EXPERIENCE OF DEVELOPMENTS AND IMPLEMENTATION OF ADVANCED FUEL CYCLES OF VVER-440 REACTORS

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ABSTRACT

The paper presents the experience of development and implementation of advance four- and five-year fuel cycles in the VVER-440 reactors, the results of experiment operation of the new fuel design and the main neutronic characteristics of the core.

In the design three-year fuel cycles of VVER-440 reactors the fuel assemblies with stee spacer grids were used, the average fuel burnup of discharged fuel was ~29 MW*day/kg an the specific consumption of natural uranium was ~ 0.24 kg/MW*day. The experience gained in operation of the fuel burnups up to ~ 50 MW*day/kg obtained data of post-reactor investigations of spent fuel, development of neutronic and thermal-hydraulic calculation codes, thermal-mechanical codes and codes of acciden analysis made it possible to substantiate the increase in fuel burnup of the VVER reactors, eliminate the excess conservatism in designing and operation, laid at that stage, and start development of advanced fuel cycles with advanced design fuel assemblies.

Lately in Russia an extensive series of calculation and R&D works were carried out for the substantiation of the possibilities of improvement of various VVER-440 fuel cycles:

- a series of developments on increasing the efficiency of fuel was carried out;
- technology of FA and fuel pins fabrication and their operation characteristics were improved (the quality of fabrication of fuel pellets and casing tubes was enhanced, the initial helium pressure to the cladding increased, the FA design optimized);
- the five-year fuel cycle with the use of 4.4% enriched working fuel assemblies (not enrichment shaped ones) was successfully implemented at the Kola NPP unit 3;
- the advanced four-year fuel cycle with the use of working FA and fuel followers with profiled average fuel enrichment 3.82% was implemented at the NovoVoronezh NPP unit 4 (Fig.1); the similar fuel cycles are being introduced at the NPP with VVER-440 in Czechia, Slovakia, Hungary (the main characteristics of the type advanced four-year fuel cycle on example of Dukovany NPP unit 4 are listed in Table 1);
- since 2000 at the NovoVoronezh NPP-4 the pilot operation of the fuel followers with modernized (based on the hafnium plates) joint eliminating the local ramps of linear heat

generation rates of fuel pins in the working fuel assemblies next to the CR, has been carried out.

The implementation of four-year fuel cycles in the VVER-440 reactors does not restrict the possibility of further increase in the efficiency of fuel utilization and enhancement of the safety of these reactor plants.

The experience of Kola NPP-3 operation with the fuel assemblies with the starting fuel enrichment 4.4% (not enrichment shaped) evidences the possibility of realization of five year fuel cycles and increase in the fuel burnup (50.0 MW*day/kg and higher).

However the implementation of the fuel cycles using the highly enriched fuel encounters difficulties associated with ensurance of safety in fuel handling. Taking this into account the realization of five-year fuel cycle in the VVER-440 of Rovno NPP unit 2 has begun. This fuel cycle is based on the use of enrichment shaped fuel assemblies with the initial average fuel enrichment 4.21%, with the fuel ponds having normal pitches of FA arrangement provided at this NPP.

For the Kola NPP unit 4 the five-year fuel cycle using enrichment shaped fuel assemblies with the average enrichment 4.40%, containing fuel pins with gadolinium-based burnable absorber integrated to the fuel has been developed and implemented since 1998 (Table 2). The use of the burnable absorber permits the multiplying properties of fuel assemblies to be effectively reduced (by ~ 8% comparing with the 3.8% enriched fuel assemblies) and enhances fuel handling safety. At present 36 fuel assemblies (12 + 24) with uranium-gadolinium fuel are used in the reactor.

At the same time the possibility of realization of the universal (suitable also for implementation at the NPP with fuel ponds with small pitches of FA arrangement) five-year fuel cycle in the VVER-440 reactors with 349 FA in the core, is demonstrated. The specific feature of this fuel cycle is the use of FA with uranium-gadolinium (U-Gd) fuel (Fig.2).

The main neutronic characteristics of this fuel cycle are given in Table 3.

The results of trials and tests and experience of fuel operation with high fuel burnup, being gained are indicative of the existence of essential resources for further improvement of the techno-economic characteristics of VVER-440 fuel cycles. The possibilities of modernization of fuel cycles involve:

- increase in the efficiency of fuel utilization due to transition to the five- and six-year fuel cycles saving the conditions for ensuring the fuel handling safety at the expense of the use of burnable absorber integrated into fuel;
- the possibility of rising the FA power due to the increase and improvement of the coolant flow rate distribution in the fuel assemblies due to increased turnkey size o FA up to 145 mm and increase in the pitch in the fuel bundles of FA up to 12.3 mm;

- reduction in the linear heat generation rate ramps due to modernization of the fue follower joint and to the optimization of refueling patterns (and, as a result of this, th increased possibility of realization of power load-following);
- the possibility of increasing the fuel load operation length due to the increase in th uranium content in the fuel assemblies by increasing the effective length of the fuel stack and change in the outer and inner diameters of fuel pellets and fuel claddings.

