Results of trial operation of new generation assemblies with improved vibration stability for WWER-440 reactors of V-230 and V-213 plants

Authors: V.B. Lushin, I.N. Vasilchenko, A.I. Shumeev,
FSUE OKB "GIDROPRESS", Russia.

1. Introduction

The design of WWER-440 fuel assemblies during the whole period of operation of these reactors is permanently modernized.

On the one hand, this is dictated by the operating conditions of the units and requirements for improvement of fuel reliability, on the other hand – by requirements of the fuel market.

In this case, the main task in developing a fuel design of new generation for WWER-440 power units (particularly for power units of V-213 type) is an increase of effectiveness of fuel utilization. With this purpose such design solutions were realized as increase of fuel loading (increase of fuel stack in a fuel rod), optimization of the water-uranium relation (at the cost of some decrease of outside diameter of a fuel rod from 9,1 mm to 9,07 mm and increase of fuel rod pitch in a bundle from 12,2 mm up to 12,3 mm), decrease of harmful absorption of neutrons (due to decrease of hafnium content in zirconium materials from 0,05 % to 0,01 % and decrease of zirconium in transition to thickness of FA casing of ERC assembly - 1,5 mm).

The parallel task is to increase vibration stability of fuel assemblies on the basis of the verified and justified technical solutions (figure 1):

- improvement of vibration stability due to SG rearrangement along the height of fuel rod bundle and increase of height of the first three grids along the course of coolant flow;
- decrease of backlashes in the assembly “fuel rod - support grid” due to introduction of a new elastic tip of fuel rods;
- introduction of a stiffening rib under the support grid and attachment of the central tube in the support grid by welding;
- introduction of special sleeve in the protective grid, which permits to fasten a bundle against radial displacements in its upper part;
- introduction of slots, located at different height marks of the central tube, permits to exclude distortion and destruction of spacing grids as a result of increase of fuel rod temperature;
- installation of filters at the inlet. According to design considerations with due regard for statistics of damage of fuel assemblies the filters will be mounted at the working assembly (WA) inlet.

In fuel assemblies of new generation the problem of decrease of local flash-up of neutrons in the WA peripheral fuel rods, surrounding the CPS FAs, in the region of FA-and-absorber rod butt joint due to arrangement of hafnium plates in the upper part of FA casing was also solved.

