Status and Prospects of VVER In-Core Fuel Management Activities

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In Russia extensive calculations and experimental studies on physics and fuel has been recently carried out to substantiate the possibilities of introducing the modernized VVER fuel cycles into practice:

- using the results of physical experiments and the operation data, a complex of codes for physical calculations of the VVER core characteristics has been developed and verified [1];
- based on the data of loop tests and post-reactor studies, codes of thermal and physical and mechanical calculations of the fuel elements (PIN-micro, PIN-mode 2, PIN-mod2 (Gd), RET (R), START, PULSAR) have been developed and verified;
- an extensive series of calculations and experimental studies on optimization of the VVER core neutronic characteristics has been carried out;
- a large volume of works on improvement of process and operation characteristics of fuel elements and fuel assemblies has been accomplished (fuel pellet fabrication quality has been increased [5], initial He-backfill pressure in VVER-440 fuel rode has been optimized [6], fuel assembly shroud tube thickness has been reduced and thus the water-uranium ratio increased;
- four-five-year positive operation experience with the VVER-440 fuel assemblies has been gained [7], transition to the use of ARK SUZ (CPS) fuel assemblies with 3.6% fuel enrichment has been substantiated and realized [8], at the Kola NPP a four-year fuel cycle using 4.4% enriched fuel assemblies has been successfully employed, with an average burnup of 48.2 *MWd/kg* being reached [9] (Fig. 1); twenty four 4.4% enriched fuel assemblies had been operated in the Kola NPP-3 reactor for five years, which made it possible to substantiate the possibility of implementing a five-year fuel cycle; at the Novo-Voronezh NPP the fuel cycle based on the fuel assemblies with zirconium spacers has been implemented [10], some of these fuel assemblies had worked for four years; in some units loading schemes with partially reduced neutron leaks are used [11];
- on enhance reactor power positive operation experience with the VVER-440 fuel has been gained (107% P_{nom}) [12];
- in order to reduce the non-uniformity of specific loads in the fuel assemblies and to facilitate realization of refueling schemes with reduced neutron leaks (LLLP) the technology of profiling the enrichment over the fuel rod bundle cross section has been mastered;

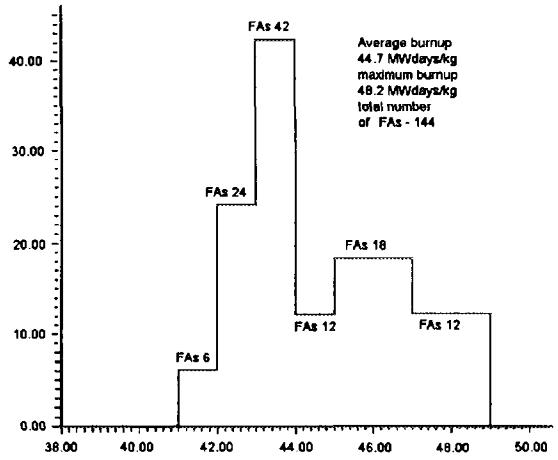

Figure 1 **Distribution of fuel burnup in VVER-440 Fas (4.4% enrichment), operating 4 years (Kola NPP, Unit 3)**

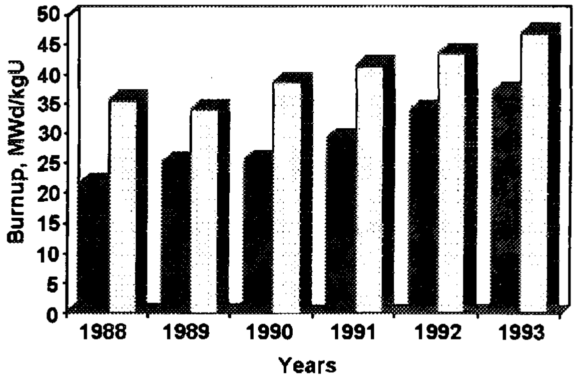

Figure 2 **Variation of average (dark columns) and maximum fuel burnup within last six years**

