OAK RIDGE NATIONAL LABORATORY

MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

ORNL/SUB/00-85B99398V-11

Mission MOX Fuel Physics Design—Preliminary Equilibrium MOX Assembly Design and Expected Operating Power for Existing Balakovo Fuel Management Scheme

A. M. Pavlovichev

A Russian Contribution to the Fissile Materials Disposition Program

UT-BATTELLE

ORNL-27 (4-00)

ORNL/SUB/00-85B99398V-11

MISSION MOX FUEL PHYSICS DESIGN—PRELIMINARY EQUILIBRIUM MOX ASSEMBLY DESIGN AND EXPECTED OPERATING POWER FOR EXISTING BALAKOVO FUEL MANAGEMENT SCHEME

A. M. Pavlovitchev

Date Published: September 2001

Prepared by
Russian Research Center “Kurchatov Institute”
Institute of Nuclear Reactors
under subcontract 85B-99398V

Funded by
Office of Fissile Materials Disposition
U.S. Department of Energy

Prepared for
Computational Physics and Engineering Division
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
managed by
UT-BATTELLE, LLC
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-00OR2272

Russian Research Center "Kurchatov Institute"
Institute of Nuclear Reactors
VVER Division

*Joint U.S. / Russian Project to Update, Verify and Validate
Reactor Design/Safety Computer Codes
Associated with Weapons-Grade Plutonium Disposition in VVER Reactors*

MISSION MOX FUEL PHYSICS DESIGN
Preliminary Equilibrium MOX Assembly Design and Expected Operating Power for Existing Balakovo Fuel Management Scheme

General Order 85B-99398V

(Report)

Project Manager

A.M.Pavlovichev

Executed by

A.M.Pavlovichev

Moscow 2000

Acronyms

Explanation	Acronyms
Absorbing Rod	AR
Beginning of Fuel Cycle	BOC
Burnable Poison Rod	BPR
Doppler Temperature Coefficient	DTC
Effective Full Power Day	EFPD
Effective Full Power Hour	EFPH
End of Fuel Cycle	EOC
Kurchatov Institute	KI
Institute of Physic and Power Engineering (Obninsk)	IPPE
Russian authority for nuclear safety	GAN
Light Water Reactor	LWR
Minimum Controllable Reactor Power Level	MCL
Moderator Density Coefficient	MDC
Mixed Oxide (uranium-plutonium fuel)	MOX
Moderator Temperature Coefficient	MTC
Nuclear Power Plant	NPP
Control Rod	CR
Pressurised Water Reactor	PWR
Repeat Criticality Temperature	RCT
Reactor Control and Protection System	CPS
Fuel Assembly	FA
Zirconium fuel for cladding	ZG
Zirconium Guide Tube	ZGT
Uranium Oxide Fuel	UOX
Uranium-Gadolinium Fuel	UGF
Russian water-water reactor	VVER

SUMMARY

The Document issued according to **Work Release 02. P. 99-3a and 99-3b** presents neutronics calculations of 30% MOX fuelled core of VVER-1000. Two options of equilibrium core with gadolinium burnable poison rods are calculated. Comparison is performed with VVER-1000 Uranium core of Project V-320.

Contents

Introduction..5

Fuel Cycle with 1/3 MOX Fuel 8

Conclusion 20

References.. 26

Introduction

Among various versions of excess weapons-grade plutonium handling the most preferred in Russia is its burning in power reactors. This is accounted for by the desire to utilize the power value of weapons-grade plutonium and the potentialities of the existing nuclear industry complex.

In Russia the versions of burning weapons-grade plutonium in the VVER-, BN-, and HTGR-type power reactors are being developed. However the analysis of the current structure of nuclear power and the energy strategy reveals that in the coming years the VVER-1000-type (designs B-320 and B-392) as well as the VVER-640 reactor (design B-407) now under development appear to be the most promising for this purpose. The experience with the use of mixed uranium/plutonium fuel in the LWR, gained in the West and the preliminary studies carried out in Russia [1]-[3] show that weapons-grade plutonium may be actually used as fuel for the Russian VVER reactors.

At present Russia has 7 operating VVER-1000 of total installed capacity 7 GWe, 11 reactors of this type are in operation in Ukraine, and 2 - in Bulgaria. Before 2003 it is planned to put into operation 2 VVER-1000 units more in Russia and at least 2 units in Ukraine.

In their designs the cores of all VVER-1000 reactors are nearly the same. The most distinctive difference consists in the number of the control rods:

- 109 at Novo-Voronezh NPP-5;

49 at South-Ukrainian NPP-1;

61 in the rest of the operating VVER-1000 reactors.

The designed fuel cycle (B-320) of the operating VVER-1000 [4], developed in the late 70s has the following characteristic features: three-year core life, OUT-IN-IN core design, stainless steel as structural material for fuel assemblies (guide tubes and grids), removable burnable boron poisons. At present the most of VVER-1000 reactors are operating using the B-320 fuel cycle. Therefore it is used as referenced cycle within the frame of these investigations. The part 2 of this report contains description of the main characteristics of the B-320 fuel cycle.

At present the extensive efforts are under way in Russia on advance of the VVER-1000 fuel cycle [5]. The distinctive features of the advanced fuel cycles are the following:

- fuel assemblies with zirconium grids and guide tubes;
- uranium-gadolinium fuel as a burnable poison;
- fuel rods with reduced diameter of the center holes in fuel pellets;
- control rod consists of two parts: the upper one contains B_4C and the lower one - $Dy_2O_3*TiO_2$;
- low leakage loading pattern.

The advanced fuel cycle of VVER-1000 has considerable advantages:

- increase in the control rod system efficiency;

- improved conditions of the reactor vessel performance due to the reduction in the fast neutron flux;
- increase in control rod operational time;
- decrease in the fuel enrichment, which increases the nuclear safety in the phases of enrichment, fabrication of fuel pellets and fuel assemblies.

By present in Russia the basic prerequisites has been established for large-scale implementation of the advanced fuel cycles with improved FAs and the uranium-gadolinium fuel. In particular:

- pilot operation of FAs with UGF is conducted at the Balakovo NPP;
- pilot operation of FAs with ZGs and ZGTs is being carried out at the Balakovo, Kalinin and Zaporozhie NPPs;
- advanced control rods (B_4C, $Dy_2O_3*TiO_2$) have been used at Balakovo, Kalinin and Zaporozhie NPPs;
- in many VVER-1000 reactors the low leakage loading pattern has been successfully used.

It is planned to transform the VVER-1000 reactors into the advanced cycle by the year 2001. Hence by the time of MOX fuel implementation VVER-1000 reactors will be working with advanced fuel cycle.

In Russia the calculation studies of the possible use of reactors- and weapons-grade plutonium in the VVER-1000 type reactors have been carried out for several years. The emphasis is made on the simplest methods of plutonium use in the VVER-1000 fuel cycle: a direct replacement of the uranium fuel by MOX fuel without any serious changes in the core design and in the power unit operating conditions. The studies were carried out for stationary 3-year fuel cycle with a core life about 7000 EFPH. The advanced FA with ZG and ZGT was used.

The investigations of Russian and West specialists showed [1, 2] that the weapons-grade plutonium is in an intermediate position between uranium fuel and civil plutonium being used in the West from the point of view of neutronics characteristics defining plutonium disposition in LWRs. Therefore the use of MOX fuel results in some changes in the physical safety relating characteristics of a core:

- 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 cycle;
- increased pin power peaking factor at the boundary between MOX and UOX FAs that makes 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.

Taking into account the results of preliminary investigations and the analysis of the experience gained in the use of MOX fuel in the western PWRs, the emphasis was made on the advanced VVER-1000 fuel cycle where the fraction of MOX FAs is about 1/3.

The calculations were carried out with the new code package that has been developed in RRC KI (TVS-M, BIPR-7A, PERMAK-A) [6],[7].
Code TVS-M. The TVS-M code calculates few-group neutron cross sections for cells (fuel rods, absorber rods, burnable absorber rods and other cells) and fuel assemblies as functions of reactor state and fuel burnup for the codes BIPR and PERMAK.
Code BIPR-7A. The code BIPR-7A calculates criticality parameters, reactivity effects and coefficients, control rod worth, three-dimensional power distribution, burnup and refueling processes, xenon and samarium transients and etc in VVER cores.
Code PERMAK-A. The code calculates pin-by-pin power and burnup distribution in VVER cores.

Verification of Russian codes in order to define calculational errors in VVER-1000 MOX fuelled core seems to be very difficult task. No experiments have been carried out in Russia with MOX fuel and there is no experience on its usage in VVER type reactors. Therefore, international co-operation becomes very important at the current stage of codes verification. Some years ago RRC "Kurchatov Institute" together with SRC "Institute of Physic and Power Engineering"(IPPE) and with colleagues from USA, France and Germany, have been engaged in the verification. Besides Russian data on uranium fuel, the results of criticality experiments with plutonium, data on post-reactor studies provided by foreign partners and the results of joint calculations of different test problems are used for verification [8],[9].