The preliminary analyses of the possibility of implementation of the five- and six-year VVER-440 fuel cycles (more than half of working fuel assemblies have been operated in the reactor for six years) were performed.

The five-year fuel cycle is realized on the basis of the use of the advanced fuel assemblies: the working fuel assembly with uranium-gadolinium fuel and profiled average fuel enrichment 4.38%, which differ from the normal fuel assemblies mainly in the larger pitch in the fuel pin array (12.3 mm), longer fuel stack (2480 mm) and the fuel-followers with increased turnkey size (145 mm), reduced casing thickness (1.5 mm) with increased pitch (12.3 mm), increased fuel stack height (2360 mm) and the hafnium plate in the joint for reducing the power distribution burst in the fuel pins of the periphery row of neighboring working fuel assemblies.

In the case of this fuel cycle the length of reactor operation between the refuelings is 324 eff.days in the established refueling pattern, including 22 eff.days as a result of prolongation of the fuel cycle at the expense of partial use of power and temperature effects.

In the established refueling regimes 72 fuel assemblies are fed up into the core: to the odd load - 66 working fuel assemblies with average enrichment 4.38% and six fuel followers with average enrichment 3.82%, to the even load-60 working assemblies and 12 fuel followers are loaded.

The average burnup of discharged fuel (over the fuel assemblies) is ~ 50-51 MWday/kg.

The average burnup in the maximum depleted working assembly is ~ 53 MWday/kg.

The possibility of realization of power load following in the use of five-year fuel cycle was preliminary analyzed.

The six-year fuel cycle is realized with the use of working fuel assemblies with the average enrichment 4.86% and fuel followers with average enrichment 3.82%. Their main difference from the normal fuel assemblies is an increased pitch in the fuel pin array 12.3 mm) higher fuel stack, 2480 mm and 2400 mm in the working assembly and in the fuel follower, respectively, decreased outer diameter of (9.0 mm) and increased inner diameter of the cladding (7.78 mm) and increased inner (7.79) and outer (1.2 mm) diameters of fuel pellets.

When using this cycle 66(60) fuel assemblies are loaded in the odd (even) load to the core in the established refueling pattern. The fuel assemblies of the last (fifth-sixth) year of operation are installed in the core periphery. In the established refueling regime the time of reactor operation between refuelings is ~ 337(~315) eff.days for the odd (even) loads of which ~ 23(~ 24) eff.days are reached at the expense of partial use of the power and temperature effects.

The average fuel burnup of discharged fuel (over all the fuel assemblies) is ~ 56-57 MWday/kg.

The average fuel burnup in the maximum spent FA is ~ 62 MWday/kg.

The main operation characteristics of five-year fuel cycles of the reactor in the established refueling pattern are compared in Tables 2,3.

Comparing with the four-year cycle the main advantages of proposed five- and six-year fuel cycles are as follows:

- essential reduction in the number of fuel assemblies transported, loaded and unloaded for storage, which cuts the additional fuel cost and transportation expenses and increases the effective capacity of spent fuel storages;
- enhancement of nuclear safety in fresh fuel handling , especially at the NPP withstorages having a small pitch of FA arrangement;
- noticeable reduction in the effective specific consumption of natural uranium;
- some reduction in the effective specific volume of separation works.

In substantiation of the possibility of implementation of advanced fuel cycles it is planned to perform the following works in the nearest years:

- substantiation and pilot operation of fuel assemblies for six years up to fuel burnups ~ 55 MWday/kg;
- generalization of the neutronic characteristics of fuel loads with U-Gd fuel, comparison of the measured data with the calculation results;
- generalization of the results of fuel operation in the regimes with power variations in substantiation of fuel performance under the load-following conditions (analysis of the dependence of coolant activity on the fuel operation regimes, results of fuel leak tightness detection on the tripped reactor);
- substantiation of installation of advanced design fuel assemblies to the reactor and their pilot operation;

- development and substantiation of calculation approximations and correction of calculation codes for ensuring the representativeness of calculations of "hybrid" fuel loads;
- correction of ICIS software for maintaining the representativeness of control of power distribution in "hybrid" fuel loads;
- substantiation of representativeness of measurements of power distribution in the core in "hybrid" fuel load operation;
- comparison of the calculation data with the results of measurements in "hybrid" load operation;
- complex of calculation-experimental works in substantiation of fuel pin operability at fuel burnups ~ 62 MWday/kg and ~ 66 MWday/kg for the five- and six-year fuel cycles, respectively;
- post-reactor investigations of fuel assembly having operated for six years up to the average fuel burnup ~ 55 MWday/kg.

