CHARACTERISTICS OF VVER-1000 WITH 1/3 CORE LOADED BY MOX FUEL WITH PLUTONIUM FROM SURPLUS RUSSIAN NUCLEAR WEAPONS

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ABSTRACT

The main scenario of the dismantlement of surplus Russian nuclear weapons for peaceful uses comprises the fuel cycle of VVER-1000 reactors with partial (1/3) loading of MOX fuel providing yearly weapon plutonium utilization of about 270 kg.
MOX FA (fuel assembly) design is based on the principle that MOX FA geometry is the same as for standard uranium FA. The preliminary parametric studies had an objective to define plutonium content in MOX fuel assembly and fuel grading. Other task was to study a necessity of uranium-gadolinium burnable poisons placement in MOX FAs, definition of gadolinium content in burnable poisons and their optimum location.
The chosen MOX FA design comprises three different Pu contents – in central, peripheral row and corner MOX fuel pins.
The equilibrium fuel cycle with 1/3 MOX fuel has been defined on the basis of advanced VVER-1000 uranium core. The proposed core loading patterns of VVER-1000 with MOX fuel ensure average irradiation level of MOX FAs about 40 MWd/kg HM and meet safety requirements developed for uranium VVER-1000 core.
Nuclear and radiation safety has been estimated in means of storage and transportation at a VVER-1000 NPP. Nuclear safety calculations showed that criticality parameters in the case of MOX fuel treatment at a NPP are not worse than for standard uranium fuel. The estimation of annual individual and collective doses of staff working with fresh and spent MOX fuel gives acceptable values. The minimal time for cooling of MOX FAs in cooling pool before transportation was estimated as ~ 4.5 year.

1. INTRODUCTION

One of considered scenarios of Russian surplus plutonium disposition comprises that weapons-grade plutonium will be converted into mixed oxide (MOX) fuel and will be burnt commercially in electricity generating reactors VVER-1000 in Russia. According to preliminary estimations the first stage of investigations included VVER-1000 reactors with

partial (1/3) loading of MOX fuel as it is realized with civil plutonium in Western reactors of PWR type. Later taking into account that weapons-grade plutonium is closer to uranium than civil plutonium (regarding neutronics characteristics) the variants with increased until 41% fraction of MOX in VVER-1000 core have been studied. In the presented work mainly 1/3 MOX fraction is considered.

Over the course of these investigations the recent development of VVER-1000 fuel cycles with uranium [1] (named below as advanced VVER-1000) has been taken into account. It comprises:
- use of advanced uranium fuel assemblies (UOX FAs) with zirconium elements and an increased weight of fuel in fuel pins
- use of gadolinium integrated fuel as a burnable poison
- use of low leakage core loading
- use of absorbers (control rods) on the basis of boron carbide with 80% ^{10}B and dysprosium titanate characterized by high efficiency and long serviceable time.

Nowadays the fuel cycle length in VVER-1000 with uranium is about 7000 effective full power hours (EFPH), uranium fuel assemblies operation time is four fuel cycles.

MOX FA design is based on the principle that MOX FA geometry is the same as for standard uranium FA. At the first stage of investigations operation time of MOX FAs was three fuel cycles that is less than uranium ones respecting the world practice.

It is seen from preliminary comparison that efficiency of boric acid introduction is less in MOX FAs than in uranium ones. At the same time dependencies of multiplication properties towards fuel burnup are close in MOX and uranium FAs (under the same boric acid concentration). Consequently it has been decided that it is reasonable to place uranium-gadolinium burnable poisons in MOX FA in order to compensate excessive reactivity and additionally to flatten power distribution over MOX FA. It is also known that power increasing takes place in peripheral rows of MOX FA bordering uranium ones. So MOX FA is to be graded in plane using fuel pins of different plutonium content. Both the definition of the mentioned grading and of burnable poison characteristics (quantity, location and relation uranium/gadolinium) is an objective of presented studies.
The presented work includes also neutronic parameters of VVER-1000 equilibrium fuel cycle with 1/3 MOX core. It should be also noted that the fuel cycle must ensure the so-called “standard of spent fuel” that is the minimum MOX fuel assembly burnup of 20 MWd/kg HM as it is indicated in American-Russian Intergovernmental Agreement.