Fuel Cycle with 1/3 MOX Fuel

The core is assembled of advanced FAs. Two assembly types are used in the equilibrium fuel cycle – MOX FA with the average fissile plutonium content of 3.43% and UOX FA with the average U^{235} enrichment of 4.08% (see Table 1). Uranium-gadolinium fuel rods with the Gd concentration of 5% and 4% wt. are used to lower a multiplication ability of fresh UOX and MOX FAs.

Under equilibrium cycle (loading pattern is given in Fig. 3) the number of FAs reloaded is 48 pcs. (18 MOX FAs and 30 UOX FAs). MOX FAs operate during 3 cycles in the central part of the core. A part of UOX FAs (11 pcs.) operate during 3 cycles in the central part of the core, the rest ones - during 4 cycles and 18 of them during two or three cycles - in the core periphery. Such mode of fuel irradiation allows to minimize the difference between the average and maximum burn-up of fuel in FAs withdrawn. Arrangement of 18 FAs of the last (the fourth) year of operation in the core periphery cells, closest to the reactor vessel, creates the conditions for reducing the fast neutron flux to the vessel and facilitates increasing of shutdown margin.

The equilibrium refuelling scheme and the main core characteristics in the course of burn-up are presented in Fig. 4.

Fuel burn-up averaged over the discharged FAs is 38.8 MWd/kg (MOX FAs) and 42.0 MWd/kg (UOX FAs), and maximum one does not exceed 39.3 MWd/kg (MOX FAs) and 49.4 MWd/kg (UOX FAs). Distribution of fuel burn-up over the core height at the BOC and EOC of cycle is presented in Tables 2 and 3. Figs 5 and 6 illustrate distribution of maximum burn-up of fuel rods and fuel pellets over FAs at the end of cycle.

Reactivity balance while emergency system actuating and reactor cooling is presented in Table 4 for B-320 Project and for MOX fuel cycle. Calculational errors in emergency system effectiveness, temperature and power effects are taken into account. The results show that sub-criticality in UOX and MOX fuel cycles are very close. RCT for EOC in all the considered variants is about 210 °C. It is seen also in Fig. 7 where after scram actuation sub-criticality is presented versus coolant temperature (Project B-320 and the MOX fuel cycle).

Fig. 8 illustrates influence of boron isotopic content in ARs on core sub-criticality in MOX fuelled core. Cooling process after scram actuation is considered. Boron-10 content in the upper part of combined absorber was varying from the natural one to 80% wt. For comparison the results of sub-criticality calculation in UOX core with standard absorbers are also presented in Fig. 8. The presented results show that increasing of Boron-10 content ensures the additional sub-criticality of 1% and 0.5% correspondingly for the coolant temperatures of 280 °C and 120 °C.

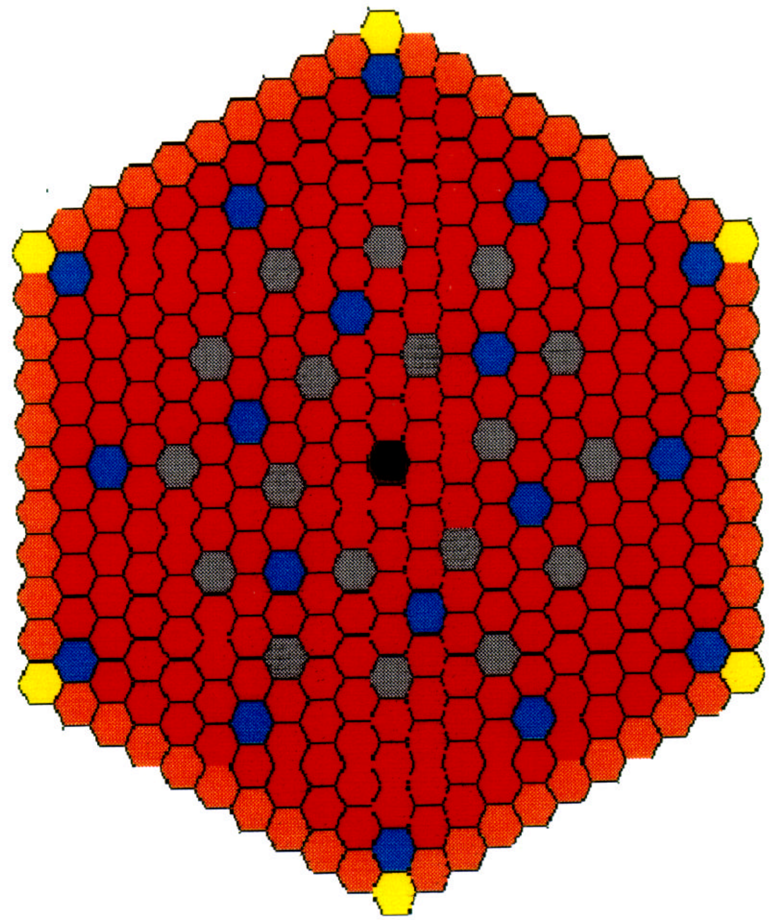
Table 1. Description of Fuel Assemblies for VVER-1000 with 1/3 MOX Fuel

Fuel assembly type	Averaged content of fissile isotopes [wt %]		Number of different fuel type rods and content of fissile isotopes (% Wt)			Characteristics of Uranium-Gadolinium Fuel Rods			Reference to Fig. with FA scheme
	U^{235}	Pu^{fiss} *	Type 1	Type 2	Type 3	Number	Uranium enrichment % Wt	Content of Gadolinium % Wt	
P2G18	0.2	3.43	234 3.6% Pu^{fiss} 0.2% U^{235}	54 2.7% Pu^{fiss} 0.2% U^{235}	6 2.4% Pu^{fiss} 0.2% U^{235}	18	3.6	4.0	Fig.1
U41G6	4.08	-	240 4.2 % U^{235}	66 3.7% U^{235}	-	6	3.3	5.0	Fig. 2

* $Pu^{239}+Pu^{241}$

Fig. 1. VVER-1000 Core with 1/3 MOX FAs.

Fuel Assembly Pattern, type –P2G18



- **Fuel Rod (Pu ^{fiss} – 3.6%)**
- **Fuel Rod (Pu ^{fiss} – 2.7%)**
- **Fuel Rod (Pu ^{fiss} – 2.4%)**
- **Guide Tube**
- **Central Tube**
- **Uranium-Gadolinium Fuel Rod**

Fig. 2. Uranium Fuel Assembly Pattern, type – U41G6 (4.2/3.7%)