Table 1.

Neutronic characteristics of fuel loads in the process of four-year advanced fuel cycle implementation (Dukovany NPP Unit 4)

№№	Characteristic	Fuel load number	
		6(18)	7(19)
1.	Reactor thermal power, MW	1375	
2.	Number of FAs in the core	349	
3.	FA geometry	standard, FA casing wall thickness - 1.5 mm fuel follower casing wall thickness - 2.1 mm	
4.	Spacer grid material	zirconium	
5.	Fuel enrichment shaping in the FA cross section	used in the type O FAs and in the type T fuel followers	
6.	Burnable poison type	not used	
7.	Refueling pattern	with a reduced neutron leak	
8.	Boric acid concentration in the coolant during refuelings, g/kg	12.9	
9.	Number of fresh FAs loaded during refuelings, including their types	84 12(T), 72(0)	84 6(T), 78(0)
10.	Time of FA operation in the reactor, yr average maximum	 4.15 5.0	 4.15 5.0
11.	Average enrichment of makeup fuel, %	3.82	3.82
12.	Average burnup of spent fuel, MW*day/kg - for all FAs - for working FAs - for fuel followers Maximum fuel burnup, MW*day/kg - in the FA - in the fuel rod - in the fuel pellet	 41.98 42.16 39.64 43.60* 52.40 59.80	 41.17 41.32 41.17 43.38 49.70 58.90
13.	Time of reactor operation between refuelings, eff.days	305	305
14.	Peaking factor over the core, Kv (layer, FA №) BOC EOC	1.74 (10, 53) 1.70 (21, 14)	1.78 (10, 17) 1.71 (21, 6)
15.	Peaking factor of fuel rod power density (K_L) in FAs, where q_l^{max} is reached (FA №) BOC EOC**	1.09 (53) 1.05 (14)	1.07 (17) 1.06 (6)
16.	Maximum linear heat generation rate of fuel rod q_l^{max}, W/cm*** BOC EOC**	289.1 269.3	289.4 271.7

* in the central fuel follower the burnup 46.3 MW*day/kg is reached.

** the end of fuel cycle by the condition of reactivity charge exhaustion at W=1375 MW (C_{H3BO3}=0, H_{cont} = 234.2 cm).

*** with allowance for the engineering hot channel factors

Table

Neutronic characteristics of five-year advanced fuel cycle (Kola NPP Unit 4)

№№	Characteristic	Fuel load number	
		6 (18)	7 (19)
1.	Reactor thermal power, MW	1375	
2.	Number of Fas in the core	349	
3.	FA geometry	standard, FA casing wall thickness - 1.5 mm fuel follower casing wall thickness - 2.1 mm	
4.	Spacer grid material	zirconium	
5.	Fuel enrichment shaping in the FA cross section	only used in the type N, P working FAs	
6.	Burnable poison type	Gd_2O_3 (N type FAs)	
7.	Refueling pattern	in-in-in-in-out	
8.	Boric acid concentration in the coolant during refuelings, g/kg	9	9
9.	Number of fresh FAs loaded during refuelings, including their types	78 12 (H) 66 (N)	78 12 (H) 66 (N)
10.	Time of FA operation in the reactor, yr average maximum	 4.47 5.0	 4.47 5.0
11.	Average enrichment of makeup fuel, %	4.28	4.28
12.	Average burnup of spent fuel, MW*day/kg - for all FAs - for working FAs - for fuel followers Maximum fuel burnup, MW*day/kg - in the FA - in the fuel rod - in the fuel pellet - in the tveg - in the tveg pellet	 48.91 51.53 (N) 33.68 (H) 53.29(P) 57.44 64.45	 48.84 51.50 (N) 32.69(H) 53.47(N) 59.19 66.81 53.19 61.24
13.	Time of reactor operation between refuelings, (at nominal power), eff.days	336.2 (300.9)	337.1 (303.0)
14.	Temperature of repeated reactivity at the end of fuel cycle (no boron in the coolant, Xe-135 poisoning, all CR, except for the most heat generating one, in the lower position),°C	47.0	47.0
15.	FA peaking factor, K_q (FA №) BOC EOC MAX T_{eff}.day	 1.35 (23) 1.38 (36) 1.40 (23) 240	 1.35 (8) 1.38 (23) 1.39 (23) 220
16.	Peaking factor over the core, Kv (layer, FA №) BOC EOC MAX $T_{eff.day}$	 1.83 (9,8) 1.87 (21,36) 1.89 (21,36) 293.6	 1.85 (9,8) 1.89 (21,36) 1.93 (21,36) 292.4