Criticality and radiation safety problems during MOX fuel storage and transportation at a NPP are also to be considered because of sufficiently different properties of fresh and spent MOX fuel in comparison with uranium one. Some fragments of these investigations are also presented below.

2. PARAMETRIC STUDIES OF MOX FUEL ASSEMBLY DESIGN

The set of parametric studies included:

- studies of acceptable plutonium content and of optimal fresh MOX FA plutonium grading (plutonium distribution over three inter-assembly zones)
- studies on evolution of multiplication factors in UOX and MOX fuel assemblies during fuel irradiation for different number of uranium-gadolinium rods per MOX FA, different gadolinium content and different ^{235}U enrichment in tvegs[1]
- studies of optimal uranium-gadolinium rods location in MOX FA.

The described parametric calculations have been made by the production code of improved accuracy RADAR developed in KI. The chosen fuel assembly design of MOX FA is shown in Fig.2.1. The standard UOX FA being actually used in VVER-1000 fuel cycles with uranium fuel is shown in Fig.2.2.

Main results of investigations justifying the chosen MOX FA design are following.
1. Average content of Pu about 3.5% seems acceptable because multiplication factor in this case does not exceed that of basic uranium FA all over fuel cycle except the very beginning. At the same time this value of plutonium content ensures rather close evolution of uranium and plutonium fuel multiplication properties during irradiation that is favorable for power distribution flattening in a core.
2. 18 tvegs allow significant decreasing of FA multiplication factor. At the same time efficiency of gadolinium content increasing after 4% reaches its "saturation level" as it is seen from Fig.2.3 and 2.4 (the figures differ by concentration of boron in coolant designated as Cb). It is also seen that efficiency of gadolinium introduction is greater for uranium FA so the chosen number of tvegs is 18 for MOX Fa in comparison with 6 in uranium FA.
3. ^{235}U content in tvegs equal to 3.6% seems acceptable. It ensures non-exceeding of power in tvegs in comparison with other fuel pins after having burnt all gadolinium.
4. Different locations of 18 tvegs have been considered. All the variants calculated are described in Table 2.1.

Table 2.1. Calculated variants

Variant	Plutonium content in center	Plutonium content in periphery	Plutonium content in corner	Tveg
1	3.5 %	3.5 %	3.5 %	-
2	3.62 %	3.0 % (42 pcs)	3.0 % (18 pcs)	-
3	3.74 %	2.5 % (42 pcs)	2.5 % (18 pcs)	-
4	3.69 %	2.7 % (42 pcs)	2.7 % (18 pcs)	-
5	3.74 %	2.7 % (42 pcs)	2.5 % (24 pcs)	-
6	3.77 %	2.7 % (42 pcs)	2.0 % (24 pcs)	-
7	3.74 %	2.7 % (42 pcs)	2.5 % (18 pcs)	-
8	3.77 %	2.7 % (42 pcs)	2.0 % (18 pcs)	-
9	3.74 %	2.7 % (42 pcs)	2.3 % (18 pcs)	-
10	3.74 %	2.7 % (42 pcs)	2.3 % (18 pcs)	+ (Fig.2.1)
11	3.74 %	2.7 % (54 pcs)	2.3 % (6 pcs)	+ (Fig.2.1)
12	3.74 %	2.7 % (48 pcs)	2.3 % (18 pcs)	+(Fig.2.1, but six peripheral tvegs are closer to the centre)

[1] Uranium-gadolinium rod is named also "tveg" in Russian reactor design practice.

A set of specific fuel pins (Fig.2.5) has been defined to register their relative powers. The results are presented in Fig.2.6. It is seen that Variant 11 ensures close power values in these fuel pins i.e. power distribution flattening.

So finally MOX FA design in Fig.2.1 has been chosen as the basis for further investigations of different aspects of MOX fuel use in VVER-1000. Fissile plutonium contents in three MOX FA zones have been defined as 3.62%, 2.69% and 2.42%. 18 uranium-gadolinium fuel pins with 4%wt. Gd_2O_3 and 3.6% ^{235}U are placed in MOX FA.

