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Evaluation of Neutron Physics Parameters and Reactivity Coefficients for Sodium Cooled Fast Reactors

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Abstract – *The need for sustainable supply of fuel to the growing demand of energy enforces the need to look again more deeply in the option of Sodium Cooled Fast Reactors (SFR). Currently investigations are undertaken in order to validate deterministic codes for neutron physics analysis of sodium cooled reactor cores, in particular for calculation of main safety parameters as sodium void effect and Doppler constant.*

In this study we use two deterministic codes for fast reactor simulations – ERANOS, developed during a long period by CEA in France, and KANEXT, the present version of a long development period at Research Center Karlsruhe (KIT) in Germany. As a reference solution the results of a Monte-Carlo simulation with MCNP are evaluated for some specific cases. Special slightly simplified SFR core design models are applied for the comparison, being representative for typical sodium cooled fast reactor cores considered as candidates in the Generation IV Forum.

The comparisons of results obtained in deterministic and Monte-Carlo calculations show good agreement for unit cell analysis. It is also shown that "lump" fission product treatment in the two deterministic codes gives quite similar results for a wide range of core states. In spite of very good agreement obtained on the unit cell level, larger but still moderate deviations for the magnitude of sodium void reactivity effect for three-dimensional core calculations are obtained. That is why the magnitude of the uncertainty estimated for any reactivity effect as result of comparison with reference value should be considered in view of the needed accuracy and of the subsequent application of these data in safety investigations along with other accuracy issues in the calculation route. But undoubtedly deterministic codes provide satisfactorily results and are well suited for parametric studies, especially if the results are qualified either by experiments or by reference calculations with alternative independent methods like Monte Carlo simulations.

I. INTRODUCTION

The need for sustainable supply of fuel to the growing demand of energy enforces the need to look again more deeply in the option of Sodium Fast Reactors (SFR) within the so called GEN-IV framework [1] for the next generation of modern reactor types. In particular due to the depletion of existing energy sources like coal, oil, gas as well as Uranium ores it became attractive to look for this type of breeding reactors.

However a peculiarity of such fast system lies in their safety coefficients. In particular, the positive sodium void coefficient in such reactors is of concern. A lot of effort is invested in reducing it in parallel to the attempts of improving the magnitude of the Doppler Effect. Further, the design of new optimized reactors necessitates dedicated tools to account for the cross section generation and the numerical methodology in a correct manner.

The necessity of numerous reactivity effect calculations along with acceptable calculation time costs certainly leaves the deterministic codes to be used for the wide scope of neutron physics tasks in the near future. In this study we use two deterministic simulation codes dedicated to fast reactor simulation – ERANOS [2], developed during a long period by CEA (France) in cooperation with European and US partners, and KANEXT [3, 4], the current version of a long development period at Research Center Karlsruhe (KIT) in Germany with support of European partners. The first goal of the present work is to analyze the safety coefficients based on the results of two independent deterministic calculation routes. As a reference solution results of a Monte-Carlo simulation with MCNP [5, 6] are

evaluated. KANEXT and ERANOS have slightly different options and approaches concerning the cross section generation scheme and the numerical solutions. It is possible to assess uncertainties of the obtained results on the unit cell basis as well as for the full-scale tree-dimensional core model. This type of comparison allows for an validation of the deterministic codes which in turn improve the availability to design a core with optimized safety coefficients.

II. OVERVIEW OF COMPARISON

A special set of models based on the SFR core design [7, 8] was elaborated for the comparisons. The design reflects typical sodium cooled fast reactor cores which are considered as candidates within the Generation IV Forum. This is a core for a large 3600 MW(th) power reactor with equivalent radius of about 250 cm and active height of 100 cm. Some core parameters are listed in Table I. The core has no fertile breeder zones and is surrounded by rows of steel reflector subassemblies. A so called "sodium plenum" of 30 cm height above the core is considered in order to mitigate the consequence of positive sodium void effect in the active core at the initial phase of an accident.