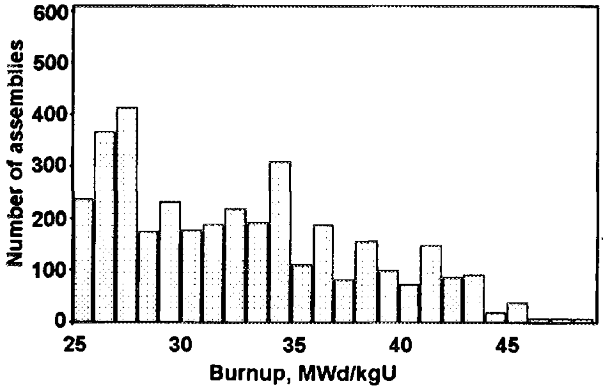

Figure 3 **Distribution of fuel assemblies over the fuel burnup**

- all VVER-1000 reactors (except for units 5 and 6 of the Kozloduy NPP) are changed over to the three-year fuel cycle with reaching average fuel burnup of about 42 *MWd/kg* and an average burnup of about 48.5 *MWd/kg* in the maximum burn-out fuel assembly (Fig. 2); a part of the fuel assemblies (about 190 *pc*) had been operated for four years; the increase in the fuel burnup with gaining the operation experience is shown in Fig. 3;
- at the Balakovo NPP experimental operation of six fuel assemblies with zirconium spacers and zirconium guiding channels has been accomplished;
- positive experience with the use of refueling schemes with reduced neutron leaks has been gained [13];
- a technology of fabricating a fuel with integrated burnable poison (uranium-gadolinium fuel) has been developed [1]; 12 fuel assemblies with uranium-gadolinium fuel (UGF) have been fabricated and installed into the Balakovo NPP-3 reactor for experimental operation, each fuel assembly containing 18 fuel elements with gadolinium dioxide (Gd_2O_3) integrated into the fuel; fuel enrichment 3.6%, Gd_2O_3 concentration - 8%.

Based on the experience gained, modernized fuel cycles have been developed. The following improvements have been introduced into the VVER fuel cycle characteristics:

- increased fuel burnup;
- reduced natural uranium consumption and decreased amount of separation work per energy output unit;
- increased efficiency of the reactor emergency protection;
- reduced fast neutron flux onto the reactor vessel.

The main comparative economic indices are listed in Tables 1 and 2.

Main Characteristics of Modernized Fuel Cycles

A. Reactor VVER-440

At present development of advanced four- and five-years fuel cycles with the use of Fas with enrichment profile in cross section of fuel rods bundle and with zirconium spacer grids has been completed.

The main characteristics of the developed fuel cycle are given in Table 3.

B. Reactor VVER-1000.

At the present development of three- and four-year fuel cycles with the use of boric rods and gadolinium dioxide as burnable poison (BPR) has been completed [13].

Pellet central hole diameter in improved fuel cycle is 1.4 *mm.*

The main characteristics of the developed fuel cycles are listed in Table 4.

Experience of operating and the fuel rod calculations show that they maintain reliability up to extended burnup.

References

[1] A.N.Novikov, V.V.Pchenin, M.P.Lizorsin et al, Problems of VVER In-Core Fuel Management, IAEA-TECDOC-567, p. 325-334, 1990.

[2] Strirhov P.A. et al, IAEA-TECDOC-657/3.4, 1988.

[3] Scheglov A.S., Proselkov V.N., Bibilashvili Yu.K. et al, Atomnaja Energia, 1993, v.74, 6, p. 450-452.

[4] Tutnov A.A., Ulijanov A.I., Atomnaja Energia, 1994, v.76, 5, p. 411-447

[5] Scheglov A.S., Proselkov V.N., Enin A.A., Statistics data on design and technological parameters of VVER-1000 fuel elements, Atomnaja Energia, v. 71, 6, 1991, p. 503-506.

[6] Dubrovin K.P., Proselkov V.N., et al, Improvement of commercial VVER-440 fuel rod design with the aim tp extend fuel burnup, Atomnaja Energia, v. 72, 2, 1992, p. 121-124.

[7] Bibilashvili Yu.K., et al, Towards hihg burnup in Russian VVER reactors and status of water reactor fuel technology, Proc. Int. Topical Meeting on Light Water Reactors Fuel Performance, Florida, April 17-21, 1994, p. 360-373.

[8] Proselkov V.N., Simonov K.V., et al, Atomnaja Energia, 1990.

[9] Proselkov V.N., Simonov K.V., et al, Atomnaja Energia, v.69, 2, 1990, p. 81-87.

[10] Proselkov V.N., Simonov K.V. et al, Use of Ziconium Spaser Grids in VVER-440, Atomnaja Energia, v.73, 5, 1992, p. 410-411.

[11] Ignatenko E.I., Matveev A., Proselkov V.N., et al, Atomnaja Energia, v.61, 4, 1986.

[12] Proselkov V.N., Nikishov O.A., Strizhov P.A., et al, Atomnaja Energia, v.67, 2, 1989, p. 101-104.

[13] Pavlov V., Pavlovichev A., General Features of VVER-1000 Three and Four Batch Cycles with Improved Fuel Utilization, 4-th AER Symp., 9-15 October, 1994, Bulgaria.

[14] Milovanov O.V., Proselkov V.N., Kileshov A.V. et al, Developement of Uranium-Gadolinium Oxide Fuel for VVER, Preprint IAE-5744/4, 1994.

