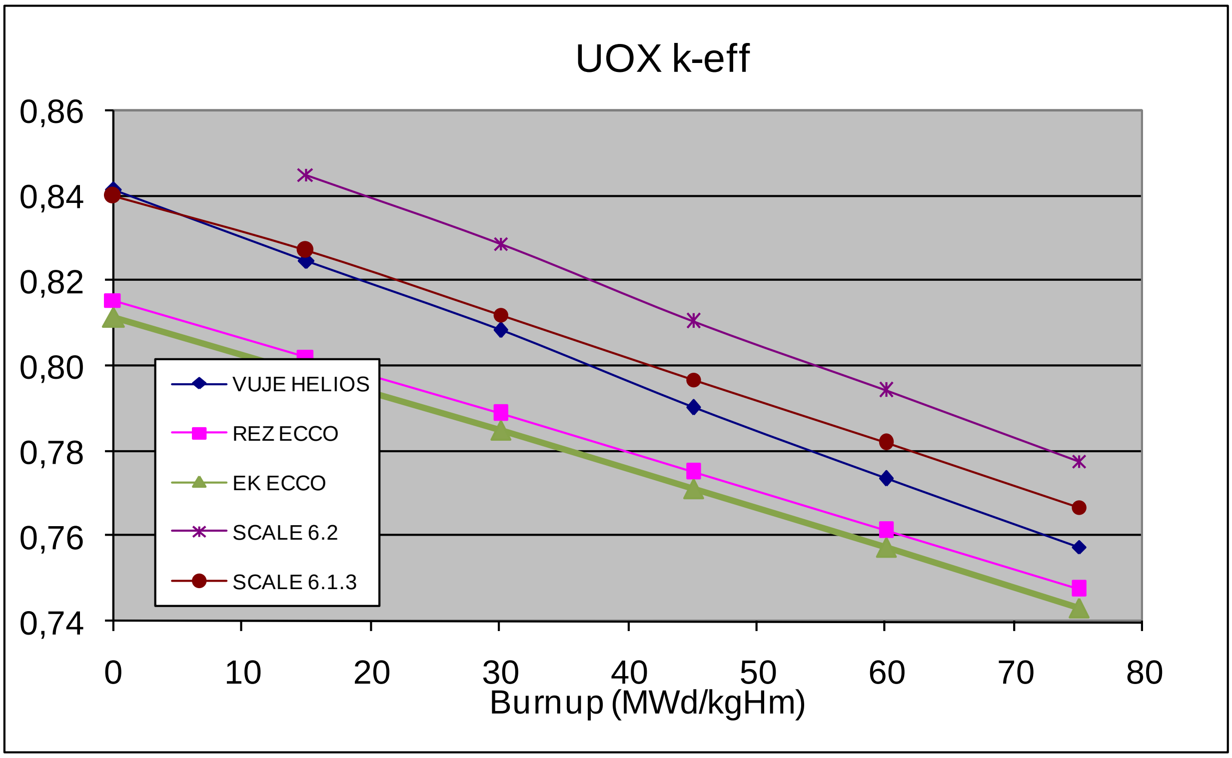

Fig.6 Comparison of the effective multiplication factor if MOX pellet material is replaced with 20% UOX but the geometry in unchanged at Methodical benchmark

Although the deviations of the results for the MOX fuel are smaller in comparison with earlier 3D calculation exercises, they are remaining considerable due to the impacts of the following modelling characteristics:

- Nuclear data uncertainties
- Resonance self-shielding in the energy region of the resolved and unresolved resonances

The not zero buckling prescription of the benchmark could show the impact of the leakage models not only for the k-eff but also for the Doppler Coefficient and the pellet expansion coefficient. The probable reason of these deviations can be the modelling differences of

- the anisotropy of the scattering in the leakage calculation and
- the anisotropy of the flux

that are leading to different migration areas and must be important also in the 3D core calculations. The problem is also demonstrated by the fact that the differences of the k-eff values are much larger than those for the k-inf.

For some isotopes, the impact of the leakage on the spectrum leads to different number densities during the burnup process.

3. VINCO NEUTRONIC ASSEMBLY ORIENTED BENCHMARK

This assembly oriented benchmark is aimed at detailed comparison of stochastic and deterministic codes on subassembly calculations without any leakage correction. Definition was motivated mainly by two reasons. First one - utilisation of the buckling (fixed or iterated) is up to now not possible at stochastic codes; consequently detailed comparison of stochastic and deterministic codes based on keff with leakage respected by buckling is practically impossible. Second one - preparation of cross section data for macrocodes was up to now based on 2-D calculation of fuel subassembly.