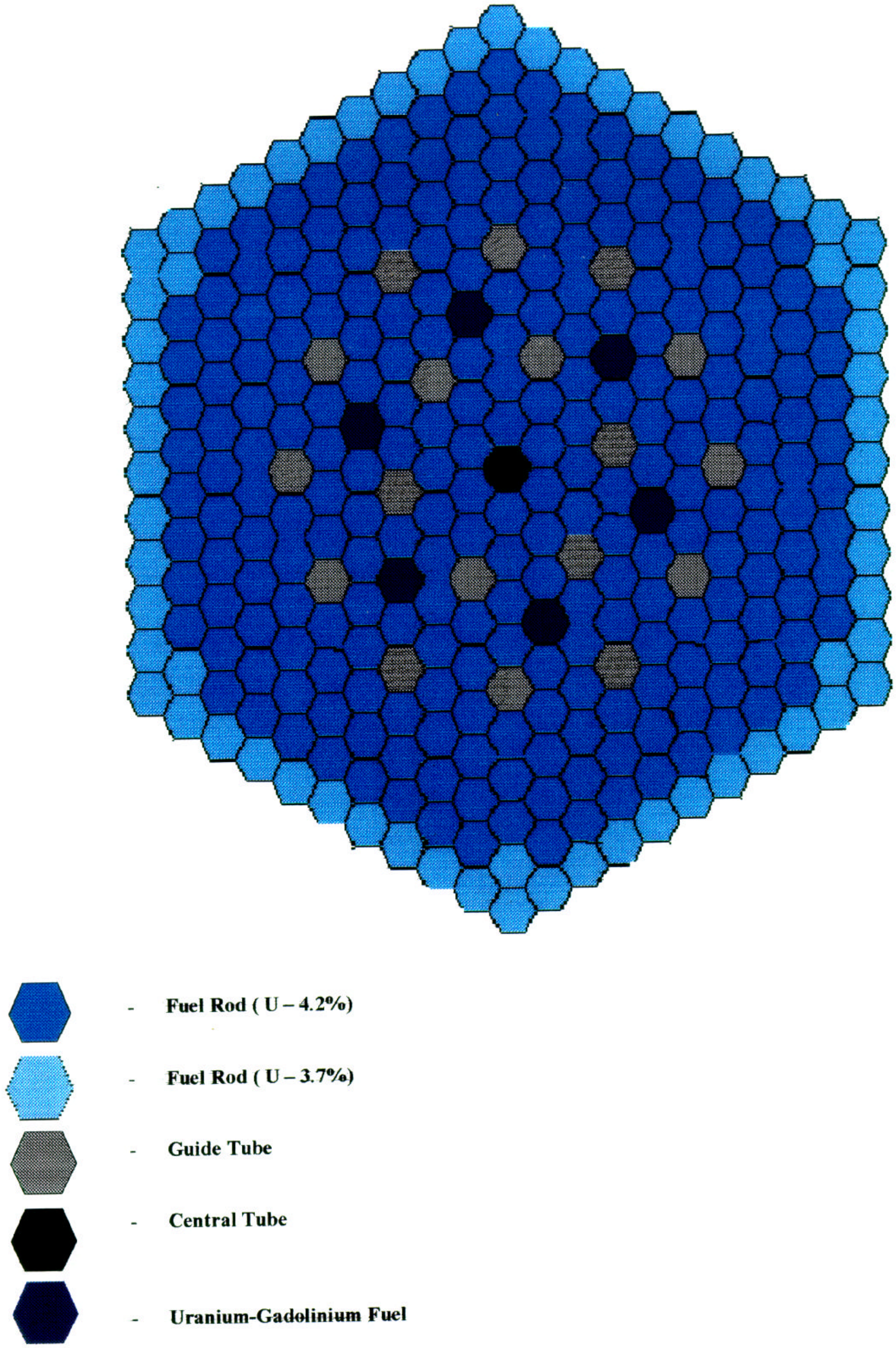
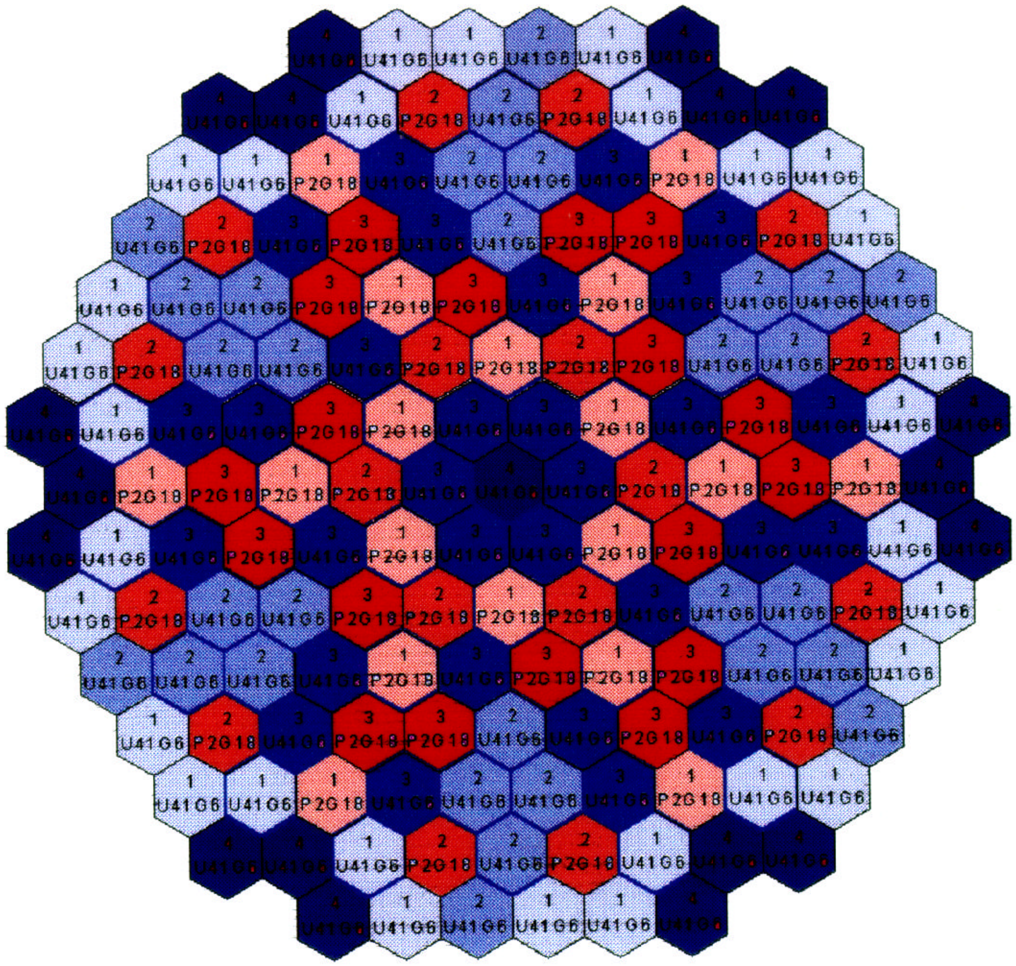


Fig. 3. Equilibrium Loading Pattern (Variant 2)



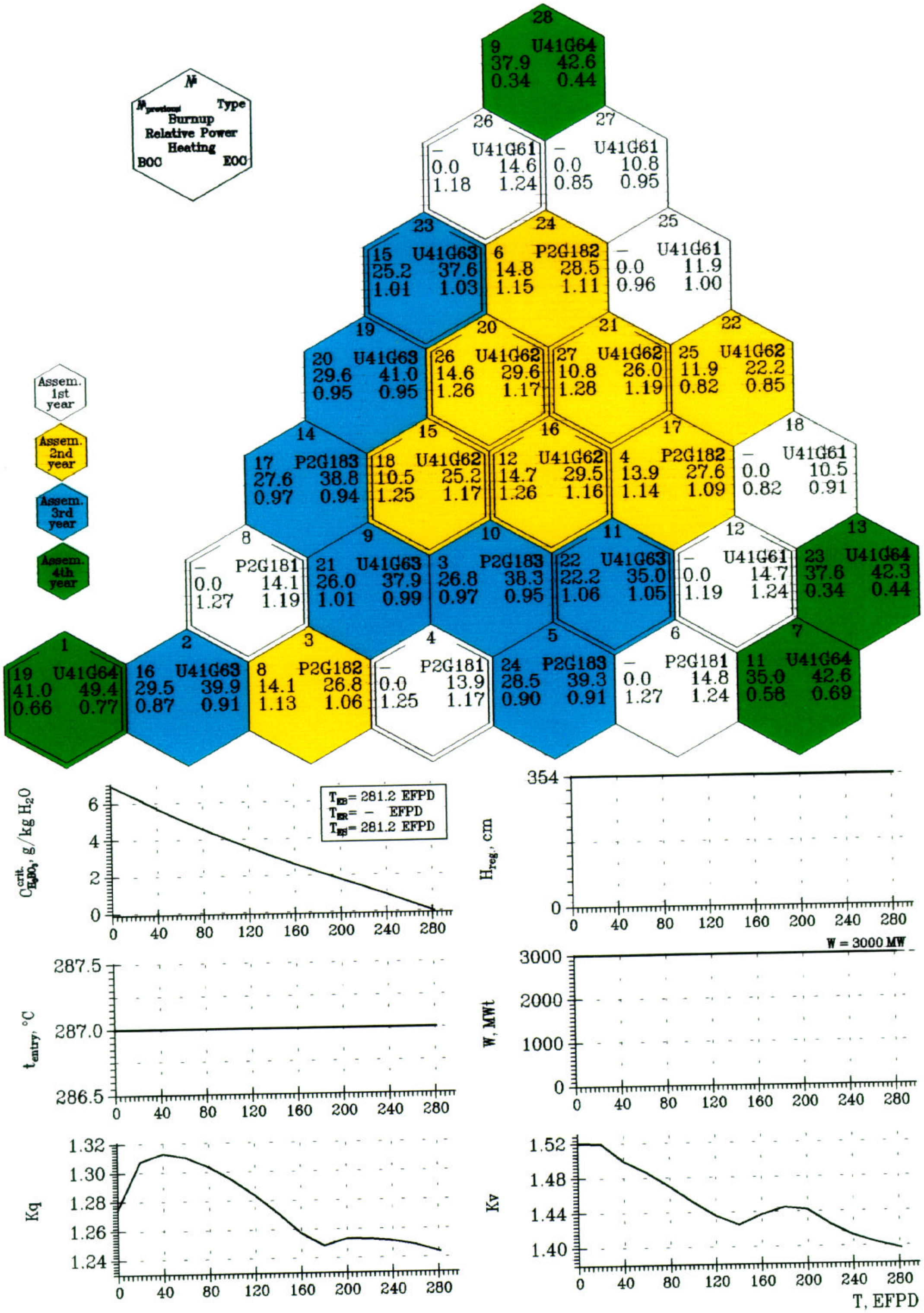


Fig. 4. Variation of the core characteristics in the course of the equilibrium fuel cycle burn-up

