VENUS-2 3-D MOX CORE BENCHMARK, RESULTS OF FRAMATOME ANP

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ABSTRACT

A solution for the VENUS-2 3D MOX core benchmark (specified by NEA/WPPR) is presented. Essentially a few-group 3D transport calculation has been performed with pin cell homogenized cross sections generated by CASMO-4 ("L-Lib" based on ENDF/B data). Despite the rather simple approach an eigenvalue very close to unity can be achieved. The comparison of the calculated 2D pin power distribution with the measured one shows an acceptable agreement. The calculated distribution is generally slightly flatter which is in accordance with most solutions already known from the VENUS-2 2D benchmark. A comparison with the pure uranium VENUS-1 core indicates that the reactivity of the MOX pins seems to be slightly overestimated relative to the uranium pins in this model.

1. INTRODUCTION

After completing the VENUS-2 2-D MOX core benchmark [1], NEA/WPPR (Working Party on the Physics of Plutonium Fuels and Innovative Fuel Cycles) have specified the same core configuration as a 3-D benchmark [2]. The VENUS-2 MOX core is a very valuable benchmark since it constitutes a full (though small) core with relatively highly enriched fuel and with a considerable MOX content. The full pin power distribution in 1/8 core symmetry has been published in [1], and axial fission rate distributions for six selected pins will be published after submittal of all solutions of the 3-D benchmark. This paper describes a solution of Framatome ANP for this benchmark.

2. LATTICE CALCULATIONS / CROSS SECTION DATA

In this paper a solution is presented with CASMO-4 [3] as cell code and cross section library generator. Using CASMO for cross section generation is the standard procedure used for Framatome ANP core code systems such as CASCADE-3D or MICROBURN-B2. However, two-group diffusion core calculations as implemented in these code systems are obviously not accurate enough for the small VENUS-2 core. Therefore, for simulation of the VENUS-2 core, a transport solution will be presented. The number of condensed energy groups was extended to five groups (two fast, one epithermal and two thermal groups). This group structure is given (together with the assumed fission spectrum) in Table 1.

Table 1: Energy Group Structure in Core Calculations

group	**upper boundary**	**fission spectrum**
1	**10.00 MeV**	**0.785**
2	**821.0 keV**	**0.215**
3	**5.53 keV**	**0.0**
4	**4.00 eV**	**0.0**
5	**0.625 eV**	**0.0**

The homogenized cross sections for the non-fissile materials (pyrex rods, baffle reflector, water etc.) have been derived from appropriate simple CASMO cell models with fuel environment.

The following table shows the CASMO-4 k-infinity values for the individual fuel zones and the corresponding values of condensed homogeneous cross sections:

Table 2: k-infinity values of fissile materials

	CASMO-4	**CASMO-4**
	k-inf	**k-inf 5 group**
UO_2 3.3	**1.40394**	**1.40201**
UO_2 4.0	**1.33469**	**1.33367**
MOX 2.0/2.7	**1.2555**	**1.25472**

The CASMO-4 k-infinity values have been calculated with the "L-lib", based on ENDF/B data in 70 energy groups.

3. 3D CALCULATIONS WITH MONTE-CARLO METHOD (MOCA)

The 3D core calculations were performed with the broad energy group Monte-Carlo transport code MOCA [4]. Only pin cell averaged cross sections were used in the 3-D calculations. In the core calculations the uniform grid with a pitch of 1.26 cm in x-y direction was preserved also in all regions outside the fissile zones, i.e. baffle, water, barrel. Therefore, baffle and barrel/neutron pad were modelled only approximately in this uniform grid, i.e. in such a way that the masses (areas) of these materials are approximately preserved (see Fig. 1). In order to get a sufficiently accurate axial power profile in the specified fuel rods, these were axially split into 7 almost equidistant regions. The axial fission rate distribution was then calculated by interpolating the rates of these 7 axial zones.

The k_{eff} of the core is 1.00110 with an uncertainty of 7 pcm (1-σ), an excellent result considering the rather simple modeling. Since the normalized radial pin power (fission rate) distribution has been published in [1], the MOCA pin power results can be directly compared to the measured values. The following table gives an overview of the main results, for both the individual fuel zones and the total core.