The benchmark is defined as broadening of methodological benchmark with the same physical effects for verification and the same participants. Physical effects for verification and potential participants are the same as in previous benchmark. Differences in comparison with methodological benchmark are as follows [7]:

- 2D numerical models of ALLEGRO fuel assembly
- infinite lattice without fixed buckling,
- approximation of realistic temperature distribution,
- requested results include also kinetic parameters and transport cross section,
- results based on infinite multiplication factor,
- more detailed comparison of deterministic and MC calculations.

At this chapter SCALE results were prepared at another company:
VUJE: SCALE 6.2 with cross section library based on ENDF/B-VII.0
Selection from first round of results covers both fuel variants: MOX - Fig.7-8, UOX - Fig.9-11. Significant numerical instability can be seen at Doppler coefficient and Void coefficient values calculated by SERPENT code - see Fig.7 and 8. Situation is similar for Void coefficient SCALE values - Fig.8.

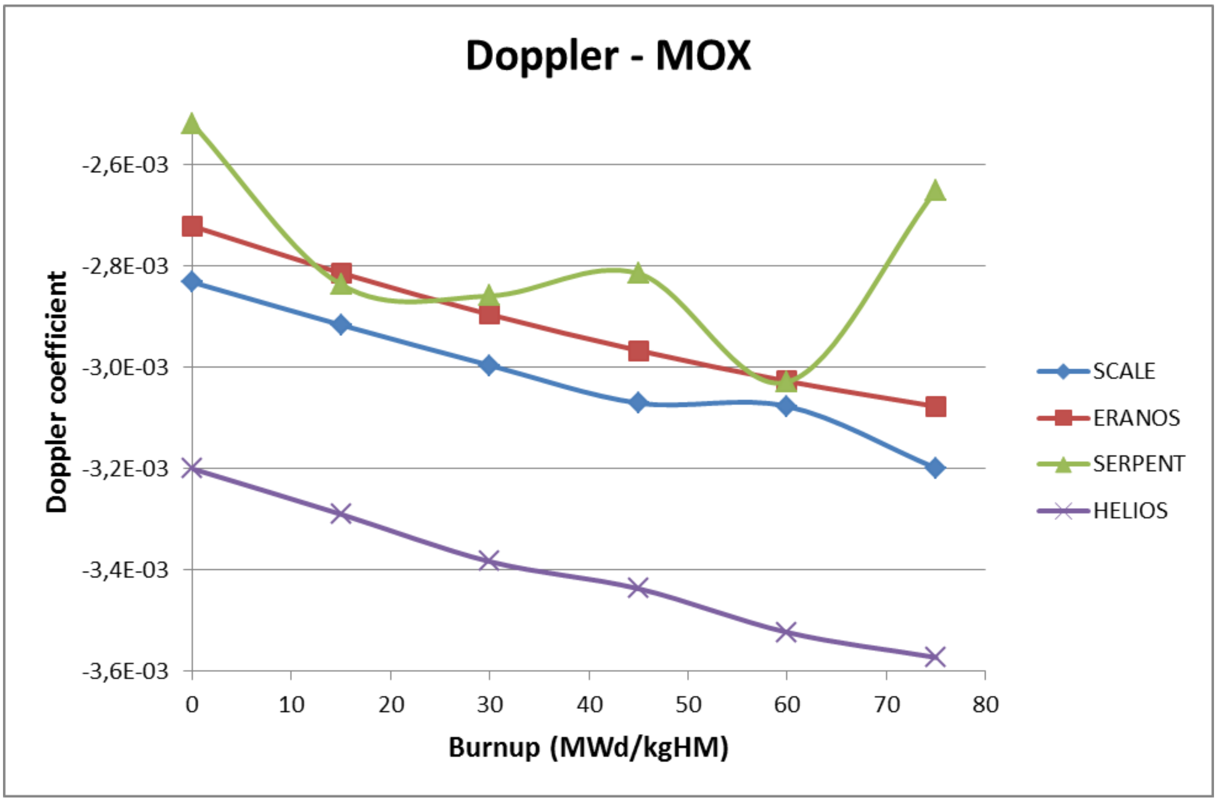

Fig.7 Comparison of the Doppler coefficient for MOX fuel at Assembly oriented benchmark