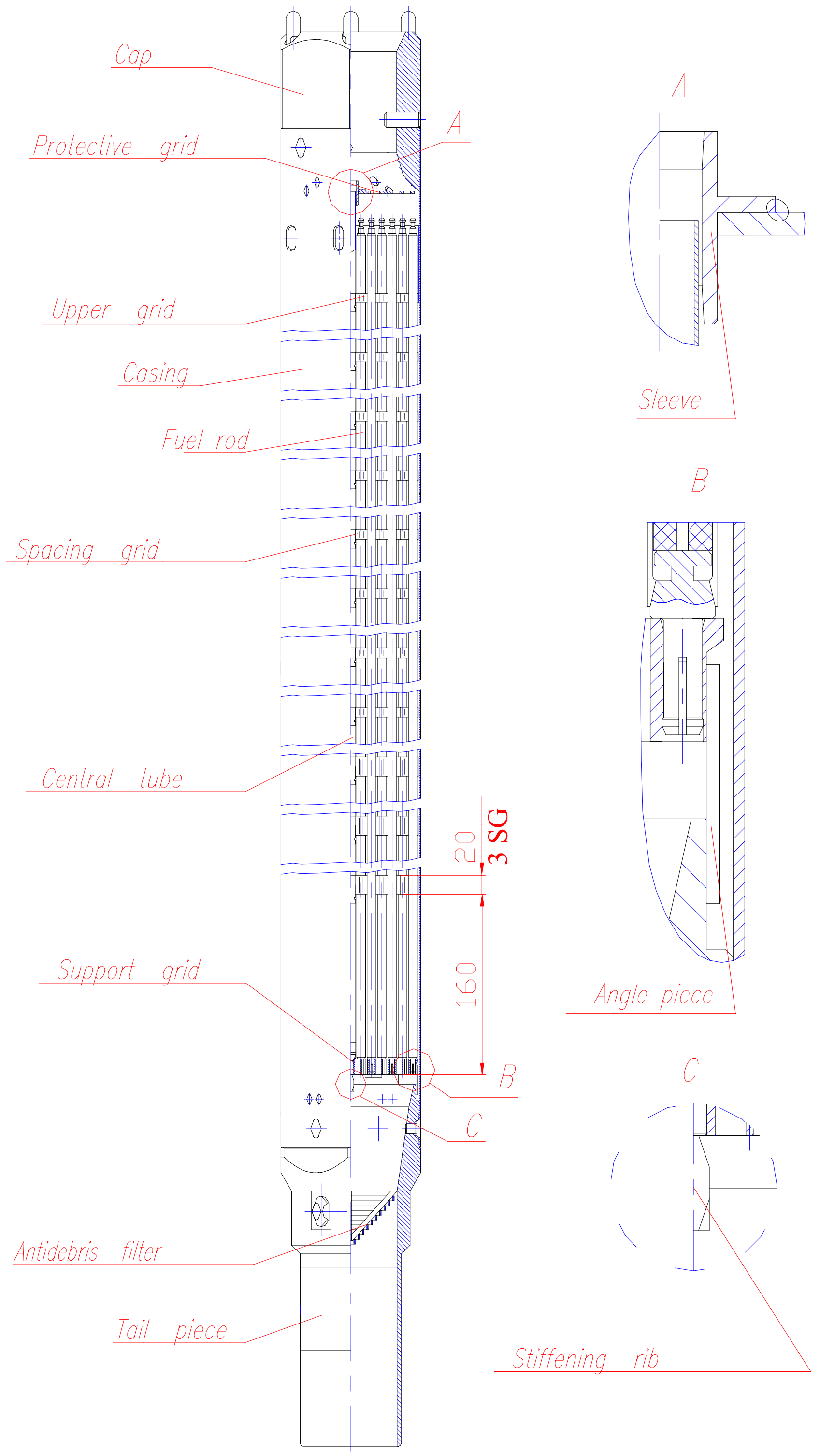

Figure 1 - Working assembly of new generation

2. Operational experience of fuel assemblies with separate structural solutions

In designing the fuel assemblies of new generation the following engineering solutions earlier justified and confirmed by results of trial operation were used:

- utilization of uranium-gadolinium fuel and fuel operation within six fuel cycles;
- attachment of fuel rods in the support grid with the help of elastic tip;
- redistribution of spacing grids along the height of fuel bundle;
- use of hafnium absorber in ERC assembly butt joint.

2.1. Utilization of uranium-gadolinium fuel and fuel operation within six fuel cycles

As it was noted, increase of cost-effectiveness of fuel utilization is a permanent requirement. In this connection, the Russian specialists for a long time conduct operations concerned with adoption of the advanced fuel cycles on the basis of non-profiled fuel with enrichment in 4,4 % and of the profiled fuel (working assemblies with profiled average enrichment in 4,4 % and presence in them of six gadolinium fuel rods with the burnable absorber, integrated in a fuel, Gd_2O_3). As a result of these operations the great experience of fuel operation within five years and more, and also operational experience of fuel assemblies with uranium-gadolinium fuel has been gained.

So, beginning from 1991, at Kola NPP, Unit 3 the fuel assemblies with enrichment in 4,4 % of the standard structure have been remained for the fifth year of operation. By 2003 at Kola NPP, Unit 3 two hundred and seventy six fuel assemblies with enrichment in 4,4 % have passed the five-year cycle of operation.

According to results of justification performed in 2001, twelve working assemblies with enrichment in 4,4 % with anticipated burn-up of about 59 MWday/kg were remained for the sixth year of operation. By the moment of unloading (2002) the time of their operation in the reactor was 1871,4 eff. days, achieved averaged burn-up across fuel assembly was about 56,44 MWday/kg.

In 1998 at Kola NPP, Unit 4 application of the universal five-year fuel cycle with use of the working assemblies with average enrichment in 4,4 % with uranium-gadolinium fuel (repetition factor of WA reloading – 4,72, the number of WAs of annual fuel makeup – 66, maximum burn-up across assemblies – 53,9 MWday/kg, average duration of fuel cycles – 336,2 eff.day) was started. In 2004 the power unit has reached the steady-state conditions.

