CORE BENCHMARKS FOR VERIFICATION OF PRODUCTION NEUTRONIC CODES AS APPLIED TO VVER-1000 WITH MOX FUEL PLUTONIUM FROM SURPLUS RUSSIAN NUCLEAR WEAPONS

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ABSTRACT

The assumed utilization of MOX fuel with weapon-grade plutonium in VVER-1000 reactors requires corresponding verification procedure for production neutronics codes actually being used for VVER-1000 design and operation. The mentioned codes include BIPR7-A and PERMAK-A created in "Kurchatov Institute" and intended for coarse-mesh and fine-mesh calculations of core neutronics characteristics.
The proposed set of benchmarks for VVER-1000 type core is based on 2D calculational benchmarks. BIPR7-A and PERMAK-A results are compared with precision (Monte Carlo) codes MCU and CONKEMO, and with production code of improved accuracy RADAR.
The verification results are presented for two types of benchmark configurations:
- "minicore" consisting of seven fuel assemblies surrounded by a simplified radial reflector
- "CORE-1000" simulating real VVER-1000 core and radial reflector structure.
Every configuration type comprises a set of variants differing by fraction of MOX fuel, irradiation level, temperature, availability of absorbers etc. Irradiation level represented by nuclear concentrations in initial data facilitates comparability of different codes.
The system of information support developed under these investigations ensures fast treatment of results.
The preliminary conclusion about discrepancies of BIPR7-A and PERMAK-A is favorable for variants close to real design states.
Presence of MOX fuel leads to some increasing of production codes discrepancies in comparison with similar uranium configurations.

1. INTRODUCTION

The assumed utilization of MOX fuel with weapon-grade plutonium in VVER-1000 reactors requires corresponding verification procedure for production neutronics codes actually being used for VVER-1000 design and operation. The mentioned codes include TVS-M [1], BIPR7-A [2] and PERMAK-A [2] created in Russian Research Center "Kurchatov Institute". Absence of experimental information both on critical test beds experiments and on utilization of MOX fuel for VVER-1000 core is proposed to replace

for the moment by detailed calculational benchmarks. Necessary scope of benchmarks calculations was performed for spectral code TVS-M [3]. A set of core benchmarks for VVER-1000 type core intended for BIPR7-A and PERMAK-A verification was proposed in [4].

The objectives of core benchmarking are following:
- preparation of reference calculations by Monte Carlo codes (MCU from KI and CONKEMO from IPPE) and also by production code of improved accuracy RADAR in order to verify production codes on VVER-1000 type configurations with MOX fuel
- verification of production codes BIPR7-A and PERMAK-A in order to define their discrepancies from mentioned reference calculations.

Precision codes and production codes of improved accuracy allow to approach considered benchmarks tasks to experiments as much as possible registering at the same time a vast set of functionals. The substantial feature of the developed benchmarks system [4] is the fact that all registered functionals can be almost directly used for verification of production codes. Experimental registration of such functionals is extremely difficult and sometimes is impossible. From the other hand involving in verification process production codes of improved accuracy together with precision Monte Carlo codes facilitates adjusting of the last ones for large calculational systems.

The verification results are presented for two types of 2D benchmark configurations:
- "minicore" consisting of seven fuel assemblies surrounded by a simplified radial reflector
- "CORE-1000" simulating real VVER-1000 core and radial reflector structure.

During the investigations some important positions have been clarified:
- an immense scope of information to be treated made it necessary to create appropriate database in order to facilitate codes comparison and to avoid eventual technical errors
- in considered "purified" benchmarks feed-backs are artificially suppressed. It can initiate more significant discrepancies between different neutronics codes than it was observed earlier in VVER-1000 operation calculations on uranium cores
- Monte Carlo codes application to large systems has specific features lined with calculation of statistical uncertainties for different functionals. So while calculating benchmarks of "CORE-1000" type the problem appeared on computing real dispersion of neutron fission and generation rates, and neutron fluxes in fuel assembly (FA). Taking account of this problem L.V.Maiorov used the methodology [11] for calculations of "CORE-1000" type benchmarks.

