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Mission Fuel Kinetics Input and RELAP-like Calculations

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A Russian Contribution to the
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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 Fuel Kinetics Input and RELAP-like Calculations

General Order 85B-99398V

Report

Project Manager

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ACRONYMS

Russian		American Equivalent
AZ	emergency (accident) protection	AP
AZ-1	state with all the control rods fully inserted except of one the most effective stuck in upper position	AP-1
AKNP	Source Range Channel	
APN	Safety Injection Pump	
ARM	Automated Power Regulator	
ASP	Emergency Diesel Generators (Loading Program)	
ATWS	Anticipated Transient Without Scram	ATWS
BOC	Beginning Of fuel Cycle	BOC
BPR	Burnable Poison Rod	BPR
BZOK	Rapid Cut-off Isolating Valve	
BRU-A	Atmospheric Steam Dump (PG Relief Valves)	
BRU-K	Condenser Steam Dump (PG Relief Valves)	
BShU	Control Room Of the Unit	
	Critical Heat Flux	CHF
	all the control rods in upper position	CRU
	all the control rods inserted	CRD
	Control Rod Drive Mechanism	CRDM
VKS	Reactor Upper Mixing Chamber	
VPEN	Auxiliary Feedwater Electrically Driven Pump	
VRK	Reactor Internal Control System	
DNBR	Departure from Nucleate Boiling Ratio	DNBR
DTC	Doppler Temperature Coefficient	DTC
EFPD	Effective Full Power Day	EFPD
EOC	End Of fuel Cycle	EOC
FGR	Fission Gas Release	FGR
FP	Fission Products	FP
GE (YT)	Hydro-tank of SAOZ system (passive part of SAOZ)	AC
GO	Containment	
GPZ	Main Steam Valve	
GZK	Primary Cooling Circuit	
GZN	Primary Cooling Pump	RCP
GZT	Main Circulation Pipeline	
IPU	Impulse protection unit	
ISA	Initial Event of an Accident	
KD	Pressurizer	
KI	Kurchatov Institute	KI
LOCA	Loss Of Coolant Accident	LOCA

LTA	Lead Test Assembly	LTA
LWR	Light Water Reactor	LWR
MCL	Minimum Controllable reactor power Level	MCL
MDC	Moderator Density Coefficient	MDC
MOX	Mixed OXide	MOX
MTC	Moderator Temperature Coefficient	MTC
NKS	Reactor Bottom Mixing Chamber	
NPP	Nuclear Power Plant	NPP
OR	Regulatory Body (Control Rod)	CR
PVD	Intermediate High Pressure Heater	
PG	Steam Generator	SG
PK	Relief Valve or Safety Valve	
PZ-1	1st-level Preventive Protection	
PZ-2	2nd-level Preventive Protection	
PND	Intermediate Low Pressure Heater	
PWR	Pressurized-Water Reactor	PWR
P_{prim}	pressure in primary circuit (in pressurizer)	P_{prim}
P_{sec}	pressure in secondary circuit	P_{sec}
RIA	Reactivity Initiated Accident	RIA
RCT	Repeat Criticality Temperature	RCT
ROM	Power Limitation Regulator	
RU	Reactor Unit	
SAOZ	Emergency Core Cooling System	ECCS
SB	Safety System	
SLA	Accident Localisation System	
SUZ	Reactor Control and Protection System	RPS
SVO	Chemical Water Purification System	
TQ12	High Pressure emergency injection of boron (active part of SAOZ)	
TQ14	Low Pressure System of core planned and emergency cooling (active part of SAOZ)	
TVS, FA	Fuel Assembly	FA
TVEL	Fuel Element	
TG	Turbine Generator	
TPN	Feedwater Turbine Driven Pump	
UOX	Uranium Oxide Fuel	UOX
VVER	Russian water-water reactor	VVER
EGSR	Electric - Hydraulic Regulatory System	

EXECUTIVE SUMMARY

In this document issued according to **Work Release 02. P. 99-4b** the neutronics parameters intended for use in 1-point kinetics RELAP model are presented. They are obtained for equilibrium 30% MOX fuelled core of VVER-1000 containing boron burnable poison rods.

CONTENTS

INTRODUCTION

The present work is a part of Joint U.S. / Russian Project with Weapons-Grade Plutonium Disposition in VVER Reactor and presents the neutronics parameters intended for use in 1-point kinetics RELAP model calculations.

Code RELAP [1] is one of the codes that are previewed for using in transient analysis of VVER-1000 core compositions with MOX fuel. 1-point kinetics of the core is used at the moment in routine RELAP calculations. Spatial (3-D) kinetics model seems to be reasonable while using for RIA calculations. Performance in RIA of MOX fuelled core can be rather different from UOX one due to significantly higher multiplication and absorbent ability of MOX fuel. This effect depends on MOX FAs fraction in core. So it was decided to compare 3-D and 1-point models on the base of MOX fuelled core with significant (1/3) fraction of MOX assemblies.

In [3] a set of benchmarks has been calculated using the code NOSTRA [2] as 3-D model on the base of 30% MOX fuelled core with boron burnable poison rods. The same list of benchmark transients is supposed to be calculated by 1-point RELAP model. This report contains the neutronics data prepared for RELAP calculations using KI codes [4] particularly BIPR-7A and PERMAK-A.

1. DEFINITIONS

Table 1. Definitions

Parameter	**Abbreviation**	**Units**	**Remarks**
Calculational system	CS		Multi-Assembly or core
CS symmetry sector	Sim		30 for 30°, 60 for 60°, 120 for 120°, 360 for full CS.
Reactivity of CS	RO	pcm	RO = (Keff-1)/Keff*1.E5
Calculational volume	Vij		Axial fraction j of assembly number i. In VVER-1000 calculations, 10-30 axial fractions of equal volume are usually used.
Effective multiplication factor of CS	Keff		
Multiplication factor of CS	Ko		Relation of neutron generation to neutron absorption. For core calculations Ko values are attributed to Vij
3-D power distribution in core	q_{ij}		Power in Vij normalised by average Vij power
Volume power peaking factor	Kv		Maximum in q_{ij} values
Radial position of volume power peaking factor	N (Kv) or N_K		Number of assembly in calculational core sector where Kv is realised
Axial position of volume power peaking factor	M (Kv) or N_Z		Number of axial level where Kv is realised
3-D burnup distribution in core	BUij	MWd/kg	Burnup in Vij.
2-D power distribution in core	q_i		Assembly powers normalised by average

			assembly power in core.
Radial power peaking factor	Kq		Maximum in qi values
Radial position of radial power peaking factor	N (Kq) or N_K		Number of assembly in calculational core sector where Kq is realised
Pin linear power	Ql	W/cm	Pin power for 1 cm of an axial calculational fraction
Moment during fuel irradiation	T	EFPD	
2-D burnup distribution in core	BUi	MWd/kg	Average-assembly burnup distribution in core.
Average burnup in Uranium assemblies	$\bar{B}_U$	MWd/kg	
Average burnup in MOX assemblies	$\bar{B}_{MOX}$	MWd/kg	
Average Boron acid (H_3BO_3) concentration[a] in coolant	Cb or C_{H3BO3}	ppm or g/kg	H_3BO_3 fraction in coolant (unit "ppm" means mg of boron acid in 1 Kg of H_2O)
Critical boron acid concentration in coolant	Cb^{crit}	ppm or g/kg	Cb (C_{H3BO3}) value ensuring Keff=1
2-D power distribution in CS	q_k-CS		Power of fuel pins normalised by average fuel pin power in CS.
Peaking factor of 2-D power distribution in CS	K_{FA}–CS		Maximum in q_k-CS values
2-D power distribution in assembly	q_k		Power of fuel pins normalised by average fuel pin power in assembly (in some axial fraction).
3-D power distribution in axial volumes of fuel pins in core	q_{ijk}		Power of axial volumes of fuel pins normalised by average power in such volumes over a whole core

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[a] Boron acid concentration divided by the coefficient 5.72 means natural boron (nat B) concentration. In VVER-1000 calculations the term of boron acid concentration is widely used. Below, Cb means boron acid concentration if there is no special indication.