Table 2. Burn-up distribution over FA height

T=0.0 EFPD

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
28.0	19.2	9.4	0.0	18.2	0.0	22.4	0.0	16.2	18.3	13.4	0.0	25.4	18.3	6.1	8.8	9.4	0.0	19.3	8.8
40.9	29.0	14.0	0.0	27.7	0.0	34.3	0.0	25.2	26.9	21.4	0.0	37.4	27.2	10.0	14.0	13.9	0.0	29.0	13.9
42.9	30.8	14.8	0.0	29.7	0.0	36.7	0.0	27.2	28.3	23.3	0.0	39.4	28.9	10.9	15.2	14.7	0.0	30.8	15.2
43.4	31.3	15.0	0.0	30.3	0.0	37.3	0.0	27.8	28.6	23.8	0.0	39.9	29.3	11.3	15.6	14.8	0.0	31.4	15.6
43.8	31.7	15.1	0.0	30.8	0.0	37.8	0.0	28.2	28.8	24.2	0.0	40.3	29.6	11.5	15.9	15.0	0.0	31.8	15.9
44.3	32.2	15.3	0.0	31.2	0.0	38.3	0.0	28.6	29.0	24.6	0.0	40.7	30.0	11.7	16.3	15.1	0.0	32.2	16.3
44.8	32.6	15.4	0.0	31.7	0.0	38.8	0.0	29.1	29.3	25.0	0.0	41.1	30.4	11.9	16.6	15.3	0.0	32.7	16.6
45.2	33.1	15.6	0.0	32.1	0.0	39.3	0.0	29.5	29.5	25.3	0.0	41.5	30.7	12.1	16.9	15.4	0.0	33.1	16.9
44.6	32.5	15.2	0.0	31.3	0.0	38.3	0.0	28.8	28.9	24.5	0.0	40.9	30.0	11.6	16.4	15.1	0.0	32.5	16.3
32.3	22.9	10.7	0.0	21.9	0.0	26.6	0.0	19.7	20.6	16.3	0.0	29.3	21.3	7.5	11.0	10.7	0.0	23.0	10.9

21	22	23	24	25	26	27	28
6.2	6.9	16.6	9.2	0.0	0.0	0.0	25.0
10.2	11.3	24.9	14.2	0.0	0.0	0.0	37.4
11.3	12.5	26.4	15.3	0.0	0.0	0.0	39.7
11.7	12.8	26.8	15.7	0.0	0.0	0.0	40.3
11.9	13.1	27.1	16.0	0.0	0.0	0.0	40.7
12.2	13.3	27.4	16.3	0.0	0.0	0.0	41.2
12.4	13.6	27.7	16.6	0.0	0.0	0.0	41.7
12.6	13.8	28.1	16.8	0.0	0.0	0.0	42.2
12.0	13.2	27.5	16.3	0.0	0.0	0.0	41.3
7.7	8.6	19.3	11.2	0.0	0.0	0.0	29.2

Table 3. Burn-up distribution over FA height

T=281.2 EFPD

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
35.1	27.3	18.3	9.4	26.3	9.2	27.8	9.4	25.0	26.9	22.4	8.8	28.7	26.7	16.6	19.2	18.3	6.1	28.0	19.3
49.8	39.8	26.9	13.9	38.8	14.2	42.0	14.0	37.4	38.6	34.3	14.0	42.2	38.8	24.9	29.0	27.2	10.0	40.9	29.0
51.8	41.8	28.3	14.7	41.1	15.3	44.7	14.8	39.7	40.3	36.7	15.2	44.4	40.8	26.4	30.8	28.9	10.9	42.9	30.8
52.2	42.3	28.6	14.9	41.7	15.7	45.4	15.0	40.3	40.7	37.3	15.6	44.9	41.2	26.8	31.3	29.3	11.3	43.4	31.4
52.6	42.7	28.8	15.0	42.2	16.0	46.0	15.1	40.7	40.9	37.8	15.9	45.3	41.6	27.1	31.7	29.6	11.5	43.8	31.8
52.9	43.1	29.0	15.1	42.7	16.3	46.5	15.3	41.2	41.2	38.3	16.3	45.8	41.9	27.4	32.2	30.0	11.7	44.3	32.2
53.3	43.6	29.3	15.3	43.3	16.6	47.1	15.4	41.7	41.5	38.8	16.6	46.3	42.3	27.7	32.6	30.4	11.9	44.7	32.7
53.8	44.0	29.5	15.4	43.7	16.8	47.6	15.6	42.2	41.8	39.3	16.9	46.7	42.7	28.1	33.1	30.7	12.1	45.2	33.1
53.2	43.4	28.9	15.1	42.8	16.3	46.5	15.2	41.3	41.1	38.3	16.4	45.9	42.0	27.5	32.5	30.0	11.6	44.6	32.5
39.3	31.3	20.6	10.7	30.6	11.2	32.6	10.7	29.2	30.0	26.6	11.0	32.9	30.4	19.3	22.9	21.3	7.5	32.3	23.0

21	22	23	24	25	26	27	28
16.2	13.4	25.4	18.2	6.9	8.8	6.2	28.3
25.2	21.4	37.4	27.7	11.3	13.9	10.2	42.2
27.2	23.3	39.4	29.7	12.5	15.2	11.3	44.7
27.8	23.8	39.9	30.3	12.8	15.6	11.7	45.3
28.2	24.2	40.3	30.8	13.1	15.9	11.9	45.8
28.6	24.6	40.7	31.2	13.3	16.3	12.2	46.3
29.1	25.0	41.1	31.7	13.6	16.6	12.4	46.8
29.5	25.3	41.5	32.1	13.8	16.9	12.6	47.3
28.8	24.5	40.9	31.3	13.2	16.3	12.0	46.4
19.7	16.3	29.3	21.9	8.6	10.9	7.7	32.8

