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OECD/NEA VVER-1000 MOX ASSEMBLY COMPUTATIONAL BENCHMARK

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ABSTRACT

The United States and Russian Federation have each declared significant quantities of weapons-grade (WG) plutonium to be surplus to their defense needs. Under a mutual agreement, both countries are working towards a plan for the final disposition of the material with one option being the conversion of the material to mixed-oxide (MOX) fuel for nuclear reactors. Recent work in Russia has focused on the certification of the calculational codes and the design of MOX fuel assemblies and core configurations. The OECD Nuclear Energy Agency Expert's Group on Reactor-Based Plutonium Disposition has performed several benchmarking efforts to help in the code certification process by providing experimental data and by sponsoring benchmarking exercises that provide useful verification of the Russian calculational methods. The VVER-1000 MOX assembly benchmark models consist of two different assemblies that are typical of the advanced designs that are under active development in Russia for the VVER-1000 reactors: a uniform LEU fuel assembly with 12 U/Gd rods (UGD variant); and a profiled MOX fuel assembly with 12 U/Gd rods (MOXGD variant). Calculational results were provided by six participants using a variety of codes and data libraries. Comparisons of k_{inf}, isotopic concentrations, and fission rate distributions were prepared as a function of burnup and operational states. Overall, excellent agreement was noted in most parameters compared.

Key Words: MOX, Plutonium Disposition, VVER-1000

1. INTRODUCTION

The United States and Russian Federation have each declared significant quantities of weapons-grade (WG) plutonium to be surplus to their defense needs. Under a mutual agreement, both countries are working towards a plan for the final disposition of the material with one option being the conversion of the material to mixed-oxide (MOX) fuel for nuclear reactors. The current agreement calls for the disposition of approximately 34 tonnes of WG plutonium by each country over the next twenty-five years. The experience with MOX fuel in these two countries is relatively small compared with that accumulated in European countries and Japan.

For this reason an international Experts Group has been established at the OECD/NEA to facilitate the sharing of existing information and experience in the physics and fuel behavior of MOX fuel as it relates to the disposition of weapons-grade plutonium. The Experts Group deals with the status and trends of reactor physics, fuel performance and fuel cycle issues related to the disposition of weapons-grade plutonium as mixed oxide fuel. Its objectives are to provide up-to-date information and develop a

consensus regarding core and fuel cycle issues with weapons-grade plutonium disposition in thermal water reactors (PWRs, BWRs, VVER-1000s, and CANDUs) and fast reactors (BN-600). The topics covered include core physics, fuel performance and reliability, thermal water reactor and fast reactor fuel designs, fuel management approaches for maximizing weapons-grade plutonium disposition rates, and fuel cycle flexibility. The Experts Group also aims to provide advice to the nuclear community on the scientific and technical developments needed to meet requirements (e.g. data, methods and validation experiments) for implementing weapons-grade plutonium disposition approaches. In this regard, activities are closely coordinated with other NEA groups such as the Working Party on Physics of Plutonium Fuels and Innovative Fuel Cycles. A summary of recent activities of the Experts Group was recently presented at an International Meeting [1]. Recent activities of particular interest include the VENUS-2 experimental benchmark [2,3] and the KRITZ-2 experimental benchmark [4], which are experiments performed with near-weapons-grade MOX.

In Russia the WG MOX fuel will be used in both fast (BN600) and light water reactors (VVER-1000). Recent work in Russia has focused on the certification of the calculational codes and the design of MOX fuel assemblies and core configurations. The Expert's group has performed several benchmarking efforts to help in the code certification process by providing experimental data and by sponsoring benchmarking exercises that provide useful verification of the Russian calculational methods. While these Russian codes and data have been certified for LEU-based fuel, the certification for MOX fuel is required because of the essential differences between reactors fueled with MOX, such as:

- Reduced worth of the control rods, boric acid, and burnable poisons
- Reduced effective fraction of delayed neutrons
- Reduced moderator temperature reactivity coefficient at the end of fuel cycle
- Increased pin power peaking factor at the boundary between MOX and UOX FAs which makes it necessary to use fuel rods with different contents of plutonium in fuel assembly
- Increased quantity of fission neutrons
- Increased neutron flux sensitivity to local changes of moderator/fuel ratio.

The design process in Russia has studied several different MOX fuel assembly configurations and has converged on a design that has a graded configuration that utilizes uranium/gadolinium fuel pins to provide an effective means of introducing burnable absorbers into the MOX assemblies. In 1999 a calculational benchmark based on this prevailing concept was formulated at the Kurchatov Institute. This is a standard problem for VVER-1000 core physics in which two assemblies are considered: a uniform LEU fuel assembly with 12 U/Gd rods (UGD variant); and a profiled MOX fuel assembly with 12 U/Gd rods (MOXGD variant).

