Development of WWER-440 fuel. Use of fuel assemblies of 2-nd and 3-d generations with increased enrichment

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1. Introduction

he problem of increasing the power of units at NPPs with WWER-440 is of current importance. There are all the necessary prerequisites for the above-stated problem as a result of updating the design of fuel assemblies and codes.

he decrease of power peaking factor in the core is achieved by using profiled fuel assemblies, fuel-integrated burning absorber, FAs with modernized docking unit, modern codes, which allows decreasing conservatism of RP safety substantiation.

wide range of experimental studies of fuel behaviour has been performed which has reached burn-up of (50-60) MW·day/kg·U in transition and emergency conditions, post-reactor studies of fuel assemblies, fuel rods and fuel pellets with a 5-year operating period have been performed, which prove high reliability of fuel, presence of a large margin in the fuel pillar, which helps reactor operation at increased power.

he results of the work performed on introduction of 5-6 fuel cycles show that the ultimate fuel state on operability in WWER-440 reactors is far from being achieved. Neutron-physical and thermal-hydraulic characteristics of the cores of working power units with RP V-213 are such that actual (design and measured) power peaking factors on fuel assemblies and fuel rods, as a rule, are smaller than the maximum design values. This factor is a real reserve for power forcing.

here is experience of operating Units 1, 2, 4 of Kola NPP and Unit 2 of Rovno NPP at increased power. Units of Loviisa NPP are operated at 109 % power.

During transfer to work at increased power it is reasonable to use fuel assemblies with increased height of the fuel pillar, which allows decreasing medium linear power distribution.

2. WWER-440 second generation fuel assemblies

2.1 This technical solution (extension of the fuel pillar in the fuel rod) was implemented during development of second generation fuel design for WWER-440 units of V-213 type (Fig.1). Such solutions as optimization of water-uranium ratio (due to increase of the pitch of fuel rod location in the bundle from 12,2 mm to 12,3 mm) (Fig.1), decrease of harmful neutron absorption (due to decrease of hafnium content in zirconium materials from 0,05% to 0,01% and decrease of the amount of zirconium during transfer to the thickness of ERC FA cladding – 1,5 mm) have been implemented together with fuel load increase.