3. EQUILIBRIUM FUEL CYCLE WITH 30% MOX FUEL

The equilibrium fuel cycle with 1/3 MOX fuel is to be defined on the basis of advanced VVER-1000 uranium core with uranium-gadolinium burnable poisons. The criteria to be used are the safety requirements such as power peaking factors, control rods worth, reactivity coefficients.

Fresh MOX FAs are not placed in the core periphery in order not to increase fluence on the vessel because fast neutron flux is about 20% greater in MOX FAs than in UOX ones.

The loading pattern defined as a result of core neutronics studies [2] is shown in Fig.3.1. In the equilibrium core loading 11 uranium FAs are irradiated during three fuel cycles, 19 uranium FAs – during 4 cycles, 18 MOX FAs – during 3 fuel cycles. Calculations have been carried out using codes of KI certified for VVER uranium cores and verified for cores with MOX fuel. The results of neutronics calculations are presented in Table 3.1.

Analysis of the results leads to the following conclusions:

- Annual weapons-grade plutonium disposition is about of 270 kg. In discharged MOX fuel the average fissile plutonium content in plutonium does not exceed 61% i.e. it is lower than in discharged uranium fuel. So the task of weapons-grade plutonium transformation into the "standard of spent fuel" is performed with a significant margin.
- For fuel cycle length of about 7000 EFPH and MOX FAs irradiation during 3 cycles, average burnup of discharged MOX assemblies is 41 MWd/kgHM. It confirms a sufficient extraction of weapons-grade plutonium power potential. The maximum value of average burnup in MOX FA attains 41.3 MWd/kgHM. Average and maximum burnup in UOX FAs are higher (maximum burnup is in the forth-year assembly located in the central core position) but do not exceed 52 MWd/kgHM.
- MOX core reactivity in the cold state with shutdown boric acid concentration (16000 ppm) is greater than in basic uranium core design of standard uranium VVER-1000 but does not exceed – 8000 pcm.
- Reactivity effects and coefficients on coolant and fuel temperature are negative for all core critical states. Absolute values of above-mentioned coefficients in the MOX fuelled core are higher than in the UOX one. So the MOX fuelled reactor possesses a more significant feedback enabling the compensation of fast reactivity variation and limiting power increase.

- Effectiveness of Control Protection System (CPS) is very close to VVER-1000 standard design with UOX fuel.
- Power peaking factors for the MOX fuel cycle meet the limits established for UOX FAs in the VVER-1000 standard design. But thermal-physical properties of MOX fuel are a little worse than the UOX ones. Moreover, according to performed estimations, the engineering margin coefficients and calculation errors are greater for MOX fuel. So the applicability of the elaborated MOX fuel cycle should be confirmed by thermal-hydraulic calculations. Also it should be noted that the complexity of core configuration with MOX fuel demands an improvement of actual in-core detecting system.
- Effective fraction of delayed neutrons and lifetime of prompt neutrons are lower by 10% in the MOX fuel cycle in comparison with VVER-1000 standard design. So more attention should be paid to calculations of reactivity accidents.

The presented results lead to the conclusion that neutronics characteristics of the considered MOX fuel cycle are close to the ones of standard VVER-1000 design with UOX fuel.

Table 3.1 Neutronics characteristics of equilibrium core loading with 1/3 MOX fuel

Name of characteristic	Clarification	Value
Number of fresh FA loaded during refuelling, pcs	^{235}U – 4.08% (4.2/3.7%) ^{235}U - 0.39%, $^{239+241}$ Pu- 3.24%	30 18
Number of uranium-gadolinium fuel rods in fresh FA, pcs	UOX FA MOX FA	6 18
Fraction of the MOX fuel in the core, %		33
Annual amount of utilized plutonium, kg		271
Content of plutonium isotopes in the fresh MOX fuel, %	^{238}Pu ^{239}Pu ^{240}Pu ^{241}Pu ^{242}Pu	0.1 91.7 6.6 1.2 0.4
Cycle length, EFPD	Including stretch-out regime	297.5
Fuel burnup, MWd/ kgHM	Average, UOX FAs Average, MOX FAs MAX, UOX FAs MAX, MOX FAs MAX, UOX Fuel Pins MAX, MOX Fuel Pins MAX, UOX Fuel Pellets MAX, MOX Fuel Pellets	44.4 41.0 51.9[1] 41.3 54.4 44.8 59.0 49.0
Weight of discharged plutonium, kg	Total UOX FAs MOX FAs	336 148 188
Content of plutonium isotopes in spent UOX fuel, %	^{238}Pu ^{239}Pu ^{240}Pu ^{241}Pu ^{242}Pu	2.4 53.7 24.2 13.4 6.3

[1] Central fuel assembly.