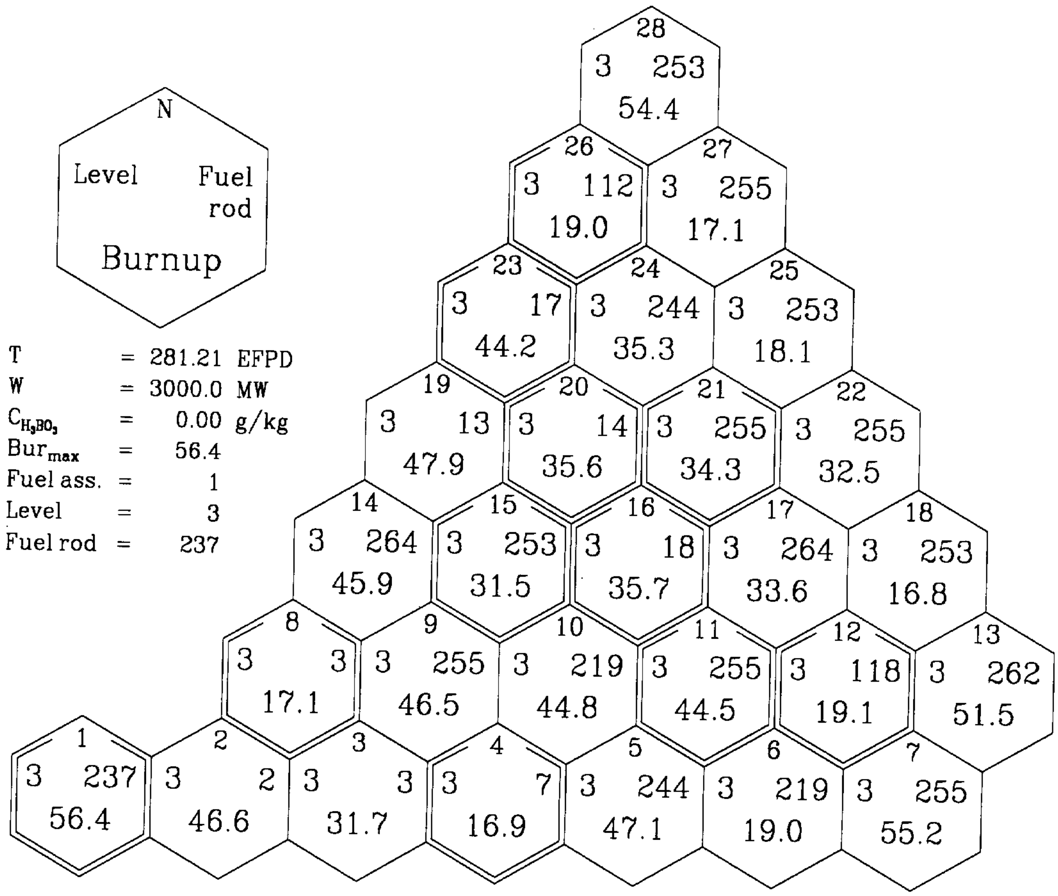


Fig. 5. Distribution of maximum burn-up of fuel pellets in FA, MWd/kg

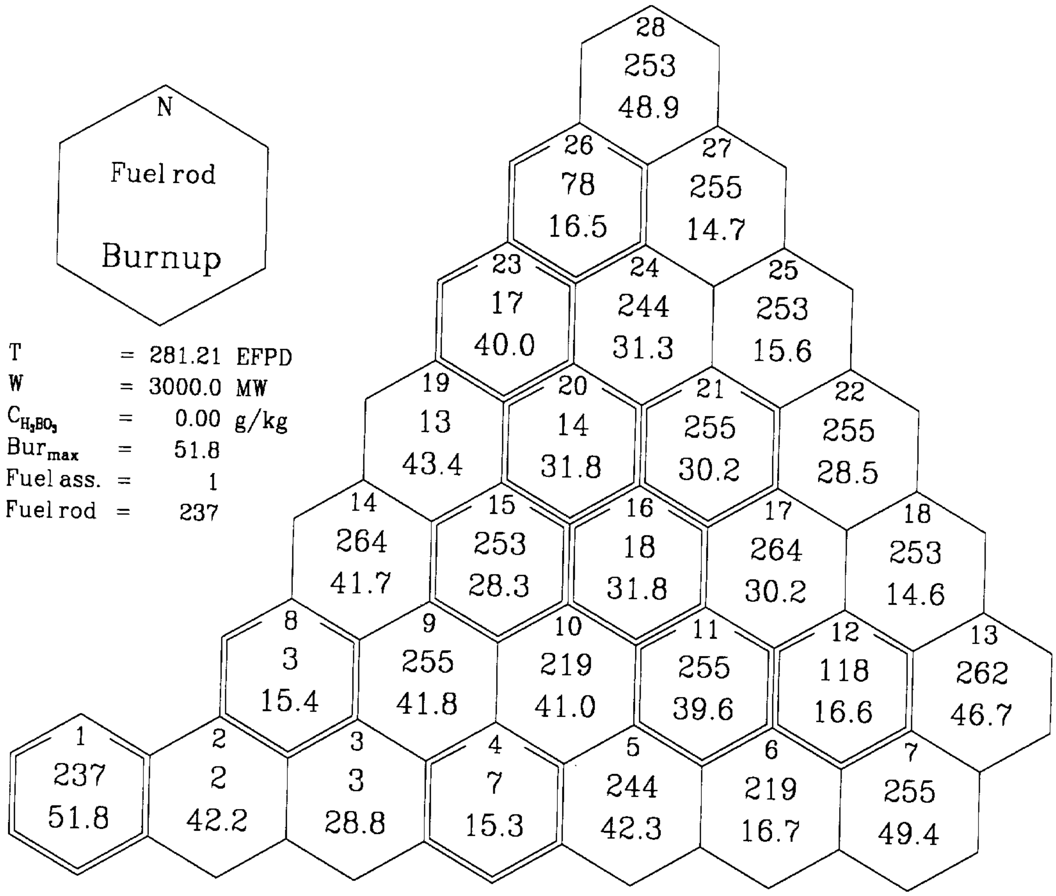


Fig. 6. Distribution of maximum burn-up of fuel rods in FA, MWd/kg

Table 4. Core Criticality (Scram Margin) in different states in the process of Scram actuation

State parameters						Reactivity, %			
						1/3 MOX FAs		UOX B-320	
State Number	Thermal Power, MW	Moderator temperature, °C	Control Bank position, %	Position of banks 1-9, %	Position of the most eff. control rod, %	BOC	EOC	BOC	EOC
1	3000	Nom.	100	100	100	+0.2	+0.3	+0.3	+0.3
	Regulation margin of reactivity								
2	3000	Nom.	70	100	100	+0.0	+0.0	+0.0	+0.0
	Scram actuation without sticking of the most effective CR								
3	3000	Nom.	0	0	0	-8.2	-8.1	-8.2	-8.2
	Scram actuation with sticking of the most effective CR								
4	3000	Nom.	0	0	100	-7.6	-7.3	-7.4	-7.1
	Uncertainty of $(RO)_{AP}$ calculation (10% of p. 4)								
5	3000	Nom.	0	0	100	-6.8	-6.5	-6.6	-6.4
	Vapor effect ($\Delta\rho$ = 100 pcm)								
6	3000	Nom.	0	0	100	-6.7	-6.4	-6.5	-6.3
	Doppler effect with 5% uncertainty								
7	0	Nom.	0	0	100	-5.5	-5.2	-5.5	-5.2
	Temperature effect with 5% uncertainty								
8	0	287	0	0	100	-4.8	-3.7	-4.7	-3.5
	Temperature effect with 5% uncertainty								
9	0	280	0	0	100	-4.5	-3.2	-4.5	-3.1
	Temperature effect with 5% uncertainty								
10	0	200	0	0	100	-2.7	+0.4	-2.8	+0.4
	Temperature effect with 5% uncertainty								
11	0	120	0	0	100	-1.8	+2.4	-2.0	+2.2
	Temperature effect with 5% uncertainty								
12	0	27	0	0	100	-1.1	+4.0	-1.2	+3.8

Remarks:

Equilibrium 100% power poisoning by Xenon and Samarium is used in all states.

Boron concentration in all states is equal to critical boron concentration in state 2.

Fig. 7. Core Reactivity versus Moderator Temperature.

