CONTEMPORARY AND PROSPECTIVE FUEL CYCLES FOR VVER-440 BASED ON NEW ASSEMBLIES WITH HIGHER URANIUM CAPACITY AND HIGHER AVERAGE FUEL ENRICHMENT

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ABSTRACT

RRC "Kurchatov Institute" has performed an extensive cycle of calculations intended to validate the opportunities of improving different fuel cycles for VVER-440 reactors. Works were performed to upgrade and improve VVER-440 fuel cycles on the basis of second-generation fuel assemblies allowing core thermal power to be uprated to 107–108% of its nominal value (1375 MW), while maintaining the same fuel operation lifetime. Currently intensive work is underway to develop fuel cycles based on second-generation assemblies with higher fuel capacity and average fuel enrichment per assembly increased up to 4.87% of U-235. Fuel capacity of second-generation assemblies was increased by means of eliminated central apertures of fuel pellets, and pellet diameter extended due to reduced fuel cladding thickness.

This paper intends to summarize the results of works performed in the field of VVER-440 fuel cycle modernization, and to present yet unemployed opportunities and prospects of further improvement of VVER-440 neutronic and operating parameters by means of additional optimization of fuel assembly designs and fuel element arrangements applied.

1. INTRODUCTION

Features such as available technologies tested by operational practice, proven economic competitiveness and technical safety put the nuclear power industry in a favorable position to produce a considerable share of the XXI century's energy. Today light water reactors (LWR) constitute over 85% of the world nuclear park and are under construction in twelve countries. One of the acknowledged LWR lines is the water-water reactor (VVER) concept conceived and developed in the former Soviet Union. For over 35 years of existence of VVER power reactors, the total of 57 units were built, and 48 of them are currently in operation. The oldest operating VVER is the third Novovoronezh NPP unit (V-179 project) with VVER-440 reactor connected to the grid in 1971, the last is the second Mochovce NPP unit with its VVER-440 launched in 1989.

Varying features and conditions of existence of large-scale nuclear power industry determine the need to develop new-generation reactors along with improving the designs of currently operating ones. As concerns selection of new development concepts, preference should be given to the proposals, which introduce new quality in the solutions of the future nuclear energy issues. It is impossible to offer a single prospective design, which would provide the best solutions for all the problems faced by nuclear energy. Instead, in future a series of reactor types will operate – each offering the best possible solution for some specific task set by large-scale nuclear industry – and VVER reactors will undoubtedly be among them.

The current development trend of nuclear reactors' development for electricity generation purposes will certainly continue. Construction of large and medium reactors, well proven by previous operation, will also continue, along with further power uprating lines. Particularly, the size of European Russia's energy grid and the requirement of competitiveness with traditional fossil-fueled power plants determine the trend towards increasing the NPP unit power, while the world market orientation makes it necessary to have for home and foreign applications a Russian VVER design competitive with Western ones in terms of its capacity and other relevant indicators.

The current phase of medium water-water reactors (VVER-440) development is characterized by their widespread second generation and by some third-generation projects currently being implemented. Second-generation VVER-440 reactors (V-213 project) are operating at the following NPPs: Loviisa (Finland), Paks (Hungary), Dukovany (Czech Republic), Bohunice and Mochovce (Slovakia), Rovno (Ukraine), Kola (Russia) and Metsamor (Armenia).

Table 1. NPPs with VVER-440

Units in operation		Decommissioned units	
VVER-440 (V-179) for NPPs:		VVER-440 (V-230) for NPPs:	
Novovoronezh	2 units	Kozloduy	4 units
VVER-440 (V-213) for NPPs:		Nord	4 units
Kola	2 units	Bohunice V-1	2 units
Rovno	2 units		
Loviisa	2 units		
Paks	4 units		
Bohunice V-2	2 units		
Dukovany	4 units		
Mochovce	2 units		
VVER-440 (V-230) for NPPs:			
Kola	2 units		
VVER-440 (V-270) for NPPs:			
Metsamor	1 unit		
TOTAL	23 units	TOTAL	10 units

First-generation VVER-440 units have demonstrated the economic competitiveness of nuclear power plants. The second generation of these units has assured safe operation of the nuclear power industry in the Soviet Union (and later in Russia and Ukraine), has shown the possibilities of confident presence at the international NPP market, and is currently assuring the technological, scientific and engineering basis for strengthening the nuclear energy positions in Russia, as well as its international competitiveness, by means of an evolutionary transition to the third generation of nuclear power units. Decisions to construct NPPs with third-generation VVER-640 reactors (at Sosnovy Bor and Kola-2 sites in Russia) are already in place. These designs possess largely improved inherent safety features, including the use of natural factors and processes, as well as passive safety equipment.