TABLE I
General data on SFR core design

Parameter	Unit	Value
Total reactor power	MW(th)	3600
Core fuel		$(U,Pu)O_2$
Core fuel smear density	%TD	~83
Pu content in fresh fuel:		
Inner core	vol%	~14.6
Outer core	vol%	~17.4
Volume of the core	m^3	19.2
Equivalent core radius	m	2.47
Height of the core	m	1.00
Volume fractions in the core:		
Fuel fraction	%	52.4
Sodium fraction	%	27.6
Structure steel	%	20.0
Total number of SAs		453
Inner core		267
Outer core		186
Number of control/shutdown rods		24/13
Core SA parameters:		
SA pitch	mm	210.8
Number of pins per SA		271
Pin outer diameter	mm	10.73
Pin clad thickness	mm	0.50
Average power density	W/cm^3	~200
Maximum power density	W/cm^3	~290
Maximum linear power rating	W/cm	~410
Volumetric power peaking factor		1.44
Radial power peaking factor		1.16

Different investigations on safety aspects of SFR made in the past years indicate that the worst behavior from safety point of view is observed at the burn-up state of the core at the end of equilibrium cycle (EOEC). In particular, for a self-breeding core the main safety parameter, Doppler constant, is decreasing with burn-up during the cycle, whereas the magnitude of the positive sodium void effect is increasing. That is why for the current investigation a typical end of equilibrium cycle (EOEC) state of the core is considered. This state of the core is obtained as result of once-through burnup evaluations in ERANOS up to 2 cycles (2*410 efpd). In order to simplify the modeling, homogeneously distributed fuel compositions are considered for the subcores 1 and 2. In the projects [7, 8] fission products (FPs) are represented by "lump fission products" for the main fissile isotopes. This option of fission product treatment is applied in ERANOS simulations. KANEXT usually utilizes a nearly complete set of fission products. For the present study, library data for lumped fission products has been prepared. However for comparing with MCNP the fuel composition without FPs had to be considered.

The model set consists of two main options, which are (1) one-dimensional (1D) fuel pin cell and (2) three-dimensional (3D) full-scale core model for comparison of integral reactivity effects. These models are applied in all three calculation tools in the most identical way. Thus the K-effective calculations are prepared using different codes and methods of solving of the neutron transport equation but with the most identical initial input data.

III. CALCULATION TOOLS DESCRIPTION

Here a brief summary is given of the applied calculation procedures. More details may be found in the corresponding references.

III.A. ERANOS 2.1 code system

ERANOS 2.1 is a deterministic code system which is widely used for different neutron physics task on fast breeder reactors, in particular it allows performing core, fuel cycle, shielding calculations etc. [2]. Core calculations are performed in two steps: at the lattice-cell or fuel assembly level and at the core level. In the first step, the ECCO code solves the resonant nuclide self-shielding using the subgroup method and computes a fine-group solution of the transport integral equation with a collision probability method. Different sets of libraries can be used such as special format libraries based on JEF-2.2, ERALIB1, JEFF-3.1, ENDFB-VI with various energy meshes such as 1968 groups (all-purpose), 175 groups (shielding purposes), the 172-group XMAS

scheme (refined in the low energy range), and 33 groups (energy mesh generally used for core calculations). The resulting broad-group cross-sections, corresponding to an equivalent homogeneous zone, can then be used in the second step for core calculations.

In the ECCO calculations the so called "reference route" was applied. The 1968-group JEFF3.1-based library is used for the cross-section preparation in detailed heterogeneous pin geometry (by calculating 1968 fine group flux spectra and by the subgroup method), subsequently, the fine fluxes are applied for cross-section collapsing to the "broad" 33-group energy structure. In the second step the transport code VARIANT (simplified spherical harmonics P_3 option) included in ERANOS system was applied for 3D core calculations.

III.B. KANEXT modular code system

The KANEXT modular code system is the current version of the code system KAPROS [3, 4], developed at FZK for more than 30 years. KAPROS was successfully used for a broad range of neutron physics tasks for critical systems with different neutron spectra as well as for modern sub-critical applications [3, 4]. The modular principle allows to efficiently couple different numerical codes which use different calculation methods. Various multi-group libraries with own structures are available (26, 69, 78, 85, 334, 350 groups) based on several evaluated data bases (KEDAK4, ENDF/B-6/7, JEFF2/3). All common tasks for neutron reactor physics simulations can be performed, either with fully integrated modules or with loosely coupled external codes (cross sections, fluxes, criticality, burn-up evaluations, exact perturbation calculations,..)