Content of plutonium isotopes in spent MOX fuel, %	^{238}Pu ^{239}Pu ^{240}Pu ^{241}Pu ^{242}Pu		0.8 45.2 31.5 15.6 6.9
Critical boric acid concentration in coolant, ppm	Full Power	BOC	6370
Reactivity at 16 000 ppm H_3BO_3, pcm	Cold state, CR[1]s out,	BOC	-8200
Boric acid coefficient of reactivity, pcm/ppm	Full power	BOC EOC	-1.26 -1.48
Moderator temperature coefficient of reactivity, pcm/ ^oC	MCL[2], CRs out, Full power	BOC BOC EOC	-7.3 -35.8 -68.3
Fuel temperature coefficient of reactivity, pcm/ ^oC	MCL, CRs out, Full power	BOC BOC EOC	-3.28 -2.87 -2.88
Shutdown margin, pcm	EOC		4000
Maximum relative power of FA over cycle	UOX FA MOX FA		1.32 1.27
Maximum relative power of fuel pin over cycle	UOX fuel pins MOX fuel pins		1.44 1.47
Effective fraction of delayed neutrons, pcm	Full power,	BOC EOC	530 510
Lifetime of prompt neutrons, sec*10^{-5}	Full power,	BOC EOC	1.78 2.12

4. NUCLEAR AND RADIATION SAFETY IN THE MEANS OF STORAGE AND TRANSPORTATION

Simplified scheme of fuel transportation at VVER-1000 NPP is shown in Fig.4.1. Fresh fuel assemblies are transported from the production plant to NPP by railway in special package sets. The package set consisting of two parallel tubes is intended for two FAs location.

Storage of fresh uranium FAs at NPP Fresh Fuel Depository is performed either in package sets stacks or in decks or in the jackets for fresh fuel.

Fuel assembly transport from the fresh fuel depository to the reactor hall is performed in the jackets for fresh fuel. The jacket for fresh fuel is intended for transport of 18 fuel assemblies placed vertically. Fuel assemblies may be loaded from the jacket directly into a reactor or into a cooling pool.

The cooling pool is intended for holding the irradiated fuel assemblies during the time necessary for decrease of the residual heat and radioactivity to the values, which allow transportation of spent fuel from NPP. In modern cooling pool at VVER-1000 NPP hexagonal tubes made of borated steel are used.

[1] CR - control rod.
[2] MCL – minimum controllable level of power.

After necessary exposure in a cooling pool, spent fuel is transported from NPP by railway in the transport casks. Such containers are intended for 12 spent fuel assemblies' transport.

4.1 NUCLEAR SAFETY

Nuclear safety (criticality) has been estimated: in a package set for fresh fuel, in a jacket for fresh fuel transportation over NPP, in a cooling pool, in a cask for spent fuel. The estimations have been made by certified Monte Carlo code MCU [3] under conservative approach (for example no axial neutron leakage). The results are presented in Table 4.1.

Table 4.1 Multiplication factors in calculations of means for transportation and storage

Means	Regime	K_{eff}
Package set	"Dry"	0.843
	Cold water inside packing set	1.060
	Cold water inside packing set in stack 4x4	0.980
Jacket for fresh fuel	"Dry"	0.215
	Water of 1.0 g/cm^3 everywhere	0.907
Cooling pool	"Dry"	0.600
	Water of 1.0 g/cm^3 everywhere	0.878
Cask for spent fuel	"Dry"	0.342
	Water of 1.0 g/cm^3 everywhere	0.868

The limiting value of K_{eff} is 0.95. It can be seen for "package set" case that for the mentioned accident with water introduction the criterion $K_{eff} < 0.95$ is not met. But this type of accident is considered as severe one. In this case safety criterion is changed for $K_{eff} < 0.98$ and for storage of packing sets in stacks 4x4 the safety requirement is met.