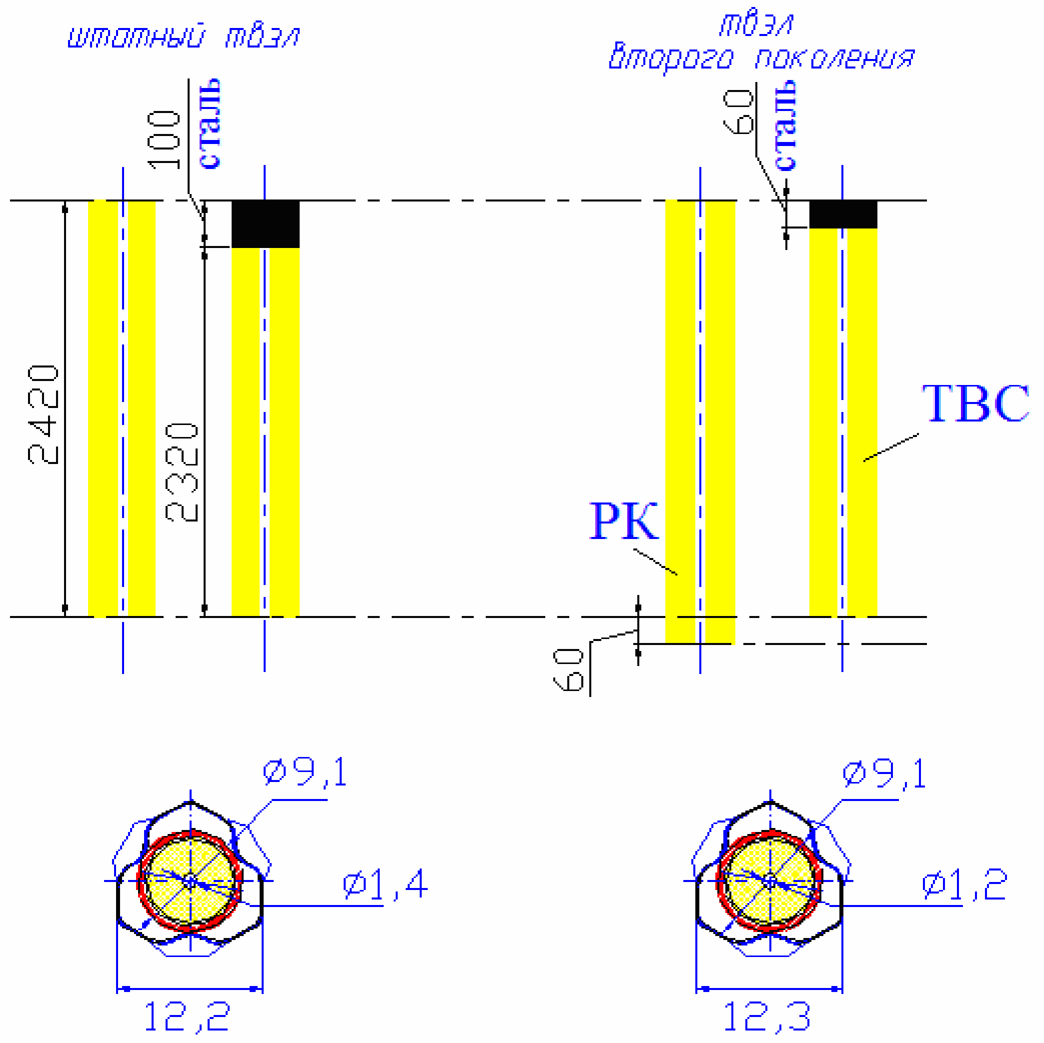


Fig. 1 – Parameters of WWER-440 FA fuel pillar

2.2 Fuel pillar extension required remaking of the WA mechanical design. The parallel problem was increase of WA vibration stability on the basis of the following justified technical solutions (Fig. 2):

- relocation of spacing grids along the fuel rod bundle and increase of the height of the first three grids along the coolant course;
- introduction of the new resilient fuel rod top nozzle;
- introduction of the propping rib under the WA support grid and fastening of the central tube in the support grid with help of welding;
- introduction of a special sleeve in the protective grid, which allows fastening the bundle against radial movements in its upper part;
- introduction of uneven slots on the central tube makes it possible to exclude spacing grid deformation and damage due to fuel rod temperature increase.