This benchmark was proposed to the OECD/NEA Experts Group on Reactor Based Plutonium Disposition to be calculated in year 2000. The primary motivations of the VVER-MOX Benchmark are:

- It provides a well-defined standard problem for VVER-1000 core physics calculations.
- The VVER-1000 assembly design with U/Gd rods is a very recent development that corresponds to the VVER-1000 core configuration in which the first MOX FAs will be installed.
- A comparison of the LEU and MOX fuel assembly properties during irradiation period is essential for understanding the changes in the behavior of the reactor core.
- Comparisons of calculational results of the complex VVER-1000 MOX assembly with U/Gd pins will provide a good indication of the adequacy of the current computational methods.

The VVER-1000 MOX Assembly Computational Benchmark was completed in 2001 and the full specifications, results, and comparisons are available in Ref. 5.

2. BENCHMARK MODEL

The benchmark model consists of two different assemblies that are typical of the advanced designs that are under active development in Russia for the VVER-1000 reactors. In particular, these assemblies are similar to the designs that are to be used in the plutonium disposition mission. The detailed benchmark specifications, as used by the participants, are given in Appendix A of Ref. 5. The benchmark exercise consists of two assembly types: a uniform LEU fuel assembly with 12 U/Gd rods (UGD variant); and a profiled MOX fuel assembly with 12 U/Gd rods (MOXGD variant).

The VVER-1000 assemblies are hexagonal in design and consist of one central tube, 312 fuel pin locations (12 of which are U/Gd rods), and 18 guide tubes. The clad and structural material is a Zr-Nb alloy. The UGD assembly is shown in Fig. 1 and consists of fuel rods with 3.7 wt. % enrichment. The 12 U/Gd pins have a ^{235}U enrichment of 3.6 wt. % and a Gd_2O_3 content of 4.0 wt. %. The MOXGD assembly is shown in Fig. 2 and contains fuel rods with three different plutonium loadings. The central region contains MOX pins with 4.2 wt. % fissile plutonium (consisting of 93 wt.% ^{239}Pu), two rings of fuel rods with 3.0 wt.% fissile plutonium, and an outer ring of fuel rods with 2.0 wt.% fissile plutonium. The 12 U/Gd rods are in the same locations as in the UGD assembly configuration and have the same design.

Several calculational states were included in the benchmark exercise. These states, listed in Table I cover the operational states and cold conditions. Burnup calculations are performed with the S1 state with a power density of 108 MWt/m^3 with a sufficient number of burnup steps to provide accurate results, particularly during the burn out of the Gd absorber. At specified burnup points, branch calculations are performed for states S2-S5 using the isotopic compositions from the burnup calculation. The parameters that are requested include:

State S1. Parameters versus burnup (0,2,4,6,8,10,12,14,15,20,40 MWd/kg)

- k_{inf}
- fuel isotopic composition
- pin by pin fission rate distribution

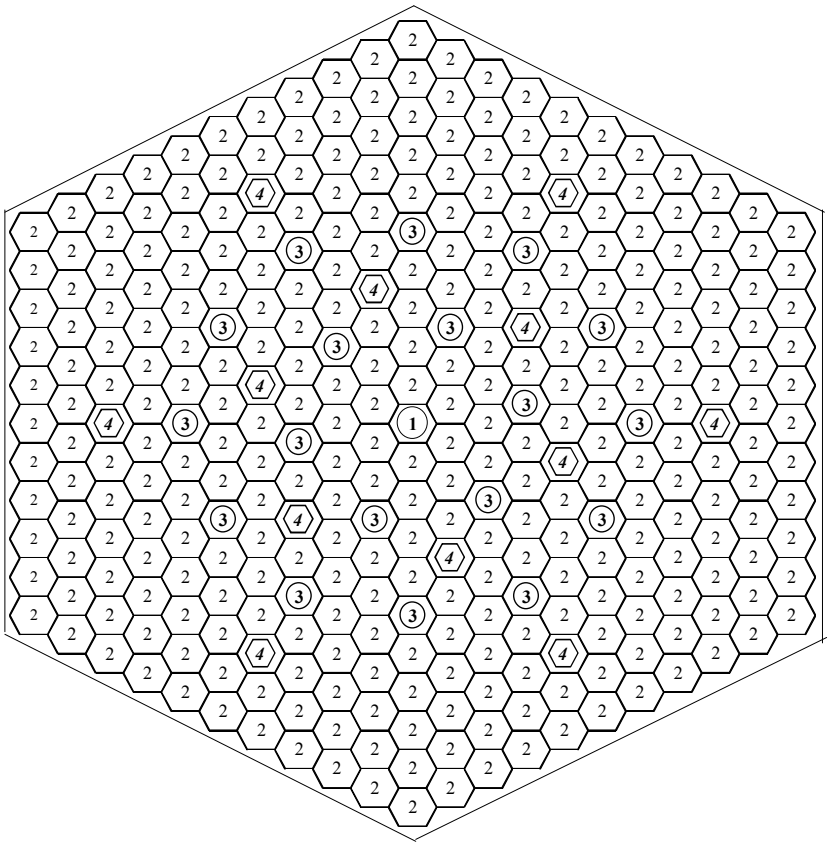
States S2-S5 with isotopic composition at burnup points 0, 20, 40 MWd/kg