The mentioned database intended for current core benchmarking project has been created in Russian Research Center "Kurchatov Institute". It is named "Model Data Base" (MDB). Indicated difficulties were analyzed using additional core benchmarks not included into [4].

Below the main results on comparison between neutronics production codes and reference codes are presented. Besides the codes involved are briefly described. Main features of core benchmarks configurations and MDB are also presented.

2. CODES INVOLVED IN VERIFICATION OF PRODUCTION NEUTRONICS CODES

2.1 COARSE-MESH CODE BIPR7-A

Production code BIPR-7A certified for uranium VVER-1000 core is a 3-dimensional coarse-mesh code intended for neutronic characteristics calculation of VVER-type core with hexagonal fuel assemblies.
Calculational cell represents assembly transversal section in horizontal plane and some fraction of core height in axial direction. Reflectors are described by border conditions. Calculation is performed in two energetic groups using the so-called modal presentation of group fluxes in diffusion equations [5]. Diffusion equation coefficients are homogeneous inside of calculational cells.

Initial data are the functionals representing combinations of neutron cross sections, neutron fluxes and diffusion coefficients in calculational cells. They are calculated by TVS-M code for an infinite grid of identical fuel assemblies using 48 energy groups. Calculational cell parameters, prepared by the code TBC-M, form a library and represent a set of polynomial coefficients. Thus one can simulate two-group neutron cross sections dependence on moderator density, moderator temperature, fuel power generation, boric acid concentration in coolant, Xe and Sm concentration in fuel.

BIPR-7A is a part of production super-code KASKAD that allows obtaining in convenient formats all the neutronics parameters necessary for safety estimations and licensing of VVER fuel cycles.

2.2 FINE-MESH CODE PERMAK-A

Production code PERMAK-A, certified for uranium VVER-1000 core, is a two-dimensional fine-mesh code intended to calculate neutronics characteristics of VVER-type core. Calculational cell is hexagonal. Pitch of calculational grid is equal to the pitch of fuel pins location in FA. Diffusion finite-difference neutron balance equation in few energetic groups (4-6) is resolved. There are considered 2 groups in the energy interval of fast neutrons, 1 – in the interval of resonance neutrons and 1-3 – in the thermal interval of neutron energy. Radial reflector is subdivided into calculational cells in the same manner as a core. Neutron flux axial gradients, obtained by 3D BIPR7-A calculation, are used while calculating corresponding core axial level by PERMAK-A.

Cell (fuel and non-fuel) parameters are prepared by the code TBC-M in the infinite grid approach or super-cell approach taking into account neutron flux gradient in a cell. Parameters form a special library and represent a number of polynomials that describe the group neutron cross sections dependence on moderator density, moderator temperature, fuel power generation, boric acid concentration in coolant, Xe and Sm concentration in fuel. Code PERMAK-A performs calculations on regular finite-difference grid; the irregular cell-between-cell pitch in peripheral FA row is taken into account by correction of group constants introducing the so-called “densification coefficients”.

PERMAK-A also is a part of mentioned production super-code KASKAD.

2.3 PRODUCTION CODE OF IMPROVED ACCURACY RADAR

Production code of improved accuracy RADAR consists of two modules: constants module and spatial calculation module.

Spectral module of TVS-M is used as constants module performing the following: 1) detailed calculation of neutron multi-group spectrum in an axial calculational FA fraction, 2) calculation of isotopic composition evolution during fuel irradiation for every pin and for every in-pin cylindrical zone, 3) generation of cell diffusion constants.

Spatial module ensures calculations of 3D distribution of neutron fluxes and powers over core in the multi-group diffusion approach. The number of energy groups varies from 1 to 48. In 48-groups approach there are considered 12 groups in the energy interval of fast neutrons, 12 – in the interval of resonance neutrons and 24 – in the thermal interval of neutron energy. Finite-difference scheme of the spatial module is corrected by the introduction of nodal functionals for every calculational point treated by the spectral module.