Pin power peaking factor in assembly	Kki		Among q_k values for an assembly number i for a fraction number j where maximum q_{ij} for this assembly is realised.
Radial pin power peaking factor	Kr		max (qi * Kki)
Radial position of radial pin power peaking factor	N (Kr) or N_K		Number of assembly in calculational core sector where Kr is realised
2-D power peaking factor in assembly	K_{FA} (in Russian exploitation calculations the notation Kk or Kk_{max} is also used)		Maximum relative power of fuel pins (maximum in q_k values)
Axial power peaking factor in assembly or in fuel pin	Kz		Maximum relative power of axial volume in assembly or in fuel pin normalised by average power in such volumes (in assembly or in fuel pin)
Total power peaking factor	Ko or $K_{o\text{-total}}$		$\max\limits_{ij} (q_{ij} * Kki) = Kr*Kz$
Radial position of total power peaking factor	N ($K_{o\text{-total}}$) or N_K		Number of assembly in calculational core sector where $K_{o\text{-total}}$ is realised
Axial position of total power peaking factor	M ($K_{o\text{-total}}$) or N_Z		Number of axial level where $K_{o\text{-total}}$ is realised
Engineering factor	K_{eng}		Coefficient taking account of uncertainty of a hot point (maximum fuel pin local power) calculations
2-D burnup distribution in assembly	BUk	MWd/kg	Average-pin burnup distribution in CS.
1-D burnup distribution in fuel pin	BUpin		Burnup distribution in concentric zones of equal volume in fuel pin, normalised by average

			zone burnup.
1-D power distribution in fuel pin	q_{pin}		Power distribution in concentric zones of equal volume in fuel pin, normalised by average zone power.
Regulation bank position	H_{reg}	cm	Distance from core bottom till rods lower edge
Control rods worth (in core)	$(RO)_{AP-1}$	ppm	Effect of control rods insertion in core supposing the most effective single CR stuck in upper position. It is defined as a reactivity difference in two states: $(RO)_{AP-1}$= RO1-RO2. The second state differs from the first one only by additional CRs inserted in core. All the other parameters correspond to the first state: Cb (that is equal to Cb crit for the first state), temperature and FP distribution in core.
Repeat Criticality Temperature	RCT	°C	Temperature that ensures a secondary critical state during core cooling in EOC in such conditions: all control rods inserted in core except one the most effective, zero boron concentration, equilibrium xenon concentration corresponding to reactor power before its shut-down.
Moderator temperature coefficient (in core)	MTC	pcm/°C	
Moderator density coefficient (in core)	MDC	pcm/g/cc	
Doppler temperature coefficient (in core)	DTC	pcm/°C	Calculated supposing average fuel temperature changing of 1°C
Doppler isotermic temperature coefficient (in core)	DTC*	pcm/°C	Calculated supposing local fuel temperature changing of 1°C
Doppler power coefficient (in core)	DPC	pcm/MW	
Boron reactivity coefficient (in core)	DRO/DCB	pcm/ppm	

Effective fraction of delayed neutrons	βeff or $\beta_{ef.}$	ppm	General characteristic of infinite grid or core
Lifetime of prompt neutrons	l_m or l_{im}	s	General characteristic of infinite grid or core
Reactor thermal power	W	MW	
Specific reactor thermal power in CS	Wv	KW/litre	Reactor thermal power in CS volume unit
Nominal reactor thermal power	Wnom	MW	Equal to 3000 MW for VVER-1000
Minimum controllable level of reactor power	MCL	MW	In calculations corresponds to Zero Power and uniform temperature 280°C in core.
Core coolant flow rate	G	m^3/h	
Average entry core temperature	t_{entry}	°C or K	
Average outer core temperature	t_{out}	°C or K	
Average coolant-moderator temperature in CS	t_{mod}	°C or K	
Average Coolant-moderator density in CS	γ_{mod}	g/cm^3	
Fuel temperature	t_{fuel}	K	
Average temperature of other CS components	t_{con}	°C or K	
Fuel pin cladding temperature	t_{clad}	°C or K	
Xenon-135 concentration distribution in core	Xe	10^{24} /cc	For 1 cc in fuel. Xe = 0 – xenon is absent; Xe = 1 – Xe=Xe eq (W).
Equilibrium Xenon-135 concentration distribution in core	Xe eq (W)	10^{24} /cc	Concentration formed during long working with W power, regulating bank in nominal position[b]
Sm-149 concentration distribution in core	Sm	10^{24} /cc	For 1 cc in fuel. Sm = 0 – samarium is absent, Sm = 1 – Sm=Sm eq, Sm = 3 – in BOC full decay of Pm-149 into

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[b] In VVER-1000 calculations Hreg in nominal position is equal to 80% if there is no special indication

			Sm-149 is simulated.
Equilibrium Sm-149 concentration distribution in core	Sm eq	10^{24} /cc	Concentration formed during long working, regulating bank in nominal position
Samarium-149 concentration distribution, all Promethium-149 decayed in Sm	Smh	10^{24} /cc	
Core reactivity while reactor shut-down	RO_{STOP}	pcm	Under conditions: W=0, Xe=0,Sm=Smh, $t_{mod}= t_{fuel}= t_{con}=20°C$, Cb= 16000 ppm

2. KINETICS PARAMETERS IN 30 % MOX FUELLED CORE

Equilibrium loading pattern of 30% MOX fuelled core of VVER-1000 with boron BPRs is presented in Fig.1 and corresponds to the so-called Variant 21 [4]. MOX FAs are of "100%Pu" type with 3 zones of different plutonium enrichment studied in [5].

Design parameters of VVER-1000 core, fuel assemblies, fuel rods, control rods and boron burnable poison rods are presented in Tables 1-8.

Evolution of main core neutronics parameters during fuel irradiation in the equilibrium cycle is presented in Table 9. The calculations are performed by the code BIPR-7A:

- assembly power peaking factors separately for the whole core and MOX FAs, their location,
- reactivity coefficients,
- average core burnup and burnup averaged over MOX FAs,
- βeff and l_m.

Power peaking factors of pin-by-pin distribution calculated by PERMAK-A are presented in Table 10. Pin-by-pin relative power distributions in the most powered UOX and MOX assemblies are presented in Figures 3-6.

In Table 11 the values of single control rods effectiveness are presented and the most effective of them are indicated. Balance of different effects on core subcriticality during scram actuation (fully insertion of all CRs) is presented in Table 12.

Step-by-step evolution of core reactivity in the process of control rods movement is presented in Table 13. The possibility of sticking of the most effective single CR (in the upper position) is taken into account. Two initial states in full power are considered. One – with the regulation group (N10 in Fig.7) in the position of 20% insertion into core that corresponds to the position adopted for Table 9, other - in the position of maximal allowed 30% insertion into the core. The indicated time from the beginning of scram actuation is of conservative value.