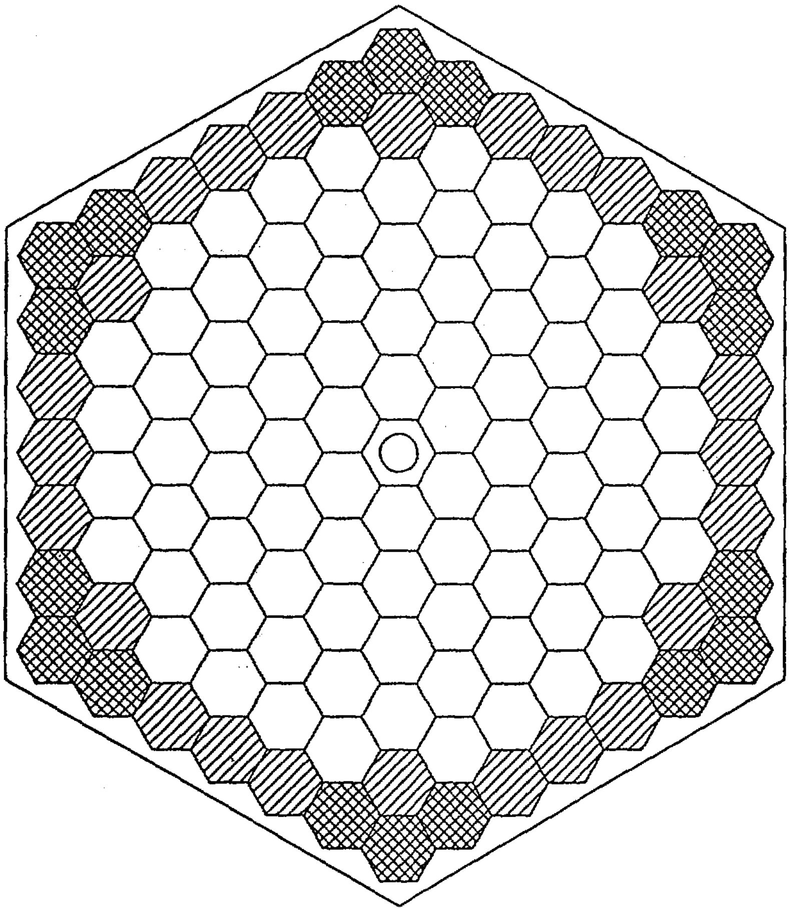
Table 3.

Neutronic characteristics of universal five-year fuel cycle .

№№	Characteristic	Fuel load number					
		five-year cycle "a"		five-year cycle "b		"five-year cycle "c"	
		odd	even	odd	even	odd	even
1.	Reactor thermal power, MW	1375					
2.	Number of FAs in the core	349					
3.	FA geometry	Standard, thickness of the working FA casing wall - 1.5 mm Thickness of the fuel follower casing wall - 2.1 mm					
4.	Structural material of spacer grids	zirconium					
5.	Fuel enrichment shaping in the FA cross section	Used in the N-type working Fas and in the T-type fuel followers			Used in the J-type working fuel assemblies and in the T-type fuel followers		
6.	Burnable poison	Gd_2O_3					
8.	Boric acid concentration in the coolant during refuelings, g/kg	□ 8.5					
9.	Number of fresh FAs loaded during the refueling6 including their types	79 66 (N), 1 (R), 12 (T)	72 66 (N), 6 (T)	72 66 (N), 6 (T)	73 69(N), 1(R), 12(T)	72 66(J), 6(T)	73 60(J), 1(R), 12(T)
10.	Time of discharged FAs operation in the reactor, yr - average - maximum	4.58 5	4.67 5	4.83 5	4.79 5	4.83 5	4.79 5
11.	Average make up fuel enrichment, %	4.28	4.36	4.36	4.27	4.10	4.04

Table 3 (continued).