While iterating the spatial module forms radial and axial border conditions for neutron fluxes for every calculational FA fraction. Multi-group border conditions are used in the spectral module. So one can take into account a real location of calculational FA fraction in a core while computing spectral characteristics and diffusion constants at any moment of core irradiation. Such approach ensures an interaction of the spatial and constants modules in RADAR.

RADAR was verified on a large set of tests based on calculations by the certified codes. Its satisfactory accuracy was confirmed by the comparison with experimental data on different critical test beds with uranium fuel in Russia and in the East Europe.

2.4 CODE COMPLEX CONKEMO

Code complex CONKEMO was specially developed for burnup calculation. It includes the following main program units: 1) CONSYST that prepares the group (299 groups) cross-sections of medium based on ABBN-93 neutron data library [6], 2) KENO-VI [7] that is used for neutron flux calculations in arbitrary geometry (including hexagonal one) by the Monte Carlo method, 3) ORIGEN-S [8] that performs isotope evolution calculations, 4) MAYAK that provides the joint work of the codes in the complex and treatment of information.

2.5 CODE MCU

MCU is a well-known Monte Carlo code developed in Kurchatov Institute [10].

3. BENCHMARKS CONFIGURATIONS

3.1 CONFIGURATIONS “MINICORE”

The calculated configurations of "minicore" type are shown in Fig.3.1. More detailed description of the calculated configurations and variants is given in [4]. The following indications are used: F – fuel assembly, S – steel, R – water.

Plutonium FAs shown in Fig.3.4 are of three options:
- non-graded with or not 18 boron rods (either absorbers of natural boron or absorbers of enriched 80% boron)
- graded with the same subdivision
- graded with 18 uranium-gadolinium burnable poison rods (tvegs) and with or not 18 boron rods (either absorbers of natural boron or absorbers of enriched 80% boron). It is the basic option.

In non-graded FAs fissile plutonium content of 3.6% is considered. In graded FAs the central part is of 3.6% content on fissile plutonium isotopes, peripheral – 2.7 %, in corners – 2.4%. Tvegs consist of uranium of 3.6% ^{235}U enrichment with 4% weight content of Gd_2O_3.

Uranium fuel assemblies shown in Fig.3.5 are also of three options:
- non-graded with or not 18 boron rods (either absorbers of natural boron or absorbers of enriched 80% boron or burnable poisons)
- graded with the same subdivision
- graded with 6 uranium-gadolinium burnable poison rods (tvegs) and with or not 18 boron rods (either absorbers of natural boron or absorbers of enriched 80% boron). It is the basic option.

In non-graded FAs uranium enrichment of 3.7% ^{235}U is considered. In graded FAs the central part is of 4.2% enrichment, peripheral – 3.7%. Tvegs consist of uranium of 3.3% enrichment with 5% weight content of Gd_2O_3.

For every configuration 9 states described in Table 3.1 are considered.

3.2 CONFIGURATIONS "CORE-1000"

The examples of calculated configurations of "CORE-1000" type are shown in Figures 3.2 and 3.3. In upper indication N1/N2 figure N1 corresponds to numeration in core sector, N2 – to assembly type: 1 - basic option of uranium FA, 2 - basic option of MOX FA. Lower indication for every FA corresponds to burnup level in MW day/kg HM (HM – heavy metals). Parameters of calculated states are described in Table 3.2.

4. INITIAL DATA AND FUNCTIONALS TO BE REGISTERED

Different moments (levels) of irradiation are described by direct introducing of nuclear concentrations estimated during fuel irradiation simulation by the code TVS-M in infinite grid. Such approach facilitates comparative analysis of results obtained by different codes.

Functionals to be registered include effective multiplication factor K_{eff}, neutron absorption, fission and generation rates, powers, multiplication factors, neutron fluxes and other parameters over calculational regions. These regions may be of assembly type (in horizontal plane) or of fuel pin cell type. In reflectors the calculational regions of size equivalent to assembly type or fuel pin cell type are also considered.

5. DEMONSTRATION FORMS OF MODEL DATABASE

Developed demonstration forms ensure rigorous information structuring in order to eliminate technical errors during comparative analysis. For the presented benchmarks the interface of EXCEL and Visual Basic possessing vast graphical, mathematical and search possibilities was used.