Currently the full-scale completion of units 3 and 4 with second-generation VVER-440 reactors is underway at Mochovce NPP in Slovakia.

Fuel for these units will be supplied by the Russian TVEL Company, which in 2009 has won the respective fuel supply tender.

Table 2. New VVER-440 units

Mochovce NPP – Project 213 (upgraded)	Thermal power	Electric power	Status by 2008 (completion degree)	Planned commissioning
Unit 3	1540 MW	~ 500 MW	70%	2012
Unit 4	1540 MW	~ 500 MW	70%	2013

It is planned to uprate these units' core thermal power to 112%, which would correspond to about 500 MW of electric power. This power uprate will be achieved by using state-of-the-art nuclear fuel and dedicated fuel cycles.

2. BASIC IMPROVEMENT DIRECTIONS FOR VVER-440 FUEL CYCLE

The basic improvement directions for VVER-440 fuel cycles are as follows:

- Increased initial enrichment of makeup fuel, with reduced share of fuel replaced with each refueling;
- Use of refueling patterns with lower neutron leakages;
- Extended operating lifetime of fuel assemblies (from 4–5 to 6–7 years);
- Higher fuel burnup (from 40–50 to 55–65 MW·day/kgU);
- Less conservative validations of fuel cycle;
- Development of fuel cycles for specific power-maneuvering applications. Validation of reactor operation in the grid load-tracking mode and in the reactor power maneuvering one.

On the whole, a large cycle of calculations, developments and design efforts has been completed in order to validate the possibilities of VVER-440 fuel cycle improvement – which would be impossible without improving fuel assembly configurations.

VVER-440 fuel assemblies are being continuously upgraded throughout the whole period of these reactors' existence. Since any changes introduced in fuel assemblies impact the neutronic parameters of core, every implementation of improved fuel assemblies was accompanied by large amount of works validating reactor operation safety. Gradual improvements of fuel assembly configurations on the basis of previous modernization experience resulted in the creation of so-called second-generation assemblies. Technical solutions incorporated in these second-generation fuel designs are based on and confirmed by the results of their pilot and industrial operation.

Profiled second-generation fuel assemblies with 4.25% average enrichment and 6 gadolinium fuel elements are in operation at Kola NPP unit 3 since 2002 (18th fuel load started operation in September 2002).

The possibility to use profiled second-generation fuel assemblies with 4.25% average enrichment and 6 gadolinium fuel elements at Dukovany units 1 to 4 since 2005 has already been validated. Validation was also performed for the introduction of profiled second-generation fuel assemblies with 4.25% average enrichment and 6 gadolinium fuel elements at all NPP units in Slovakia since 2006.

Table 3. Introduction of second-generation fuel at VVER-440 units

NPP	Unit #	Year of 2nd-generation assembly introduction
Kola	3, 4	2002, 2005
Dukovany	3	2005
Dukovany	1	2007
Mochovce	1, 2	2006
Bohunice	3, 4	2006

Second-generation fuel was used to develop and implement complete 5-year fuel cycles with some assemblies left to operate for the 6th year. Initial enrichment of the fresh fuel is 4.25%. Refueling takes place according to in-in-in-in-out pattern, which considerably reduces neutron leakage from the core. Fuel cycles were developed specifically for maneuvering modes of reactor operation. The possibilities of reactor operation in the grid load-tracking mode and in power maneuvering mode were validated. These operation modes are permanently used by NPPs in Slovakia (Mochovce 1, 2).

Implementation of second-generation fuel assemblies with average enrichment of 4.38%+Gd and 4.25%+Gd has reduced (relative to fuel 3.82%) the effective specific consumption of natural uranium by additional 3–10%, while the effective specific amount of separation work has reduced by 1–6% compared with the previous fuel configurations. Transition to second-generation fuel allowed the number of fuel assemblies loaded to be reduced by 16–27%, depending on specific fuel arrangements .

The figures below show the basic enrichment profiles in fuel bundle cross-sections for second-generation fuel assemblies.

RRC Kurchatov Institute conducts intensive R&D in the field of modernization and improvement of VVER-440 fuel cycles involving lower specific fuel consumption, better working parameters of fuel elements and assemblies, and higher fuel management safety. An extensive cycle of calculations, developments and design efforts has been completed in order to validate improvement possibilities for different VVER-440 fuel cycles.