2.2. Attachment of fuel rods in the support grid with the help of elastic tip

The greatest operational experience of fuel assemblies with attachment of fuel rods in the support grid with the help of elastic tip in the form of split sleeve is obtained at NPP “Loviisa”. Reliability of the design of improved attachment unit of fuel rods in the lower grid is confirmed by the results of investigations of two irradiated WAs of dismountable structure # 73856634 and # 73856631 in 2002, which have operated at NPP “Loviisa” within three years and were unloaded from the core in 2001. The obtained values of withdrawal forces of fuel rods from 430 to 540 N testify to a reliable fixation of fuel rods in the bundle and possibility of withdrawal of defective fuel rod.

2.3. Redistribution of spacing grids along the height of fuel bundle

2.3.1. At the power units of NPP “Kozloduy” in the late nineties a significant level of loss of integrity of fuel rods of the working assemblies of base version was observed. For the purpose of solving the given problem it was offered to apply vibration-proof WAs, manufactured at JSC “NZKhK”, at NPP “Kozloduy”, wherein such a component of vibration stability was introduced in them as a shift of the first spacing grid towards the support grid by a distance of 80 mm (instead of 196 mm of the base version manufactured at JSC “NZKhK”).

The realization of only this solution in the design of WWER-440 assemblies has permitted to a considerable extent to solve the problem with increased loss of integrity of fuel at power units of NPP “Kozloduy” (V-230 type).

2.3.2. The trial operation of three vibration-proof WAs with redistributed SGs along the height of fuel bundle and with the rigid attachment of fuel rods (flattened tip) in the support grid was completed in the core of NVNPP, Unit 3. In the presented assemblies an attachment of the central tube in the support grid by welding was also realized.

The fuel assemblies were loaded into the core of power unit during PM-1999 as a part of the 26-th fuel loading and have passed the trial operation during the 26-th, 27-th and 28-th fuel cycles.

According to the program of the reactor tests of test assemblies on completion of each fuel loading (during PM) the leak check of fuel rod claddings of the given assemblies was performed. All fuel assemblies are leak-tight.

The scope of the reactor tests in full measure has confirmed serviceability of the given vibration-proof WAs. The test results permit to recommend the presented design for commercial operation as a part of WWER-440 core. However, considering the requirements for dismountable structure of fuel bundle, in the design of fuel assemblies of new generation the fastening element of fuel rods in the support grid with the help of the flattened tip was not applied.

2.3.3. At JSC “MSZ” there were manufactured 24 vibration-proof WAs with SGs redistributed along the height of fuel bundle (distance from the first SG to the support grid is reduced to 80 mm) and with the rigid attachment of fuel rods in the support grid (in the design of fuel assemblies of new generation the given fastening element was not applied), which operate in the core of NV NPP, Unit 3 since PM-2002.

2.4. Use of hafnium absorber in ERC assembly butt joint

In the course of reactor operation the CPS working group is lowered a little and the upper areas of CPS FAs initiate the excursion of power in the peripheral fuel rods of the working assemblies surrounding the CPS working group. To suppress the specified excursions of power in FA of ERC assembly, six hafnium plates (by ones per a side) of 0,6 mm thick are placed on the internal surface of casing from the upper face of column in the fuel rod up to the lower face of FA cap. The attachment of plates to the casing is provided by spot welding.

In 2000 the first experimental FA batch of ERC assemblies (12 FAs) with modernized butt joint (MBJ) was placed at NVNPP, Unit 4. By present moment the given batch of FAs is unloaded from the core on termination of service life. The fuel rods of all FAs have kept their tightness. For the period of operation of these FAs as a part of the control group from the number of working assemblies surrounding the given CPS FAs, only a single leaking assembly was revealed, and its leakage is not related to the location of fuel assembly in the core.

At present, FAs with modernized butt joint operate at NVNPP, Unit 3, at Kola NPP, Units 2 and 3, NPP “Dukovany”, NPP “Bohunice” and NPP “Mochovce”.

The results of operation of FAs with modernized butt joint prove the validity of made decision.

3. Operation experience of new generation assemblies for WWER-440 units of V-213 type

Design of new generation assemblies for power units of V-213 type has involved all the above-stated decisions. Its basic characteristics are given in reference /1/.