Table 14 shows the dependence of core reactivity versus regulation group position.

Table 15 and Fig.2 show the dependence of core reactivity versus coolant density in BOC and EOC, and can be used for calculations of accidents with deep core cooling for example the accidents with steam line rupture.

Situations with reactor power variations can be considered using the data of Table 16.

Table 17 describes the axial distribution in the FAs with the most powered fuel rods according to Table 10.

In Table 18 the fractions of delayed neutrons and decay rates over groups of delayed neutrons are presented.

CONCLUSION

The report presents neutronics data necessary for transient analysis codes while safety studying of VVER-1000 core with 30% MOX fuel. The base uranium core is the one with zirconium space grids and zirconium guide tubes using boron burnable poison rods. The MOX assembly is graded by three concentric zones with fissile plutonium enrichment of 4.2, 3.0 and 2.0%.

The presented set of kinetics parameters can be applied to 1-point kinetics model of RELAP-type codes in best-estimate calculations.

References

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4. In-core fuel management code package validation for WWERs. IAEA-TECDOC-847. November 1995.

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Table 2. Composition of weapons grade plutonium

Isotope / content (Wt. %)				
Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
0.0	93.0	6.0	1.0	0.0

Table 3. Main Core Parameters

Parameter	Units	Value
Thermal Power	MW thermal	3000
Electrical Power	MW	1000
Number of Coolant Loops		4
Number of Fuel Assemblies		163
Core Equivalent Diameter	m	3.164
Core Fuel Height	m	3.53
Core Volume	m^3	27.8
Core Power Density	W/cm^3	108
Control / Shut off Rod Banks		10
Position of Regulating Rod Bank	%	80
Core Coolant Flow Rate	m^3/hr	84000
Pressure at Core Inlet	MPa	15.7
Core Inlet Temperature	°C	287

Table 4. Fuel Assembly Design Parameters

Parameter	Units	Value
Shape of Fuel Assembly		Hexagonal
Distance Across Assembly (between flats)	cm	23.4
Distance Between Fuel Assembly Centres	cm	23.6
Fuel Pin Lattice Pitch	cm	1.275
Number of Fuel Pins in Fuel Assembly		312
Number of Guide Tubes for Control Rods / Burnable Absorber Pins		18
Inner Diameter of Guide Thimbles	cm	1.1
Thickness of Guide Thimbles	cm	0.1
Material of Guide Thimbles		Zirconium Alloy*
Central Instrumentation Tube Inner Diameter	cm	1.1
Thickness of Central Instrumentation Tube	cm	0.1
Material of Central Guide Tube		Zirconium Alloy *
Number of Spacer Grids in Fuel Assembly		13
Material of Spacer Grids		Zirconium Alloy*
Spacer Grid Weight (each)	Kg	0.55

Compositions Weight percent:

*

Zr	Nb	Hf
98.97	1.0	0.03

Table 5. Uranium Fuel Pin Design Parameters

Parameter	Units	Value
		Advanced Core Design
Inner Clad Diameter	cm	0.772
Clad Thickness	cm	0.069
Clad Material		Zirconium Alloy*
Clad Density	g / cc	6.5153
Fuel Pellet Diameter	cm	0.755
Central Hole Diameter	cm	0.15
Fuel Pellet Material		L.E. UO2
Height of Fuel Column	cm	353 (cold) 355 (hot)
Mass of UO2 in Fuel Pin	kg	1.575

Compositions Weight percent:

*

Zr	Nb	Hf
98.97	1.0	0.03

Table 6. MOX fuel Pin Design Parameters

Parameter	Units	Value
Inner Clad Diameter	cm	0.772
Clad Thickness	cm	0.069
Clad Material		Zirconium Alloy*
Clad Density	g / cc	6.5153
Fuel Pellet Diameter	cm	0.755
Central Hole Diameter	cm	0.15
U-235 content in MOX fuel	%	0.2
Fuel Pellet Material		PuO2-UO2
Height of Fuel Column	cm	353 (cold) 355 (hot)
Mass of MOX fuel in Fuel Pin	kg	1.600

Compositions Weight percent:

*

Zr	Nb	Hf
98.97	1.0	0.03

Table 7. Discrete Burnable Poison Pin Design Parameters

Parameter	Units	Value		
Clad Inner Diameter	cm	0.772		
Clad Thickness	cm	0.069		
Clad Material		Zirconium Alloy*		
Clad Density	g / cc	6.5153		
Absorber Diameter	cm	0.758		
Absorber Density	g / cc	2.869	2.896	2.945
Absorber Composition		Boron g / cc		
		0.020	0.036	0.065
B10	W%	0.1278	0.2279	0.4046
B11		0.5694	1.0153	1.8028
Al		93.5246	91.7424	88.5951
Fe		0.1952	0.1915	0.1850
Ni		1.9525	1.9153	1.8496
Cr		1.6780	2.9923	5.3133
Zr		1.9525	1.9153	1.8496

Compositions Weight percent:

*

Zr	Nb	Hf
98.97	1.0	0.03

Table 8. Control Rod Design Parameters

Parameter	Units	Value
Clad Inner Diameter	cm	0.700
Clad Thickness	cm	0.06
Clad Material		Stainless Steel*
Absorber Diameter	cm	0.700
Absorber Material		Natural B4C**
Absorber Density	g / cc	1.80

*Compositions Weight percent:

C	Cr	Ni	Ti	Fe
0.12	18.5	10.5	1.0	69.88

** Content of ^{10}B is 19.8% atoms.

Remark. The lower part (30 cm) of control rods consists of Dy_2O_3 TiO_2 of density 4.9 g / cc.

Table 9. Evolution of main neutronics parameters. Equilibrium Fuel Cycle in 30% MOX Fuelled Core