In total nuclear safety calculations under conservative assumptions showed that criticality parameters in the case of MOX fuel treatment at a NPP are not worse than for standard uranium fuel.

4.2 RADIATION SAFETY

Equivalent doze rate from unshielded fresh MOX FA is greater by about 10 times than for UOX FA if regarding distances until 200 cm from assembly surface. Dose rate on the uranium FA surface is determined by braking and gamma-radiation, neutron component is negligibly small. By contrast, when using MOX fuel, contributions of neutron and gamma components in dose rate on FA surface are approximately equal.

While regarding spent fuel, three years delay of storing in a cooling pool has been taken into account. Equivalent doze rate from spent MOX fuel assemblies placed in a container is greater by about 50% than in the case of UOX FAs in a container. In both cases major contribution to dose rate is made by capture gamma-radiation.

Preliminary radiation safety calculations have been performed for all stages of MOX fuel treatment during stocking and transportation at a VVER-1000 NPP. It is shown that after

switching from the standard uranium core to the core with 1/3 MOX FAs the annual individual and collective doses of staff working with fresh and spent fuel is about 50 % higher in comparison with the respective dose for uranium core. But it rests significantly lower that the allowable value.

4.3 RESIDUAL HEATING OF MOX FUEL

Heating of MOX FA exceeds it in UOX one and this relative discrepancy grows in the course of time according to estimations made after 3 days and later after discharging from a core. Shorter time after discharging is to be studied in future in order to calculate transient accidental regimes in VVER-1000 with MOX fuel.

The minimal time for cooling of MOX FAs in water pool before their loading into cask for spent fuel was estimated as ~ 4.5 year (uranium FAs are to be cooled during 3 years before their transportation). This time is defined both by spent fuel activity and level of residual heat.

5. ALTERNATIVE SCENARIOS OF MOX FUEL UTILIZATION IN VVER-1000

Some alternative scenarios of utilization of MOX fuel from weapon plutonium in VVER-1000 core are also considered or to be considered. They are intended to increase Pu consummation rate by using increased fraction of MOX fuel in a core or/and by reducing MOX FAs stay in a core. Some obtained results are of very preliminary manner. The cycle with fraction 41% of MOX fuel and combined two/three year cycle for MOX fuel assemblies can ensure annual consumption of 450 kg of Pu.

6. CONCLUSIONS

Presented investigations show that utilization of weapons-grade MOX fuel is possible in VVER-1000 reactors. The chosen MOX fuel assembly composition is close to optimum (regarding fuel pin peaking factor, location of uranium-gadolinium burnable poisons and other parameters).

Three-year fuel cycle with annual introduction of 18 fresh MOX fuel assemblies can ensure consumption of 270 kg of Pu per year. All safety requirements applicable to uranium core of VVER-1000 are met for core with 30% MOX fuel.

Analysis of nuclear safety (criticality) and radiation safety show that transportation means actually being used at VVER-1000 NPP can be used in the case of 30% MOX core loading.

Estimation show that an increased disposition rate of weapon Pu can be realized in VVER-1000 reactors.

7. REFERENCES

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3. E. A. Gomin, M. I. Gurevich, L. V. Maiorov, and S. V. Marin, "Annotation of the MCU-RFFI code", *VANT, Reactor Physics Series*, **vol.3**, pp.48-53 (1995).

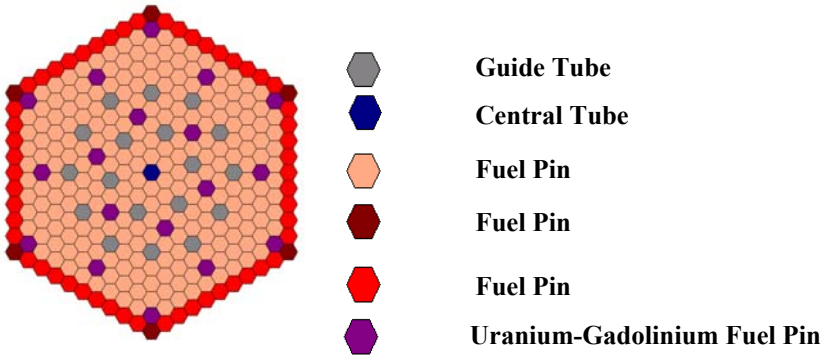

Fig. 2.1 MOX FA pattern (P39G8)