Fuel efficiency – as well as the whole VVER-440 fuel cycle – are being improved towards achieving higher fuel enrichment, increased fuel content in fuel elements (by eliminating the central fuel pellet aperture and by extending the fuel column height), and optimized water/fuel ratio in assemblies (by extending the pitch between fuel elements). These developments allow fuel efficiency to be increased.

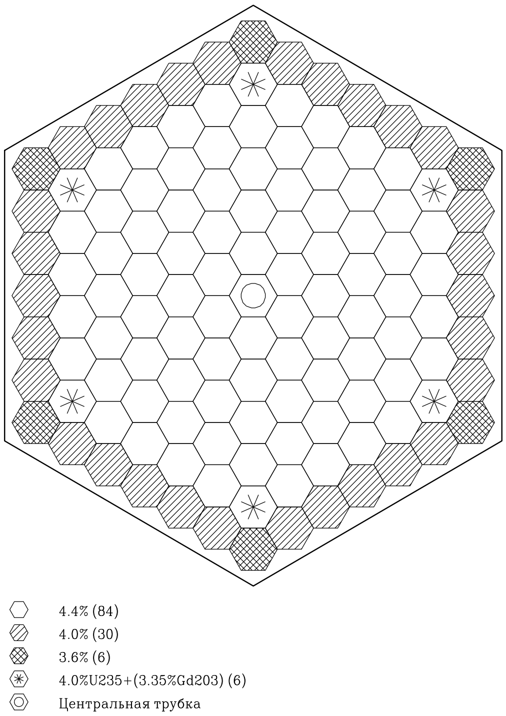


Figure 1. Fuel enrichment profile for 4.25%-enriched assemblies with six Gd_2O_3 fuel rods

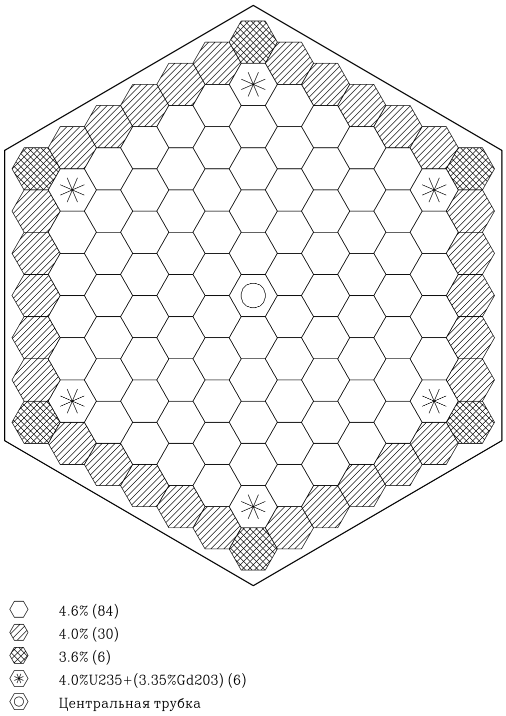


Figure 2. Fuel enrichment profile for 4.38%-enriched assemblies with six Gd_2O_3 fuel rods

Table 4. Basic improvement lines for VVER-440 fuel and fuel cycles

Fuel assembly parameter	Initial fuel cycle	Modern designs	Advanced designs – 2010
Structural material	Zr(Hf≤0.05%)	Zr(Hf≤0.05%)	Zr (Hf≤0.01%)
Shroud material	Zr(Hf≤0.05%)	Zr (Hf=0.01%)	None
Burnable absorber	-	UO_2-Gd_2O_3	UO_2-Gd_2O_3
Enrichment profiling			
- horizontal	Yes	Yes	Yes
- axial	No	No	No
UO_2 mass in fuel rod, relative units	1.00	1.05	1.14
Axial aperture diameter, relative units/ Fuel column height, relative units	1.00/1.00	0.86/1.02	0.0/1.02
Pitch between rods in fuel bundle, relative units/ External rod diameter, relative units	1.00/1.00	1.01/1.00	1.032/1.00
Maximum fuel enrichment admissible, %	4.40	4.6	4.95
Maximum fuel burnup rate for an assembly, MW·day/kgU	53.9	57.5	65.0
Number of refuelings	4 – 5	5 – 6	6 – 7

3. USE OF SECOND-GENERATION FUEL FOR UNIT POWER UPRATING

Currently nuclear power plants with VVER-440 reactors are facing urgent issue of their power uprating.