The following main demonstration forms were proposed:
- information forms on geometry of considered systems
- information tables on calculational states
- initial and comparative tables concerning K_{eff} of different systems in different states
- graphical forms demonstrating assembly-by-assembly distribution of different functionals
- graphical forms demonstrating cell-by-cell distribution of different functionals
- forms demonstrating compiled graphical information on discrepancies (between different codes) of different functionals for FAs in "minicore" type configuration
- compiled tables of the most specific discrepancies.

Besides a set of auxiliary forms of structural support and control of different information has been developed.

The interface of model database allows to modify easily an existing information, ensures automatic connection with initial information sources and allows to compare the obtained results in convenient normalized form between different codes, states and systems. Main demonstration forms are located on one standard list of paper. The most important part of verification material is minimized and integrally included in compiled tables of specific discrepancies necessary for expert estimation of production code quality.

6. RESULTS

It may be preliminarily concluded about discrepancies (from precision codes and code RADAR) of production codes BIPR7-A and PERMAK-A being based on the calculated benchmarks.

- Analyzing "minicore" tests:

- PERMAK-A calculates K_{eff} with discrepancy 1.0% in states with inserted control rods (CRs) that reduces to 0.8% if no CRs are inserted
- PERMAK-A calculates cell-by-cell distribution of multiplication factors with the discrepancy of 0.7% if there are no absorbers. In states with absorbers, near steel reflectors and in uranium-gadolinium fuel pins the discrepancies are greater
- PERMAK-A calculates assembly-by-assembly average powers with discrepancy 2%, for FAs with absorbers – 4.0%
- PERMAK-A calculates fuel pin powers with discrepancy 7% in the regions important for fuel assembly design.

- Analyzing "CORE-1000" tests:

- PERMAK-A calculates K_{eff} with discrepancy 0.5% in states without control rods that weakly increases if CRs are inserted
- BIPR7-A calculates K_{eff} with discrepancy 0.7%

- PERMAK-A calculates assembly-by-assembly average powers with discrepancy 5% in states without CRs. If CRs inserted the discrepancies increase until 10%
- BIPR7-A calculates assembly-by-assembly average powers with discrepancy 7% in states without CRs. For states with inserted CRs and with high boric acid concentration the discrepancies are noticeably greater.

Presence of MOX fuel in the calculated configurations leads to a certain increasing of production codes discrepancies in comparison with similar all uranium configurations (for example, in average fuel assembly powers calculated by BIPR7-A – by about 2%). This factor should be taken into consideration in core safety calculations of VVER-1000 with MOX fuel by introducing appropriate corrections in engineering safety factors.

It should be noted that all states in the calculated benchmarks have been simulated under artificial suppression of feedbacks in codes BIPR7-A and PERMAK-A. In real reactor operation calculations of uranium VVER-1000 loadings by BIPR7-A and PERMAK-A (with feedbacks involved) discrepancies calculation/operation in power distributions are noticeably lower. So production codes discrepancies will be specified definitely in future after comparison with reactor operation data and also with experiments in critical test beds. The program of such experiments is actually under development. It should be also noted that precision codes have their proper uncertainty that is the subject of separate investigation.

7. CONCLUSIONS

Verification of Kurchatov Institute production codes is intended for core neutronics calculations of VVER-1000 core in view of utilization of MOX fuel with weapon-grade plutonium.

Verification has been performed on the basis of developed set of 2D calculational benchmarks where production codes are to be compared with precision (Monte Carlo) codes MCU and CONKEMO, and with production code of improved accuracy RADAR. Production codes have included the fine-mesh code PERMAK-A and the coarse-mesh code BIPR7-A. Discrepancies of production codes from precision codes and code RADAR have been calculated.

The results of comparison show that BIPR7-A and PERMAK-A ensure acceptable discrepancies of neutronics parameters calculations ($K_{eff,}$ assembly-by-assembly and pin-by-pin power distributions) for main design core states. The results do not indicate significant difference in code discrepancies between purely uranium configurations and that containing MOX fuel. The obtained results are to be a part of verification report needed for production codes certification.