For the current application a standard route with two steps, being similar to the ERANOS steps, was used in the KANEXT system. In the first step the cross-section preparation on the unit cell basis is done. The dedicated module KARBUS starts from a 350-group JEFF3.1.1-based library for group cross section preparation. Using best estimate weighting fluxes, any group structure of condensed cross-sections is allowed for core calculations. In the current calculations nearly the same 33-group structure as used in ERANOS was chosen. In the second step, the transport code VARIANT with the same options was applied, resulting in quite similar calculation routes in both deterministic code solutions.

III.C. MCNP code

The well-known Monte-Carlo simulation code MCNP [5] allows modeling of almost any detailed core geometries for core neutron physics tasks. A detailed core model with pin structure description in the core and homogenized compositions in other non-fuel and structural regions was applied in the current investigations. The standard set of JEFF3.1 cross-section libraries was applied [6].

IV. MODEL DESCRIPTION

IV.A. Fuel pin geometry model for unit cell basis comparison

Simple one-dimensional three-region cylindrical unit cell geometry with white reflection boundary condition is suggested for the first step of the comparisons. The fuel pellet stack material is considered to be smeared inside the pin clad. Although a single pin is considered in the calculations, the wrapper material is taken into account for the calculation of the pin clad thickness. The geometry data of the cell and volume fractions of compositions considered are given in Table II.

TABLE II
Geometry data of the fuel pin cell

	Radius of region , cm	Volume fraction, %	Volumetric sodium-to-pin ratio
Fuel	0.490600	52.54	0.376235
Clad	0.576965	20.12	
Sodium	0.676855	27.34	

Two types of core fuel are investigated: inner subcore 1 with low Pu content and outer subcore 2 with high plutonium content (identical cells with different fuel content). All geometry data are considered at so called "hot" nominal operating conditions of the core with fuel, clad and sodium temperatures to be equal to 1500 K, 900 K and 800 K respectively.

IV.B. Core geometry model for three-dimensional comparison

For the subsequent second step of investigations a relatively simple full-scale three-dimensional geometry model was elaborated. As mentioned before, this core is representative for a typical sodium cooled fast reactor design, considered as candidate in Generation IV Forum. In particular, main parameters as fuel content, number of SA and SA pitch, arrangement of SAs and control rods in the core and their design are typical for modern SFR proposals.

The 3-D hexagonal geometry contains different types of calculation zones which are arranged according to the real core structure. The appropriate number of zones is chosen in order to fulfill the ability to calculate different configurations of the core, such as control rods insertion, partial and total sodium voiding, different local

perturbations of material properties. The vertical cross-section of the model for neutron physics calculations, control and shutdown rods structure and subassembly arrangement are presented in Fig. 1 and Fig. 2.

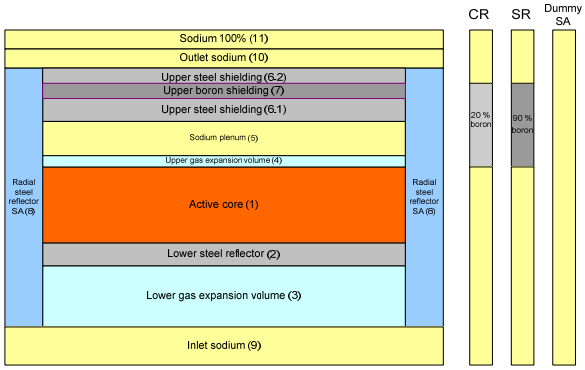

Fig. 1. Axial cross-section of the core model

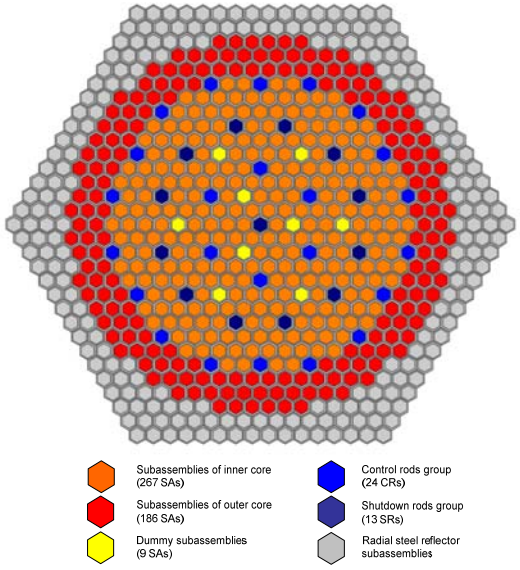

Fig. 2. Subassembly arrangement

The calculation model includes the following regions:

1 – Active core with two zones with different plutonium content (267/186 subassemblies) of 100 cm height;

2 – Lower steel reflector of 30 cm height;

3 – Lower gas expansion volume;

4 – Upper gas expansion volume of about 1 cm height;

5 – Sodium layer between fuel pins and shielding pins in core SA of 30 cm height;

6.1 and 6.2 – Upper steel shielding;

7 – Upper boron shielding;

8 – Radial steel reflector;

9 – Inlet sodium and steel mixture;

10 – Outlet sodium and steel mixture;

11 – Outlet sodium.

IV.C. Material data for calculations

As mentioned above, a one-dimensional three-region cylindrical unit cell is applied for the first comparison step, so three material compositions are used:

1. inner/outer subcore oxide fuel with content at equilibrium state with and without taking into account of fission products;
2. steel cladding, typical for sodium cooling, and
3. pure sodium.

For cases with burnt fuel the "lump" fission products for the isotopes U-235, U-238, Pu-239, Pu-240, Pu-241 and Pu-242 are considered separately.

Other regions of the model which do not contain fuel isotopes are represented as homogenized mixtures of steel, sodium and in some zones of boron.

V. CALCULATION RESULTS

V.A. K-effective values and some reactivity effects for unit cells

The results of calculations of K-effective values for cases with and without fission products are given in Tables III and IV for inner subcore (pin cell type 1) and outer subcore (pin cell type 2). Calculations are prepared for the fuel temperature 1500 and 2000 K and for half-voided (50% of density) and totally voided cell (without sodium). The obtained values of Doppler constant and void reactivity effect are given in Tables V and VI. The Doppler effect as result of heavy nuclide cross section dependence on temperature is calculated as K-effective value change due to increase of the fuel temperature only, without physical density change.

It could be noted that both deterministic methods give good agreement with the reference Monte-Carlo calculations for the cases without FPs. In the whole range calculated differences of about 200 pcm with the reference are obtained in the KARBUS calculations, while in ERANOS the differences become higher in the voided conditions. This fact is reflected in the results for the Doppler constant and for the void reactivity effects, given in Table V. Most values obtained with KARBUS are in good agreement with MCNP, while the magnitude of void effect in ECCO is underestimated by 200 pcm.

Also due to this underestimation, in ERANOS the Doppler constant has slightly lower change when going in void conditions of about 22-25% for both subcores 1 and 2, while in KARBUS the change is about 28%. Due

to lower plutonium content in subcore 1 the Doppler constant is higher then in subcore 2, but for subcore 2 the MCNP value is considerably lower then for both deterministic values.

TABLE III
K-effective values for cell without fission products

Calculation case	Pin cell type	KARBUS (absolute difference with MCNP)	ECCO (absolute difference with MCNP)	MCNP (estimated standard deviation is 0.00030)
1500 K normal	1	1.17824 (+0.00201)	1.17711 (+0.00089)	1.17622
1500 K normal	2	1.24227 (+0.00171)	1.24100 (+0.00045)	1.24055
1500 K voided	1	1.22000 (+0.00220)	1.21554 (-0.00226)	1.21780
1500 K voided	2	1.28630 (+0.00189)	1.28109 (-0.00332)	1.28441
1500 K half-voided	1	1.19732 (+0.00157)	1.19546 (-0.00029)	1.19575
1500 K half-voided	2	1.26236 (+0.00177)	1.26014 (-0.00045)	1.26059
2000 K normal	1	1.17475 (+0.00190)	1.17394 (+0.00109)	1.17285
2000 K normal	2	1.23908 (+0.00097)	1.23805 (-0.00006)	1.23811
2000 K voided	1	1.21729	1.21293	–
2000 K voided	2	1.28384	1.27865	–