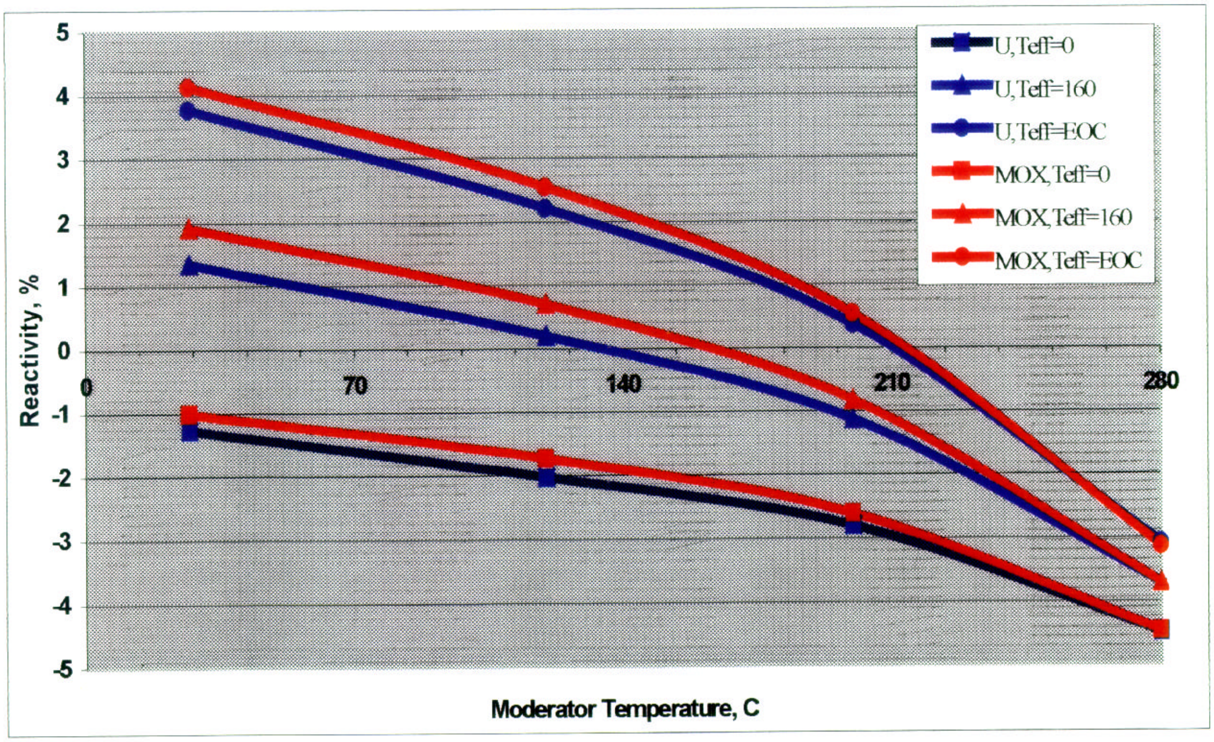
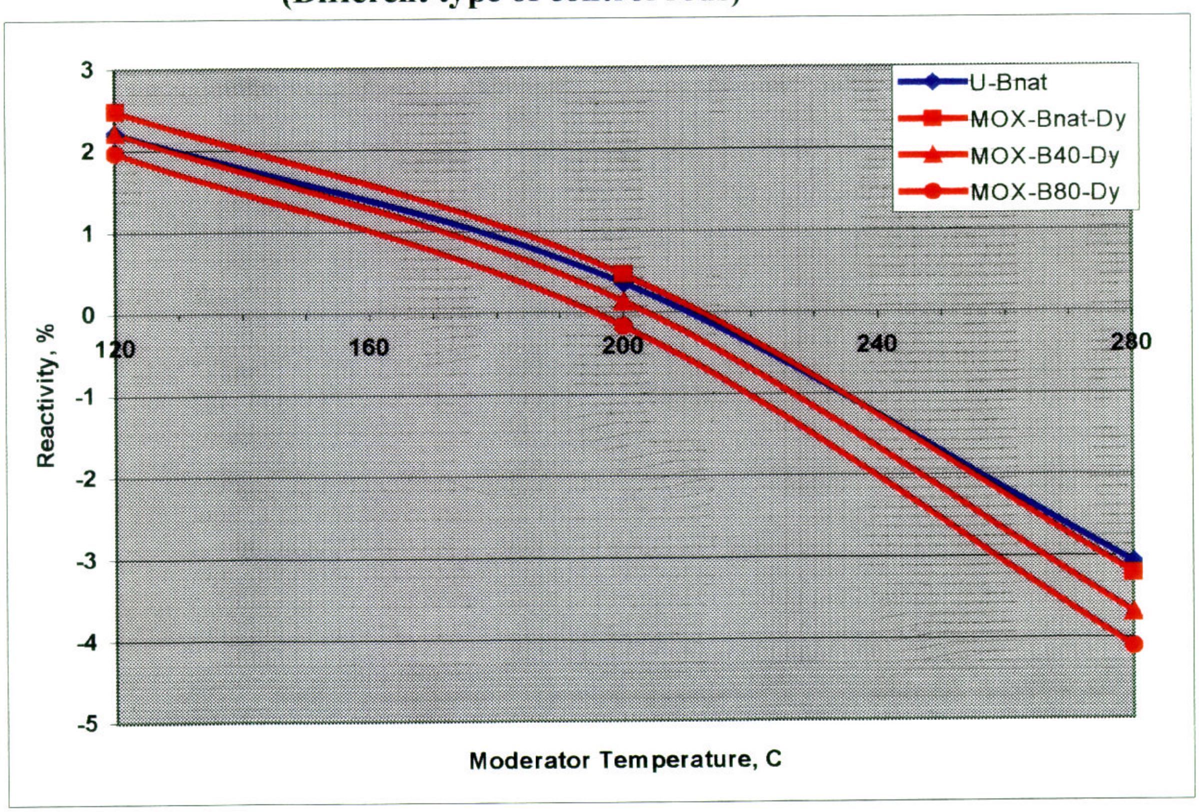


Fig. 8. Core Reactivity versus Moderator Temperature (Different type of control rods)



Conclusion

1. The report presents equilibrium fuel cycle in VVER-1000 core with 1/3 MOX assemblies of weapons-grade plutonium. The main features of proposed cycles are the following:

- Equilibrium fuel cycle is elaborated on the base of advanced assembly with Zirconium construction elements. The principle of direct replacement of UOX fuel by MOX one, without noticeable assembly and core design modifications, has been used.
- MOX fuel fraction in core is about 1/3. The only type of MOX assembly with average fissile plutonium content of 3.43% and U^{235} - 0.2% is used. MOX assembly is graded in plane by three types of fuel rods with different plutonium content for power inter-assembly flattening. Maximum content of fissile plutonium isotopes is of 3.6%, minimum one – 2.4%.
- In the equilibrium fuel cycle 11 UOX assemblies burn during 3 cycles, 19 Uranium assemblies – four cycles, 18 MOX assemblies (all in core center) – three cycles.
- BPRs in the form of uranium-gadolinium fuel elements are located in a part of UOX assemblies and in all MOX assemblies in order to suppress an excess of core reactivity and to flatten additionally a power distribution. MOX assemblies contain 18 uranium-gadolinium BPRs with Gd_2O_3 fraction of 4%wt. and U^{235} enrichment of 3.6%.
- Combined absorber rods with the upper part of B_4C (natural B_{10} content) and the lower part of Dy_2O_3*TiO_2 are used in the mechanical part of emergency-regulation reactor system.
- A part of irradiated assemblies is placed in the core periphery in the nearest to reactor vessel locations in order to lower vessel neutron fluence and to increase emergency system effectiveness. Fresh MOX assemblies are not placed in the core periphery as they are characterized by approximately 20% more fission neutrons than fresh Uranium assemblies.

2. The calculational results for fuel cycle with 1/3 MOX core are accumulated in Table C.1. For comparison the characteristics of equilibrium uranium fuel cycle (Project B-320) are also presented in the Table. Analysis of the results leads to the following conclusions:

- Annual weapons-grade plutonium disposition is about of 270 kg in both options. In discharged MOX fuel the average fissile plutonium content in plutonium does not exceed 65% i.e. it is lower than in discharged uranium fuel. So the task of weapons-grade plutonium transformation into the "standard of irradiated fuel" is performed with a significant margin.
- For fuel cycle length of about 7000 EFPH and MOX assemblies irradiation during 3 cycles, average burn-up of discharged MOX assemblies is 38.8 MW*d/kgHM. It confirms a sufficient extraction of weapons-grade plutonium power potential. Maximum average burn-up in MOX assembly attains 39.3 MW*d/kgHM. Average and maximum burn-ups in UOX assemblies are higher (maximum burn-up is in the forth-year assembly located in the central core position) but do not exceed 50 MW*d/kgHM.
- Mox core reactivity in the cold state with shut-down boron acid concentration (16000 ppm) is greater than in UOX core but does not exceed –7000 pcm. It should be noted that this calculated value is not conservative because calculation errors and eventual operator errors during assemblies reloading are not taken into account. Necessary analysis must be performed in future.
- Reactivity effects and coefficients on coolant and fuel temperature are negative and on coolant density is positive for all core critical states. Absolute values of above-mentioned coefficients in MOX fuelled core is higher than in UOX one. So the MOX fuelled reactor possesses more significant feed back allowing compensation of fast reactivity variation and limiting power increase.
- Regulating CR bank in VVER-1000 MOX fuelled core is transferred to the position № 15 (in 60 degr. symmetry) from the position № 4 (in the Project B-320). Such positioning ensures a necessary effectiveness of Regulating CR bank, facilitates core loading composing with low peaking power factors and lowers power distribution perturbations while the bank moving. Effectiveness of Regulating CR bank meets the safety requirements on both negative and positive reactivity introduction speed.
- Effectiveness criteria of the mechanical part of emergency-regulation reactor system (effectiveness of emergency system and core sub-criticality after emergency system actuation) are very close both in MOX and UOX cores. As it is shown in the Document, it could be possible to use in AR a boron with 60-80% enrichment in B_{10}, in order to create some margin on emergency system effectiveness in MOX fuel cycles.

- Power peaking factors for MOX fuel cycles meet with a small margin the limits established for UOX FAs in VVER-1000 Project. But MOX fuel thermo-physical properties are a little worse than the UOX ones. Besides, according to performed estimation studies, the engineering margin coefficients and calculational errors are greater for MOX fuel. So the applicability of the elaborated MOX fuel cycles should be confirmed by thermo-hydraulic calculations. It should be noted that the mentioned MOX fuel particularity and also the necessity of irradiated MOX fuel positioning in a core periphery demand an improvement of representativity of in-core detecting system in MOX fuelled VVER-1000
- Effective fraction of delayed neutrons and lifetime of prompt neutrons are lower of 10% in MOX fuel cycle in comparison with UOX ones. So more attention should pay to safety analysis in reactivity accidents calculations.
- MOX core in comparison with UOX core is more stable in respect to xenon oscillations of integral power and spatial power distribution, that provides more reliable operation of reactor.

3. Presented results leads to the conclusion that neutronics characteristics defining reactor safety are close for MOX fuel cycle and Project UOX fuel cycle.