Sim = 60 , Xe = 1 , Sm = 3

№	T EFPD	$H_{reg.}$ cm	t_{entry} °C	W MW	$Cb^{crit.}$ ppm	G m^3/h	Kq	Nk	Kq^{MOX}	Nk	Kv	Nk	Nz	$\bar{B}_U$ MW• d/kg	$\bar{B}_{MOX}$ MW• d/kg	MDC pcm• $(g/cm^3)^{-1}$	MTC pcm• $°C^{-1}$	DTC pcm• $°C^{-1}$	DTC* pcm• $°C^{-1}$	DPC pcm• MW^{-1}	DRo/DCb pcm• ppm^{-1}	$\beta_{ef.}$ pcm	l_{im} •10^5 sec
1	0.0	283.2	287.0	3000	6765	84000	1.31	10	1.28	21	1.64	19	4	15.23	11.74	14134	−29.20	−2.94	−2.42	−0.30	−1.33	572	1.92
2	20.0	283.2	287.0	3000	6264	84000	1.34	3	1.21	21	1.64	3	4	16.08	12.61	14903	−30.70	−2.96	−2.45	−0.30	−1.34	567	1.94
3	40.0	283.2	287.0	3000	5724	84000	1.35	3	1.18	21	1.63	3	4	16.93	13.47	16039	−33.15	−2.98	−2.48	−0.30	−1.36	562	1.96
4	60.0	283.2	287.0	3000	5197	84000	1.35	3	1.17	21	1.60	3	4	17.78	14.33	17250	−35.80	−2.99	−2.51	−0.30	−1.37	556	1.98
5	80.0	283.2	287.0	3000	4671	84000	1.35	3	1.16	21	1.58	3	3	18.63	15.18	18491	−38.54	−3.00	−2.54	−0.30	−1.39	551	2.01
6	100.0	283.2	287.0	3000	4148	84000	1.35	3	1.15	21	1.57	3	3	19.49	16.03	19744	−41.32	−3.01	−2.56	−0.31	−1.40	545	2.03
7	120.0	283.2	287.0	3000	3629	84000	1.35	3	1.15	21	1.56	3	3	20.34	16.87	21003	−44.13	−3.02	−2.58	−0.31	−1.42	540	2.06
8	140.0	283.2	287.0	3000	3115	84000	1.35	3	1.14	21	1.55	3	3	21.20	17.72	22267	−46.97	−3.02	−2.60	−0.31	−1.43	535	2.08
9	160.0	283.2	287.0	3000	2606	84000	1.35	3	1.14	21	1.53	3	3	22.06	18.56	23537	−49.82	−3.03	−2.62	−0.31	−1.45	530	2.11
10	180.0	283.2	287.0	3000	2102	84000	1.34	3	1.14	21	1.52	3	2	22.91	19.40	24813	−52.70	−3.04	−2.64	−0.31	−1.47	526	2.14
11	200.0	283.2	287.0	3000	1602	84000	1.34	3	1.14	21	1.52	3	2	23.77	20.25	26094	−55.60	−3.04	−2.66	−0.31	−1.48	522	2.17
12	220.0	283.2	287.0	3000	1108	84000	1.33	3	1.14	21	1.51	3	2	24.63	21.09	27377	−58.50	−3.04	−2.67	−0.31	−1.50	517	2.20
13	240.0	283.2	287.0	3000	621	84000	1.33	3	1.14	21	1.51	3	2	25.49	21.93	28656	−61.40	−3.05	−2.68	−0.31	−1.52	514	2.23
14	260.0	283.2	287.0	3000	140	84000	1.32	3	1.14	21	1.50	3	2	26.34	22.78	29933	−64.30	−3.05	−2.69	−0.31	−1.53	510	2.26
15	265.9	283.2	287.0	3000	0	84000	1.32	3	1.14	21	1.50	3	2	26.60	23.03	30310	−65.16	−3.05	−2.70	−0.31	−1.54	509	2.27

Table 10. Power Peaking Factors Attained During Fuel Cycle

T, EFPD	Kr	N (Kr)	Ko-total	N (Ko-total)	M(Ko-total)
0	1.50	6	1.89	10	4
20	1.49	10	1.84	10	4
40	1.49	10	1.81	10	4
60	1.48	10	1.77	10	4
80	1.47	10	1.73	10	3
100	1.46	10	1.71	10	3
120	1.45	10	1.69	10	3
140	1.44	10	1.66	10	3
160	1.43	10	1.64	10	3
180	1.42	10	1.62	10	3
200	1.41	10	1.61	10	2
220	1.41	10	1.60	10	2
240	1.40	10	1.59	10	2
260	1.39	10	1.58	10	2
265.9	1.38	10	1.58	10	2

Table 11. Effectiveness of Single Control Rods

RO, pcm (Hreg=70%)				No (Ngr)
BOC		EOC		
Wnom	MCL	Wnom	MCL	
76	72	78	75	21 (1)
77	73	82	79	20 (2)
58	58	59	60	13 (3)
57	58	58	60	9 (4)
84	63	104	85	82 (5)
87	79	90	81	52(5)
105	85	117	97	55 (6)
87	79	90	81	31(6)
89	84	92	87	22 (7)
88	83	91	88	19 (8)
71	71	67	67	11 (9)
90	64	87	27	41 (10)

RO, pcm (Hreg=20%)				No (Ngr)
BOC		EOC		
Wnom	MCL	Wnom	MCL	
78	74	80	76	21 (1)
80	75	85	80	20 (2)
63	63	64	61	13 (3)
63	63	63	61	9 (4)
79	57	99	84	82 (5)
81	73	85	79	52(5)
91	71	105	92	55 (6)
81	73	85	79	31(6)
91	84	94	87	22 (7)
90	84	93	88	19 (8)
77	77	73	69	11 (9)
16	2	17	0	41 (10)

Table 12. Core Subcriticality (Scram Margin) in different states in the process of Scram actuation

State parameters						RO, pcm	
State Number	W, MW	t_{entry}, °C	Hreg, %	Positions of banks 1-9, %	Positions of the most eff. CR, %	UOX	
						BOC	EOC
1	3000	Nominal.	100	100	100	+183	+355
	Regulation margin of reactivity						
2	3000	Nominal.	70	100	100	0.	0.
	Scram actuation without sticking of the most effective CR						
3	3000	Nominal.	0	0	0	-8329	-8796
	Scram actuation with sticking of the most effective CR						
4	3000	Nominal.	0	0	100	-7809	-8214
	Doppler effect						
5	0	Nominal.	0	0	100	-5695	-5312
	Moderator temperature effect						
6	0	287	0	0	100	-5195	-4309
	Moderator temperature effect						
7	0	280	0	0	100	-5001	-3919
	Moderator temperature effect						
8	0	200	0	0	100	-3623	-855
	Moderator temperature effect						
9	0	120	0	0	100	-2965	+1905
	Moderator temperature effect						
10	0	20	0	0	100	-2476	+2252

Table 13. Core reactivity in the process of control rods movement.

A. Full power. Initial H_{reg}=70%

T, s	AP Position,%	BOC, CB=6765 pcm		EOC, CB=0	
		No stuck	Stuck N 55	No stuck	Stuck N 55
0	100	-61	-61	-110	-110
0,4	90	-202	-202	-255	-255
0,8	80	-324	-324	-332	-332
1,2	70	-473	-473	-427	-427
1,6	60	-691	-691	-582	-581
2,0	50	-1037	-1035	-859	-858
2,4	40	-1568	-1564	-1348	-1346
2,8	30	-2309	-2300	-1993	-1987
3,2	20	-3694	-3663	-3091	-3068
3,6	10	-6859	-6628	-6129	-5968
4,0	0	-8268	-7599	-8442	-7672

B. Full power. Initial H_{reg}=80%

T, s	AP Position,%	BOC, CB=6765 pcm		EOC, CB=0	
		No stuck	Stuck N 55	No stuck	Stuck N 55
0	100	0	0	0	0
0,4	90	-136	-136	--154	--154
0,8	80	-237	-237	-216	-216
1,2	70	-349	-349	-283	-283
1,6	60	-512	-511	-387	-387
2,0	50	-775	-773	-567	-567
2,4	40	-1240	-1237	-921	-919
2,8	30	-2098	-2089	-1649	-1642
3,2	20	-3675	-3644	-3024	-3000
3,6	10	-6840	-6609	-6064	-5901
4,0	0	-8312	-7667	-8534	-7778

Table 14. Core reactivity versus regulation group position

Hreg, %	RO, pcm	
	BOC	EOC
100	180	360
90	120	200
80	0	0
70	-120	-150
60	-240	-260
50	-350	-350
40	-460	-420
30	-550	-490
20	-640	-540
10	-700	-600
0	-720	-620

Table 15. Core Reactivity Versus Coolant Density

Density, G/cm3	RO, pcm	
	BOC	EOC
	Hreg=70%	Hreg=70%
0.2 (W=0)	-27763	-42329
0.4 (W=0)	-7837	-14142
0.6 (W=0)	-753	-2527
0.723 (W=Wnom)	0	0
0.766 (W=0)	1750	2539