TABLE IV
K-effective values for cell with "lump" fission products

Calculation case	Pin cell type	KARBUS (absolute difference with ECCO)	ECCO
1500 K normal	1	1.14176 (+0.00325)	1.13851
1500 K normal	2	1.21118 (+0.00316)	1.20801
1500 K voided	1	1.18390 (+0.00693)	1.17697
1500 K voided	2	1.25538 (+0.00734)	1.24803
2000 K normal	1	1.13891 (+0.00300)	1.13592
2000 K normal	2	1.20847 (+0.00296)	1.20551
2000 K voided	1	1.18178 (+0.00697)	1.17481
2000 K voided	2	1.25327 (+0.00732)	1.24595

The sodium void effect is higher by 150-200 pcm for subcore 1 and the effect is increasing by 50-70 pcm when the temperature is increasing from 1500 K to 2000 K.

TABLE V
Doppler constant and void reactivity effect for cell without FPs

Parameter	Pin cell type	KARBUS (absolute difference with MCNP)	ECCO (absolute difference with MCNP)	MCNP (estimated standard deviation is 42)
1500 K void effect, pcm	1	2905.4 (+2.5)	2686.4 (-216.4)	2902.8
1500 K void effect, pcm	2	2756.0 (+3.4)	2521.4 (-231.2)	2752.6
1500 K half-void effect, pcm	1	1353.1 (-35.5)	1304.1 (-84.4)	1388.6
1500 K half-void effect, pcm	2	1281.6 (+0.1)	1224.0 (-57.5)	1281.5
2000 K void effect, pcm	1	2974.8	2738.8	–
2000 K void effect, pcm	2	2813.7	2565.0	–
Doppler constant, pcm	1	874.2 (+25.0)	797.8 (-51.4)	849.2
Doppler constant, pcm	2	720.2 (+168.0)	667.8 (+115.6)	552.2
"Dry" Doppler constant , pcm	1	632.9	615.5	–
"Dry" Doppler constant , pcm	2	519.5	516.3	–

TABLE VI
Doppler constant and void reactivity effect for cell with FPs

Parameter	Pin cell type	KARBUS (absolute difference with ECCO)	ECCO
1500 K void effect, pcm	1	3117.2 (+246.6)	2870.6
1500 K void effect, pcm	2	2907.0 (+252.6)	2654.5
2000 K void effect, pcm	1	3185.1 (+270.1)	2914.9
2000 K void effect, pcm	2	2958.0 (+265.5)	2692.5
Doppler constant, pcm	1	762.4 (+65.4)	697.0
Doppler constant, pcm	2	643.1 (+44.4)	598.8
"Dry" Doppler constant , pcm	1	526.5 (-16.4)	542.8
"Dry" Doppler constant , pcm	2	466.0 (-0.8)	466.7

For calculations with "lump" fission products, which are presented in Table VI, also quite good agreement is shown in normal condition for different fuel temperature but the difference of about 100 pcm in "weight" of fission

product should be mentioned taking also into account the initial difference of 200 pcm for the same fuel without FPs.

The sodium void effect becomes higher by 200 pcm due to the influence of FP as obtained for both codes. Doppler constants are decreasing by about 13% and 11% for subcore 1 and 2 respectively for both codes due to the influence of FP whereas all normal values for both cases without and with FPs are higher by 7-9% for KARBUS and are almost equal in voided conditions.

As conclusion for this first step, quite good agreement was observed for two deterministic codes which use specific multi-group libraries based on JEFF3.1 cross-section data. These results are confirmed with MCNP calculations using the same JEFF3.1 basis.