Table 1 **Specific fuel consumption in design and modernized VVER-440 fuel cycles (estimates)**

No	Characteristics	Design	Requirement	Effect of specific fuel consumption decrease, %	State
1	Number of refueling	3	3 4 5 3 (in 18 months)	- 7.8 ~6.3 ~14 ~9.2 ~16 ~3.0 ~4.7	yes yes 4 - 5 years
2	Structural material of spacing grids	steel	zirconium	2.0 - 2.5	yes
3	Loading pattern	out-in-in	in-in-out (LLLP)	4.0 - 5.0	yes
4	Type of burnable absorber	no	no Gd_2O_3	18-month f.c.	yes
5	Profiling of fuel enrichment in cross section	no	yes	0.5 - 1.0	1 year
6	Profiling of fuel enrichment in high of fuel rod	no	yes	0.5	

Table 2 **Specific fuel consumption in design and modernized VVER-1000 fuel cycles (estimates)**

No.	Characteristics	Design	Advanced fuel cycle	Effect of specific fuel consumption decrease, %	State
1	Number of refueling	2	3	13	yes
2	Structural material of spacing grids, GTs	steel	zirconium	8	~3 - 4 years
3	Loading pattern	out-in	in-in-out (LLLP)	4.0	yes
4	Type of burnable absorber	Boron rods	Gd_2O_3	2.0	~3 - 4 years
5	Material of absorber rod	B_4C (natural)	B_4C enriched Ag-In-Cd		
6	Profiling of fuel enrichment in high of fuel rod	no	yes	0.5	

Table 3 **Refined neutron physical characteristics of reference four year fuel cycle (equilibrium fuel reloading regime) for VVER-440**

Serial No.	Characteristics	Value		
		Odd year of operation	Even year of operation	Design fuel cycle
1	Reactor power, *MW (th)*	1375		1375
2	Number of fuel assemblies in the core	349		349
3	Number of CPS members	37		37
4	Geometry of fuel assemblies	standard, thickness of independent FA shroud is 1.5 *mm*		stainl
5	Structural material of spacing greeds	zirconium		stainl
6	Profiling of fuel enrichment in FA	used		not used
7	Type of burnable absorber	not used		not used
8	Total weight of uranium in the core, *t*	41.8		41.8
9	Time between refuelings, months	12		12

Table 3 (cont.)

Serial No.	Characteristics	Value		
		Odd year of operation	Even year of operation	Design fuel cycle
10	Loading patten	L^3P		out-in^2
11	Boron concentration in the coolant during refuelings, *ppm*	2450		2100
12	Number of fuel assemblies to be replaced at refueling,	90	91	117.5
	including types	78A, 12H	78A, 12H, 1I	12.5E, 84C, 21B
13	Operation time of fuel assemblies in the reactor, *years*			
	average	3.87	3.85	2.98
	maximum	4	4	3
14	Average enrichment of make-up fuel, *weight* %	3.663	3.611	3.26
15	Average burnup depth of inloaded fuel, *MWd/kg*			
	for all FA	38.22	38.02	27.9
	for independent FA	39.95 (A)	40.17 (A)	
	for control FA	26.98 (H)	25.86 (H), 16.32 (I)	
16	Duration of reactor operation between refuelings, eff. days	303.7	301.8	286
17	Water temperature coefficient of reactivity (TH2O=260°C, zero power, unpoisoned state, all members of CPS are in upper position), 10^{-5} °C^{-1}			
	BOC	-0.63	-0.65	-2.95
	EOC	-22.36	-22.35	-23.2
18	Uranium temperature coefficiet of reactivity (see p.17 above), 10^{-5} °C^{-1}			
	BOC	-2.43	-2.43	-2.52
	EOC	-2.43	-2.44	-2.51
19	Effective delayed - neutron fraction, %			
	BOC	0.696	0.697	0.70
	EOC	0.613	0.613	0.69
20	Prompt neutron lifetime, μs			
	BOC	21.08	20.98	20.9
	EOC	23.46	23.44	22.7
21	Efficiency of control rod group at TH_2O=260°C, %			
	BOC	1.869	1.813	1.83
	EOC	1.918	1.867	1.85
22	Power coefficient of reactivity (at constant average temperature of coolant), 10^{-5} MW^{-1}			
	BOC	-0.62	-0.61	-0.62
	EOC	-0.60	-0.60	-0.62
23	Power effect, %			
	BOC	1.31	1.31	1.21
	EOC	1.46	1.46	1.44
24	Xe-135 poisoning effect, %			
	BOC	2.87	2.87	2.87
	EOC	2.97	2.97	2.82
25	Reactivity margin compensating fuel burnup, %	8.77	8.73	8.04

Table 3 (cont.)