- k_{inf}
- pin by pin fission rate distribution

Table I. Calculation States

State	Description	Fuel temp., K	Non-fuel temp., K	^{135}Xe, ^{149}Sm
S1	Operating poisoned state	1027	575	Eq[a].
S2	Operating non-poisoned state	1027	575	0.0
S3	Hot state	575	575	0.0
S4	Hot state without boric acid	575	575	0.0
S5	Cold state	300	300	0.0

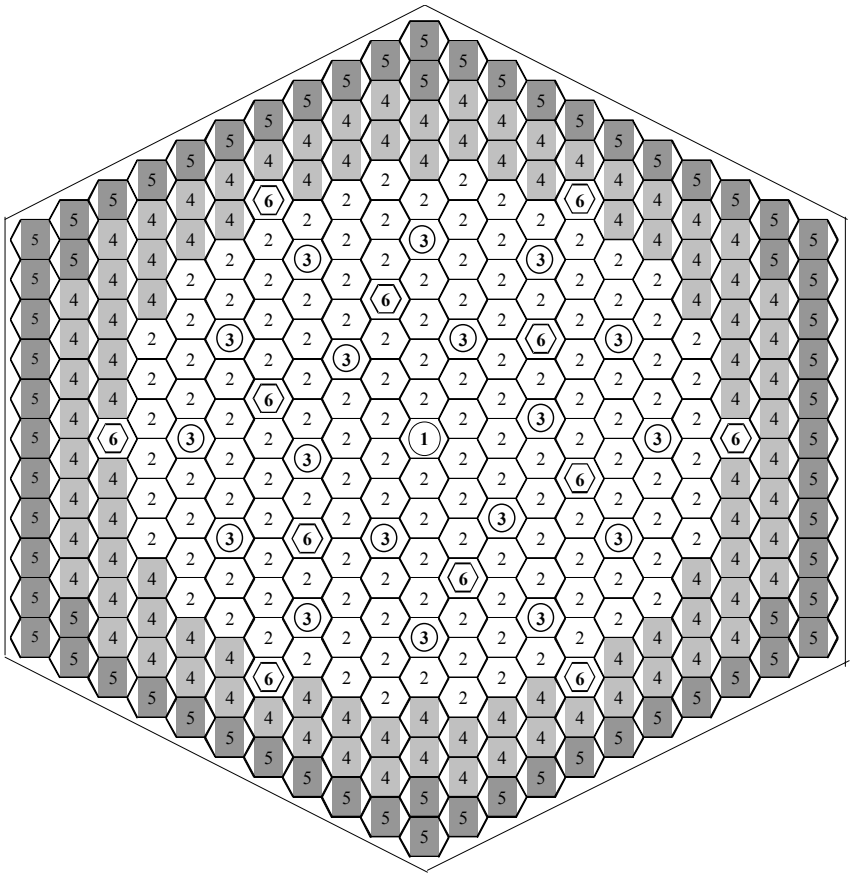
[a]Eq. Indicates equilibrium ^{135}Xe and ^{149}Sm concentrations.



Cell types

1 – Central tube cell
2 – Fuel cell (with U1, 37. wt. % LEU)
3 – Guide tube cell
4 – Fuel cell (with GD1, 3.6 % LEU with 4.0 wt.% Gd_2O_3)

Fig. 1 UGD assembly configuration.



Cell types

1 – Central tube cell
2 – Fuel cell (with PU3, 4.2 wt. % Pu)
3 – Guide tube cell
4 – Fuel cell (with PU2, 3.0 wt. % Pu)
5 – Fuel cell (with PU1, 2.0 wt. % Pu)
6 – Fuel cell (with GD1, 3.6 % LEU with 4.0 wt.% Gd_2O_3)

Fig. 2 MOXGD assembly configuration.

3. PARTICIPANTS, CODES, AND DATA

A total of six solutions were received from five countries with each participant using different methods and data combinations. Two of the solutions are based on continuous energy Monte Carlo methods, while the remaining solutions are based on collision probability (or similar) methods. The submitted solutions cover several data libraries. The complete list of participants, basic libraries, and codes used are summarized in Table II.

Four of the submitted solutions are based on deterministic methods. The RRC-KI calculations performed with the two-dimensional lattice code TVS-M is based on the so-called "method of passing through probability," which is similar to collision probability methods commonly used in other codes. The TVS-M library contains 48 energy groups with 24 thermal groups and the data is based on a standard formulation used at the RRC-KI known as MCUDAT-2.1. MCUDAT-2.1 has been derived from several sources and is described in more detail in Appendix B of Ref 5. The ORNL calculations were performed with the HELIOS fuel assembly analysis code version 1.4. The HELIOS methods are based on collision probability with current coupling. The calculations were performed with 190 energy groups (62 thermal