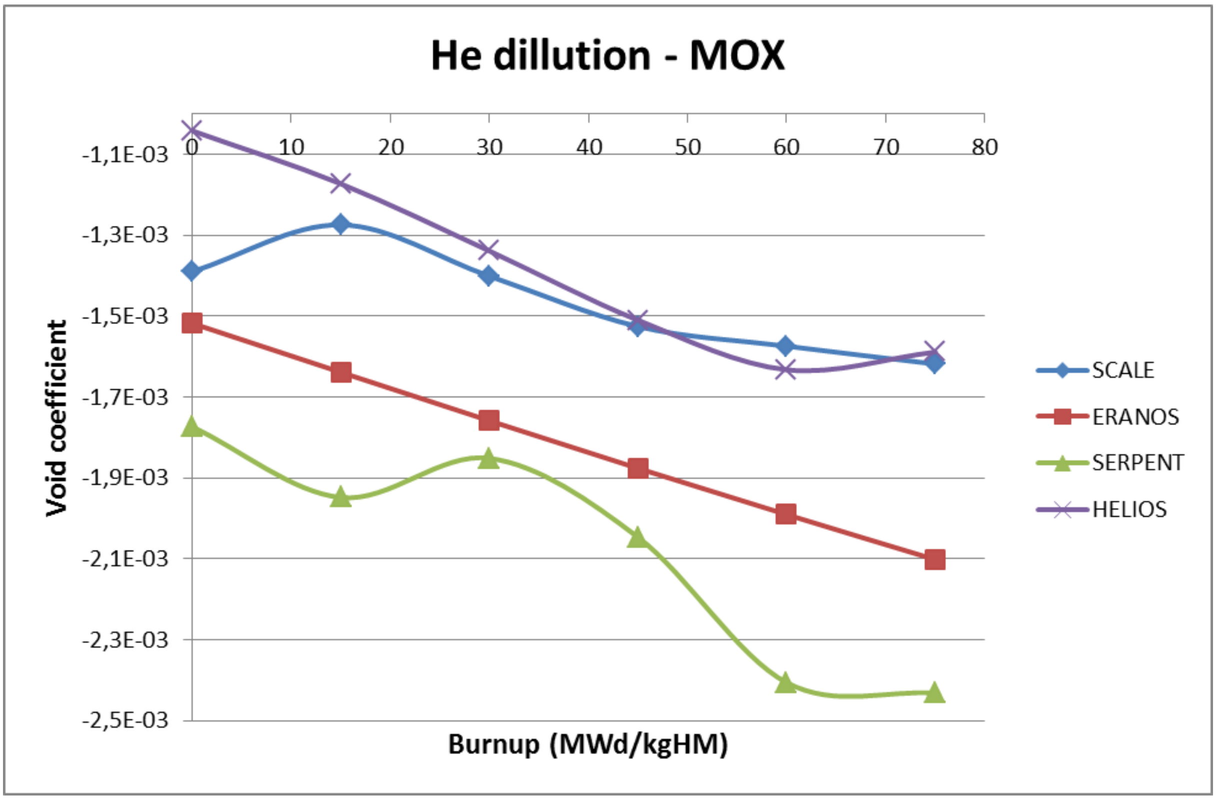

Fig.8 Comparison of Void coefficient for MOX fuel at Assembly oriented benchmark

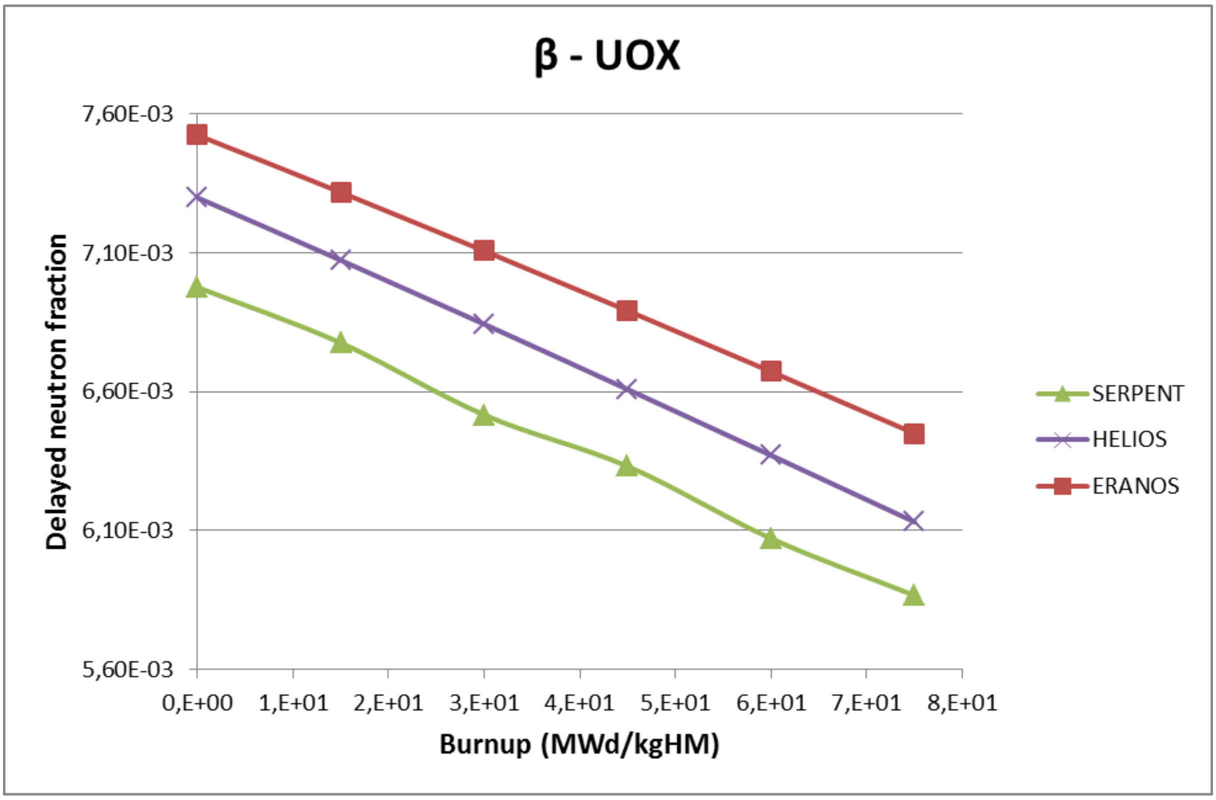

Fig.9 Comparison of delayed