

# Core Designs of Modern VVER Projects

*I. Vasilchenko, S. Kushmanov, V. Vjalitsyn, R. Vasilchenko*

JSC OKB "GIDROPRESS", Podolsk, Russian Federation

## 1. Introduction

Semi-centennial anniversary of VVER safe operation was commemorated at Novovoronezh NPP (NvNPP) in 2014. The VVER history has included several generations of designs. The basic of them are the following:

- generation of small and medium power reactors V-1, V-2, V-3M, V-189, V-213;
- the first (and the single) reactor with 1000 MW of type V-187 (NvNPP, Unit 5) with jacketed fuel assemblies;
- generation of large power reactors V-302 (V-338), V-320 (V-428, V-412, V-446) with jacket-free fuel assemblies;
- designs of the 21-st century: AES - 2006, VVER-TOI.

Reference operational experience is one of the most attractive features at the modern market of nuclear - hazardous objects. Due to the initial design solutions successfully arrived at, designs of VVER reactor plants of 21-st century have inherited them and, respectively, a positive operational experience both of installations as a whole and of their separate components.

From the viewpoint of influences on fuel operation such design solutions of reactor are successful as the elliptic bottom of the core barrel providing preliminary distribution of flowrate at the core inlet; protective tubes of PTU preventing, together with a shell, FA top nozzle, from flow-induced effect on CPS RCCA; design of CPS RCCA itself and the system of its damping. Application of the 6-facet shape of fuel assemblies provides more uniform mechanical interaction of fuel assemblies and, respectively, their mutual supporting influence. Besides, PTU structure and its fastening enables to adjust holding-down of fuel assemblies in the reactor considering their radiation growth.

## 2. Reference Feature of Core New Designs

Starting from plants V-302 and V-320, cores contain 163 fuel assemblies. This number is governed by the dimensions of fuel assemblies and the re-

actor vessel. Number of CPS RCCA during evolutionary designing varied from 49 pcs. (V-302) and 61 pcs. (V-320) to 121 pcs. (AES - 2006) and 94 pcs. (VVER-TOI). The requirements for safety (temperature of repeated criticality) and for fuel composition (possibility of application of MOX fuel) called for this change. And possibility of increase in the number of drives to 121 pcs. is realized already in designs of Tianwan NPP, Bushehr NPP, Kudankulam NPP. For VVER-TOI 94 CPS RCCAs are chosen considering the experience of previous designs. For arrangement of sufficient number of ICIS indicators (54 pcs.) in 15 controllable cells of protective tube unit, in addition to those uncontrollable, channels for ICIS indicators are installed. With this purpose CPS RCCAs contain not 18 absorbing rods but 16 absorber rods (fig. 1) in these cells, and one of the respective fuel assembly guiding tubes, (GT) happened to get free, can also be used for arrangement of the ICIS indicator.

For measurement of coolant temperature at the FA outlet one of GT of fuel assemblies is perforated in the section between fuel rod bundle and the top nozzle. This has enabled to arrange 313 fuel rods instead of 312 in the bundle.

The design of fuel assemblies of new projects follows basic design solutions of TVS - 2M, having an extensive positive operational experience [1]. The basic element, providing stability of shape, is a welded skeleton of GT and spacing grids (SG). A distinctive feature of fuel assemblies of designs of AES - 2006 and VVER-TOI is fuel stack height extended by 50 mm in comparison with TVS - 2M. Respectively, the height of fuel assembly top nozzle is reduced as compared with TVS - 2M. The

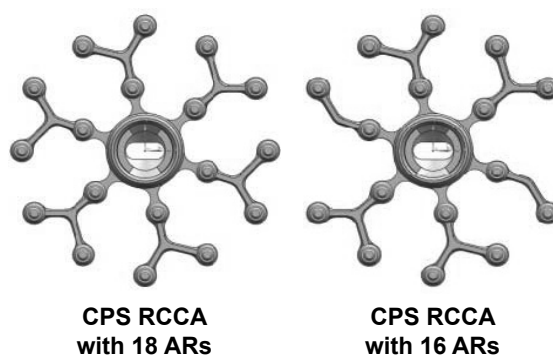


Figure 1.

design of other components is considerably unified and technologically developed. Application of zirconium materials only within the core space that have low neutron absorption together with other specified properties makes possible to use this design to reactor plants of Generation 3 +.