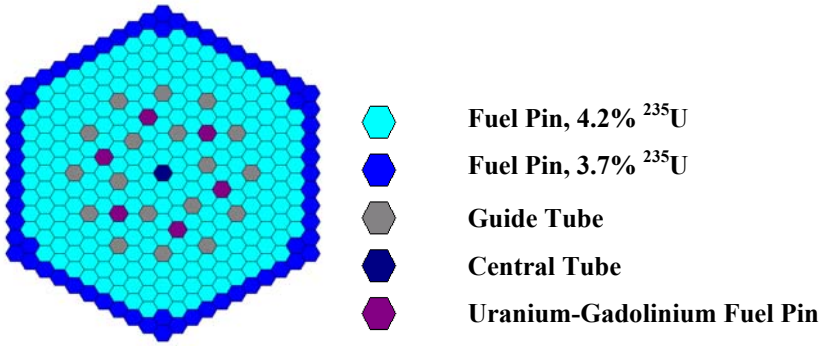

Fig. 2.2 UOX FA Pattern (U42G6)

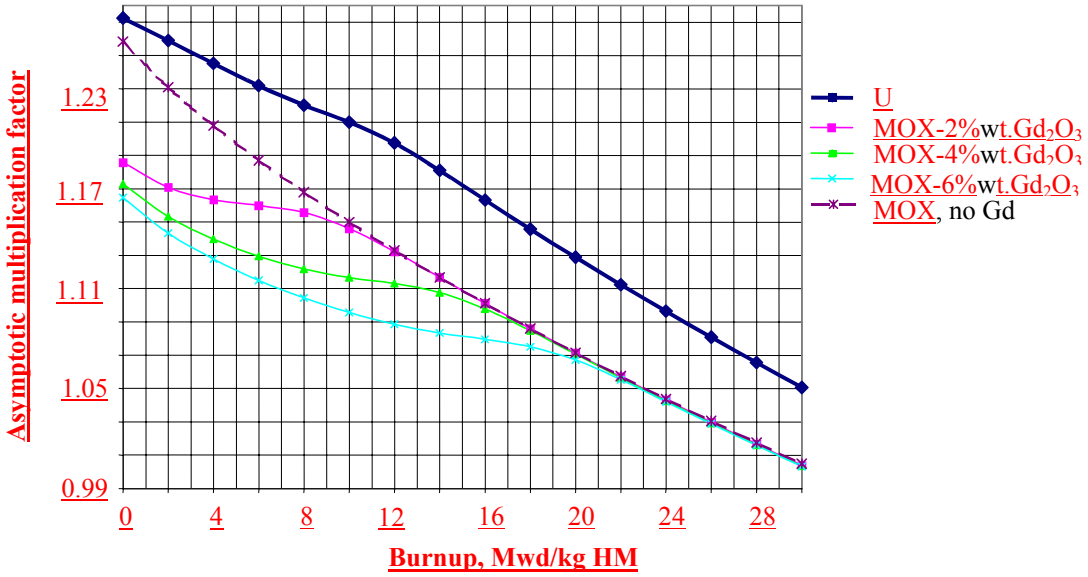

Fig.2.3 Multiplication factor of Uranium and MOX assemblies during irradiation for different gadolinium content in tvegs. Cb=0