V.B. Criticality calculations for full-scale SFR core with sodium plenum

V.B.1. K-effective values summary

In a similar way calculations for different core states are prepared for the full-scale model of the core, such as normal state with different fuel temperature 1500 and 2000 K, with different voided regions of the core and with heated sodium (increased up to 1000 K) for the calculation of the sodium density effect as well. The application of homogenization for regions without fuel assumes that no empty regions appear in VARIANT calculations. In particular, in case of sodium plenum the steel fraction of wrapper is considered in homogenized voided unit cell. The Doppler Effect, as result of heavy nuclide cross section dependence on temperature, is calculated as K-effective value change due to increasing of fuel temperature, without physical density change. For the calculation of the sodium density reactivity effect the core state with fuel temperature of 1500 K is taken and the sodium temperature increase by 200 K is applied in the different regions. Thus the reactivity effect is due to corresponding change of sodium density and cross sections change with the temperature.

In Tables VII and VIII the obtained K-effective values are given for core calculations without and with fission products in the fuel. As it was mentioned before, the VARIANT code is applied in both deterministic systems with cross-sections condensed to 33 groups. For the cases without FPs when comparison with the reference Monte-Carlo calculation can be carried out, the differences for the KANEXT results are in general considerably less than for ERANOS, about 500 pcm in KANEXT for whole set of calculations compared to 1000 pcm in ERANOS. The data obtained for the normal state without fission products for both codes shows that there is quite good agreement with Monte-Carlo if some systematic effects are taken into account. Approximately the same picture is obtained for the set with FPs, so the "weight" of "lump" fission product looks consistently. But the overall picture now, especially for the sodium void effect, is that the scattering in the results is considerably higher, as shown below for the different reactivity effects.

TABLE VII
Core calculation results for cases without FPs

Fuel T, K	Calculation case	KANEXT (absolute difference with MCNP)	ERANOS (absolute difference with MCNP)	MCNP (estimated standard deviation is 0.00030)
1500	normal	1.03434 (-0.00546)	1.02962 (-0.01018)	1.03980
1500	voided core	1.05424 (-0.00416)	1.04879 (-0.00961)	1.05840
1500	voided core and plenum	1.04856 (-0.00573)	1.04247 (-0.01182)	1.05429
1500	voided subcore 1	1.05032 (-0.00477)	–	1.05509
1500	voided subcore 2	1.03890 (-0.00468)	–	1.04358
1500	voided plenum only	1.02952 (-0.00660)	1.02434 (-0.01178)	1.03612
1500	increased sodium density in core (+200 K)	1.03536	1.03061	–
1500	increased sodium density in core and plenum (+200 K)	1.03518	1.03040	–
2000	normal	1.03130 (-0.00536)	1.02647 (-0.01019)	1.03666
2000	voided core	1.05180 (-0.00392)	1.04626 (-0.00946)	1.05572

TABLE VIII
Core calculation results for cases with FPs

Fuel T, K	Case	KANEXT (absolute difference with ERANOS)	ERANOS
1500	normal	1.00723 (+0.00585)	1.00138
1500	voided core	1.02814 (+0.00644)	1.02170
1500	voided core and plenum	1.02297 (+0.00693)	1.01604
1500	voided subcore 1	1.02366	–
1500	voided subcore 2	1.01257	–
1500	voided plenum only	1.00285 (+0.00620)	0.99665
1500	increased sodium density in core (+200 K)	1.00831 (+0.00588)	1.00243
1500	increased sodium density in core and plenum (+200 K)	1.00814 (+0.00590)	1.00224
2000	normal	1.00471 (+0.00593)	0.99878
2000	voided core	1.02611 (+0.00652)	1.01960

V.B.2. Sodium void effect values

Using calculated K-effective values important sodium void effects are listed in the Tables IX and X. The simultaneous overestimation of the positive value of void effect in the core regions and of the negative effect in the sodium plenum is observed for both deterministic codes. Thus, in general for KANEXT this overestimation seems to be not more than 100-150 pcm however for the plenum it is 25-40%. The value of the core void effect in ERANOS seems to be in a good agreement with the MCNP result, but for both core and "problematic" plenum region voided, an overestimation of "plenum efficiency" takes place which is somewhat higher than in KANEXT. It has to be noted that the total deviation after summarizing of partial effects is in general two times lower than the difference of integral effect and reference value.