Adoption of the improved five-year fuel cycle with a part of WAs remained for the sixth year of operation on the basis of a new fuel started at Kola NPP, Unit 3 in the 18-th f.c. since PM-2004. The first batch involved 54 WAs and six ECR FAs.

During PM-2003 (19-th f.c.) the second batch of a new fuel consisting of 54 WAs and 12 FAs was placed into the core of Kola NPP, Unit 3, and the third batch consisting of 60 WAs and six FAs was installed during PM-2004 (20-th f.c.).

The duration of fuel cycles amounted: 18-th f.c. - from 15.09.02 till 14.07.03 (302 cal.days); 19-th f.c. – from 12.09.03 till 28.07.04 (320 cal.days); 20-th f.c. - from 01.09.04 till 18.07.05 (320 cal.days). Thus, the assemblies of the first experimental batch have worked in the reactor core 942 cal.days, and total service life of the given assemblies was 1037 cal.days. In this case the burn-up fraction in the maximum burnt out fuel assembly was about 31,2 MW.day/kgU.

The most important neutron-physics and thermal-hydraulic characteristics of fuel assemblies of new generation obtained during physical experiments at MCL and by the results of their operation are presented in Tables 1, 2.

Table 1 – Results of the in-core monitoring in reaching MCL at Kola NPP, Unit 3 (data for fuel assemblies of new generation for WWER-440 units of V-213 type)

Parameter	Date of measuring			Setpoint
	08.10.02 18-th f.c.	27.10.03 19-th f.c.	17.01.05 20-th f.c.	
Nth, MW (% Nnom)	1310 (~95)	1373 (~100)	1373 (~100)	1375
Kq^{max}	1,35	1,33	1,38	Kq^{max}≤1,42 Nnom/Ncur≤1,5
$(KqKk)^{max}$	1,51	1,51	1,51	$(KqKk)^{max}$≤1,61 Nnom/Ncur≤1,75
Kv^{max}	1,62	1,74	1,57	Kv^{max}≤1,97 Nnom/Ncur≤2,5
Nass., MW	5,44	5,50	5,75	≤6,17
$Nf.r.^{max}$, kW	46,8	49,0	50,3	≤56,6
Ql^{max}, MW	275	296	267	≤325
Tout, ^oC	307,7	307,6	309,3	317
$\Delta tass.^{max}$, ^oC (central cells)	42,1	43,2	44,5	44,9

Table 2 - Results of processing of experimental data in comparison with the calculated ones at MCL of Kola NPP, Unit 3 (after PM-2004)

Characteristic	Values		Reached concurrence (success criterion)	Conditions	
	calcu-lation	experi-ment		experiment	calculation
Critical boric acid concentration, g/kg	7,56	7,3	-3,3% (±10%)	$T_{1c}=256^oC$ H_6=100cm	$T_{1c}=260^oC$ H_6=100cm
Temperature coefficient of reactivity, $(\%/^oC)x1000$	-13,35	-15,8	negative (negative)	$T_{1c}=(255-258)^oC$ H_6=150cm	$T_{1c}=260^oC$ H_6=150cm
Worth of CPS control group, %	1,06	1,07	1,0% (±15%)	$T_{1c}=260^oC$ H_6=(100-210)cm	$T_{1c}=260^oC$ H_6=(100-210)cm
Efficiency of mechanical CPS in the mode of emergency protection without control rods, %	7,29	8,37	more than 0,85 (not less than 0,85 of the calculated)	$T_{1c}=260^oC$ H_6=210cm	$T_{1c}=260^oC$ H_6=210cm

As it is seen from Tables 1 and 2, the test results at MCL and trial operation have confirmed adherence to the conditions and limits of safe operation of the new fuel, and also have shown a high level of concurrence of the calculated and experimental data.

During operation of the new fuel at Kola NPP, Unit 3 the reactor scram didn't take place, the number of conditions of power variation is less than justified in the design of WWER-440 fuel assemblies.

However, it is necessary to note, that in connection with the requirements of electric power consumers in the district, the power units of Kola NPP are compelled to work in the mode of dispatcher restriction of power (example of the curve of variation of thermal power of power unit is given in figure 2), in this case the fuel operation at power units of Kola NPP is characterized by a large amount of variations of reactor power in the hot state at the rate of not more than 0,05 %/s by a value from 10 up to 50 % and for one fuel cycle can amount to approximately from 30 up to 50.