neutron fraction („β“) for UOX fuel at Assembly oriented benchmark

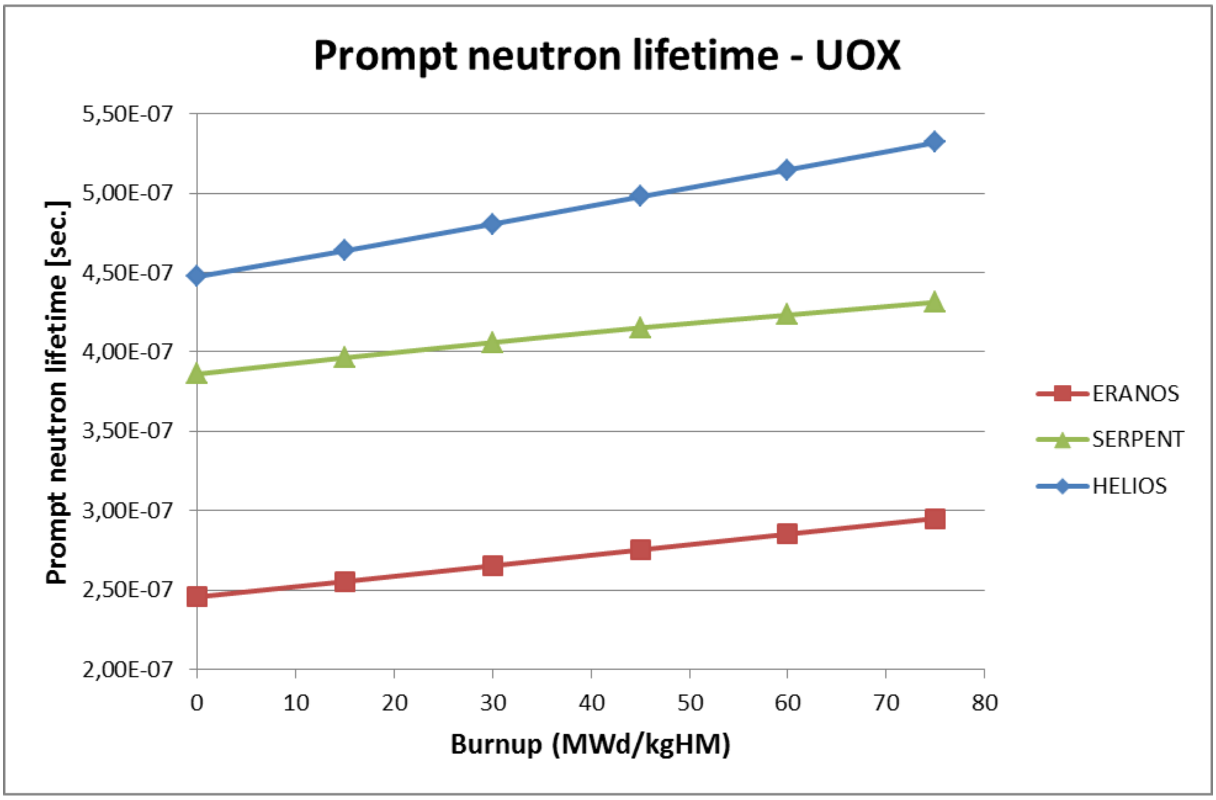

Fig.10 Comparison of prompt neutron lifetime for UOX fuel at Assembly oriented benchmark