Serial No.	Characteristics	Value		
		Odd year of operation	Even year of operation	Design fuel cycle
26	Total efficiency of emergency protection, %			
	BOC	10.727	10.496	9.41
	EOC	11.015	10.790	10.95
	under conditions of stricking of more effective CPS member in upper position, %			
	BOC	8.125	7.617	7.02
	EOC	8.324	7.796	6.79
27	Temperature of repeated critically at the end of fuel loading when boron in coolant is absent, °C			
	Xe-135 poisoned state			
	CPS all members in lower position	<20	<20	<100
	CPS all members except for more effective one in lower position	<100	<100	150
	Xe-135 unpoisoned state			
	CPS all members in lower position	20	20	<100
	CPS all members except for more effective one in lower position	<200	<200	230
28	Initial value of critical boron concentration in the coolant (poisoned state of reactor at full power), *ppm*	1041	1036	935
29	Power peaking of fuel assemblies, K_q			
	BOC	1.349 (53)	1.343 (15)	1.24
	EOC	1.344 (42)	1.341 (15)	1.26
30	Maximum value of average coolant temperature at fuel assembly outlet, °C			
	BOC	311.9	312	308.1
	EOC	311.8	311.9	308.5
31	Core volume power peaking (for 3490 nodes), K_v			
	BOC	1.720	1.682	1.66
	EOC	1.617	1.613	1.75
32	Power peaking of fuel pins in cross-section of fuel assembly fuel bundle having the greatest power, K_k			
	BOC	1.06	1.08	1.15
	EOC	1.05	1.05	1.12
33	Maximum value of specific linear load of fuel pins (with regard for engineering safety factor), *W/cm*			
	BOC	292	286	287
	EOC	275	274	285
34	Effective specific natural uranium consumption, *kg/MWd*	0.212	0.212	0.258
35	Effective specific separated work, *SWU/MWd*	0.120	0.120	0.142
36	Average power of periphery FA's (K_q), relative unit			
	BOC	0.379	0.387	0.74
	EOC	0.440	0.442	0.74

Table 4 **VVER-100 neutronic characteristics in various methods of fuel cycle organization (steady-state refueling conditions)**

No.	Characteristic	Version of fuel cycle organization				
		Designed 3-y cycle	Modernized 3-y cycle	Modernized 4-y cycle	Modernized 3-y cycle	Modernized 4-y cycle
1	Thermal power, *MW*	3000	3000	3000	3000	3000
2	Number of fuel assemblies in the core, *pcs*	163	163	163	163	163
3	Number of control rods (SUZ)	61	61	61	61	61
4	Fuel assembly geometry, fuel rod design	normal	Increased diametr of control rod guide tubes			
5	Structural material of spacing grids and guiding tube of control rods	Stainless steel	Zirconium alloy	Zirconium alloy	Zirconium alloy	Zirconium alloy
6	Profiling of fuel enrichment overthe fuel assembly cross section	used	used	used	not used	not used
7	Burnable absorber	Boric BAR	Boric BAR	Boric BAR	Gd_2O_3	Gd_2O_3
8	Weight of uranium in the core, *t*	65.	71.1	71.1	70.9	71.0
9	Refueling scheme	out-in-in	LLLP	LLLP	LLLP	LLLP
10	No. of fuel assemblies changed in refueling	54	54	42	54	42
11	Average enrichment of make-up fuel, *wt%*	4.31	3.52	4.23	3.53	4.16
12	Average burnup of discharged fuel *MWd/kg*	40.3	37.1	48.1	37.9	47.6
13	Time of reactor operation between refueling, eff.day	291	292	294	297	290
14	Efficiency of emergency protection, %					
	total, BOC	6.6	8.8	8.0	8.5	8.5
	total, EOC	6.6	8.7	8.1	8.4	8.6
	with one most efficient control rod stuck in the upper position					
	BOC	6.0	7.9	7.2	7.5	7.5
	EOC	6.0	7.7	7.3	7.6	7.4
15	Fuel assembly power peaking factor, K_q					
	BOC	1.28	1.31	1.32	1.31	1.33
	EOC	1.27	1.30	1.31	1.30	1.32
16	Volume power peaking factor, K_v					
	BOC	1.44	1.50	1.46	1.39	1.50
	EOC	1.34	1.42	1.40	1.41	1.46
	maximum	1.44	1.50	1.46	1.47	1.50
18	Max. linear power of fuel rod (with allowance for engineering hot channel factor for heat flux $K_{eng}=1.20$) *W/cm*					
	BOC	340	365	343	344	378
	EOC	300	313	309	315	324
19	Specific consumption of natural uranium, *kg/MWd*	0.243	0.211	0.199	0.208	0.198
20	Specific volume of separated works, *SWU/MWd*	0.146	0.118	0.119	0.116	0.118
21	Average power of periphery fuel assemblies, relative unit					
	BOC	0.78	0.40	0.57	0.58	0.58
	EOC	0.90	0.53	0.62	0.62	0.63