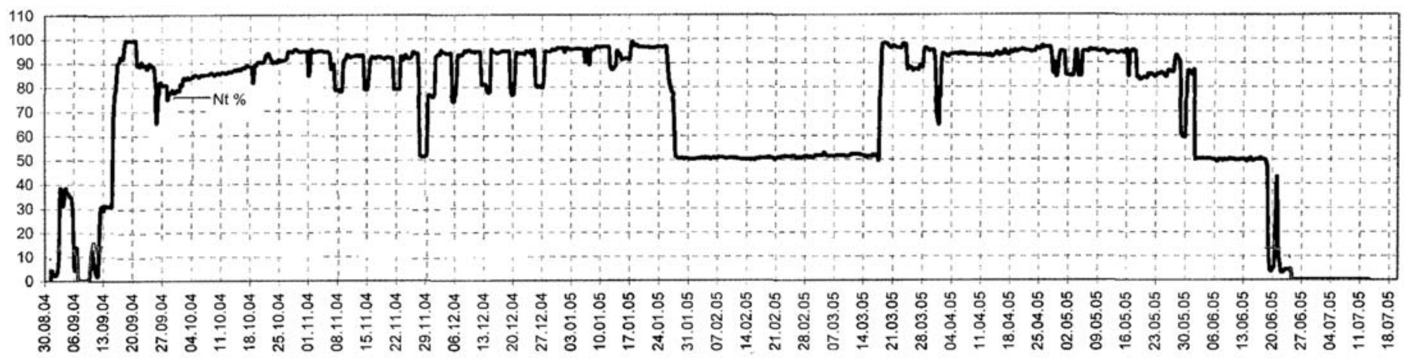

Figure 2 – Curve of thermal power variation at Kola NPP, Unit 3 during the 20-th fuel cycle.

Specific activity of the primary coolant during the 18-th, 19-th and 20-th fuel cycles (with fuel assemblies of new generation) by the sum of iodines did not exceed the limits of safe operation $2x10^{-3}$ Ci/kg (figure 3 gives the data of measuring a specific activity of coolant for the 18-th fuel cycle).