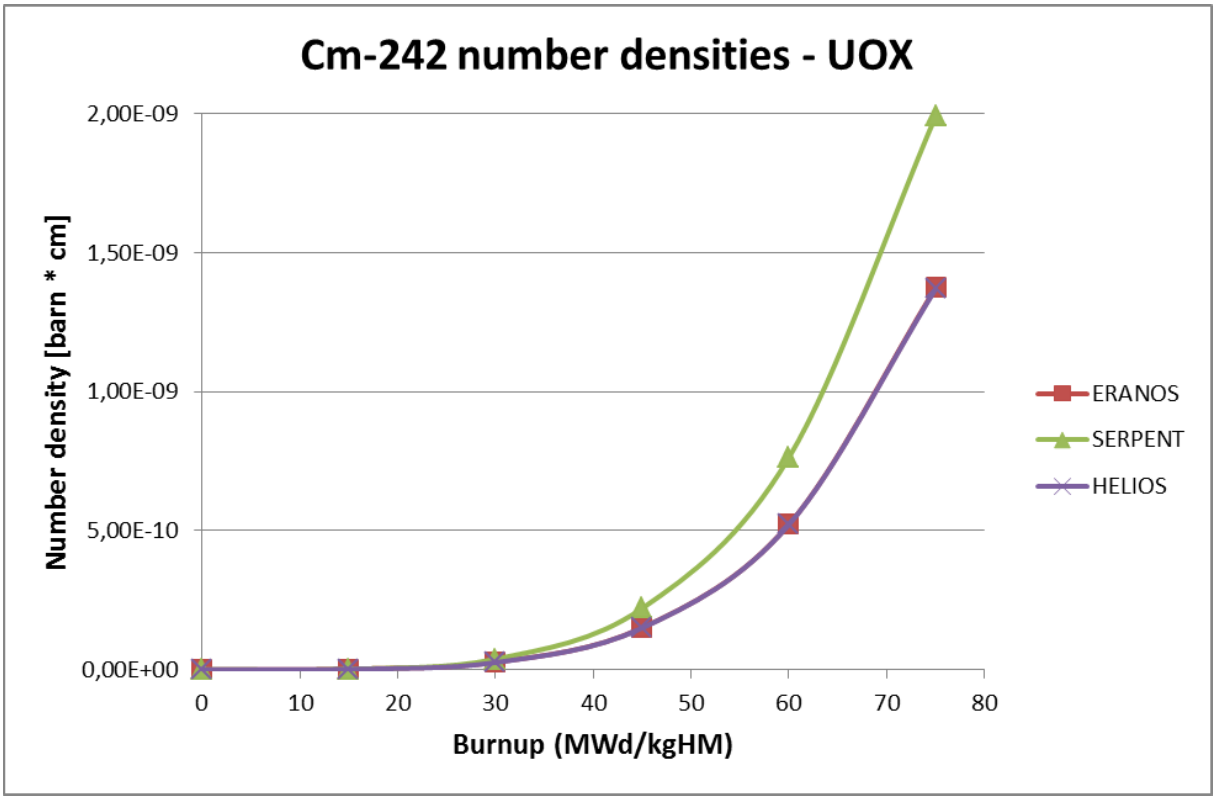

Fig.11 Comparison of the burnup dependent Cm-242 numb. dens. for UOX fuel at Assembly oriented benchmark

Regardless of relatively good kinf agreement, significant differences at burnup process (surprising differences even at U-235 and Pu-239 concentrations, high discrepancies for Cm-242), reactivity effects and kinetic parameters indicate influence of nuclear data libraries (and its uncertainties) and methods used. Another effort is needed to eliminate discrepancies caused by user effect.

4. UOX ALLEGRO

Problematic availability of MOX fuel with high Pu content initiated evaluation of UOX fuel feasibility at ALLEGRO reactor. Uranium enrichment is limited by 20% U235 to eliminate nuclear fuel misuse. Results of first neutronic analyses are shown at following chapters.

4.1 UOX core analysis by SERPENT at VUJE

Core scenarios were taken into account as follows [8]:

- Original core was fuelled by UOX assemblies and enlarged:
  - I 1 ring more + axial enlargement, 75 MWth
  - II 1 ring more + axial enlargement, 37.5 MWth
  - III 2 rings more + axial enlargement, 75 MWth
  - IV 2 rings more + axial enlargement, 37.5 MWth
  - V 2 rings more + axial enlargement, 3 exp. positions only, 75 MWth - see Fig.12
  - VI 2 rings more + axial enlargement, 3 exp. positions only, 37.5 MWth
- Ratio: core diameter / core height was kept
- Fuel Composition: UOX (VINCO Benchmark), MOX (ESNII+ Project)
- Used code: SERPENT 2.1.25 + ENDF/B-VII