Production codes verification will be supplemented in future by comparison with experimental data from critical test beds and with operation reactor data.

8. REFERENCES

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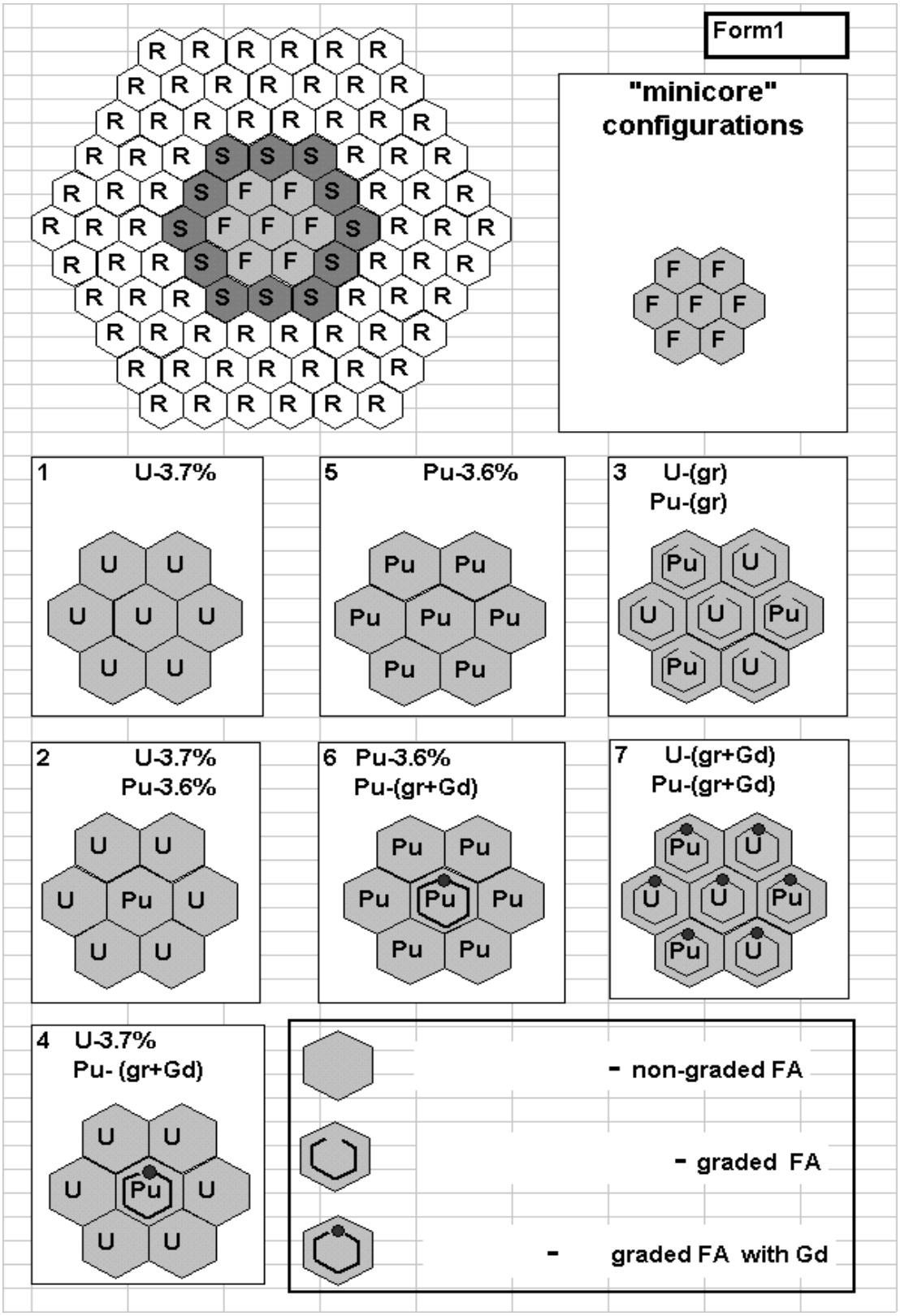