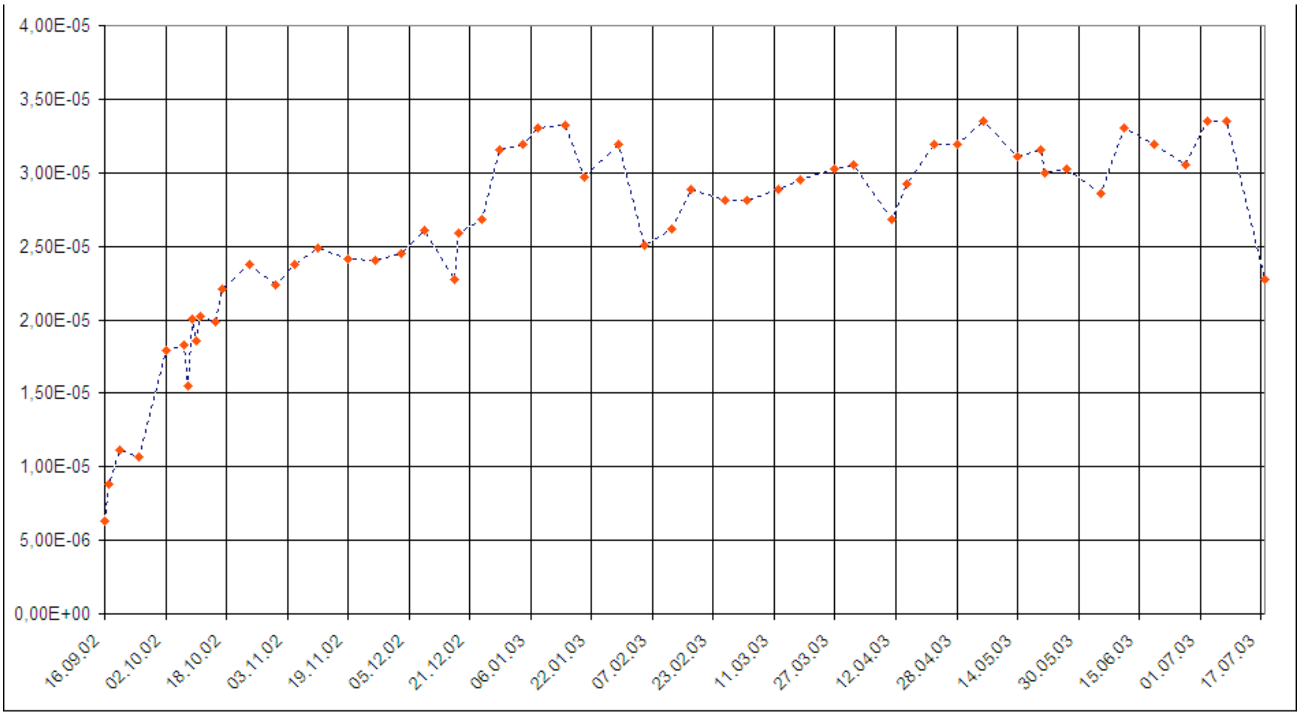

Figure 3 – Data of measuring a specific activity of coolant at Kola NPP, Unit 3 during the 18-th fuel cycle

The leaking fuel assemblies of new generation by the results of operation have not been detected.

The important factor in adoption of the new fuel is its neutron-physics and thermal-hydraulic compatibility with a standard fuel. The results of trial operation of the new fuel at Kola NPP, Unit 3 prove, that in adoption of the new fuel its compatibility with the standard fuel is ensured and the operational limits for standard fuel are not violated (Table 3).

Table 3 – Results of the in-core monitoring in reaching MCL at Kola NPP, Unit 3 (data for the standard fuel)

Parameter	Date of measuring			Setpoint
	08.10.02 18-th f.c.	27.10.03 19-th f.c.	17.01.05 20-th f.c.	
Nth, MW (% Nnom)	1310 (~95)	1373 (~100)	1373 (~100)	1375
Kq^{max}	1,37	1,30	1,13	$Kq^{max} \leq 1,35$ Nnom/Ncur≤1,5
$(KqKk)^{max}$	1,57	1,54	1,26	$(KqKk)^{max} \leq 1,55$ Nnom/Ncur≤1,75
Kv^{max}	1,62	1,74	1,57	$Kv^{max} \leq 1,9$ Nnom/Ncur≤2,5
Nass., MW	5,44	5,50	5,75	≤5,95
$Nf.r.^{max}$, kW	48,6	50,3	40,9	≤54,5
$\Delta tass.^{max}$, ^{o}C (central cells)	42,4	42,4	36,4	42,8
Note - the rest data are presented in Table 3				

During PM-2005 the first batch of fuel assemblies of new generation is installed at Kola NPP, Unit 4.

4. Operation experience of vibration-proof assemblies of new generation for WWER-440 units (V-230 type)

The operating conditions of a fuel in V-230 type reactors are more stringent, than in the subsequent series V-213. They are reached by increased flow rates, less ideal hydrodynamics of the flowing path, presence of large amount of corrosion products.

Proceeding from these conditions, in the design of new generation WA for the presented reactors there are used, in the main, the structural solutions aimed at increasing vibration stability of fuel rod bundle.

Considering this, specific feature of the presented WAs as distinct from the assemblies of new generation for the power units of WWER-440 (V-213) consists in application of fuel rods of 9,1 mm in diameter of the standard length without the increased fuel loading, and, hence, standard tail-piece of fuel assembly and decreased pitch of SG arrangement along the bundle height (80 mm - up to the first SG, 240 mm - between SGs).

During PM-2004 sixty six vibration-proof WAs of new generation were placed into the core of Kola NPP, Unit 2 (V-230).

During start-up and in the course of operation the calculated neutron-physics characteristics of new fuel are verified (Tables 4, 5). Violation of the limits and conditions of safe operation during tests was not observed. Specific activity of the primary coolant in the 27-th fuel cycle (with vibration-proof WAs) during operation at power of about 95 % Nnom by the sum of iodines didn't exceed the limit of safe operation. With adoption of fuel assemblies of new generation a tendency to decrease specific activity is observed.

In future it is planned to change over the power unit to operation with the core completely filled with vibration-proof WAs of new generation for WWER-440 power units of V-230 type.