Table II. Participants, basic library and computer codes

Institution	Library used	Codes used
KI (Russian Federation) M. Kalugin D. Shkarovsky	MCUDAT-2.1	MCU
KI (Russian Federation) V. Sidorenko A. Lazarenko	48-group library with 24 thermal groups (with boundary energy of 0.625 eV). For resonance nuclides (Th, U, Pu) files of resonance parameters are also available giving a possibility to obtain cross sections for any point in energy region of resolved resonances above 0.625 eV. The data library is obtained from the same source as MCUDAT-2.1.	TVS-M
Belgonucléaire s.a. (Belgium) B. Lance P. Brusselaers	WIMS97 library based on JEF2.2, composed of 172 energy groups	WIMS8A
ORNL (USA) Jess C. Gehin	ENDF/B-VI with adjustments to the U^{238} absorption cross section (The U-238 resonance integral has been reduced by 3.4% to match integral experiments)	HELIOS (ver. 1.4)
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH (Germany) Winfried Zwermann	Point data generated by IKE Stuttgart with NJOY: H-1, O-16, Zr-nat, Gd-152: ENDF/B-VI.4 all other materials: JEF-2.2	MCNP-4B
KFKI Atomic Energy Research Institute (Hungary) Cs. Maráczy	ENDF/B-VI	MULTICELL

groups) with the data based on ENDF/B-VI. Note that in the production HELIOS library the ^{238}U resonance integral has been adjusted to match critical experiments. The Belgonucléaire calculations were performed with WIMS8A using the method of characteristics. The cross section library (WIMS97) is based on JEF-2.2 and consists of 172 energy groups. The KFKI Atomic Energy Research Institute provided results using the MULTICELL collision probability code. The MULTICELL cross sections are based on ENDF/B-VI and use 70 energy groups (35 thermal groups).

Two solutions based on Monte Carlo calculations were submitted. One of these solutions was provided by the RRC-KI using the MCU Monte Carlo code. MCU uses a continuous energy formulation and the MCUDAT-2.1 cross section data, as previously discussed above in regards to the TVS-M code. Burnup calculations were performed using MCU in combination with a standard burnup code using 39 actinides and 165 fission products. The MCU calculations were performed with a sufficient number of particle histories such that the statistical uncertainty in k_{inf} is less than 0.1% and in local fission rates is approximately 1% (one standard deviation). The other Monte Carlo solution was submitted by GRS using MCNP4B with H-1, O-16, Zr-nat, Gd-152 cross sections from ENDF/B-VI.4 and the data for all other materials is from JEF-2.2. The MCNP calculations were performed for fresh fuel conditions and used 1,000,000 particle histories.

4. RESULTS OF BENCHMARK CALCULATIONS

As outlined above, six participants of this benchmark exercise provided six distinct solutions. Because this benchmark is computational in nature, all calculation parameters are compared to the average value of the solutions. The average solution therefore represents a sort of "consensus" solution to the benchmark problem and will provide a reasonable means to show the level of agreement among the solutions and to identify outliers. Also note that the solutions were obtained with the calculational tools and data available at the participating institutions in 2000. In this section, the calculated quantities are compared and discussed.

The complete results are given in Ref. 5, but a summary of the results and comparisons will be given below. The k_{inf} values versus burnup are presented in Table III, Fig. 3 and Table VI, Fig. 4 for variants UGD and MOXGD respectively. Assembly average isotopic composition versus burnup is presented in Tables IV and VII for variants UGD and MOXGD respectively. Tables V and VIII contain the data on reactivity effects calculated with various codes. The following reactivity effects at burnup points 0, 20, 40 MWd/kg are shown in these tables:

- ^{135}Xe and ^{149}Sm poisoning
- Soluble boron effect
- Fuel temperature (Doppler) effect
- Total temperature effect

The fission rate distribution results are summarized in Tables IX and X. The comparison of results (maximum values of the root mean squares and deviations from mean) is given in the Tables and the following definitions and symbols are used:

$$\textit{Relative Root Mean Square Deviation (R.M.S)} = \frac{1}{\bar{x}}\sqrt{\frac{\sum_{i=1}^{N}(x_i-\bar{x})^2}{(N-1)}}$$

Absolute Root Mean Square Deviation(Δ) = $\sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{(N-1)}}$

Relative deviation from mean value = $100\% \times \frac{x_i - \bar{x}}{\bar{x}}$

Absolute deviation from mean value = $x_i - \bar{x}$

where

i code number, i=1,N

N total number of codes used to obtain the parameter (in this report N=5, except for tables on fission rate distributions and reactivity effects that include the results obtained by means of MCNP-4B, where N=6 in corresponding rows and columns).

x_i value of parameter obtained by code i, $\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$ - mean values of parameter

4.1 Effective Multiplication Factor

The k_{inf} values versus burnup obtained by various codes are presented in Table III, Fig. 3 and Table VI, Fig. 4 for variants UGD and MOXGD respectively. The results show generally good agreement, but it should be noted that:

- All the codes give very similar behavior of k_{inf} vs. burnup for both UGD and MOXGD variants.
- The results for the UGD variant demonstrate very good agreement among all of the submitted solutions with a maximum difference of 0.004 δk at high burnup. The WIMS8A slightly underestimates k_{inf} at the beginning of burnup in comparison with the other solutions while TVS-M and MULTICELL slightly underestimate k_{inf} values at the higher burnups (0.004 δk in comparison to the mean value).
- The results for the MOXGD variant show slightly larger discrepancies in k_{inf} with deviations exceeding 0.007 δk at high burnup. Similar to the UGD results, WIMS8A underestimates k_{inf} relatively to mean value at the beginning of burnup (0.007 δk), and TVS-M and MULTICELL underestimate k_{inf} values at the higher burnups (~0.007 δk relatively to mean value).