From the viewpoint of energy producers, NPP power uprates would bring considerable economic effect by generating additional electricity, while involving relatively low supplementary modernization costs.

VVER-440 (V-213) reactor facility was designed on the basis of effective engineered safety margins available for thermal performance parameters, which allow the thermal power of the reactor to be increased, with account taken of its operation experience. Cores of operating V-213 units have neutronic and thermal hydraulic parameters, which assure actual (calculated and measured) power density non-uniformity factors per rod or assembly, as a rule, to be below maximum design-basis values or limits. This circumstance provides an effective margin for power uprating.

Improved configurations of fuel assemblies and updated computing codes have made it possible to develop fuel cycles allowing the reactor to operate at 105–112% of its nominal thermal power.

Currently the following units with this reactor type have uprated capacities: Loviisa (Finland) – 109% (1500 MW with core reduced to 313 assemblies); Paks (Hungary) – 108%; Dukovany (Czech Republic) – up to 105%; Bohunice and Mochovce (Slovakia) – up to 107%. Calculations were also performed to assess the feasibility of uprating the power of Mochovce units 3 and 4 (which are currently under construction) to 112% (1540 MW).

Table 5. NPP capacities uprated with second-generation fuel assemblies

NPP	Planned unit power, N_{nom}	Average U-235 enrichment of fuel assemblies (FA), %	Average U-235 enrichment of control rod assemblies (CA), %	Scheduled date of completion of calculations/technical justification
Kola	107	4.25	3.82	2008 (unit 4) 2009 (unit 3)
Dukovany	105	4.38	4.25	Completed in 2008
Mochovce	107	4.25	3.84	Units 1 and 2 operate at 107%
Bohunice V-2	107	4.25	3.84	Unit 3 operates at 107%
Paks	108	4.20	4.20	2008
Loviisa	109	4.37	4.0	2008
Rovno	108	4.38	4.25	2010 – 2011

Table 6. Basic parameters of fixed 5-year fuel load for Kola units 3 & 4 operating at 107% power.

Parameter		Stationary fuel reloading
Number of assemblies loaded	Total	78
	CA 3.82%	6
	FA 4.25%	72
Average makeup fuel enrichment, weight %		4.22
Fuel operation period, effective days		302.5
Thermal power of core, MW		1471
Discharged fuel burnup, MW·day/kgU	Average	45.5
	Maximum	58.0
Coolant temperature reactivity factor, pcm/°C	Start of fuel operation, hot state, CPS rods up	< 0
Design and maximum admissible relative power of fuel rods, ($^{N}F_{dh}$) Kr		1.55 / 1.55
Maximum thermal linear load (Ql) (including margin), W/cm		< 325
Maximum admissible power of fuel rod, kW		56.6

Table 7. Basic parameters of fixed 5-year fuel load for Dukovany NPP operating at 105% power.

Parameter		Stationary fuel reloading
Number of assemblies loaded	Total	72 / 72
	FA 4,38%	66 / 60
	CA 4.25%	6 / 12
Average makeup fuel enrichment, weight %		4.37 / 4.36
Fuel operation period (including lifetime extension due to uprate), effective days		325 (30) / 324 (30)
Thermal power of core, MW		1444
Discharged fuel burnup, MW·day/kgU	Average	51.9 / 51.6
	Maximum	55.5
Coolant temperature reactivity factor, pcm/°C	Start of fuel operation, hot state, CPS rods up	< 0
Design and maximum admissible relative power of fuel rods, ($^{N}F_{dh}$) Kr		1.48 / 1.56
Maximum thermal linear load (Ql) (including margin), W/cm		< 325
Maximum admissible power of fuel rod, kW		56.6

Table 8.
Basic parameters of fixed 5-year fuel load for Rovno NPP operating at 108% power

Parameter		Stationary fuel reloading
Number of assemblies loaded	Total	78
	CA 4,25%	6 / 12
	FA 4,38%	72 / 60
Average makeup fuel enrichment, weight %		4.37
Fuel operation period (including lifetime extension due to uprate), effective days		320.9 / 317.1 (9)
Thermal power of core, MW		1485
Discharged fuel burnup, MW·day/kgU	Average	50.2
	Maximum	55.1
Coolant temperature reactivity factor, pcm/°C	Start of fuel operation, hot state, CPS rods up	< 0
Design and maximum admissible relative power of fuel rods, ($^{N}F_{dh}$) Kr		1.51 / 1.52
Maximum thermal linear load (Ql) (including margin), W/cm		< 325
Maximum admissible power of fuel rod, kW		56.6