Operational experience of TVS - 2M that is given below enables to use it as reference for new projects because of similarity in designs and operational conditions.

### 3. Operational Experience of the Prototype

Pilot-commercial operation of TVS - 2M started in 2006 at Balakovo NPP -1. Further, it was introduced at all units of this plant and also at Rostov NPP. To provide compatibility with fuel assemblies of a previous design with the reduced core height, modification of TVS - 2M with the blankets containing natural uranium was used in transition loadings. After transition to the cores having the same height, transition of the power units to uprated power to 104% as well as to 18-month fuel cycle of operation was provided on the basis of this design. It has become feasible due to TVS - 2M stability of shape demonstrated from the very beginning.

Fig. 2 shows typical graph of change of CPS RCCA exercising force and also PTU position in

the unsealed reactor. From the graph it follows, that from the very beginning of implementation of such fuel assemblies forces of motion of control rods were considerably decreased that has removed the comment on reactor scram time.

That fact, that PTU before refuelling occupies higher position than after refuelling proves absence of “contraction” of fuel assemblies as a result of bowing or creeping of GT, and natural radiation growth of GT occurs. It qualitatively differs from operation of previous fuel assemblies having insufficient rigid structure when PTU after refuelling occupied higher position than before refuelling due to “fresh” more rigid fuel assemblies. Moreover, forces of CPS RCCA exercising at the end of cycle, at least, were not increased in comparison with those measured at the beginning of cycle. The given graph also demonstrates that change in number of loaded fuel assemblies from 54 up to 66 in transition to 18-month fuel cycle did not bring a noticeable influence on the character of change of friction forces during CPS RCCA motion. Respectively, friction force does not depend on fuel cycle with fuel assemblies being operated. Formation of the core is provided without limitations that were earlier imposed in connection with changing in the shape of fuel assemblies. To be more precise, CPS RCCA can be installed in any fuel assembly determined by physical calculation of loading. There is not also a necessity of inter-sector shuffling of fuel assemblies. Retrofitting of PTU tablets did not change friction force of CPS RCCA either.

All this is a demonstration of margin of stability in shape of TVS - 2M fuel assembly.

This circumstance has become a convincing proof of necessary transition to fuel assemblies of TVS - 2M type at power units and since 2014 the very transition has started at two units of Tianwan NPP. The same transition is planned to realize at Bushehr NPP and Kudankulam NPP.

Development and implementation of TVS - 2M have provided fulfillment of top priority safety requirement: reliability of reactor scram. It has been achieved without loss of fuel utilization economy, namely, on the basis of zirconium structural components (Zr-110 for SG and Zr-635 for GT).

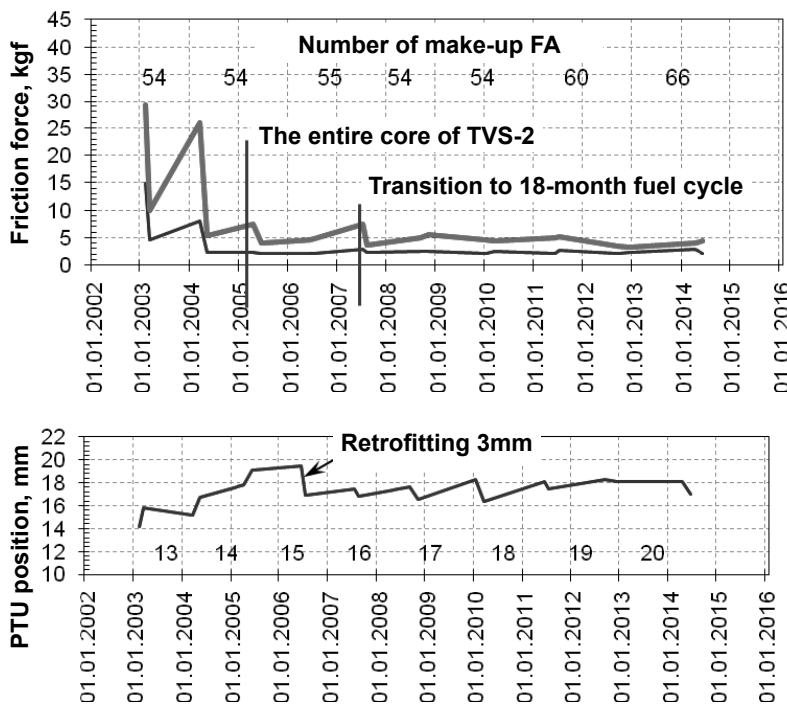


Figure 2.