The k_{inf} results of separate state calculations (for specific states see Table I) obtained for several burnup points show that the maximum differences between codes are observed at high burnups and for some states the deviations are as large as ~1.5% in case of uranium assembly and up to ~2.5% in case of MOX assembly. A comparison of Figs. 3 and 4 show the different behavior of the Gd absorber in the uranium and MOX environments. The Gd takes longer to burnup out in the harder spectrum of the MOX assembly and burns out in a more uniform manner.

The multiplication factors for fuel assembly variants were used to compute various reactivity effects. Corresponding results obtained with six codes are presented in Tables V and VIII and show generally good agreement with a few exceptions:

- Discrepancies for reactivity effects are approximately the same both for UGD and MOXGD variants and are somewhat increased at high burnup.
- The R.M.S. deviation for ^{135}Xe and ^{149}Sm poisoning effect is ~5% δk.
- The deviations in the boron effect are smaller and equal to 2-2.5% δk
- The R.M.S. deviation for fuel temperature effect is equal to 5-7% δk for all the burnup point with exception of UGD variant in zero burnup point, where the R.M.S. deviation is 8.7% δk.
- Deviations of the total temperature effect have a tendency to increase with burnup; at high burnups it tends to 6% δk for UGD and 7% δk for MOXGD variants.

4.2 Isotopic Concentrations

Comparisons of the assembly average isotopic composition versus burnup for uranium, plutonium, xenon, and samarium nuclides are presented in Tables IV and VII for variants UGD and MOXGD, respectively. For assembly average isotopic composition the R.M.S. deviation is ~ 2% for ^{235}U and ~3% for ^{239}Pu for both the UGD and MOXGD variants. In both variants, the WIMS8A results over-estimate the ^{239}Pu concentration by about 5%. For Sm-149 the R.M.S. deviation is approximately 7%, with the largest deviations in the TVS-M results. Additional comparisons of the isotopic concentrations for selected pins are given in Ref. 5.

4.3 Fission Rate Distributions

The results of comparison of pin-by-pin power distributions computed by various codes are shown in Tables IX and X. Comparison results are presented for state S1 burnup points 0, 20, and 40 MWd/kg. The tables make it possible to conclude that pin-by-pin fission rate distribution calculations show very good agreement. The maximum discrepancies do not exceed 3.0% and the R.M.S. discrepancies are ~1%. There is no significant difference in accuracy of the comparisons between the UGD and MOXGD variants.

For UGD variant at the beginning of burnup, the pin with maximum deviation is the uranium-gadolinium pin and is located at a centrally located position. At the end of burnup pin with maximum deviation is at the corner of the fuel assembly. For the MOXGD variant at the beginning of burnup the pin with maximum deviation is at the corner of the assembly, and at the end of burnup the pin with maximum deviation is the uranium-gadolinium pin at a central location.

5. CONCLUSIONS

Six participants analyzed the VVER-MOX Calculational Benchmark. The codes used a variety of methods and different nuclear data. A comparison shows rather good agreement among the results obtained by the various codes. Five codes were used to simulate burnup behavior and trents. All five codes give very similar trends in k_{inf} versus burnup, but TVS-M and MULTICELL codes have a tendency to underestimate somewhat a k_{inf} at the end of burnup relative to the other three codes. Pin-by-pin fission rate distribution calculations show very good agreement with maximum discrepancies not exceeding 3.0%. For most of the parameters, the level of agreement in the results for the MOXGD variant was similar to that of the UGD variant.

As was mentioned in the introduction, the verification of spectral codes is only a part of overall verification of the whole code package for VVERs calculations. Another part of this package (codes for core coarse-mesh and fine-mesh calculations) needs to be verified as well. So the work along these lines

should be continued and benchmarking efforts should be extended to the whole-core methods involving fuel cycle and kinetics calculations. Further, it should be emphasized that a verification on the base of calculational benchmarks does not eliminate the necessity of comparison with the results obtained at MOX fueled experimental facilities.

ACKNOWLEGEMENTS

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Table III. UGD variant k_{inf} comparisons