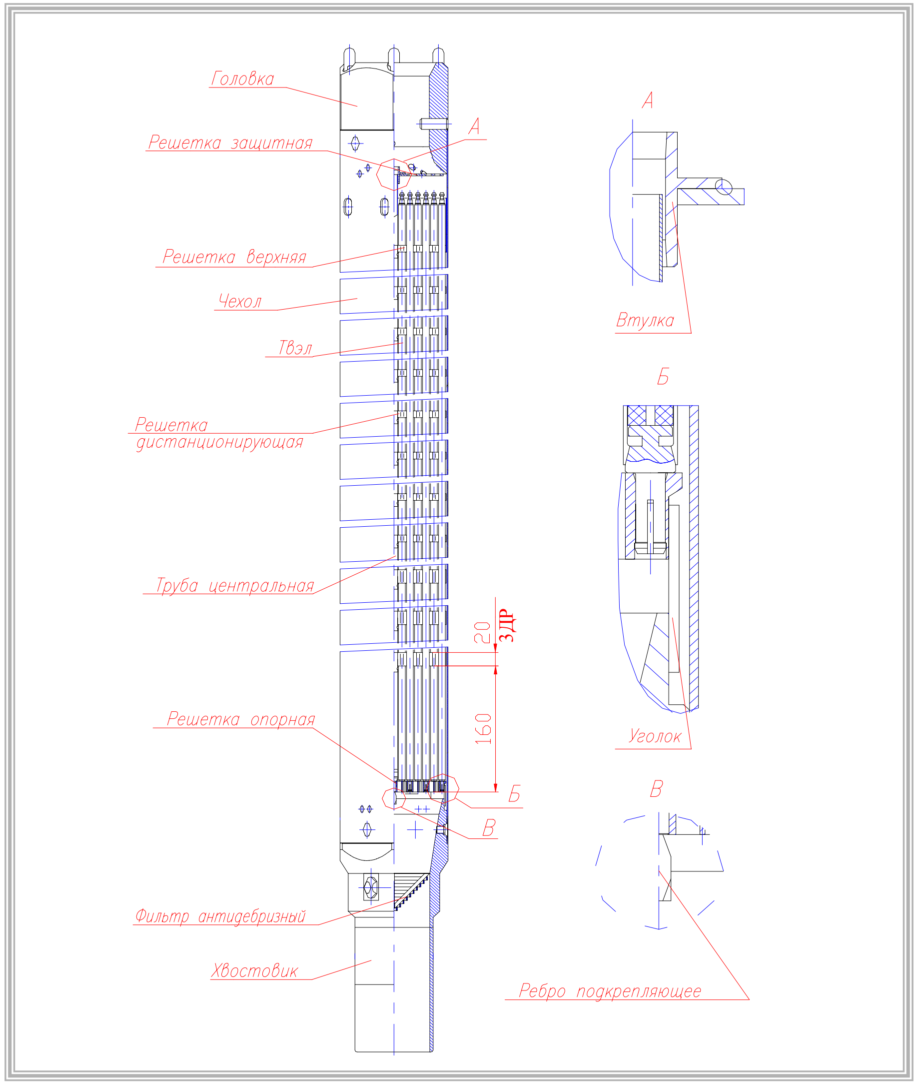


Fig. 2 – Second generation fuel assembly

Introduction of the way of fuel rods fastening in the support grid with help of the resilient top nozzle and change of the angle of cladding fastening to the bottom nozzle in WA ensure operability of the assembly of this design.

2.3 A project of introduction of a five-year fuel cycle with leaving a part of assemblies for the sixth year of operation at NPP with V-213 WWER-440 was developed on the basis of fuel assemblies with modernized design using profiled fuel with average enrichment of 4,25 % (with gadolinium absorber) in WA and 3,82 % in FA.

his project was developed for RP nominal power of 1375 MW as applied to Unit 3 of Kola NPP, and later redeveloped for a number of other units of NPP with WWER-440 in Russia and abroad (Unit 4 of Kola NPP, Dukovany NPP, Mohovce NPP and Bohunice V-2 NPP).

econd generation fuel of WWER-440, except Unit 3 of Kola NPP, was commissioned at a number of other units of NPP with WWER-440 in Russia and abroad by the beginning of 2009 (Table 1).

Table 1

NPP	Unit	Year of commissioning second generation fuel assemblies
Kola NPP	4	2005
Dukovany NPP	3	2005
Dukovany NPP	1,2, 4	2006
Mohovce NPP	1, 2	2006
Bogunice V-2 NPP	3, 4	2006

2.4 The maximum experience of second generation FA operation for WWER-440 units was obtained by the beginning of 2008.

The core of Unit 3 of Kola NPP is practically fully completed with second generation assemblies during the 22-nd fuel cycle (Table 2), except 32 WA of regular design loaded in 2001.

Table 2

No. of fuel load (PM)	Number of WAs	Number of FAs
18 (PM-2002)	53	1
19 (PM-2003)	53	12
20 (PM-2004)	60	6
21 (PM-2006)	54	12
22 (PM-2007)	60	6

he core of Unit 3 was fully completed with second generation fuel assemblies during the 23-d fuel loading.

he duration of unit operation during 18-22 fuel cycles is shown in Table 3.

able 3

Fuel cycle	Date of beginning	Date of ending	Duration, eff.days
18	15.09.2002	18.07.2003	286
19	12.09.2003	26.07.2004	263,4
20	01.09.2004	07.03.2006	335,1
21	12.04.2006	29.03.2007	268,1
22	18.06.2007	01.03.2009	162,1
22 пп	27.04.2008	01.03.2009	175

Thus, by the end of the 22-nd fuel cycle (after intermediate fuel rearrangement) the second generation fuel assemblies of the first pilot lot worked for 1490,1 eff.days in the reactor core. The burnup depth in the maximum burnt FA was 43,84 MW·days/kgU, and by the end of the 22-nd fuel cycle (after five years) the burnup depth in the maximum burnt FA should be ~50,5 MW·days/kgU (according to the preliminary calculations the burnup depth in the maximum burnt FA will be ~52 MW·days/kgU after six years).

n the loads considered with the reactor working the maximum values of total specific activity of the primary coolant on nongaseous fission products for two hours after sampling were at a level considerably lower than the criterion of mandatory LCC of fuel rods in a tripped reactor of all FAs operated in the core.

o fuel assemblies were detected which fell under the criterion of individual culling (failure criterion) for the whole period of pilot operation of second generation fuel assemblies by the results of LCC of fuel rods in the unit at a tripped reactor.

he results of the in-core inspection during power development at Unit 3 (Table 4) and pilot operation confirmed observance of the conditions and limits of safe operation of second generation fuel.