Fig.3.1 ”Minicore” configurations

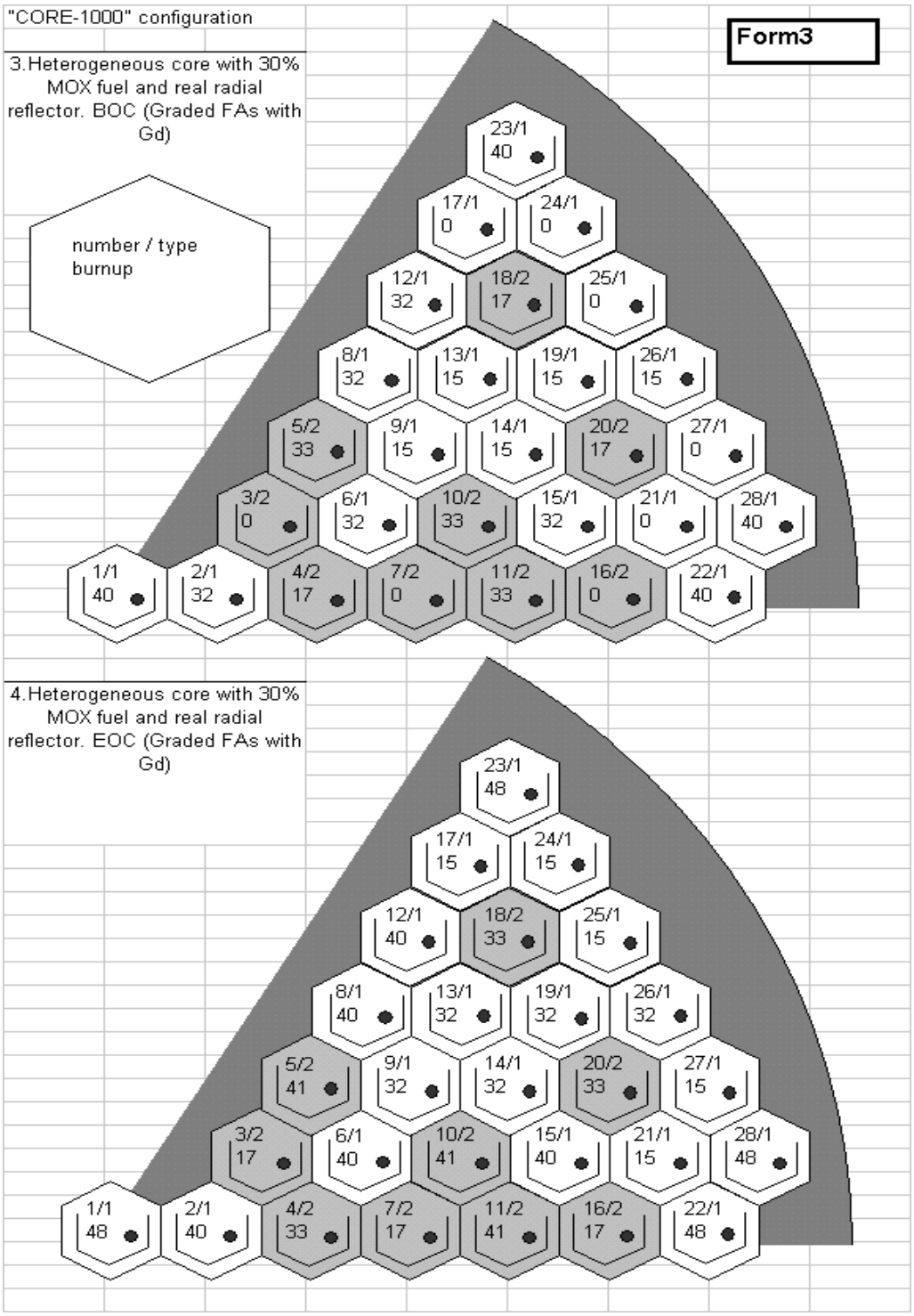

Fig.3.2 Heterogeneous “CORE-1000” configurations