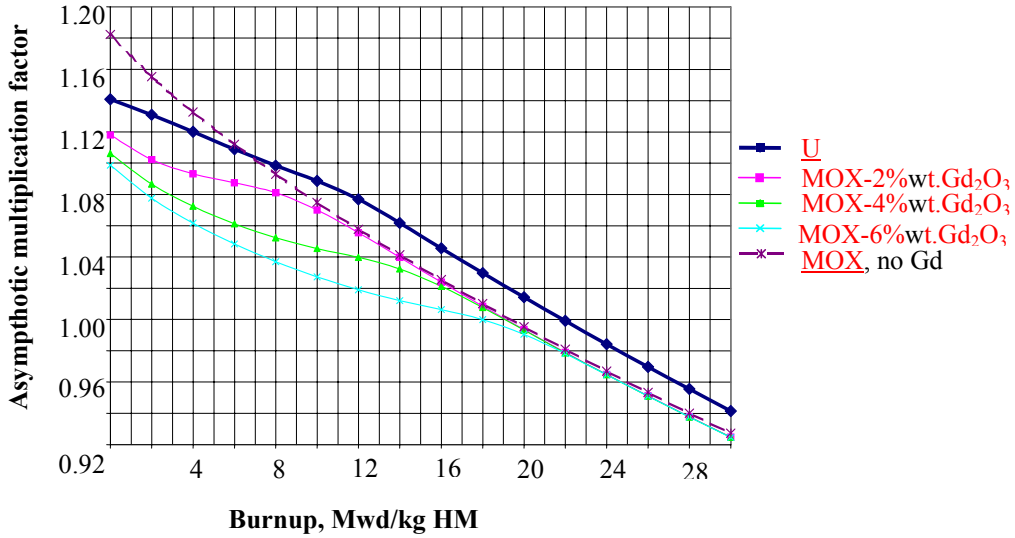

Fig.2.4 Multiplication factor of Uranium and MOX assemblies during irradiation for different gadolinium content in tvegs. Cb=1400 ppm