12.	Average burnup of spent fuel, MW*day/kg - for all FAs - for the working FAs - for the fuel followers Maximum fuel burnup, MW*day/kg - in the FAs - in the fuel rods - in the fuel pellet	47.75 49.42 39.27 51.11 53.50 61.20	49.22 50.13 39.25 53.22 55.40 62.00	49.45 50.41 38.89 51.82 54.80 61.80	47.87 50.07 37.69 51.03 53.50 61.00	46.67 47.55 37.02 48.38 50.40 58.10	45.48 47.38 36.73 48.38 50.40 58.10
13.	Time of reactor operation between refuelings (including at the expense of prolongation of core lifetime with the power effect), eff.day	333.42 (-)	305.88 (-)	309.44 (-)	306.91 (-)	293.65 (-)	290.04 (-)
14	Temperature of repeated criticality at the end of fuel cycle (absence of boron in the coolant, Xe-135 poisoning, all the CR, except for one most heat generating one, in the lower position) □C	88	86	88	88	86	79
15	FA peaking factor, K_q (FA №.) BOC EOC	1.36 (13) 1.36 (13)	1.36 (13) 1.38 (11)	1.37 (30) 1.36 (11)	1.34 (49) 1.36 (9)	1.36 (4) 1.35 (9)	1.33 (45) 1.33 (9)
16	Peaking factor over the core volume Kv (FA № , layer) BOC EOC	1.71 (48,10) 1.80 (13,21)	1.71 (17, 9) 1.81 (11,21)	1.81 (16, 9) 1.75 (11,21)	1.76 (8,10) 1.76 (28,21)	1.82 (8,9) 1.75 (36,21)	1.72 (8,10) 1.74 (13,21)



URANIUM ENRICHMENT (number of fuel rods)

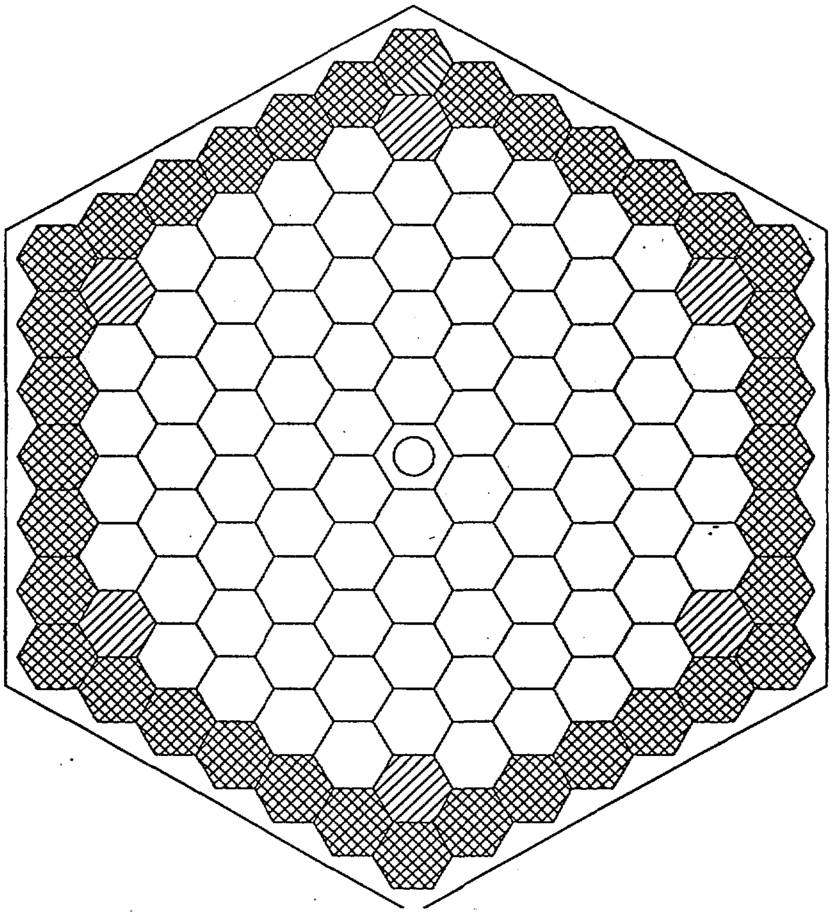
4.0% (84)

3.6% (24)

3.3% (18)

CENTRAL TUBE

Fig.1. Diagram of fuel enrichment profiling in the FA of O and T types



URANIUM ENRICHMENT (number of fuel rods)

Type N

4.6 % (84)

4.0 % (6) (3 % Gd_2O_3)

4.0 % (36)

CENTRAL TUBE

Fig.2. Diagram of fuel enrichment profiling in the FA of N (4.4 %) c Gd2O3 types