Burnup (MWd/kg)	Mean k_{inf}	Δ	Deviation from the mean				
			MCU	TVS-M	WIMS8A	HELIOS	MULTICELL
0	1.1350	0.001	0.000	0.000	-0.002	0.000	0.001
1	1.1349	0.002	0.002	0.000	-0.005	0.001	0.002
2	1.1357	0.002	0.000	0.000	-0.004	0.002	0.002
3	1.1370	0.002	0.002	-0.001	-0.004	0.002	0.002
4	1.1373	0.002	0.000	-0.001	-0.003	0.002	0.002
5	1.1385	0.002	0.001	-0.001	-0.003	0.002	0.001
6	1.1401	0.001	0.001	-0.001	-0.002	0.002	0.000
7	1.1413	0.001	0.001	-0.001	-0.002	0.002	0.000
8	1.1400	0.002	0.002	-0.001	-0.003	0.001	0.000
9	1.1347	0.002	0.000	0.000	-0.003	0.002	0.002
10	1.1277	0.002	0.001	0.000	-0.004	0.001	0.002
11	1.1185	0.002	-0.001	0.000	-0.003	0.002	0.002
12	1.1096	0.002	0.000	0.000	-0.004	0.002	0.002
13	1.1002	0.002	-0.001	0.000	-0.004	0.002	0.002
14	1.0915	0.002	0.001	-0.001	-0.004	0.002	0.002
15	1.0825	0.002	0.000	0.000	-0.004	0.002	0.002
20	1.0411	0.002	-0.001	-0.001	-0.003	0.002	0.002
25	1.0036	0.002	0.000	-0.001	-0.002	0.003	0.001
30	0.9689	0.002	0.001	-0.002	-0.001	0.003	-0.001
35	0.9371	0.004	0.004	-0.004	0.000	0.002	-0.003
40	0.9065	0.004	0.003	-0.004	0.002	0.003	-0.004

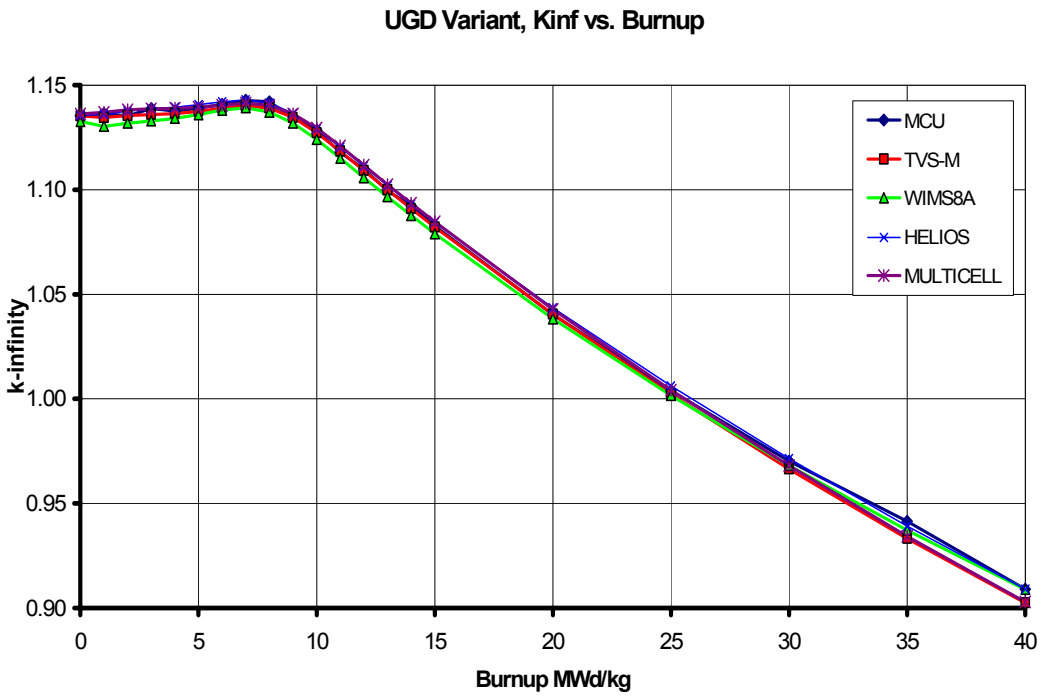

Fig. 3 UGD Variant, k_{inf} vs burnup

Table IV. UGD variant, comparison of assembly average isotopic composition at 40 MWd/kg

Code	Deviation from the Average Value (%)								
	U-235	**U-236**	**U-238**	**Pu-239**	**Pu-240**	**Pu-241**	**Pu-242**	**Xe-135**	**Sm-149**
MCU	-1.46	0.62	-0.06	0.33	1.14	-0.66	6.74	-0.48	-6.93
TVS-M	-1.07	-0.21	0.01	0.90	5.20	-3.88	4.06	-3.40	-7.95
WIMS8A	3.47	-2.44	-0.05	4.95	0.07	6.09	0.03	2.92	6.00
HELIOS	0.03	2.77	0.05	-3.81	-7.26	1.15	-2.73	0.55	3.84
MULTICELL	-0.97	-0.74	0.05	-2.37	0.85	-2.70	-8.09	0.41	5.04
MEAN Value (a/b-cm)	6.315-5[a]	3.210-5	6.469-3	4.429-5	1.808-5	1.104-5	4.177-6	2.593-9	2.978-8
R.M.S. %	2.01	1.91	0.05	3.38	4.52	3.91	5.81	2.28	6.84

[a] Read as 6.315×10^{-5} a/b-cm.