Table C.1. Characteristics of UOX and MOX (1/3) Equilibrium Fuel Cycle

Name of characteristic	Clarification	Type of Cycle	
		UOX B-320	**1/3 MOX**
Number of fresh FA loaded during refuelling, pcs	U^{235} - 4.23%	**30**	**-**
	U^{235} - 4.40%	**24**	**-**
	U^{235} – 4.08% (4.2/3.7%)	**-**	**30**
	U^{235} - 3.70%	**-**	**-**
	U^{235} - 0.20%, $Pu^{239+241}$ - 3.43%	**-**	**18**
Weight of fuel rod $UO_2/(UO_2+PuO_2)$, kg		**1.465**	**1.575/1.600**
Number of burnable poisons rods in fresh FA, pcs	Boron BPR (in UOX FA)	**18**	**-**
	U-Gd Fuel (in UOX FA)	**-**	**6**
	U-Gd Fuel (in MOX FA)	**-**	**18**
Material of tubes and grids		**Fe**	**Zr**
Part of MOX fuel, %		**-**	**33**
Annular plutonium utilization, kg		**-**	**270**
Weight of discharged plutonium, kg	Total	**238**	**337**
	UOX FAs	**238**	**147**
	MOX FAs	**-**	**190**
Fuel burn-up, MWd/ kg	Average, UOX FAs	**41.2**	**42.0**
	Average, MOX FAs	**-**	**38.8**
	MAX, UOX FAs	**48.1** [1)]	**49.4** [1)]
	MAX, MOX FAs	**-**	**39.3**
	MAX, UOX Fuel Rods	**54.0** [1)]	**52.0** [1)]
	MAX, MOX Fuel Rods	**-**	**42.3**
Content of Plutonium Isotopes in Fresh MOX Fuel, %	Pu^{239}	**-**	**93**
	Pu^{240}	**-**	**6**
	Pu^{241}	**-**	**1**

Table C.1. Characteristics of UOX and MOX (1/3) Equilibrium Fuel Cycles (continuation 1)

Content of Plutonium Isotopes in Spent UOX Fuel, %	Pu^{239} Pu^{240} Pu^{241} Pu^{242}		**56.4** **23.4** **13.3** **5.2**	**55.2** **23.9** **13.4** **5.7**
Content of Plutonium Isotopes in Spent MOX Fuel, %	Pu^{239} Pu^{240} Pu^{241} Pu^{242}		- - - -	**46.5** **31.5** **15.6** **5.9**
Cycle length, EFPD	CRs out		**298**	**282**
Critical boron acid concentration in coolant, ppm	Full Power	BOC	**6720**	**6930**
Reactivity at 16 g/kg H_3BO_3	Cold state, CRs out,	BOC	**-10.6**	**-7.4**
Boron acid coefficient of reactivity, %/(g/kg)	Full power EOC	BOC	**1.4** **1.6**	**1.2** **1.5**
Moderator temperature coefficient of reactivity, pcm/ ^{o}C	MCL, CRs out, Full power	BOC BOC EOC	**0.** **-23** **-61**	**-5** **-30** **-66**
Fuel temperature coefficient of reactivity, pcm/ ^{o}C	MCL, CRs out, Full power	BOC BOC EOC	**-2.8** **-2.5** **-2.7**	**-3.2** **-2.6** **-2.7**
Moderator density coefficient of reactivity, $1/(g/cm^3)*10^{-2}$	MCL, CRs out, Full power	BOC BOC EOC	**2.2** **10.9** **28.8**	**5.4** **14.8** **33.1**
Regulation bank worth, %	Full power	BOC EOC	**0.75** **0.70**	**0.80** **0.79**
Control and protection system efficiency, %	Full power, MECR[2)] out, EOC MCL, MECR out, EOC	BOC BOC	**7.4** **7.1** **6.6** **6.3**	**7.6** **7.3** **6.7** **6.7**

Table C.1. Characteristics of UOX and MOX (1/3) Equilibrium Fuel Cycles (continuation 2)

Repeat criticality temperature, °C	Xe eq, MECR out Direct calculation Conservative estimation	 EOC EOC	 **157** **210**	 **161** **210**
Shut-down margin, %	280°C, Xe eq, MECR out, Direct calculation Conservative estimation	 EOC EOC	 **4.3** **3.1**	 **4.5** **3.2**
Maximum normalised power of FA over cycle	UOX FA MOX FA		**1.29** **-**	**1.31** **1.27**
Maximum normalised power of fuel pin over cycle	UOX fuel rods MOX fuel rods		**1.46** **-**	**1.45** **1.45**
Maximum fuel pin linear power over cycle, W/cm	UOX fuel rods MOX fuel rods		**271** **-**	**287** **288**
Effective Fraction of Delayed Neutrons, %	Full power,	BOC EOC	**0.64** **0.56**	**0.53** **0.51**
Lifetime of prompt neutrons, сек*10^{-5}	Full power,	BOC EOC	**2.1** **2.4**	**1.8** **2.1**

[1] Central Fuel Assembly
[2] MECR – Maximum efficient Control Rod

References

1. Physics and Fuel Performance of Reactor-Based Plutonium Disposition. AEN/NEA, Workshop Proceedings, Paris, France, 28-30 September 1998.
2. Novikov A.N. et al. Use of MOX (R-U and W-U) Fuel in VVER-1000 (Neutron-Physical aspects of possibilities). Proc. of Meeting of Workshop on Managing The Plutonium Surplus: Application and Options. London, 24-25 January 1994.
3. Use of Weapon-Grade Plutonium from Dismantled Nuclear Weapons for the Peaceful Objective of Electric Power Generation. AIDA/MOX1 (1993-1996). Final Report. 1997.
4. Вознесенский В.А., Семенов В.В. и др. Эксплуатационные режимы АЭС с ВВЭР-1000. М., Энергоатомиздат, 1992
5. Novikov A. Prospects for improvement of VVER fuel management and MOX Utilization. Safety Issues Associated with Plutonium Improvement in the Nuclear Fuel Cycle, p.111.Kluwer Academic Publishers, 1999.
6. Sidorenko V. et al. Spectral Code TBC-M for Calculation of Characteristics of Cells, Super-cells and Fuel Assemblies of VVER-Type Reactors. 5-th Symposium of the AER, Dobogoko, Hungary, October 15-20, 1995.
7. Novikov A. et al. Problems of VVER In-core Fuel Management, IAEA-TECDOC-567, In-core Fuel Management Practices, IAEA, Vienna,1990
8. Bychkov S. et al. Benchmarks for neutronics codes. Comparison of results obtained with various codes. Joint US/Russian Project. RRC KI, 1999.
9. Pavlovichev A. Validation of Neutronic Computer Codes Assosiatd with MOX Fuel Usage in VVER-1000 Reactor. Third Topical Meeting on DOE Spent Nuclear Fuel and Fissile Materials Management. Vol. 2, p. 606. Charleston, SC, 1998.

Review of *Mission MOX Fuel Physics Design—Preliminary Equilibrium MOX Assembly Design and Expected Operating Power for Existing Balakovo Fuel Management Scheme* by D. T. Ingersoll and R. T. Santoro, Oak Ridge National Laboratory

General Comments

The work appears to be technically correct. The results presented in the figures and tables are consistent. The main criticism of the report is that it is not a "stand-alone" document. For example, after the introduction, the results are presented with no clear indication of how the data were obtained. The author does not explain the sequence in which the calculations were carried out although he did mention the use of several codes, including attempts to benchmark them.

It is suggested that future documents either provide a complete set of references or follow a more systematic approach such as the following:

Introduction
Methods of Calculation
Include descriptions of the codes and data and details on the reactor models.
Discussion of Results
Include discussion of uncertainties.
Conclusions

Corrections to Acronyms for Consistency

Change the following terms:

- "Russian authority for nuclear safety" to "Russian Authority for Nuclear Safety"
- "Mixed Oxide (uranium-plutonium fuel)" to "Mixed Oxide (Uranium-Plutonium Fuel)"
- "Zirconium fuel for cladding" to "Zirconium Fuel for Cladding"
- "Russian water-water reactor" to "Russian Water-Water Reactor"

Text Comments

1. Page 5, paragraph 1, line 1: Add "," after "handling."
2. Page 5, paragraph 1, line 3: Change "power value" to "energy content."
3. Page 5, paragraph 2, suggested wording for first sentence: "Options for burning weapons grade plutonium in VVER-, BN-, HTGR-type reactors are being developed in Russia."
4. Page 5, paragraph 2, suggested wording for second sentence: "Experience in the use of mixed uranium-plutonium fuel gained in the West along with preliminary results obtained in Russia [1–3] show that ….."
5. Page 5, paragraph 3, suggested wording: "Russia has seven VVER-1000 in operation with a total capacity of 11GWE. Eleven of these reactors are in operation in the Ukraine and two are running in Bulgaria. It is planned to put two additional VVER-1000 units into operation in Russia and at leas two into operation in the Ukraine before the tear 2003."
6. Page 5, paragraph 4, suggested wording: "The core designs of all VVERs are essentially the same. The main differences are in the number of control rods."
7. Page 5, paragraph 5, suggested wording: "Therefore, it is used as the reference cycle….."
8. Page 5, paragraph 5, suggested wording: "Part 2 describes the main characteristics of the ….."
9. Page 5, paragraph 6, suggested wording: "At present, extensive efforts are underway in Russia on the VVER-1000 [5] advanced fuel cycle."
10. Page 5, paragraph 6, suggested wording: "…..control rods consisting of two parts: the upper region comprised of B_4C and the lower region comprised of $Dy_2O_3 \cdot TiO_2$."