Table 3: Evaluation of VENUS-2 pin power data with MOCA

Zone	**power calc.**	**Power exp.**	**Power (C/E)**	**peaking calc.**	**peaking exp.**	**peaking (C/E)**	**1-σ [%]**
UO_2 3.3	**1.29579**	**1.33151**	**0.97317**	**1.13888**	**1.14381**	**0.99568**	**1.77**
UO_2 4.0	**1.16243**	**1.16831**	**0.99497**	**1.3135**	**1.33611**	**0.98308**	**2.04**
MOX 2/2.7	**0.62559**	**0.59258**	**1.05571**	**1.75606**	**1.79722**	**0.9771**	**2.58**
total	**1.00525**	**1.00595**	**0.9993**	**1.52686**	**1.561**	**0.97813**	**4.61**

In this table "power" is defined as the average of all power factor values of the individual fuel zones or of all 325 power factors in the core (as 10 out of the 325 rods are on a diagonal symmetry line in the inner zone, the "mean total power" is not exactly unity according to this definition). A similar behavior as in many solutions of the 2-D benchmark [1] is noted, i.e. the calculated radial power distribution is flatter than the measured one. Typically, the outer MOX rod powers are overestimated and the rod powers of the inner UO_2 3.3 zone are underestimated by the code. Additionally, the local peaking factors (maximum power factor divided by the "mean power") of the individual zones are given in the table above. In general the calculated peaking factors are slightly smaller than the experimental ones, which is consistent with the flatter calculated power distribution. The mean deviation of the calculated power distribution of the individual zones is also indicated in Table 3. These deviations are of the same order of magnitude as the average values of the solutions in [1]. Only the deviation for the total core is slightly higher, due to the fact that the calculated power factors near the periphery are overestimated by almost 10%. This seems to be typical for most solutions using pin cell homogenized cross sections for VENUS-2 [1]. The mean deviations are in an acceptable range considering the strong neutron flux gradients in the core.

Another interesting aspect of this benchmark is the interface between MOX and UO_2 fuel. Here the calculated MOX rod power C/E shows an overestimation of around 1.6 % relative to the rod power C/E of the adjacent UO_2 row. This fact indicates that the reactivity of the MOX rods is slightly overestimated by this model.

The calculated normalized axial power profiles are almost identical for all six specified rods. For the central 40 cm of the core the calculated axial power peaking factor is around 1.19 (measured values are not yet available).

4. DETERMINISTIC 3D CALCULATION WITH TORT

In addition to these calculations, further analyses were performed with the deterministic code TORT [5]. In the geometrical model a grid of 55x55 "meshes" has been chosen on the x/y axis. In order to get an accurate axial power profile in the specified fuel rods, the rods were split axially into 25 equidistant regions (2 cm per region). All results have been obtained by assuming quarter core symmetry.

For the upper axial reflector a thickness of 13 cm has been assumed and for the lower a thickness of 21.5 cm. For these regions a combination of plexiglass and water zones has been used.
The 3D calculations with TORT were performed in x-y-z geometry with P_0 S_8 approximation with essentially the same five group cross section set as in the MOCA calculations. For comparison with the S_8 calculation an extra S_2 calculation was performed which is - regarding the angular flux order - equivalent to a diffusion approximation.

The k_{eff} of the core is 0.99719, which is slightly lower than the MOCA result but nevertheless acceptable. The main S_8 results are summarized similarly in Table 4:

Table 4: Evaluation of VENUS-2 pin power data with TORT

Zone	power calc.	power exp.	power (C/E)	peaking calc.	peaking exp.	peaking (C/E)	1-σ [%]
UO_2 3.3	1.29143	1.33151	0.96990	1.15531	1.14381	1.01006	2.35
UO_2 4.0	1.16296	1.16831	0.99542	1.29755	1.33611	0.97114	2.57
MOX 2/2.7	0.62912	0.59258	1.06166	1.77709	1.79722	0.98880	2.38
total	1.00538	1.00595	0.99943	1.50900	1.56100	0.96669	4.99

Generally, the results are quite similar to the MOCA solution. Unfortunately, the 1σ deviations of the pin power distribution are somewhat larger, especially in the UO_2 3.3 and the UO_2 4.0 zone. This may be due to the spatial and angular discretization effects. These effects are probably also responsible for the lower k_{eff} compared to MOCA and the slightly higher MOX rod powers adjacent to the UO_2 4.0 zone. The axial power peaking factor for the central 40 cm of the core is around 1.20 in the TORT solution for all specified rod positions.

A comparison with the TORT S_2 solution shows that transport effects are significant: the k_{eff} value is around 300 pcm lower and the 1σ deviations of the pin power distribution increase further. Especially, the calculated rod powers adjacent to the baffle steel and to the pyrex rods show larger deviations compared to the experimental data.

5. COMPARISON WITH A URANIUM CORE (VENUS-1)

In order to separate MOX-specific effects from bias effects originating from the calculational model, it is helpful to compare a partially MOX fueled core as VENUS-2 with a pure uranium core such as VENUS-1 using the same model. As a measured pin power distribution for the uranium VENUS-1 core has been published in [6] (one should keep in mind that the majority of these "measured" rod powers is interpolated), a detailed comparison of the measured-to-calculated pin power distribution of this uranium core has also been performed.