Table 9.
Basic parameters of fixed 5-year fuel load for Mochovce NPP operating at 107% power

Parameter		Stationary fuel reloading
Number of assemblies loaded	Total	79 / 84
	FA 4,25%	72 / 72
	CA 3,84%+ 1,6%	6+1 / 12
Average makeup fuel enrichment, weight %		4.19 / 4.19
Fuel operation period (including lifetime extension due to uprate), effective days		330.0 (22.1) / 330.0 (21.1)
Thermal power of core, MW		1471
Discharged fuel burnup, MW·day/kgU	Average	48.3 / 46.9
	Maximum	53.73
Coolant temperature reactivity factor, pcm/°C	Start of fuel operation, hot state, CPS rods up	< 0
Design and maximum admissible relative power of fuel rods, $({}^{N}F_{dh})$ Kr		1.52 / 1.55
Maximum thermal linear load (Ql) (including margin), W/cm		< 325
Maximum admissible power of fuel rod, kW		56.6

Table 10.
Basic parameters of fixed 4-year fuel load for Paks NPP operating at 108% power

Parameter		Stationary fuel reloading
Number of assemblies loaded	Total	85 / 84
	CA 4,2% + 1,6%	6+1 / 12
	FA 4,2%	78 / 72
Average makeup fuel enrichment, weight %		4,17 / 4,20
Fuel operation period, effective days		328 / 322
Thermal power of core, MW		1471
Discharged fuel burnup, MW·day/kgU	Average	45.7 / 45.3
	Maximum	49,7
Coolant temperature reactivity factor, pcm/°C	Start of fuel operation, hot state, CPS rods up	< 0
Design and maximum admissible relative power of fuel rods, $({}^{N}F_{dh})$ Kr		1.43 / 1.54
Maximum thermal linear load (Ql) (including margin), W/cm		< 325
Maximum admissible power of fuel rod, kW		57.0

Table 11. Basic parameters of fixed 4-year fuel load for Loviisa NPP operating at 109% power

Parameter		Stationary fuel reloading
Number of assemblies loaded	Total	84
	CA 4,0%	6 / 12
	FA 4,37%	78 / 72
Average makeup fuel enrichment, weight %		4.34 / 4.32
Fuel operation period, effective days		335(26.5)/ 332 (26.5)
Thermal power of core, MW		1500
Discharged fuel burnup, MW·day/kgU	Average	47.5
	Maximum	53.3
Coolant temperature reactivity factor, pcm/°C	Start of fuel operation, hot state, CPS rods up	< 0
Design and maximum admissible relative power of fuel rods, (${}^{N}F_{dh}$) Kr		1.47 / 1.48
Maximum thermal linear load (Ql) (including margin), W/cm		< 325
Maximum admissible power of fuel rod, kW		61.6

At the current stage, VVER-440 fuel efficiency and fuel cycles are being further improved towards higher fuel enrichment (in order to allow operation at uprated power) and implementation of 6-year fuel cycles involving at least 300 effective days of fuel operation. Average fuel enrichment for second-generation assemblies is increased to 4.87%, while the maximum enrichment in these assemblies (in gadolinium rods) can reach 4.95%.

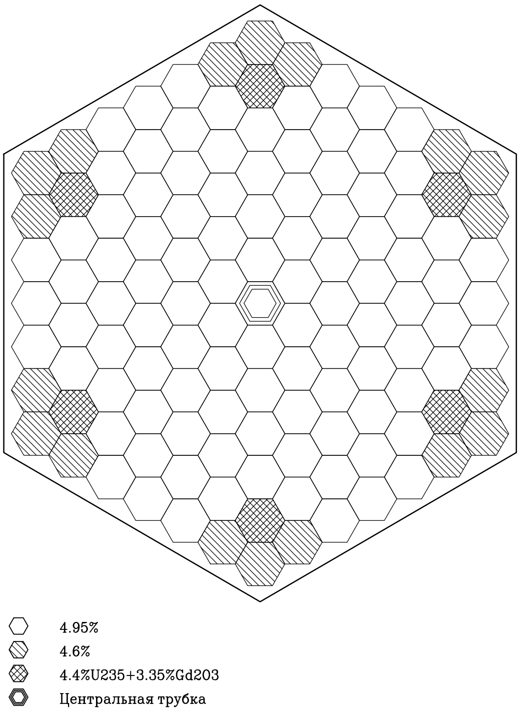


Figure 3. Fuel enrichment profile for 4.87%-enriched 2nd-generation assemblies with six Gd_2O_3 fuel rods, for operation at uprated (107%) power in the prospective 6-year fuel cycle intended for Russian and foreign NPPs after 2010.