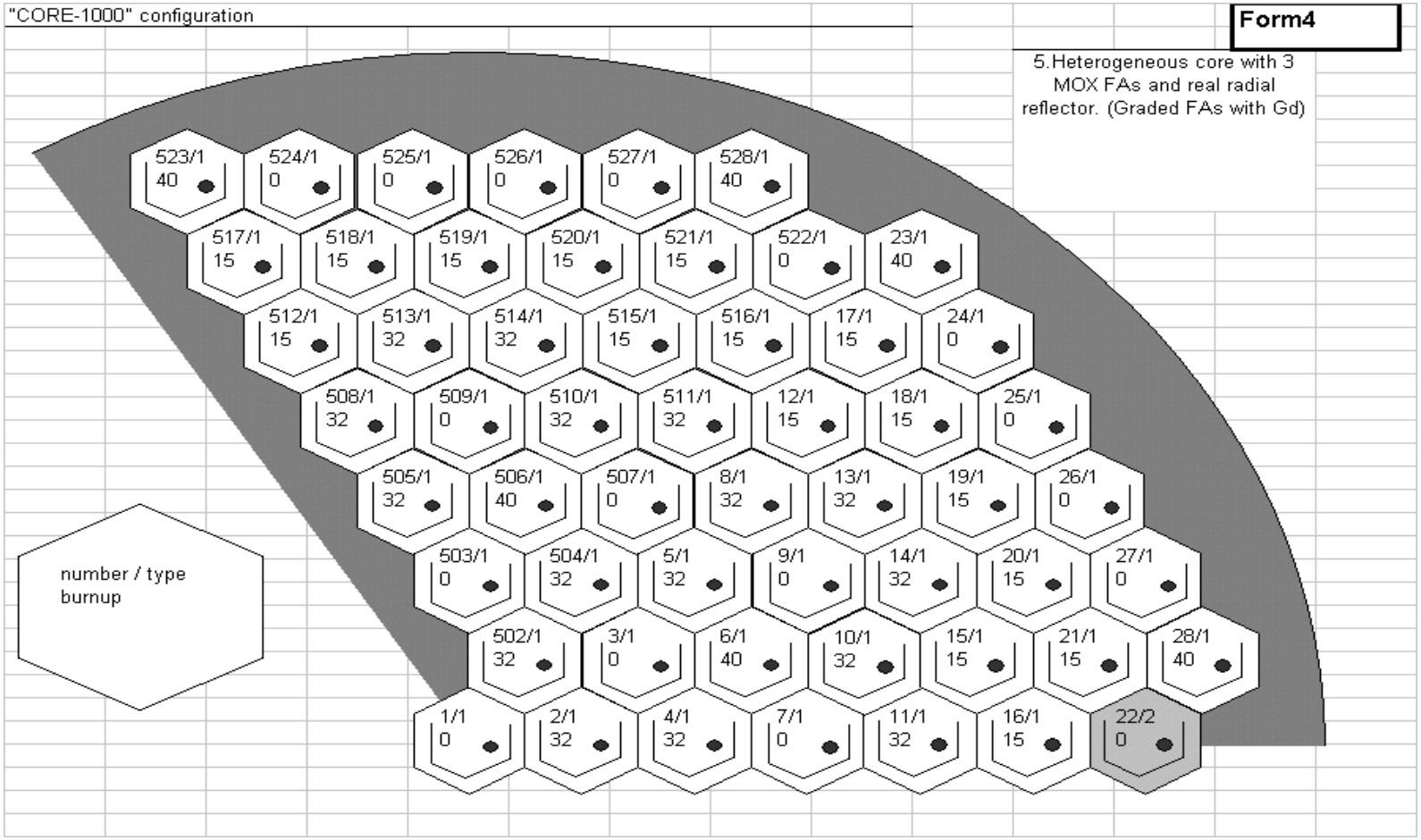

Fig. 3.3 Heterogeneous “CORE-1000” configuration with 3 MOX leading test assemblies