Table 16. Core Reactivity versus Core Power and Average Core Fuel Temperature in MOX Fuelled Core (Doppler Effect)

Power, MW	t_{fuel}, K	RO, pcm	
		BOC, Xe eq, Hreg=80%	EOC, Xe eq, Hreg=80%
6000	1207	-731	-742
5400	1146	-635	-620
4800	1085	-501	-484
4500	1055	-428	-411
3900	994	-269	-255
3600	963	-184	-172
3300	933	-94	-86
3000	902	0	0
2700	871	99	97
2400	839	202	194
1800	775	420	397
1200	711	657	614
600	645	913	844
300	612	1049	965
0	579	1194	1091

Table 17. Axial Relative Power Distribution in the Assemblies with the Most Powered Fuel Rods

Axial position, cm	BOC	EOC
	Ass. N 6	Ass. N 10
337.250	0.438	0.678
301.750	0.779	0.973
266.250	1.014	1.045
230.750	1.144	1.042
195.250	1.218	0.998
159.750	1.257	1.038
124.250	1.257	1.068
88.750	1.205	1.107
53.250	1.053	1.139
17.750	0.635	0.864

Table 18. Kinetics Parameters

Group	1	2	3	4	5	6
βeff (BOC), pcm	17.1	101	93.4	215	104	41.2
βeff (EOC), pcm	14.4	92.5	81.8	188	95.8	36.7
Decay rate, 1/s	0.0124	0.0305	0.111	0.301	1.13	3

Fig.1. Equilibrium Loading Pattern for 30% MOX Fuelled Core with Boron BPRs. Core 60 ° Sector