Table 12. NPP capacities uprated with second-generation fuel assemblies with higher enrichment

NPP	Planned unit power, N_{nom}, %	Average U-235 enrichment of fuel assemblies (FA), %	Average U-235 enrichment of control rod assemblies (CA), %	Scheduled date of completion of calculations/ technical justification
Kola	107	4.87	4.25	2010 (unit 4)
Mochovce	107	4.87	4.87	2010 (units 1, 2)
Bohunice	107	4.87	4.87	2011 (units 3, 4)

Table 13. Basic parameters of fixed 6-year fuel load for Kola NPP unit 4 operating at 107% power

Parameter		Stationary fuel reloading
Number of assemblies loaded	Total	60
	CA 4,25%	6
	FA 4,87%	54
Average makeup fuel enrichment, weight %		4,81
Fuel operation period (including lifetime extension due to uprate), effective days		298.9 (30.0)
Thermal power of core, MW		1471
Discharged fuel burnup, MW·day/kgU	Average	58.6
	Maximum	70.3
Coolant temperature reactivity factor, pcm/°C	Start of fuel operation, hot state, CPS rods up	< 0
Design and maximum admissible relative power of fuel rods, $(^{N}F_{dh})$ Kr		1.55 / 1.58
Maximum thermal linear load (Ql) (including margin), W/cm		< 325
Maximum admissible power of fuel rod, kW		59.8 (to be validated)

Table 14.
Basic parameters of fixed 6-year fuel load for Mochovce NPP operating at 107% power

Parameter		Fixed load
Number of assemblies loaded	Total	67 / 66
	FA 4,87%	60 / 60
	CA 4,87%+ 1,6%	6+1 / 6
Average makeup fuel enrichment, weight %		4.82 / 4.87
Fuel operation period (including lifetime extension due to uprate), effective days		324.7 (8.0) / 321.6 (8.0)
Thermal power of core, MW		1471
Discharged fuel burnup, MW·day/kgU	Average	57.1 / 56.6
	Maximum	65.7
Coolant temperature reactivity factor, pcm/°C	Start of fuel operation, hot state, CPS rods up	< 0
Design and maximum admissible relative power of fuel rods, $(^{N}F_{dh})$ Kr		1.56 / 1.56
Maximum thermal linear load (Ql) (including margin), W/cm		< 325
Maximum admissible power of fuel rod, kW		58.0

The latest – but not the final – improvement of the second-generation fuel asemblies (so-called RK2+) intended to improve VVER-440 fuel efficiency and fuel cycle consists of increasing the mass of uranium in fuel elements (not gadolinium ones). The mass of U in fuel elements can be increased by means of eliminated central fuel pellet apertures and by larger pellet diameters allowed by the use of thinner cladding.

Table 15.

Fuel pellet parameters		Fuel element parameters	
Diameter		Cladding diameter	
external	central aperture	internal	external
7.57	1.4	7.73	9.1
7.60	1.2	7.73	9.1
7.80	0	7.93	9.1

4. THIRD-GENERATION ASSEMBLIES FOR VVER-440

The next step towards improving fuel cycle parameters is the development of detailed design for third-generation fuel assemblies, which is currently underway.

In 2005–2006 extensive R&D and calculations have been performed to optimize fuel assembly charts and fuel cycle parameters in established refueling conditions with the use of various optional configurations of 3rd-generation working assemblies for VVER-440.

The basic task of 3rd-generation working assemblies' (RK3) designing for VVER-440 (V-213) units was to enhance fuel efficiency, so their design provided for:

- lower parasitic capture of thermal neutrons resulting from the mass of zirconium alloys reduced by 8.3 kg by using a shroudless frame of six angle bars and three support tubes;
- water/U ratio optimized by using a larger pitch between elements in fuel bundle;
- fuel load increased by using fuel pellets with larger external diameter and without central apertures.

Development of third-generation working assemblies for VVER-440 was performed on the basis of the experience and results of development of second-generation assemblies, alternative fuel elements and TVS-2 rods for VVER-1000.