The geometry of the VENUS-1 core is almost identical to that of the VENUS-2 core. There are essentially two differences:

- The outer 15x15 assembly consists entirely of UO_2 4.0 fuel. In VENUS-2 there are eight outer rows of MOX pins.
- In the inner UO_2 3.3 zone there are six pyrex rods in 1/8 core symmetry instead of five pyrex rods as in VENUS-2.

Otherwise the materials and geometrical data of the cores are almost identical. Only 3D calculations with MOCA have been performed for VENUS-1.

The k_{eff}-value for VENUS-1 is 0.99858 with an uncertainty of 11 pcm (1-σ), which is about 250 pcm lower than the k_{eff} for VENUS-2.

The main results of the comparison of the calculated vs. measured pin powers are given in Table 5:

Table 5: Evaluation of VENUS-1 pin power data with MOCA

Zone	power calc.	power exp.	power (C/E)	peaking calc.	peaking exp.	peaking (C/E)	1-σ [%]
UO_2 3.3	1.19446	1.21689	0.98157	1.11509	1.11842	0.99702	1.81
UO_2 4.0 (I)	1.15846	1.15090	1.00658	1.27575	1.28335	0.99408	1.15
UO_2 4.0 (II)	0.71063	0.69717	1.01931	1.59407	1.60650	0.99226	1.50
total	1.00360	1.00301	1.00058	1.47791	1.47700	1.00062	2.26

Here the UO_2 4.0 (I) zone corresponds to the pin positions of the total UO_2 4.0 zone in VENUS-2 and the UO_2 4.0 (II) zone corresponds to the pin positions of the total MOX 2/2.7 zone in VENUS-2.

The results for theVENUS-1 core (given in Table 5) can be summarized as follows:

- There is still an overestimation of the pin powers in the outer zone resulting in an overall flatter calculated power distribution, but this effect is much smaller in the UO_2 core (1.9 % vs. 5.6 % in the outer zone).
- The calculated power peaking factors of the individual zones and of the total VENUS-1 core

are excellent.

- Mean pin power deviations of below 2% in each individual zone and slightly above 2% for the total core are excellent.

Thus, it is obvious that the present methods can also describe a pure UO_2 core quite well. There are just minor effects that cause the absorption of the pyrex rods in the inner zone to be slightly overestimated (which is a well known observation for homogenized absorber pins) and that cause rod powers to be overestimated by a few percent near the outer boundary (probably due to pin cell homogenization).

Therefore, a better target eigenvalue (taking the bias of the method into account) should have been 0.9986 instead of 1.0. Thus, the VENUS-2 MOX core misses this target value by about 250 pcm. Keeping in mind that the MOX rods constitute about one third of the core in rod positions with minor importance, there appears to be an overestimation of k-infinity of the MOX fuel of the order of 0.01. This is also indicated by the increase of the pin power C/E of the first MOX pin row adjacent to the 4.0 UO_2 zone in VENUS-2 (see above).

CONCLUSIONS

The present calculations show that a few-group approach with pin cell homogenized cross sections can give reasonable results for 3D transport calculations regarding both k_{eff} and pin power distributions, even for a small high leakage core such as VENUS-2 with partially loaded MOX fuel. The cross sections generated by CASMO-4 are obviously adequate for this purpose.

Compared to the pure uranium core such as VENUS-1, there appears to be a slight overestimation of the reactivity of the MOX fuel which is seen in both the k_{eff}-value and the pin power distribution. As long as there is a mix of MOX and UO_2 in the core, this will have only minor effects on nuclear design calculations.

A similar behavior (regarding pin powers) can also be found in most solutions of the VENUS-2 2D Benchmark [1]. Hence this appears primarily to be a general result of data libraries rather than a specific CASMO-4 effect.

Nodal core design codes of Framatome ANP such as CASCADE-3D or MICROBURN-B2 are hardly affected by this observation, since the validation of these codes is based to a large extent on hot condition states of large LWR cores, consisting mainly of exposed fuel. Nevertheless it is demonstrated that the spectral design code CASMO-4 can be applied with good results also to small heterogeneous high-leakage cores such as VENUS-2.