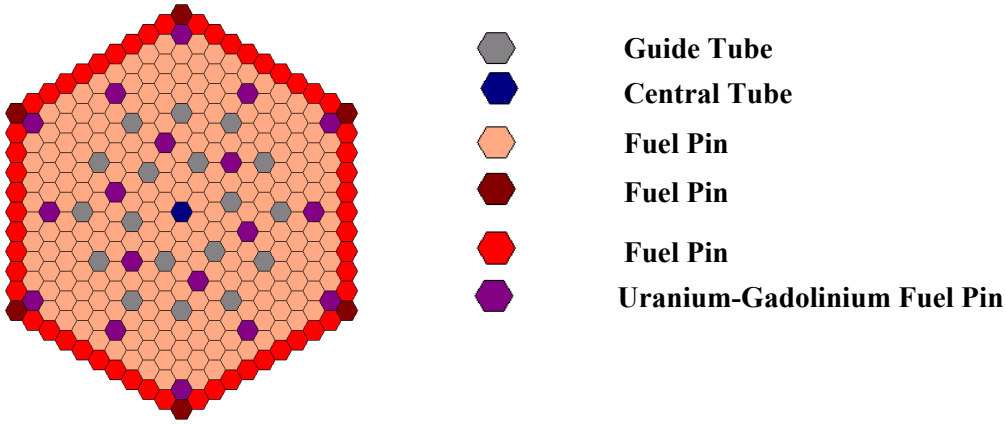

Fig. 3.4 MOX FA Pattern

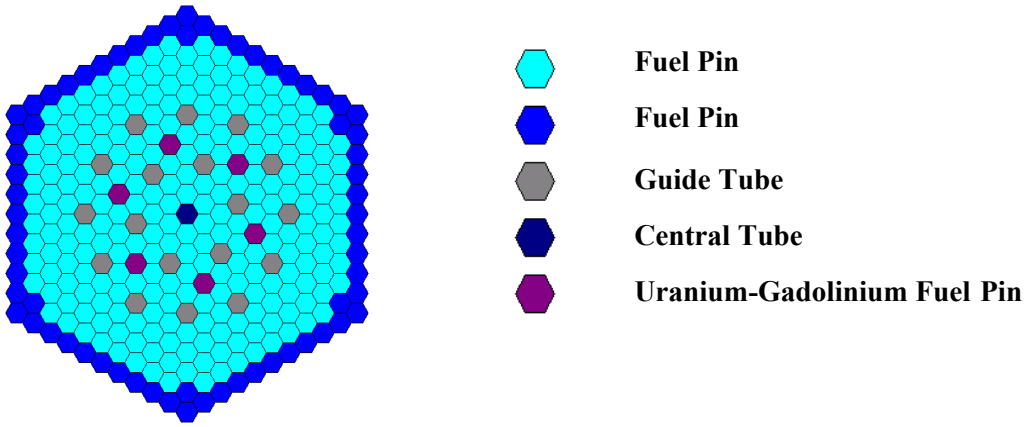

Fig. 3.5 UOX FA pattern

Table 3.1 States in "minicore" calculations

State Number	Absorber zones (guide tubes)	Fuel (temp., K)	Non_Fuel (temp., K)	Boron concentration (ppm)
1	moderator	1027	575	600
2	moderator	575	575	600
3	moderator	575	575	600
4	moderator	575	575	0, γ_{H20}=0.2g/cm^3
5	moderator	300	300	600
6	moderator	300	300	0
7	B_4C (natural)	1027	575	600
8	B_4C (enriched)	1027	575	600
9	Boron poison rod	1027	575	600

Table 3.2 States in "CORE-1000" calculations

State Number	Absorber zones (guide tubes)	Materials out of FAs (temp., K)	Fuel (temp., K)	Non_Fuel in FAs (temp., K)	Boron concentration (ppm)
1	moderator	560	1027	575	1300
2	moderator	560	575	575	1300
3	moderator	300	300	300	2800
4	moderator	560	1027	575	0
5	moderator	560	575	575	0
6	B_4C (natural)	553	553	553	0
7	B_4C (natural)	553	553	553	0