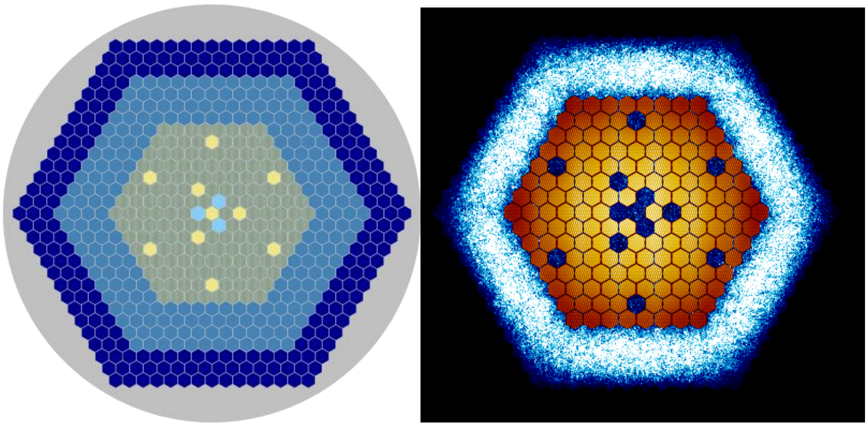

Fig.12 UOX Core, 2 rings more + axial enlargement, 3 exp. positions only, 75 MW_{th} and 37.5 MW_{th}

Comparison of scenarios can be seen at Fig.13.

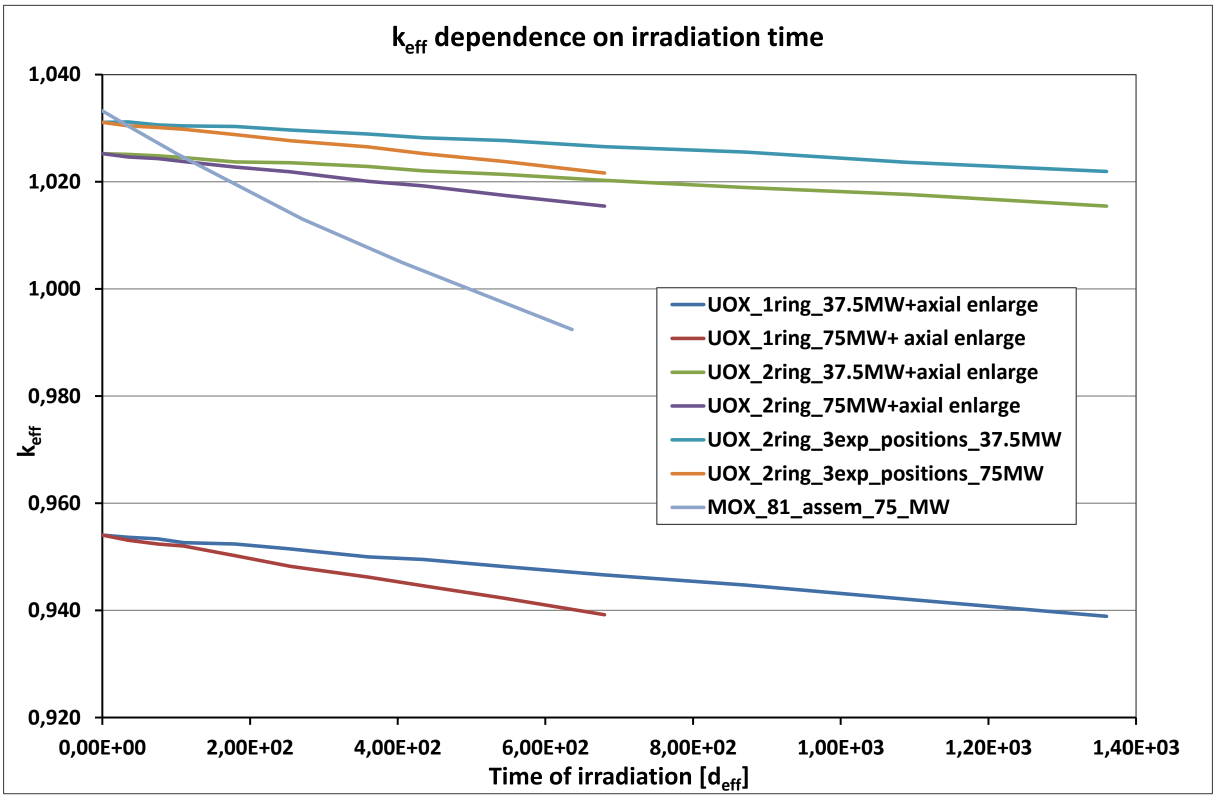

Fig. 13 Burnup dependent k_{eff} for selected variants

Core with 2 more fuel assembly rings, appropriate axial enlargement and 3 experimental positions filled with fuel assemblies seems to be feasible for utilisation of UOX fuel at the ALLEGRO reactor.