Table V. UGD variant, comparison of reactivity effects (% δk)

Initial State	Final State	Comment	Burnup (MWd/kg)	MCU	TVS-M	WIMS8A	HELIOS	MULTICELL	MCNP4B	Mean % δk	R.M.S (%)
S1	S2	Xe+Sm Cb>0	0	-4.26	-4.15	-3.67	-3.95	-4.13		-4.03	-5.69
			20	-4.06	-3.76	-3.98	-3.92	-4.08		-3.96	-3.23
			40	-3.41	-3.00	-3.33	-3.30	-3.39		-3.29	-5.02
S3	S4	Boron 0.6 g/kg	0	-6.00	-6.04	-5.88	-5.96	-5.99	-6.06	-5.99	-1.10
			20	-5.46	-5.56	-5.36	-5.48	-5.54		-5.48	-1.39
			40	-5.01	-4.94	-4.75	-4.91	-4.96		-4.91	-2.04
S3	S2	T fuel Cb>0	0	1.20	1.32	1.50	1.44	1.43	1.25	1.36	8.74
			20	1.41	1.47	1.60	1.60	1.54		1.52	5.55
			40	1.30	1.35	1.44	1.50	1.41		1.40	5.57
S4	S5	T all Cb=0	0	-6.98	-7.09	-6.89	-6.91	-6.46	-7.04	-6.90	-3.27
			20	-6.96	-6.54	-6.95	-6.63	-6.49		-6.72	-3.36
			40	-5.69	-5.16	-5.63	-5.15	-5.00		-5.33	-5.87

Table VI. MOXGD variant, k_{inf} comparisons

Burnup (MWd/kg)	Mean k_{inf}	Δ	Deviation from the mean				
			MCU	TVS-M	WIMS8A	HELIOS	MULTICELL
0	1.1566	0.004	-0.002	0.002	-0.007	0.003	0.004
1	1.1427	0.004	-0.001	0.002	-0.007	0.003	0.003
2	1.1308	0.005	-0.003	0.003	-0.008	0.004	0.004
3	1.1213	0.005	-0.003	0.003	-0.008	0.004	0.004
4	1.1130	0.005	-0.002	0.002	-0.008	0.003	0.004
5	1.1048	0.005	-0.003	0.003	-0.008	0.004	0.004
6	1.0970	0.005	-0.006	0.003	-0.007	0.005	0.005
7	1.0907	0.005	-0.005	0.003	-0.007	0.004	0.004
8	1.0847	0.005	-0.005	0.003	-0.007	0.005	0.004
9	1.0789	0.005	-0.006	0.003	-0.006	0.005	0.005
10	1.0744	0.005	-0.005	0.003	-0.006	0.004	0.004
11	1.0696	0.005	-0.006	0.003	-0.006	0.005	0.004
12	1.0653	0.004	-0.005	0.002	-0.006	0.004	0.004
13	1.0605	0.004	-0.004	0.002	-0.006	0.004	0.003
14	1.0552	0.004	-0.004	0.001	-0.005	0.005	0.003
15	1.0495	0.004	-0.003	0.001	-0.005	0.005	0.003
20	1.0160	0.004	-0.003	-0.001	-0.003	0.006	0.002
25	0.9839	0.004	0.000	-0.004	-0.002	0.006	0.000
30	0.9544	0.005	0.003	-0.006	0.000	0.005	-0.002
35	0.9270	0.006	0.005	-0.007	0.001	0.005	-0.004
40	0.9015	0.007	0.006	-0.008	0.003	0.005	-0.006

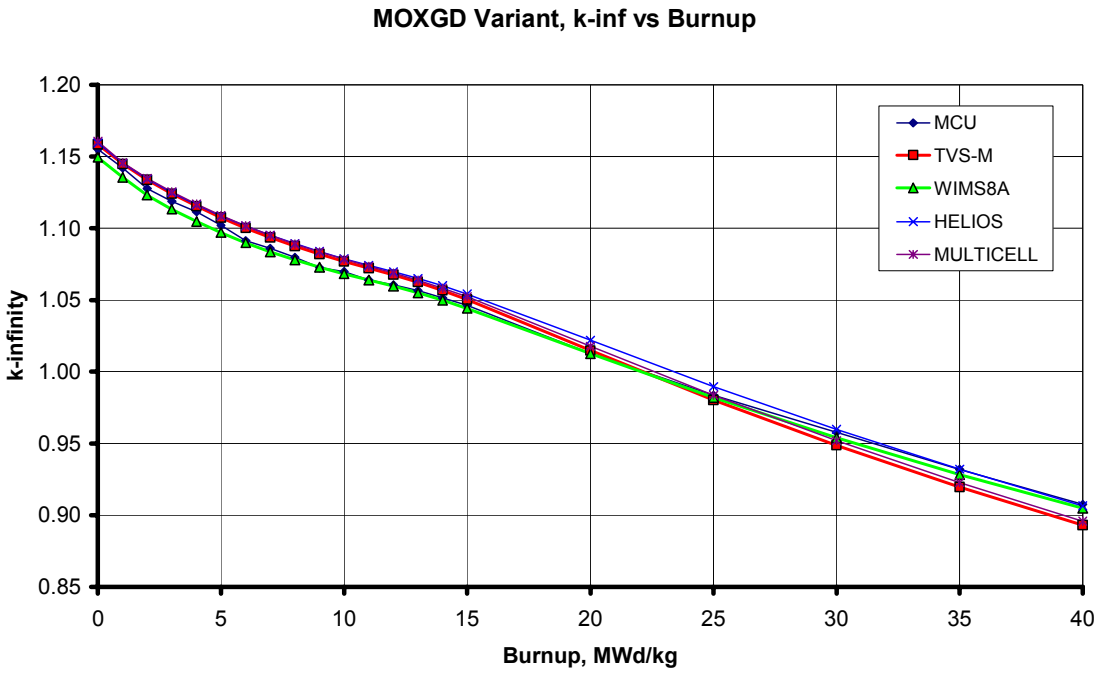

Fig. 4 MOXGD variant, k_{inf} vs burnup.