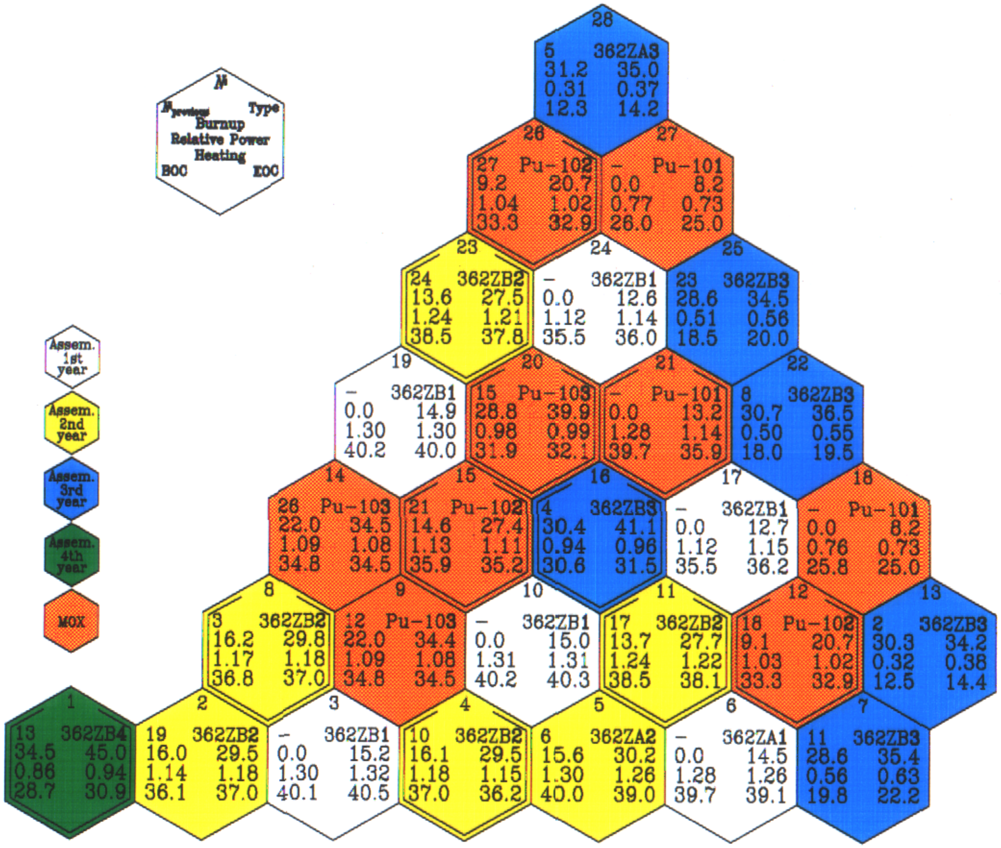


Fig.2. Core Reactivity Versus Coolant Density

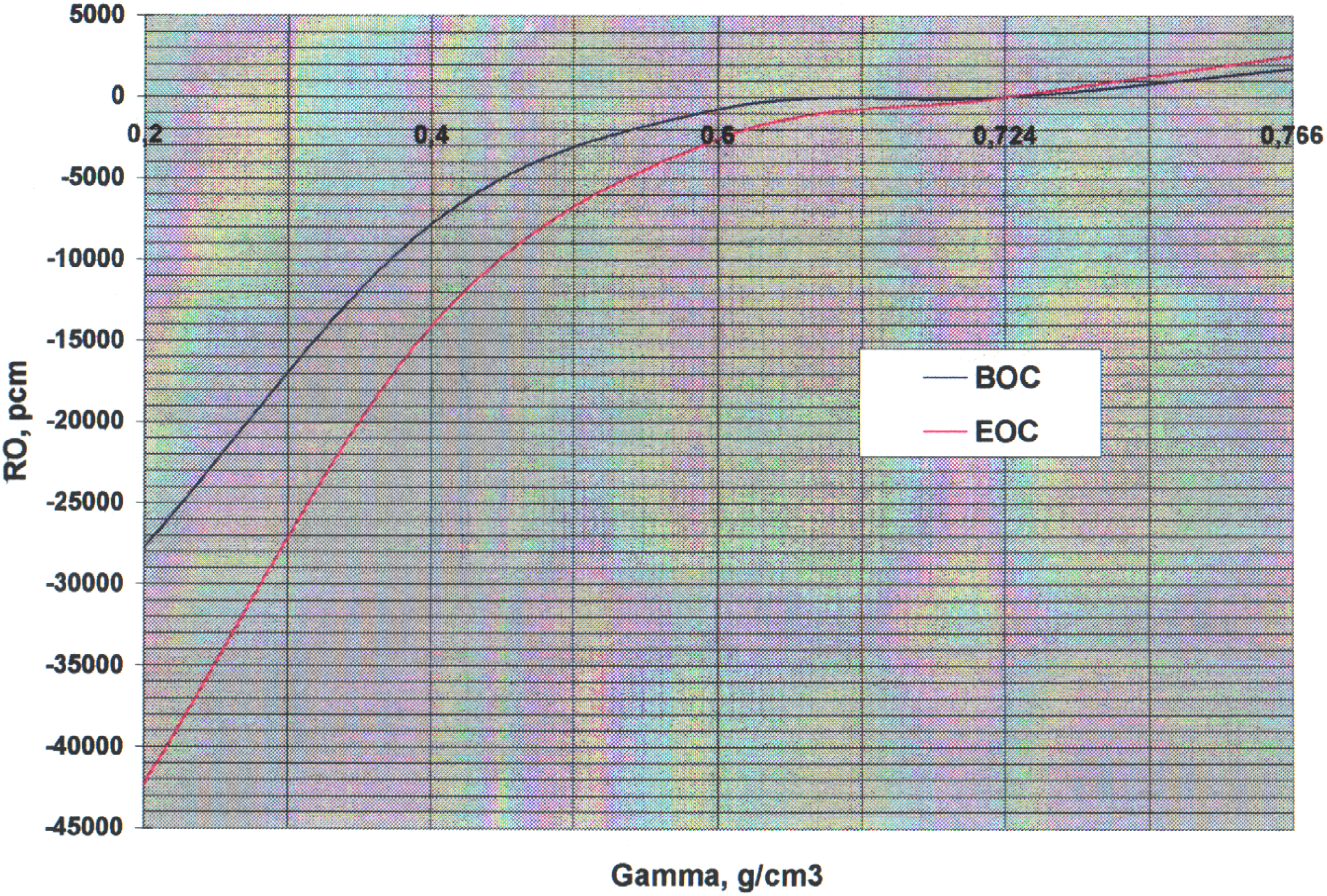
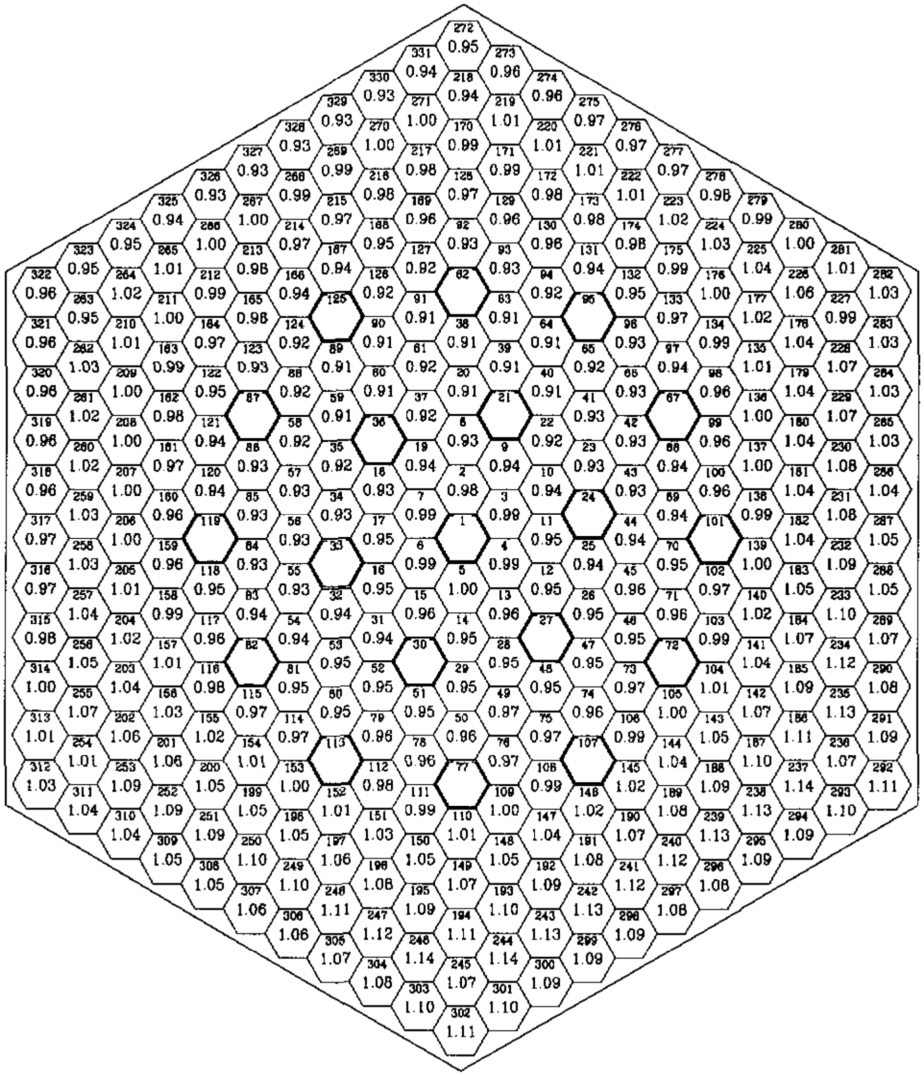
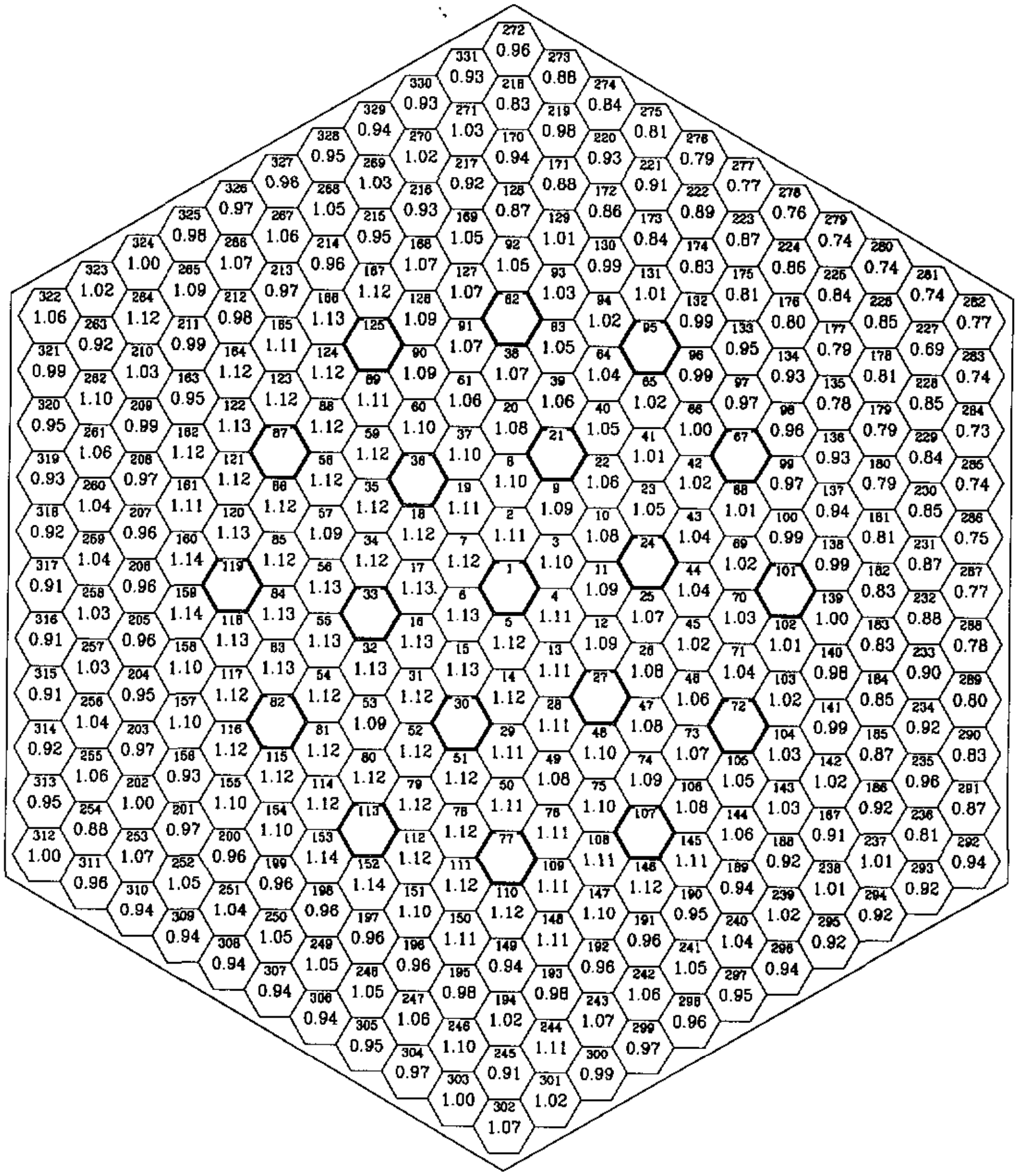