4.2 UOX core analysis by ERANOS at UJV

The parametric core study on multiplication factor brings several reasonable core modifications ensuring the criticality [9]. The presented core feasibility study does not treat any nonfuel areas - the radial and axial reflector and shielding as well as the control and the shutdown rods are not subject matter.

Reference Calculations

There are defined three reference calculations for the three ALLEGRO core variants.

1) MOX/MC (mixed carbides) original CEA design (2009)
2) only MOX (25.5% enrichment) fuel assemblies in the core – in this case all the MC experimental assemblies with thermal shielding of the original CEA design are replaced with MOX assemblies
3) only UOX (20% enrichment) fuel assemblies in the core – all the MOX and all the MC assemblies of the original CEA design are replaced with UOX assemblies

Below there are listed keff values for all the defined variants

1) MOX/MC: keff = 1.03498

2) only MOX: keff = 1.0464
3) only UOX: keff = 0.8673

The UOX core variant is deeply subcritical and therefore significant ALLEGRO core design modifications in order to reach the criticality have to be done.

Parametric Study

Number of fuel assembly rings, **fuel height** and **fuel pellet diameter** are considered as a set of parameters suitable for the core feasibility study. The original values of the considered parameters can be seen at Tab.1.

	Unit	Value
Number of Fuel Rings		6
Fuel Height	cm	86
Fuel Pellet Diameter	cm	0.542 (cold)

Tab.1 Original values of parameters

The parametric study is described at the Tab.2. There are defined two cases depending on the number of the fuel rings in the core – for the **Case 1** there is one ring added to the core and for the **Case 2** there are two rings added to the core. For both the cases the fuel pellet diameter and the fuel height are being increased. Due to a requirement to keep the assembly coolant area the original, the fuel rod pin pitch is increased together with the fuel pellet diameter – **the gap between two surrounding fuel rods remains constant**.

	Rings	Fuel pellet diameter (cold) [cm]	Fuel height [cm]
Case 1	7	0.542 to 0.7046 (+30%)	86 to 118
Case 2	8	0.542 to 0.7046 (+30%)	86 to 118