Table VII. MOXGD variant, comparison of assembly average isotopic composition at 40 MWd/kgHM

Code	Deviation From Average Value (%)								
	U-235	U-236	U-238	Pu-239	Pu-240	Pu-241	Pu-242	Xe-135	Sm-149
MCU	-0.59	-0.17	-0.07	0.34	-1.21	0.84	8.40	1.28	-3.25
TVS-M	-2.81	-0.64	0.01	-0.99	5.59	-4.96	5.54	-5.23	-11.05
WIMS8A	2.81	-1.93	-0.05	5.04	-1.31	4.66	-0.68	2.06	6.01
HELIOS	1.37	2.44	0.06	-2.19	-4.26	1.80	-3.47	1.50	5.24
MULTICELL	-0.78	0.30	0.05	-2.20	1.18	-2.34	-9.79	0.39	3.06
MEAN	7.826-6[a]	2.372-6	6.063-3	7.278-5	4.656-5	2.592-5	9.227-6	3.211-9	3.832-8
R.M.S. %	2.16	1.60	0.06	3.00	3.67	3.73	7.24	2.99	7.17

[a] Read as 7.826×10^{-6}.

Table VIII. MOXGD variant, comparison of reactivity effects (% δk)

Initial State	Final State	Comment	Burnup (MWd/kg)	MCU	TVS-M	WIMS8A	HELIOS	MULTICELL	MCNP 4B	Mean % δk	R.M.S. (%)
S1	S2	Xe+Sm Cb>0	0	-3.22	-3.57	-3.18	-3.28	-3.38		-3.33	-4.70
			20	-3.56	-3.31	-3.40	-3.38	-3.54		-3.44	-3.15
			40	-3.15	-2.84	-3.13	-3.10	-3.19		-3.08	-4.58
S3	S4	Boron 0.6 g/kg	0	-3.39	-3.61	-3.41	-3.45	-3.53	-3.39	-3.46	-2.57
			20	-3.79	-3.96	-3.73	-3.80	-3.89		-3.83	-2.32
			40	-4.04	-4.05	-3.85	-3.96	-4.02		-3.98	-2.10
S3	S2	T fuel Cb>0	0	1.72	1.62	1.81	1.75	1.86	1.69	1.74	4.90
			20	1.44	1.46	1.68	1.65	1.54		1.55	6.88
			40	1.39	1.30	1.46	1.51	1.36		1.40	5.76
S4	S5	T all Cb=0	0	-7.92	-7.64	-8.14	-7.98	-7.66	-8.27	-7.93	-3.18
			20	-7.34	-6.58	-7.37	-6.97	-6.90		-7.03	-4.68
			40	-5.89	-5.00	-5.75	-5.27	-5.16		-5.41	-7.14

Table IX. UGD variant, comparison of fission rate distributions. R.M.S. deviation over all the pins and Max deviation (%)

Code		Burnup (MWd/kg)		
		0	20	40
MCU	R.M.S. Dev	0.8	0.5	0.7
	Max Dev.	1.8	-1.3	2.1
TVS-M	R.M.S. Dev	0.9	0.3	0.4
	Max Dev.	2.1	0.8	-0.9
WIMS8A	R.M.S. Dev	0.9	0.6	0.5
	Max Dev.	-1.8	-1.1	-1.1
HELIOS	R.M.S. Dev	0.7	0.4	0.5
	Max Dev.	1.9	-0.9	-0.9
MULTICELL	R.M.S. Dev	1.6	0.3	0.3
	Max Dev.	-3.0	-0.7	0.7

Table X. MOXGD variant, comparison of fission rate distributions. R.M.S. deviation over all the pins and Max deviation (%)

Code		Burnup (MWd/kg)		
		0	20	40
MCU	R.M.S. Dev	0.8	0.7	0.7
	Max Dev.	-1.9	-1.7	-1.8
TVS-M	R.M.S. Dev	0.7	0.8	0.7
	Max Dev.	1.6	2.4	1.1
WIMS8A	R.M.S. Dev	1.2	0.7	0.6
	Max Dev.	-2.8	1.7	2.0
HELIOS	R.M.S. Dev	0.6	0.6	0.5
	Max Dev.	-1.1	-1.7	-1.6
MULTICELL	R.M.S. Dev	0.8	1.5	1.2
	Max Dev.	1.8	2.8	2.2