The respective detailed design was developed in 2007.

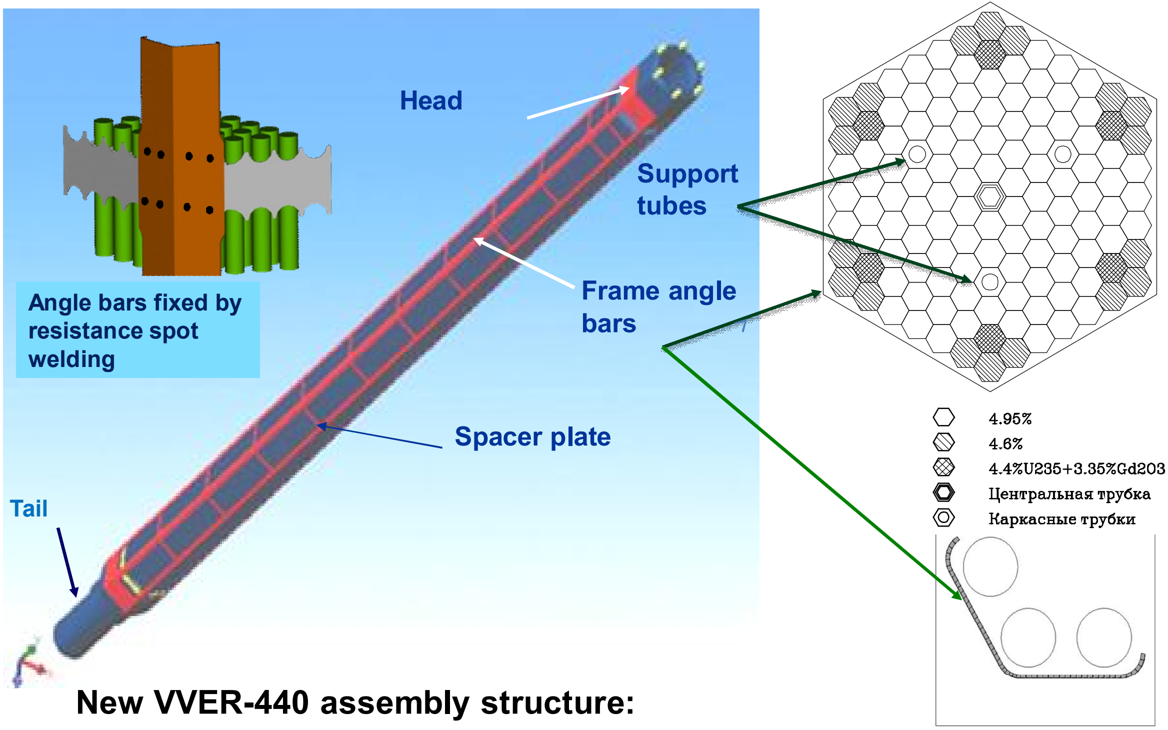
The configuration of VVER-440 3rd-generation working assemblies (RK3), which was finally adopted, has the following specific features:

- fuel assembly shrouds replaced by angle bars;
- three zirconium support tubes sized 12.6×1 mm present in the fuel bundle;
- fuel pellet diameter increased to 7.8 mm plus eliminated central aperture;
- pitch between rods in the fuel bundle increased to 12.6 mm;
- admissible fuel enrichment in assemblies increased to 4.95%.

Shroud replacement with angle bars yields 4% of energy output – this is another confirmation of importance of water/U ratio for neutronic parameters of VVER reactors. Fuel mass changed in the 3rd-generation assemblies allowed additional 8% increase of energy output. Consequently, if the trial industrial operation of RK3 proves successful, its wide implementation would be commendable.

In accordance with the respective decision, a trial batch of 12 third-generation assemblies will start operation at power uprated to 107% at Kola NPP unit 4 after its planned maintenance outage-2010.

3rd-generation VVER-440 fuel (RK3)



New VVER-440 assembly structure:
Shroudless assembly with a frame of angle bars and support tubes

In order to compare the economic efficiency of fuel with higher uranium content, let's consider the above three fuel cycles in the established refueling phase. In all these cycles the reactor operates at uprated power of up to 112% (1540 MW). In the first cycle 66 2^{nd}-generation assemblies with 4.87% enrichment are loaded in the core; in the second – 66 2^{nd}-generation assemblies containing more uranium (RK2+); and in the third – 3^{rd}-generation fuel assemblies together with 2^{nd}-generation emergency control ones (CA), also with higher U contents (RK2+). Tables 16 and 17 show the parameters of these new fuel assembly designs. Table 18 gives the basic neutronic parameters of fuel cycles. These parameters confirm that the introduction of RK3 would increase fuel efficiency by about 10%.