TABLE IX
Sodium void effect for cases without FPs (pcm)

Fuel T, K	Calculation case	KANEXT (absolute difference with MCNP)	ERANOS (absolute difference with MCNP)	MCNP (estimated standard deviation is 42)
1500	voided core	1825.3 (+135.2)	1775.1 (+85.0)	1690.1
1500	voided core and plenum	1311.4 (-10.3)	1196.5 (-125.3)	1321.8
1500	sodium plenum effect (as difference)	-513.7 (-145.5)	-578.6 (-210.2)	-368.3
1500	voided subcore 1	1470.9 (+77.2)	–	1393.7
1500	voided subcore 2	424.6 (+76.2)	–	348.4
1500	voided plenum	-452.1 (-110.5)	-501.3 (-159.8)	-341.6
2000	voided core	1889.8	–	–

TABLE X
Sodium void effect for cases with FPs (pcm)

Fuel T, K	Calculation case	KANEXT (absolute difference with ERANOS)	ERANOS
1500	voided core	2019.7 (+33.5)	1986.2
1500	voided core and plenum	1527.8 (+86.5)	1441.3
1500	sodium plenum effect (as difference)	-491.8 (+53.0)	-544.8
1500	voided subcore 1	1593.8	–
1500	voided subcore 2	524.3	–
1500	voided plenum	-433.5 (+40.3)	-473.8
2000	voided core	2075.6 (+31.6)	2044.0

The same tendency is obtained for cases with FPs, indicating similar influence of the "lump" approaches. Thus in general the presence of FP gives about 200 pcm more in core void effect. Whereas in KANEXT calculations for the core the magnitude is somewhat higher and for the plenum is also lower than in ERANOS.

V.B.3. Doppler constant values for normal and "dry" conditions

Using calculated K-effective values the values of Doppler constant for normal and voided conditions with and without fission products are obtained and presented in Table XI. Along with very good agreement with the reference calculation in normal conditions for both deterministic codes a slightly lower value is obtained in KANEXT for "dry" condition. For the cases with FPs, the values in KANEXT are slightly lower but both codes give the same decrease for voided conditions of about 22%.

TABLE XI
Doppler constant for normal and "dry" conditions (pcm)

Parameter	KANEXT-VARIANT (absolute difference with *MCNP/with **ERANOS)	ERANOS (absolute difference with MCNP)	MCNP (estimated standard deviation is 42)
normal without FP	988.4 (-24.2)*	1038.1 (+25.5)	1012.6
„dry“ without FPs	764.0 (-69.8)*	802.8 (-30.9)	833.7
normal with FPs	862.5 (-39.1)**	901.7	–
„dry“ with FP	668.0 (-32.5)**	700.6	–

TABLE XII
Sodium density reactivity effect (pcm/K)

Fuel T, K	Calculation case	KANEXT-VARIANT (absolute difference with *MCNP/with **ERANOS)	ERANOS (absolute difference with MCNP)	MCNP (estimated standard deviation is ~0.1)
1500	core	+0.481 (+0.030)*	+0.464 (+0.013)	+0.451
1500	core and plenum	+0.392 (+0.116)*	+0.364 (+0.088)	+0.276
1500	plenum effect (as difference)	-0.088 (+0.086)*	-0.100 (+0.075)	-0.175
1500	core with FPs	+0.534 (+0.012)**	+0.523	–
1500	core and plenum (with FPs)	0.450 (+0.019)**	+0.431	–
1500	plenum effect (with FPs)	-0.084 (0.007)**	-0.092	–

V.B.4. Sodium density reactivity effect

The density reactivity effect values obtained for the core as well as for core and plenum together are given in Table XII. Good agreement is observed between the deterministic codes. For the cases with FPs, the effect is slightly higher. It also should be noted for MCNP that the standard deviation of K-effective values leads to quite large relative error in such effect with small magnitude, so the standard deviation in calculations should be considerably lower.

V.B.5. Subassembly power distributions

Finally, as an example a subassembly power map is presented in Fig. 3. This map is obtained with KANEXT for normal state of the core without FPs. In Fig. 4 a map of the relative differences in % between ERANOS and KANEXT subassembly power is presented, where the color reflects the absolute value of the difference. It should be noted that the ERANOS power map was not created directly in ERANOS, but in the KANEXT environment by transfer of the VARIANT input files. The specific symmetric pattern of the deviations in Fig. 4 indicates that differences exist in ERANOS and KANEXT geometry specifications for VARIANT. However, the relative deviations obtained for these corresponding calculations do not exceed 3.5%, being satisfactorily for any numerical neutron physics task.