11. Page 6, paragraph 1, line 1: Change “By present” to “At present.”
12. Page 6, paragraph 1, line 1: Change “has” to “have.”
13. Page 6, paragraph 1, suggested wording: “In Russia, the basic parameters for large-scale implementation of advanced fuel cycles improved FAs and uranium-gadolinium fuel have been established.
    – pilot operation of FAs with UGF is being conducted at the Balakovo NPP.
    –
    –
    – in many VVER1000 reactors, low leakage loading patterns have been successfully used.”
14. Page 6, paragraph 3, suggested wording:
    “In Russia, calculational studies ……….
    Emphasis is placed on the most simple …….”
15. Page 6, paragraph 4, suggested wording:
    – Investigations by Russian and Western specialists have shown [1,2] that the ….
    –
    –
    – …. between MOX and UOX FAs making it necessary to use …..”
16. Page 6, paragraph 4, line 2: Change “civil” to “civilian.”
17. Page 7, paragraph 1, suggested wording:
    “*Code BIPR-7A* ………samarium transients, etc.,
    Code PERMAK-A ……power and burn-up distributions”
18. Page 7, paragraph 2, suggested wording:
    “……calculated errors in MOX fuelled core is a difficult task.
    Therefore, ……….current stage of code verification.
    Some years ago, ………….were engaged in code verification.”
19. Page 8, paragraph 1, suggested wording: “…..5% and 4% to lower the neutron multiplication in fresh UOX and MOX FAs.”
20. Page 8, paragraph 5, suggested wording: “…..calculated errors associated with emergency systems …….”
21. Page 8, paragraph 6, suggested wording: “…..Boron-10 content in the upper part of the combined absorber was varied from natural boron to 80 wt % enriched boron.”
22. Table 1. Use the notation wt % throughout.
23. Table C.1 (continuation 2), last row should read: “Lifetime of prompt neutrons, sec*10^{-5}”
24. Page 13, Fig. 4: Should define symbols on graph axes (Kq, Kv, etc.).
25. Page 14, Table 2: Should specify core height values corresponding to rows.
26. Page 20, first set of conclusions, suggested wording:
    First bullet: “The equilibrium fuel cycle is reviewed on the basis of ……….."
    “The principle of direct replacement of UOX fuel with MOX …..”
    Third bullet: “In the equilibrium fuel cycle, eleven UOX assemblies burn-up during three cycles, nineteen U assemblies burn-up during four cycles, and eighteen MOX assemblies (all in the core center) burn-up in three cycles.”
    Fourth bullet: “……are located in parts of the UOX assemblies ………….and to additionally flatten the power distribution.”
    Fifth bullet: “…….upper part comprised of B_4C and the lower part comprised of $Dy_2O_3 \cdot TiO_2$.”
    Sixth bullet: “Some of the irradiated samples are placed in the core periphery close to the reactor vessel to lower the neutron fluence in the vessel.”
27. Page 18, Table 4: Need to define “$(RO)_{AP}$.”
28. Page 20, second set of conclusions, suggested wording: “……1/3 MOX core is summarized in Table C.1. For comparison, …….”

29. Page 21, third bullet: Change “Mox” to “MOX.”
30. Page 21, suggested wording for first bullet: “…..deposition is about 270 kg in both options.”
31. Page 22, suggested wording for second bullet: “prompt neutrons are 10% lower in MOX …”
32. Page 23, Table C.1: Change “Annular plutonium” to “Annual plutonium.”

INTERNAL DISTRIBUTION

1–4. B. B. Bevard
5. R. J. Belles
6. J. J. Carbajo
7. M. D. DeHart
8. F. C. Difilippo
9. M. E. Dunn
10. R. J. Ellis
11. J. C. Gehin
12. S. R. Greene
13. S. Goluoglu
14. R. F. Holdaway
15. D. Hollenbach
16. C. M. Hopper
17. D. T. Ingersoll
18. M. A. Kuliasha
19. S. B. Ludwig
20. G. E. Michaels
21. L. J. Ott
22–23. R. T. Primm III
24. C. E. Sanders
25. C. C. Southmayd
26. D. L. Williams, Jr.
27. Central Research Library
28. ORNL Laboratory Records-RC

EXTERNAL DISTRIBUTION

29. M. L. Adams, Department of Nuclear Engineering, Texas A&M University, Zachry 129, 3133 TAMU, College Station, TX 77843
30. H. Akkurt, 2919 Cooley Building, 2355 Bonisteel Boulevard, Ann Arbor, MI 48109-2104
31. D. Alberstein, Office of Fissile Materials Disposition, U.S. Department of Energy, NN-63, 1000 Independence Avenue SW, Washington, DC 20585
32. J. B. Briggs, Idaho National Environmental and Engineering Laboratory, P.O. Box 1625-3855, Idaho Falls, ID 83415-3855
33. J. Baker, Office of Fissile Materials Disposition, U.S. Department of Energy, NN-63, 1000 Independence Avenue SW, Washington, DC 20585
34. K. Chidester, Los Alamos National Laboratory, P.O. Box 1663, MS-E502, Los Alamos, NM 87545
35. W. Danker, U.S. Department of Energy, NN-62, 1000 Independence Avenue SW, Washington, DC 20585
36. T. Gould, Lawrence Livermore National Laboratory, P.O. Box 808, MS-L186, Livermore, CA 94551
37. L. Jardine, Lawrence Livermore National Laboratory, P.O. Box 808, MS-L166, Livermore, CA 94551
38. Dr. Alexander Kalashnikov, Institute of Physics and Power Engineering, 1 Bondarenko Square, Obninsk, Kaluga Region, Russia 249020
39–43. Dr. Alexander Pavlovichev, Russian Research Center “Kurchatov Institute,” Institute of Nuclear Reactors, VVER Division, VVER Physics Department, 123182, Kurchatov Square, 1, Moscow, Russia
44. K. L. Peddicord, Associate Vice Chancellor, Texas A&M University, 120 Zachry, College Station, TX 77843-3133
45. G. Radulescu, Framatom Cogema Fuels, 1261 Town Center Drive, MS-423, Las Vegas, Nevada 89143

46. J. Thompson, Office of Fissile Materials Disposition, U.S. Department of Energy, NN-61, 1000 Independence Avenue SW, Washington, DC 20585
47. F. Trumble, Westinghouse Savannah River Company, Building 730R, Room 3402, WSRC, Aiken, SC 29808
48. R. H. Clark, Duke/Cogema/Stone & Webster, 400 South Tryon Street, WC-32G, P.O. Box 1004, Charlotte, NC 28202
49. S. Nesbit, Duke/Cogema/Stone & Webster, 400 South Tryon Street, WC-32G, P.O. Box 1004, Charlotte, NC 28202
50. M. S. Chatterton, Office of Nuclear Reactor Regulation, MS O10B3, U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001
51. R. W. Lee, Office of Nuclear Reactor Regulation, MS O10B3, U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001
52. U. Shoop, Office of Nuclear Reactor Regulation, MS O10B3, U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001
53. Aldo Ferri, Scandpower, Inc., 101 Lakeforest Blvd., Suite 340, Gaithersburg, MD 20877
54. Nagao Ogawa; Director and General Manager; Plant Engineering Department; Nuclear Power Engineering Corporation; Shuwa-Kamiyacho Building, 2F; 3-13, 4-Chome Toranomon; Minato-Ku, Tokyo 105-0001, Japan
55. Dr. Kiyonori Aratani; Surplus Weapons Plutonium Disposition Group; International Cooperation and Nuclear Material Control Division; Japan Nuclear Cycle Development Institute; 4-49 Muramatsu, Tokai-mura, Naka-gun, Ibaraki-ken, Japan
56. Boris E. Volkov; Head of Division; EDO Gidropress; 21 Ordzhonikidze Street; Podolsk, Moscow District, Russia 142103
57. Dr. Alexandre Ermolaev; Balakovo Nuclear Power Plant, Saratov Region, Balakovo-26, Russia, 413866