Tab.2 Parametric study extent

Results of the Parametric Study - see Fig. 14 and 15

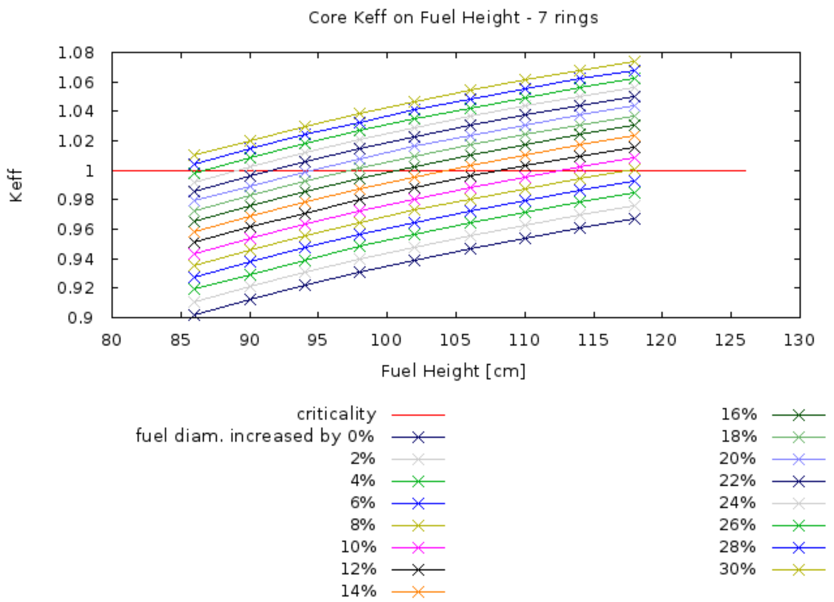

*Fig. 14 Keff dependency on fuel height and fuel diameter for **Case 1***

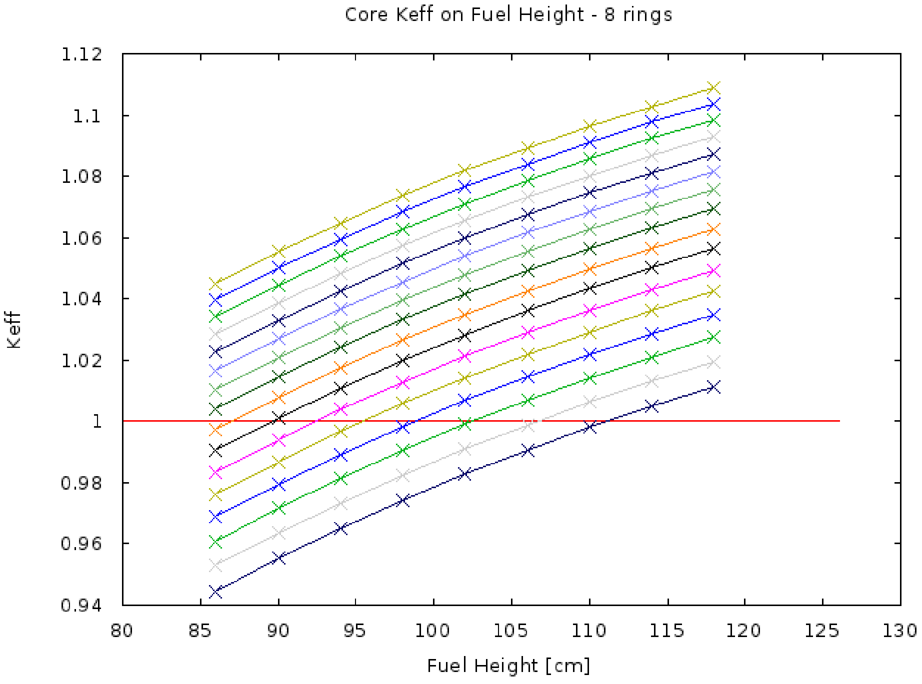

Fig. 15 Keff dependency on fuel height and fuel diameter for ***Case 2***

Discussion

It seems that **Case 2** introducing 2 additional rings in the core is appropriate due to a broad range of the fuel pellet diameter and core height increase combinations reaching the criticality. On the other side, if there is no pellet increase limitation, especially in context with the fuel melting, then **Case 1** together with significant pellet diameter increase could be the most appropriate solution to make the UOX core overcritical.

4.3 UOX core analysis by ERANOS at CEA

Results of core analysis by 3D diffusion calculation at ERANOS code can be seen at Tab.3 [10].

Modification	Reactivity change (pcm) (ERANOS)
MOX (25,5%) > UOX (20%)	-19000
Remove 6 diluents for experimental S/As	+3800
81>117 S/As (+1 ring) (Pvol - 44%)	+8900
81>159 S/As (+2 rings) (Pvol -50%)	+15000
Fissile height 86 cm > 106 cm (Pvol -23%)	+6100
Fuel fraction 36% > 39% (Pin section -11% and wire diameter 1,3 mm > 1 mm)	+6300
Fuel fraction 36% > 43% (ASTRID)	+11500

Tab.3 Fresh core reactivity changes

Discussion of ERANOS calculations at CEA:

- The 19 000 pcm, may be recovered by significant increasing of the core volume (50% to 100%),
- Take advantage of the decrease of the power density to increase the fuel fraction to around 40% (if feasible from the aerolics point of view),
- The resulting reduction on the neutron flux would be around 50%.

4.4 Partial conclusions

Comparison of UOX core analyses by ERANOS, SERPENT and MCNP [11] codes can be seen at Tab.4. In this table, the ERANOS cases differ from the cases introduced in the section 4.2 – Tab.2; the fuel assembly pin pitch remains constant.

Source	Computer code	Additional fuel rings	Active core height	Fuel pin diameter	k-eff
UJV Rez “26”	ERANOS	2	117 cm	Original	1.02492
UJV “145”	ERANOS	1	102 cm	10 % increased	1.02957
VUJE	SERPENT	2	117 cm	Original	1.02526
VUJE	SERPENT	2*(+3SA)	117 cm	Original	1.03151
BTU	MCNP	2	106 cm	5 % increased	1.02742

Tab.4 Comparison of k_{eff} from ERANOS, SERPENT and MCNP analyses

Limitation on UOX enrichment < 20 % was solved mainly by increase of core volume:

- addition of fuel assembly rings
- axial prolongation of the core
- increase of fuel pin diameter

Acceptable combinations:

- +2 UOX rings and proportional axial prolongation (118,4 cm)
- +1 UOX ring, axial prolongation and thicker fuel pin (fuel fraction increase)

Positive consequence of UOX utilisation - more negative Doppler coefficient for UOX (in comparison with MOX) can lead to more advantageous results of unprotected transients analyses.

Negative consequence - UOX core enlargement caused significant decrease of power density connected with 2-3 times weaker irradiation abilities of the UOX core in comparison with MOX core with original high volume power density 100 MW/m^3. But possible future reduction of MOX core power initiated by safety improvements can reduce significantly this ratio.

5. CONCLUSION

Development activities of GFR demonstrator ALLEGRO reactor physics at V4G4 countries were presented. This effort is oriented on benchmarking of neutronic codes (ERANOS, HELIOS, SERPENT, SCALE) and feasibility of UOX fuel utilisation in combination with enrichment limit. Presented partial results show that after phase of familiarisation with GFR technology and connected problems V4G4 community is in the process of the ALLEGRO design evolution connected with the solution of remaining technological problems.

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