Fig.3. Pin-by-Pin Power Distribution in the Most Powered UOX Assembly in BOC



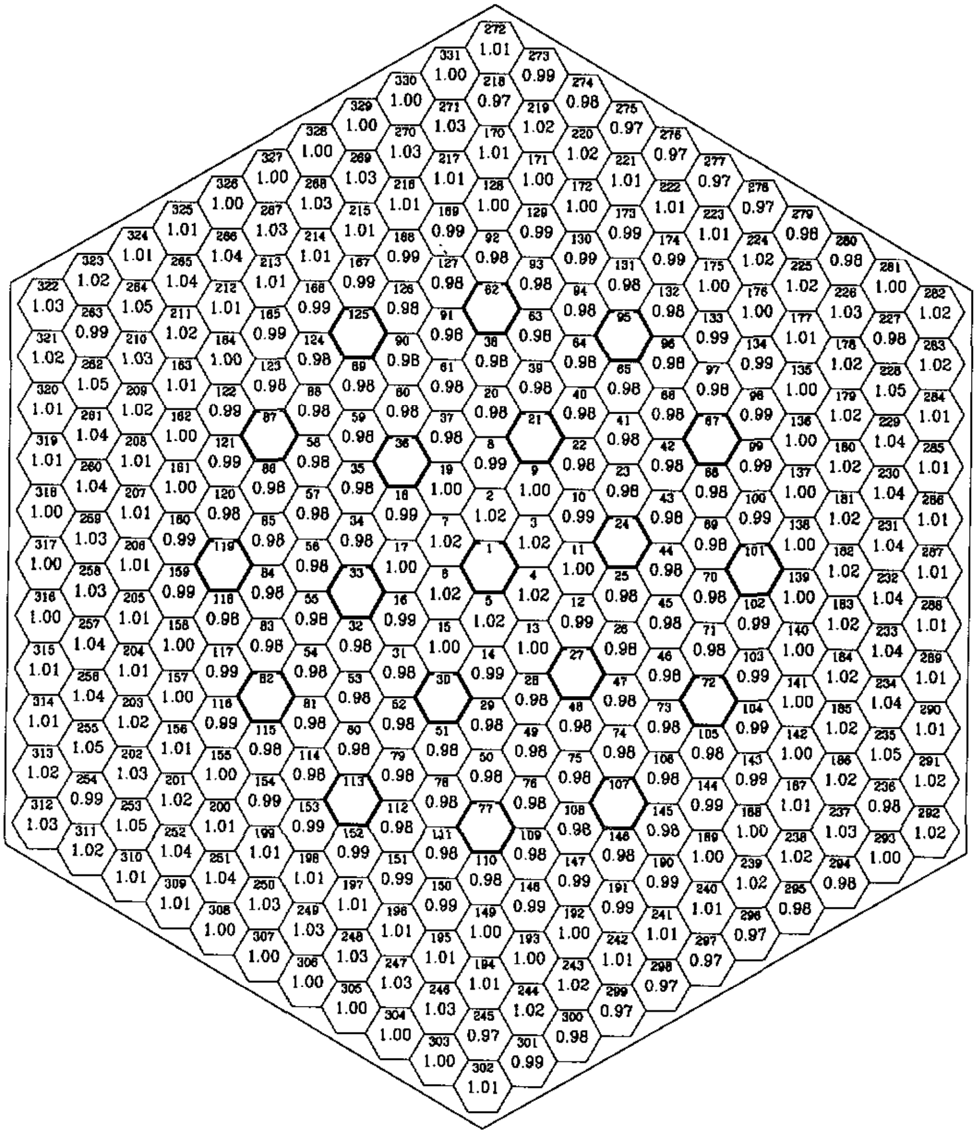
T	0.00	EFPD
W	3000.0	MW
$C_{H_3BO_3}$	6.86	g/kg
Ql	303.3	W/cm
Fuel assembly	10	
Level	4	
Fuel rod	244	
Kk_{max}	1.14	

Fig.4. Pin-by-Pin Power Distribution in the Most Powered MOX Assembly in BOC



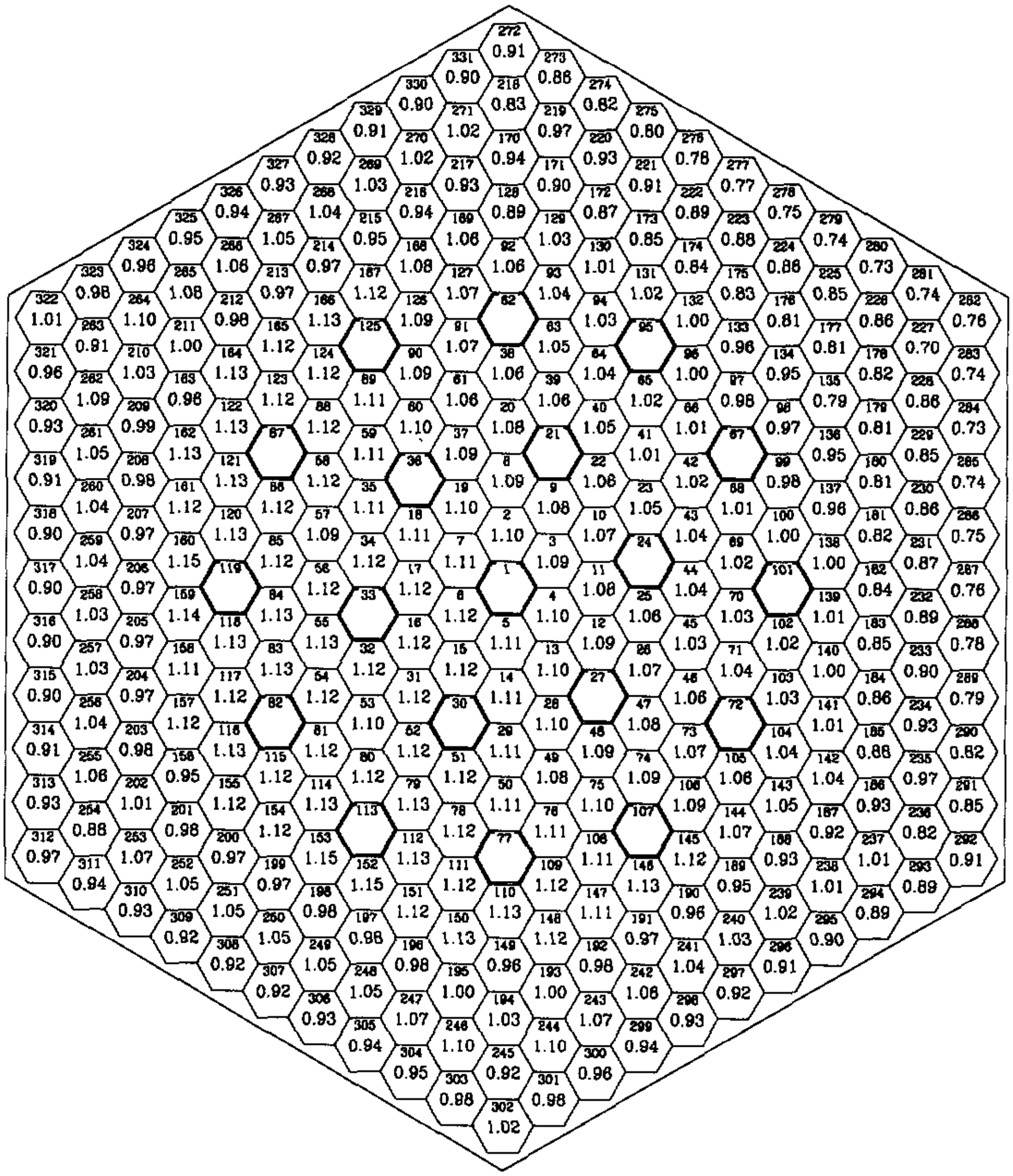
T	0.00	EFPD
W	3000.0	MW
$C_{H_3BO_3}$	6.76	g/kg
Ql	306.5	W/cm
Fuel assembly	21	
Level	4	
Fuel rod	160	
Kk_{max}	1.14	