Table 4 – Results of in-core inspection during power development at Unit 3 of Kola NPP (selected data for second generation fuel assemblies for WWER-440 units)

Parameter	Date of measurement					Setting
	08.10.2002 18 т.ц.	27.10.2003 19 т.ц.	17.01.2005 20 т.ц.	18.04.2006 21 т.ц.	01.10.2007 22 т.ц.	
$N_Т$, MW (% N_{nom})	1310 (~95)	1373 (~100)	1373 (~100)	1375 (100)	1370 (~100)	1375
Kq^{max}	1,35	1,33	1,38	1,35	1,37	$Kq^{max} \leq 1{,}42\ N_{ном}/N_{тек} \leq 1{,}5$
$(KqKk)^{max}$	1,51	1,51	1,51	1,45	1,48	$(KqKk)^{max} \leq 1{,}61\ N_{ном}/N_{тек} \leq 1{,}75$
$N_{касс}$, МВт	5,44	5,50	5,75	5,59	5,65	≤6,17
$N_{твэл}^{max}$, кВт	46,8	49,0	50,3	47,2	47,9	≤56,6
Ql^{max}, Вт/см	275	296	267	270	259	≤325
$T_{вых}$, °C	307,7	307,6	309,3	311,3	311,8	317

he results of pilot operation of the new fuel at Unit 3 of Kola NPP show that during introduction of second generation fuel the operation limits for the regular fuel are not violated, which proves compatibility of the new and regular fuel.

3. The state and prospects of work on fuel

3.1 The further step of second generation fuel development is a transfer to increase of fuel enrichment in WA and FA, the third generation fuel rods being the most prospective ones, fundamentally different from the second generation fuel rods in further increase of fuel loading (Table 5) implemented due to:

• exception of the central hole in the fuel pellet;

• increase of the fuel pellet diameter.

Table 5 – Comparative characteristics of the second and third generation fuel rods

Parameter	Value	
	Fuel rod (gadolinium fuel rod) of the second generation	Fuel rod (gadolinium fuel rod) of the third generation
Fuel rod cladding outside diameter, mm	9,1	
Fuel rod (gadolinium fuel rod) cladding inside diameter, mm	7,73	7,93 (7,73)
Fuel pellet outside diameter, mm	7,6	7,8 (7,6)
Diameter of the central hole, mm	1,2	Non-available (1,2)
Nominal mass of uranium dioxide in the fuel rod (gadolinium fuel rod, considering gadolinium dioxide), g - WA - FA	 1141 1085	 1230 (1141) 1170 (1085)
Height of the fuel pillar, mm - WA - FA	 2480 2360	
Fuel rod (gadolinium fuel rod) length, mm - WA - FA	 2601,5 2540	

ix versions of fuel cycle as applied to Unit 3 of Dukovany NPP and work at power of 105 % N_{nom} (1444 MW) are considered for the comparative analysis:

version 1

verage fuel enrichment in WA was 4,87%, in FA - 4,65% (second generation fuel rods were used), refueling was in compliance with the introduction project for power of 105% (1444 MW) [1].

akeup was performed with 60 WAs and 12 FAs during the odd loading in this fuel cycle, and with 66 WAs and 6 FAs during the even loading. Among them 6 WAs work in 6 loads, the other WAs work in 5 loads. FAs work in four loads, one in five loads.

he duration of the even load work was $T_{чет}$=356,7 days, of the odd one - $T_{нечет}$=353,8 days. The averaged order of refueling was n=4,85.

version 2

he average fuel enrichment in FA and WA was 4,87% (second generation fuel rods are used). Refueling is in line with [2]. Makeup consisted of 54 WA and 6 FA, refueling order was n=5,82. In this fuel cycle 12 WAs work in five loads, 42 WAs РК work in six loads, FAs work in six loads, and one of them works in seven loads.

he duration of work of a stationary fuel load was $T_{эф}$=306,4 days.

version 3

he average enrichment, refueling, number of makeup assemblies are the same as in the first version. Fuel rods with decreased cladding thickness ($\Delta_{об}$=0,57 mm, outside diameter is 8,9 mm) and those having second generation pellets are used.

he duration of the stationary fuel load was 311,4 days.

version 4

he same fuel rods as in the first version are used, but without the central hole in fuel pellets, and the mass of the fuel pillar valuations of economy of the considered versions of fuel cycles in comparison with the existing fuel cycle taken as the basic one are given in Table 6.