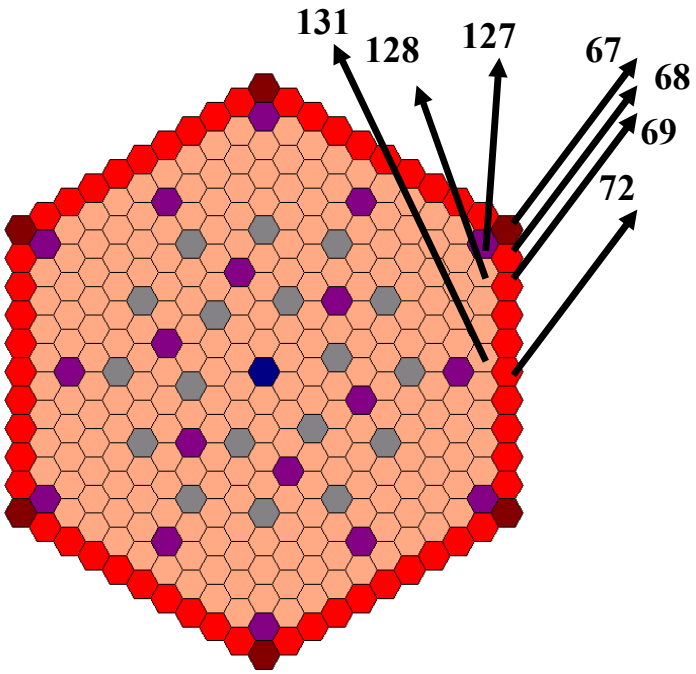

Fig.2.5 Indication of registered fuel rods

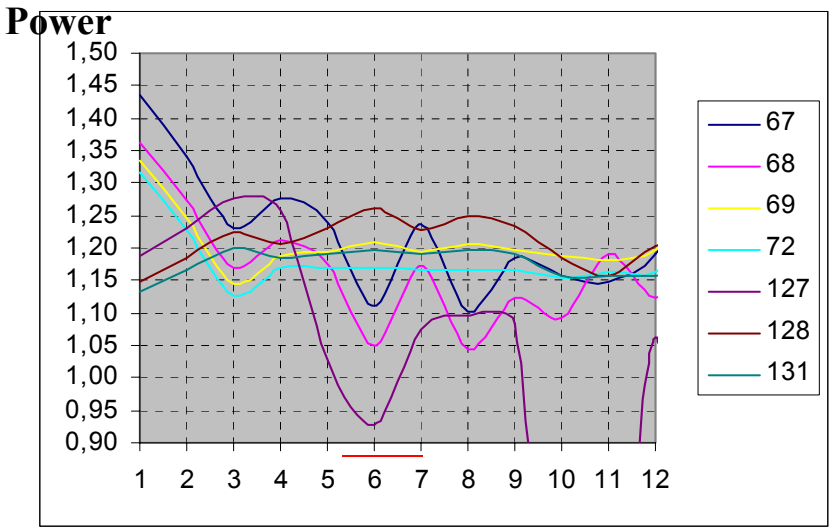

Fig. 2.6 Relative power distribution in registered fuel pins

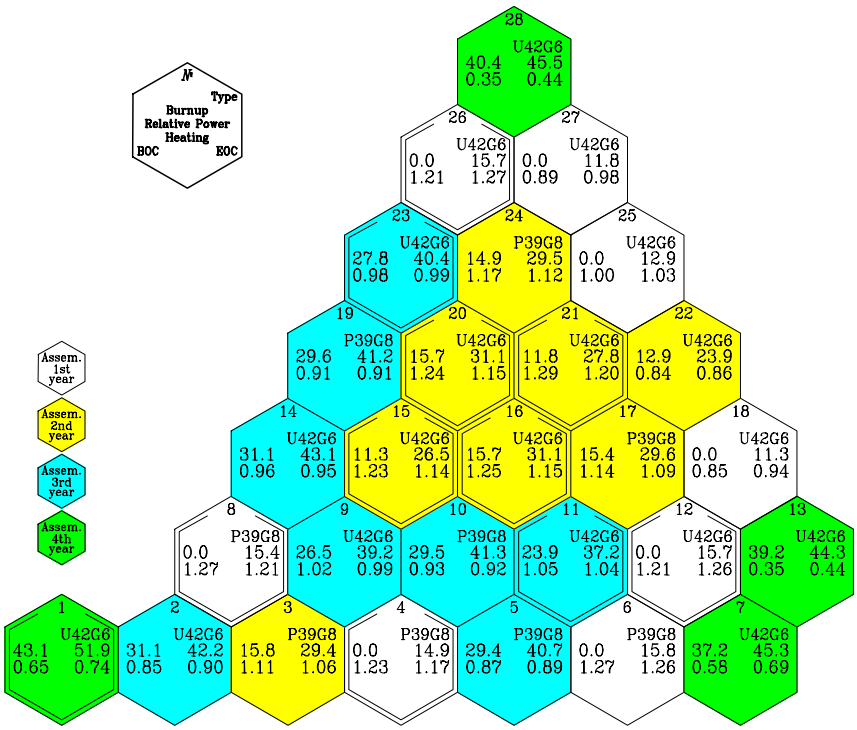

Fig.3.1 Assembly-by-assembly Power and Burnup Distributions and Reloading Scheme. Equilibrium cycle with 30% MOX fuel

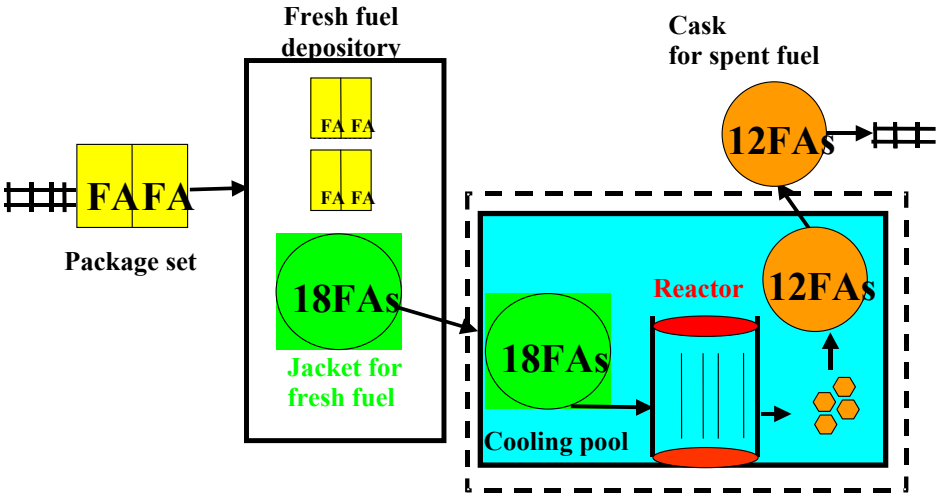

Fig. 4.1 Transportation scheme at VVER-1000 NPP