Fig.5. Pin-by-Pin Power Distribution in the Most Powered UOX Assembly in EOC



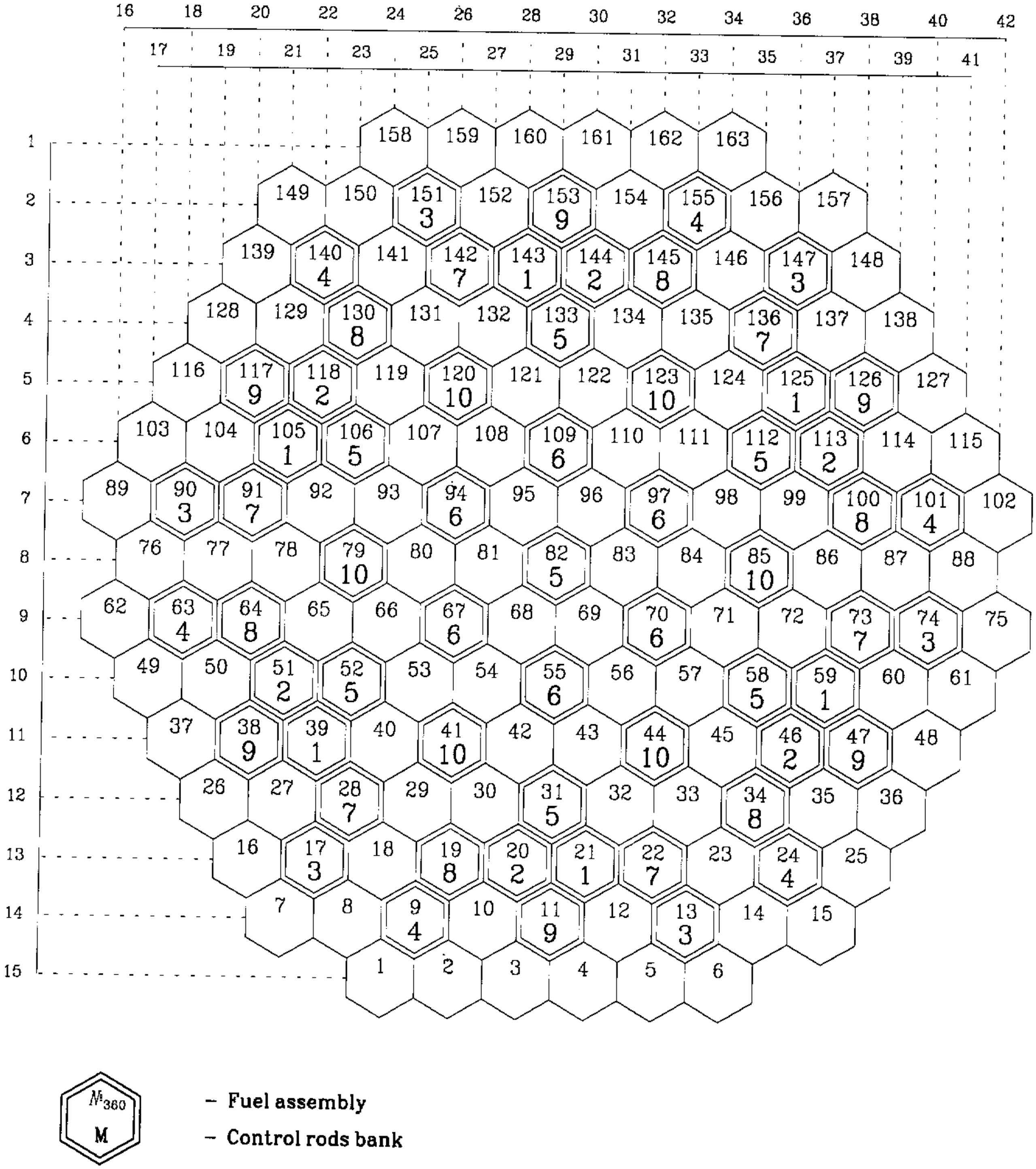
T	265.91	EFPD
W	3000.0	MW
$C_{H_3BO_3}$	0.00	g/kg
Burnup	18.2	
Fuel assembly	3	
Level	4	
Fuel rod	264	
Kb_{max}	1.05	

Fig.6. Pin-by-Pin Power Distribution in the Most Powered MOX Assembly in EOC



T	265.91	EFPD
W	3000.0	MW
$C_{H_3BO_3}$	0.00	g/kg
Burnup	17.2	
Fuel assembly	21	
Level	4	
Fuel rod	152	
Kb_{max}	1.15	

Fig.7. Control Rods Grouping



– Fuel assembly
– Control rods bank

Comments from F. C. Difilippo, ORNL, on the report, *Mission Fuel Kinetics Input and RELAP-like Calculations*

General Comments

The report makes reference to computer programs that are used to calculate the kinetic parameters but these programs might not be easily available to the average reader. Statements about their definition (are adjoint calculations possible; what is the definition of the six precursor groups), the nuclear data (especially as related to the treatment of delayed neutrons), and relative importance of various fissionable materials (in order to check sensitivities with respect to burnup calculations) could have been very useful in order to evaluate the results summarized in Table 9.

The summary of results seems to fulfill the objective of the report, that is, to generate data for RELAP calculations. The report also includes many details of the calculated reactor but they are not enough to make possible an independent calculation. References to previous reports published under the sponsorship of this program would be useful to the reader.

Specific Comments

Table 11, entitled "Effectiveness of Single Control Rods" is difficult to understand. According to the head of the column, the unit is pcm but the parameters tabulated are the magnitudes of Wnom and MCL. According to Table 1, Wnom is the nominal reactor power (Mw) and MCNL is the minimum controllable level of reactor power (Mw). Also, Table 1 states that Hreg is measured in cm rather than %. So the meaning of Table 11 is unclear.

Table 13 does not indicate which control bank is being moved (could it be all of them?). Also, CB seems to be critical boron concentration so the units at the head of the columns should be ppm rather than pcm.

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