able 6 – Characteristics of economy of fuel cycles

Version	Number of makeup assemblies, pcs		n	$T_{эфф}$, days	$У_{u\ ест}$, $\frac{kgU}{MW \cdot days}$	$У_{epp}$, $\frac{epp}{MW \cdot days}$	$У_{эф}$, $\frac{MW \cdot h}{\$}$	$У_{э\ U}$, $\frac{MMW_{эл} \cdot h}{kgU}$	B, $\frac{MW \cdot days}{kgU}$
	WA	FA							
Basic	63	9	4,85	324,1	0,1911	0,1154	0,7816	397,4	51,76
1	63	9	4,85	355,3	0,1949	0,1216	0,7723	435,5	56,72
2	54	6	5,82	306,4	0,1896	0,1185	0,7940	450,2	58,64
3	54	6	5,82	311,4	0,1866	0,1166	0,8070	457,6	59,59
4	54	6	5,82	321,4	0,1868	0,1167	0,8061	457,1	59,52
5	54	6	5,82	328,7	0,1909	0,1192	0,7889	447,3	58,25
6	48	6	6,46	300,2	0,1880	0,1174	0,8009	454,2	59,15

he following prices are considered in the assembly cost:

rice of natural uranium– 50 $/kg;

rice of separating work- 110 $/epp;

ost of fuel fabrication – 312,5 $/kg

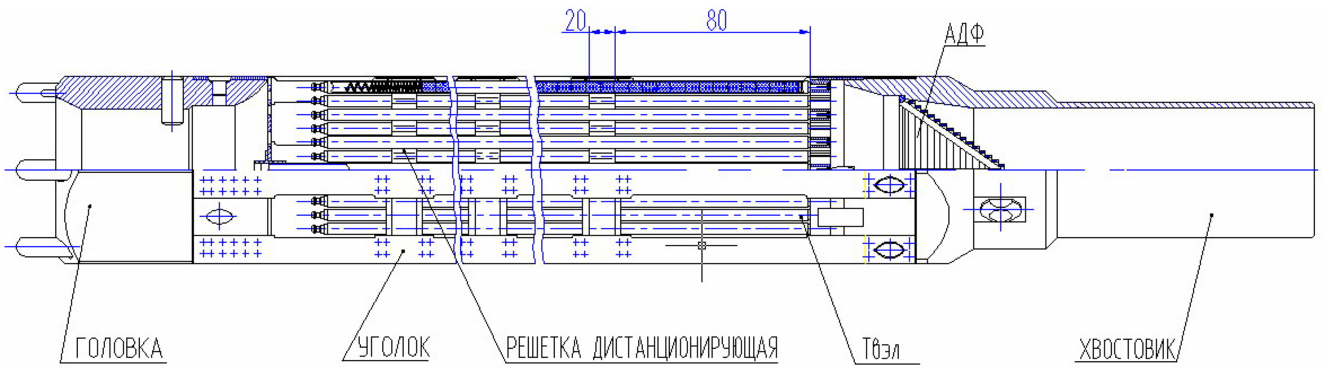
The data given in the Table show that increase of makeup fuel enrichment without decrease in the number of makeup assemblies (refueling order has not changed) leads to an increase of specific consumption of natural uranium and cost of separation work, as well as to decrease of energy production for 1$ spent on purchase of assemblies (version 1 in comparison with the basic one).

Use of second generation assemblies with third generation fuel rods of increased enrichment and increase in refueling order (decrease in the number of makeup assemblies to 54) increases specific energy production for 1$ spent on purchase of assemblies by 1 %. Specific energy production for kg of fuel and depth of its burnup increases by ≈ 12,5%.

In order to increase economy the fuel cycle from version 5 is recommended, in which 54 second generation makeup assemblies are used with third generation fuel rods of average enrichment of 4,87%. Besides the above-stated advantages this fuel cycle increases effective capacitance of the storehouse.

However, the most prospective is **version 4**, which may be implemented while making a fuel rod with outside diameter of 8,9 mm, cladding thickness of 0,57 mm, with second generation pellets.

3.2 The alternative version of fuel development for NPP with V-213 WWER-440 is making and introduction of third generation assemblies (RK-3), different from the second generation assemblies in using a corner frame instead of cladding (Fig.3).



ig. 3 –Working assembly of third generation

Basic design for the complex of VVER-440 fuel assemblies of the third generation is aimed at enhancement of fuel consumption economic efficiency and consumer qualities of fuel assemblies with ensuring of safe operation. The following design solutions are provided in RK-3 design for this purpose:

- increase of fuel rod pitch in the bundle;
- sheathless FA with the frame of 6 angles and three bearing tubes;
- increase of fuel rod clad internal diameter and fuel pellet diameter;
- non-availability of central hole in fuel rod pellets;
- introduction of SG optimized arrangement and number;
- spacing grids of vaulted type and increased height;
- introduction of new shape for spillage slots of "daisy" type in the supporting grid;
- increase of the stroke of spring-loaded pins in the top nozzle.