Table 16. Parameters of new fuel assembly designs

Name	Type	Average fuel enrichment	U weight, kg	Type of fuel elements	Pitch between elements, cm	Assembly shroud thickness, mm	Burnable absorber	Number of U (U-Gd) elements
RK2	FA	4.87	126.3	1	1.23	1.5	Gd_2O_3	120(6)
RK2	CA	4.87	120.3	2	1.23	1.5	Gd_2O_3	120(6)
RK2+	FA	4.87	135.5	3	1.23	1.5	Gd_2O_3	120(6)
RK2+	CA	4.87	128.9	4	1.23	1.5	Gd_2O_3	120(6)
RK3	FA	4.87	132.3	3	1.26	-	Gd_2O_3	117(6)
RK2+	CA	4.87	128.9	4	1.23	1.5	Gd_2O_3	120(6)

Table 17. Parameters of fuel elements for new assembly designs

Type of fuel rod	External diameter of U (U-Gd) rod, mm	Internal diameter of U (U-Gd) rod cladding, mm	Effective height of fuel column in cold state, mm	External diameter of U (U-Gd) fuel pellet, mm	Diameter of U (U-Gd) pellet central aperture, mm	Mass of pellets in U rod (U-Gd) rod, g
1	9.10 (9.10)	7.73 (7.73)	2480	7.60 (7.60)	1.2	1141 (1141)
2	9.10 (9.10)	7.73 (7.73)	2360	7.60 (7.60)	1.2	1085 (1085)
3	9.10 (9.10)	7.93 (7.73)	2480	7.80 (7.60)	0.0 (1.2)	1230 (1141)
4	9.10 (9.10)	7.93 (7.73)	2360	7.80 (7.60)	0.0 (1.2)	1170 (1085)

Table 18.

Parameter	2^{nd}-generation assemblies		2^{nd}-generation assemblies with higher UO_2 content		3^{rd}-generation assemblies	
fixed	even	odd	even	odd	even	odd
Number of fresh assemblies FA CA	66 RK2 (54) RK2 (12)	66 RK2 (60) RK2 (6)	66 RK2+ (54) RK2+ (12)	66 RK2+(60) RK2+(6)	66 RK3 (54) RK2+ (12)	66 RK3 (60) RK2+ (6)
Operating lifetime, effective days	296.7	307.0	315.9	326.9	325.5	338.91
Operating lifetime of discharged assemblies, years - average - maximum	5.20 6.00	5.38 6.00	5.20 6.00	5.38 6.00	5.20 6.00	5.38 6.00
Fuel burnup, MW·days/kg - average - maximum	56.9 58.3	55.0 60.9	54.2 57.6	56.1 60.4	59.6 62.2	56.9 60.9
Design and maximum admissible relative power of fuel elements, (F^{N}_{dh}) **Kr**	1.53 1.55	1.53 1.55	1.52 1.55	1.52 1.55	1.51 1.51	1.51 1.51
Maximum admissible power of fuel elements, kW	59.8	59.8	59.8	59.8	59.8	59.8

5. CONCLUSION

Development of advanced fuel cycles with second-generation assemblies for VVER-440 NPP units has made it possible to:

- introduce a five-year fuel cycle (with some working assemblies left in operation for the sixth year) at units of V-213 type;
- increase the thermal power of VVER-440 units, while preserving acceptable lifetimes and refueling frequencies;
- implement reactor maneuvering modes, when the reactor power varies considerably within a short period of time.

Higher U-235 enrichment in second-generation assemblies would allow fuel efficiency to be increased in conditions of VVER-440 operation at uprated power levels.

The achieved level of VVER-440 fuel/fuel cycle improvement, along with the available experience of validation and operation of units at uprated power, makes it possible to increase the thermal power of V-213 reactor units up to 1540 MW (depending on specific equipment of different units).

Fuel cycles using third-generation assemblies for VVER-440 are more efficient from fuel consumption viewpoint, compared with those using second-generation fuel.

Contemporary fuel cycles for VVER-440 reactors allow different fuel operational lifetimes to be implemented. This would allow an optimal grid-specific adaptation of electricity generated by nuclear power plants.

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