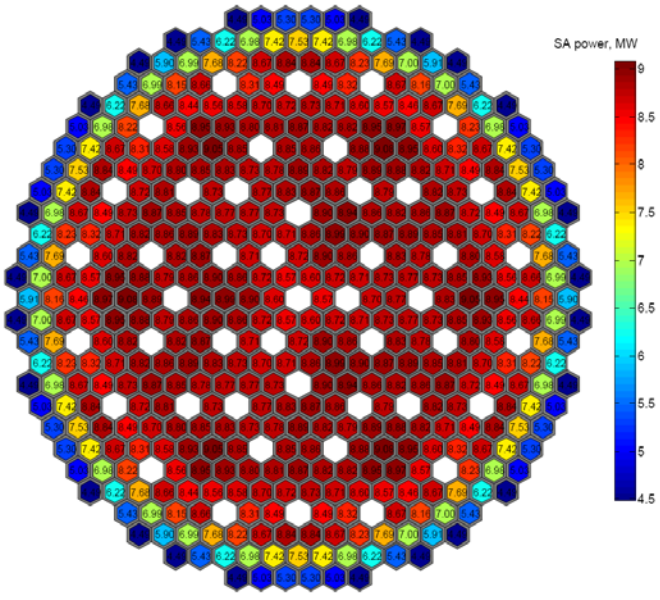

Fig 3. SA power map obtained in KANEXT

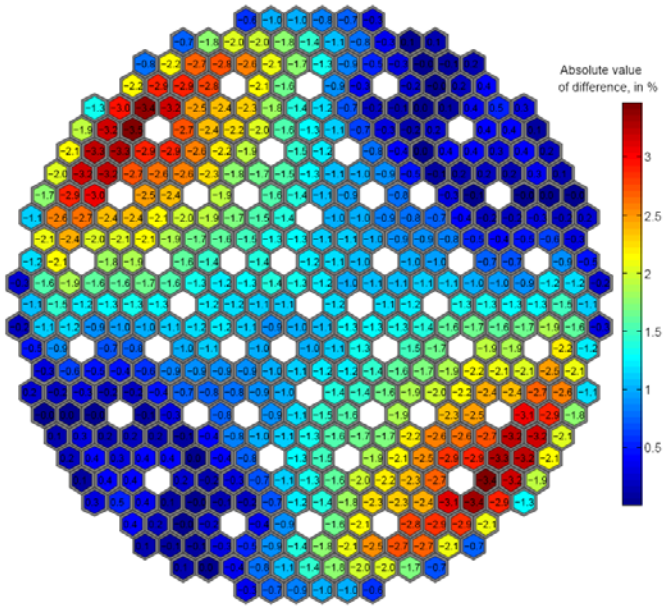

Fig. 4. The map of relative difference between ERANOS and KANEXT subassembly power values in %

VI. CONCLUSIONS

Results of neutron physics calculations are presented for models of innovative sodium cooled reactors. The comparisons of results obtained by the deterministic code systems KANEXT and ERANOS and the Monte-Carlo code MCNP show good agreement. A wide range of results is obtained for main safety parameters such as Doppler constant and void reactivity effect. It is also shown that "lump" fission product treatment in the two deterministic codes gives quite similar results for a wide range of core states with differences around 100 pcm at the EOEC state. However, qualified application of lumped fission products for current sodium cooled reactor designs is still under investigation within the KANEXT modular code system.

Very good agreement on the unit cell level is followed by somewhat larger, but still moderate deviations for the magnitude of sodium void reactivity effects for full-scale calculations. Moreover, the consideration of a nearly complete list of fission product isotopes for the three codes is of interest for the analysis of a core with significant burnup.

Finally, it should be noted that he magnitude of the uncertainty in the estimation of any reactivity effect should be considered in view of the needed accuracy and of the subsequent application of these data, as well as in view of a conservative approach in safety analysis. In particular these accuracies should be estimated and compared with other accuracy issues in the calculation route for safety investigations.

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