RK-3 are purposed for operation in VVER-440 type reactors V-213 with six-year fuel life and possibility to keep a number of FA in the core for the seventh year of operation.

Fuel cycle with the following parameters is calculated in RK-3 basic design - 24 RK-3 and five FA are unloaded on completion of six fuel cycles in steady-state operating conditions, and 24 RK-3 and one FA – on completion of seven fuel cycles. Annual core additional charge is 48 RK-3 and 6 FA.

Experimental study and calculation analysis are provided to prove safety operation of assumed RK-3 design. The scope of experimental study assumes RK-3 model bench hydraulic, life and vibration as well as process tests. Calculation analysis includes the calculations of neutron-physical characteristics, thermal-hydraulic calculations of stationary and accident conditions, hydro-dynamical calculations for the set of WWER-440 fuel assemblies of the third generation and also RK-3 strength calculations for stationary and accident conditions and thermal mechanical calculations of the core with RK-3.

Organization of pilot-commercial operation of RK-3 with average enrichment 4,87 % in Kola NPP power units of the second turn is under consideration at present.

4. Aspects of RP power increase

The analyses provided for core increased power are required for validation not only fuel operation at a new power level, but also for all reactor plant systems:

- reactor;
- steam generator;
- pressurizer;
- main coolant the pipeline;
- safety systems;
- systems important to safety.

Development of document package is required, which validates increase of power for RP and a certain unit with available unit configuration and satisfies contemporary requirements in the field of designing and safe operation of NPP systems and components.

Such analyses alongside with feasibility study of core safe operation with increased power, developed by JSC "TVEL" are required to obtain the license for NPP units operation with increased power.

The effects of power increase:

•brittle failure resistance of reactor vessels;

•condition and fulfillment of design functions by primary systems and equipment, auxiliary and safety systems;

•serviceability of unit localizing safety systems purposed to prove meeting of the design criteria for non-exceeding of maximum permissible pressure in the pressurized area and the time of required de-pressurization reaching under DBA, including the analysis of system protections and interlockings operation;

•requirement of setpoints for system protections and interlockings updating for unit operation with increased power;

possibility of SG steam generation increase proceeding from separation tests experience and calculation analysis as well as the analysis of available level measurements, protections and interlockings for SG level;

•requirements for reactor compartment systems from the side of reactor plant;

•requirements for the secondary and common-plant systems from the side of RP;

•requirements for minimum and maximum flow through the reactor.

Conclusion

Further development of the 2-nd generation fuel assembly design and consequent transition to working fuel assemblies of the 3-rd generation provides significant improvement of fuel consumption under the conditions of WWER-440 reactors operation with more continuous fuel cycles and increased power.

List of accepted abbreviations and symbols

ERC - emergency, regulating and compensating assembly
NPP - nuclear power plant
WWER - water-cooled water-moderated power reactor
SG - spacing grid
LCC - leak check of cladding
PM - preventive maintenance
WA - working assembly
RP - reactor plant
FA - fuel assembly
твэг - fuel rod with gadolinium absorber
твэл - fuel rod
eff. days - effective days
B - burn-up, MW·day/kgU
Kq^{max} - maximum power peaking factor in fuel assembly power
$(KqKk)^{max}$ - maximum power peaking factor in fuel rod power
n - ratio of refuellings
$N_{касс}$ - fuel assembly power, MW
$N_{ном}$ - reactor nominal power, MW
$N_{т}$ - reactor thermal power, MW
$N_{твэл}^{max}$ - fuel rod maximum power, kW
Ql^{max} - fuel rod maximum heat rate, W/cm
$T_{вых}$ - assembly outlet temperature, °C
$У_{u\ ест}$ - specific consumption of natural uranium, $\frac{kgU}{MW \cdot day}$
$У_{epp}$ - specific consumption of separating operations, $\frac{epp}{MW \cdot day}$
$У_{э\ U}$ - specific electric power generation per 1 kg of enriched uranium, $\frac{MW_{el} \cdot h}{кгU}$
$У_{эф}$ - specific power generation per 1$, spent for purchase of fuel assemblies, $\frac{MW \cdot h}{\$}$

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