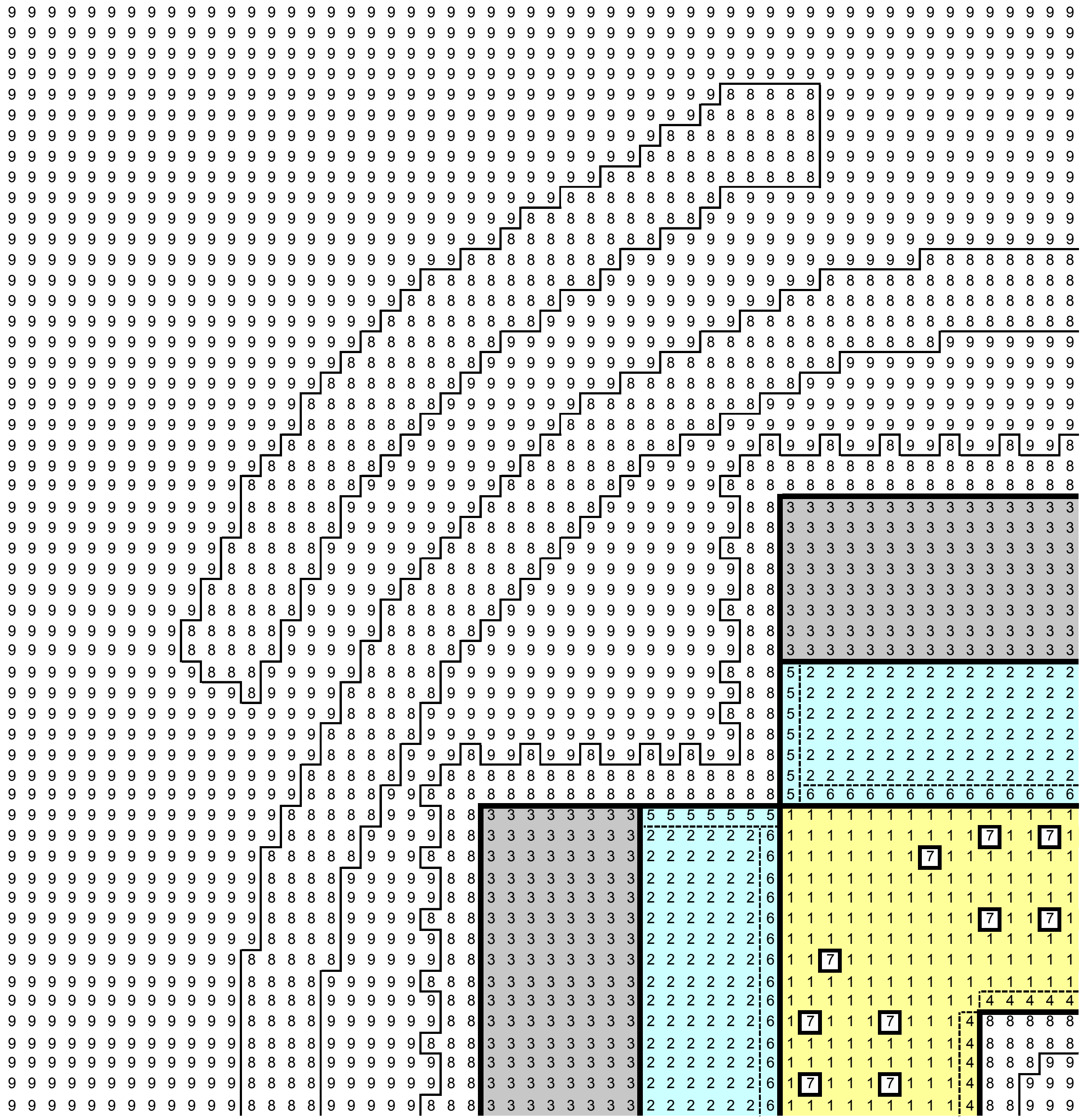

Fig. 1 Simplified Core Model for VENUS-2 (MOCA)
(quarter core symmetry, center bottom right)

Materials / cross section sets:

1, 4 :	UO_2 3.3
2, 5, 6 :	UO_2 4.0
3 :	MOX 2/2.7
7 :	pyrex rods
8 :	steel (baffle/barrel/neutron pad)
9 :	water

REFERENCES:

1. Benchmark of the VENUS-2 MOX Core Measurements
NEA/NSC/DOC(2000), http://www.nea.fr/

2. Blind Benchmark on the 3-D VENUS-2 MOX Core Measurements
Final Specification,
NEA/SEN/NSC/WPPR(2001), http://www.nea.fr/

3. M. Edenius, B. H. Forssen and C. Gragg,
The Physics Model of CASMO-4, Proc. Adv. in Math., Comp. & Reactor Physics, Vol. 10-1, Pittsburgh (1991)

4. J. Lieberoth
A Monte Carlo technique to solve the static eigenvalue problem of the Boltzman transport equation; Nukleonik 11, 213-219 (1968)

5. Rhoades, Childs
TORT-DORT Two- and Three-Dimensional Discrete Ordinates Transport
Version 2.7.3, RSIC CODE PACKAGE CCC-543
ORNL, Oak Ridge, Tennessee, 1993

6. Prediction of Neutron Embrittlement in the Reactor Pressure Vessel:
VENUS-1 and VENUS-3 Benchmarks,
NEA/NSC/OECD(2000) ISBN 92-64-17637-3, http://www.nea.fr/