Table 4 – Results of the in-core monitoring in reaching MCL at Kola NPP, Unit 2 after PM-2004 (data for vibration-proof WAs)

Parameter	Date of measuring				Setpoint
	01.02.05	02.02.05	03.02.05	04.02.05	
Nth, MW (% Nnom)	1370 (99,6)	1375 (100)	1368 (99,5)	1374 (99,9)	1375
Kq^{max}	1,34	1,34	1,34	1,35	Kq^{max}≤1,36 Nnom/Ncur≤1,5
$(KqKk)^{max}$	1,48	1,48	1,48	1,47	$(KqKk)^{max}$≤1,48 Nnom/Ncur≤1,75
Kv^{max}	1,26	1,26	1,26	1,26	Kv^{max}≤1,94 Nnom/Ncur≤2,5
Nass., MW	5,86	5,54	5,52	5,57	≤6,58
Ql^{max}, MW	246	247	246	246	≤325
Tout, ^{o}C	311,1	311,3	311,0	311,8	315
$\Delta tass.^{max}$, ^{o}C	43,32	43,58	43,41	43,68	45,2

Table 5 - Results of processing of the experimental data in comparison with the calculated ones at MCL at Kola NPP, Unit 2 after PM-2004

Characteristic	Values		Reached concurrence (success criterion)	Conditions	
	calculation	experiment		experiment	calculation
Critical boric acid concentration, g/kg	9,2	9,3	1,08% (±10%)	T_{1c}=261,3^{o}C H_6=100cm	T_{1c}=260^{o}C H_6=100cm
Temperature coefficient of reactivity, (%/^{o}C)x1000	(δρ/δt H_2O) -(4,2-5,8) (δρ/δt U) -3,1	-6,5	negative (negative)	T_{1c}=(256,8-258,8)^{o}C H_6=100cm	$T1_c$=(255-265)^{o}C H_6=100cm
Worth of CPS control group, %	1,06	1,11	4,7% (±15%)	T_{1c}=(260,5-259,6)^{o}C H_6=(100-210)cm	T_{1c}=260^{o}C H_6=(100-210)cm
Efficiency of mechanical CPS in the mode of emergency protection without control rods, %	8,0	8,3	3,75% (not less than 0,85 of the calculation)	$T_{1к}$=259,2^{o}C H_6=210cm	$T_{1к}$=260^{o}C H_6=210cm

3. Conclusion

The complex of activities related to modernization of WA and ECR FA of WWER-440 has permitted to develop a new generation fuel for V-213 type reactors, which has a significantly improved economy and reliability, and also to introduce some improvements in WA design for power units of WWER-440 of V- 230 type, permitting to a significant extent to enhance vibration stability of fuel rod bundle.

The correctness of solutions, laid down in the design of fuel assemblies of new generation, is successfully confirmed by the results of trial operation.

It is planned to apply the fuel of new generation for WWER-440 reactors of V-213 type at power units of NPP “Dukovany” (Czechia) in 2005, and in 2006 at NPP “Mochovce” and at power units 3, 4 of NPP V-2 “Bohunice” and (Slovakia).

In 2007 it is planned to extend an application of vibration-proof working assemblies of new generation for power units of V-230 type at Kola NPP, Unit 1.

References

1. *I. Vasilchenko, Yr. Ananyev* “Status and Future Perspectives of PWR and Comparing Views on WWER Fuel Tehnology”. Proceedings of the Fifth International Conference “WWER Fuel. Performance, Modelling and Experimental Support”, 29 September – 3 October 2003, Albena, Bulgaria.

List of abbreviations accepted

cal.day	-	calendar day
LCC	-	leak check of cladding
CPS	-	control and protection system
eff.day	-	effective day
ERC	-	emergency, regulating, compensating
f.c.	-	fuel cycle
f.r.	-	fuel rod
FA	-	fuel assembly
MBJ	-	modernized butt joint
MCL	-	minimum controlled level of power
NPP	-	nuclear power plant
Nth	-	thermal power
Ncur	-	current power
NVNPP	-	Novo-Voronezh NPP
PM	-	preventive maintenance
SG	-	spacing grid
Tout	-	outlet temperature
T_{1c}		temperature of the primary circuit
Δtass		temperature difference in assembly
WA	-	working assembly
WWER	-	water-cooled water-moderated power reactor