**Table 1.**

Design	VVER-1000 V-320 104%	AES-2006 (MIR-1200)	VVER-TOI
Average enrichment in $^{235}\text{U}$ , %	4,736 / 4,730	4,71	4,78
Number of FA of make-up, pcs.	66 / 67	72-73	73 / 72
Length of fuel cycle, eff. days	510 / 515	505	511 / 506
Average burn-up of FA, MWD/kg U	48,5 / 49,9 *	47,5	49,4 / 49,5

## 2.1. Main Parameters of Fuel Cycles

Table 1 gives the basic design parameters of 18-month equilibrium fuel cycle for various designs. The fuel cycle of new designs is seen to develop at practical operation of fuel in installations V-320. (Considering that burn-up of 55 MWD/kg U is actually achieved).

## 2.2. Stability to Impact of Damaging Factors

The concept of zero fuel failure formulates the basic damaging factors. Counter factors of TVS-2M are given below.

One of the major factors is clad fretting-wear. Numerous tests of FA with spacing from 240 mm up to 340 mm, used in the structure of VVER fuel assemblies show significant margins of dynamic accelerations critical for occurrence of fretting-wear. Judging by operational experience it follows that with defects in fuel rod fastening, fretting-wear starts to appear in the first spans of fuel assemblies, in the area with maximum coolant flow-induced instability. To improve reliability, TVS-2M was provided with the 13-th SG at 100 mm distance from the lower grid. This grid essentially increases frequency of natural oscillations of fuel rod making it farther from rotational and vane frequencies in coolant flow.

Debris is another the most frequently occurring damages of fuel rod claddings. A very favorable statistics is available on TVS-2M tightness. Since the moment of implementation (2006) the level of damageability is less than  $1 \cdot 10^{-5}$ . Thimbles at the core inlet with perforation, having 3 mm dimension, can be referred to a number of factors preventing from getting the firm particles into the fuel rod bundles. To decrease probability of getting the particles into the core, ADF structure was devel-

oped and undergone the pilot operation. Not less effective measure is rigorous arrangement of the repair work pertained to formation of particles.

The crucial role in counteraction to failures due to clad corrosion belongs to application of corrosion resistant alloys. They are alloy Э -110. Nevertheless, activities are under way on implementation of modified alloys Э -110M for fuel rod claddings and Э -635M for GT.

FA forming. The data of measurements of drop time and CPS RCCA motion forces, forces of motion of fuel assemblies and position of PTU, show, that no changes in shape occur. To improve operating conditions of fuel assemblies axial forces are essentially reduced due to application of thinner spring wire and PTU pressing forces providing necessary margins on non-lifting of fuel assemblies during operation.

Fuel rod heat rate. VVER –1000 reactor is a powered reactor. Nevertheless, the statistics shows absence of cases of fuel rod damage as a result of superheating of fuel rod claddings, at power operation of 104%, inclusive.

Fabrication errors. They are reduced to minimum due to maximum automation during production and inspection of FA and its completing articles.

Mechanical damage at fuel handling procedures (FHP). No cases of mechanical damage of FA during 12 years of operation of the given type of fuel assemblies are observed including those during refuelling tests at the velocities of motion of 4 m/min. It is because of rigidity of fuel assembly structural components.

Foreign objects are prevented by fabrication process of FA as well as strict arrangement of recording the objects at PM.

Errors at designing cores. This is the key factor of FA reliability. Quality of designing is involved in

application of the verified calculation procedures, availability and use of experimental methods providing simulation, integrated approach of designing, possibility of consideration of operational experience of prototypes. All this has been realized at designing TVS - 2 and its further upgrading.

Deposits on the components. No influence of the given factor on fuel rod damage of TVS - 2M is observed, however, the root-cause of occurrence of deposits on the components of separate units has not been revealed up now. Post-reactor studies are planning.

### 2.3. Pilot Operation of MG, New Alloys, ADF and NTMC

Pilot operation of new components of FA and the core has been at full speed for the last four years.

A batch of TVS - 2M with mixing grids and anti-debris filter (ADF) operated at Balakovo NPP, Unit 4 in 2010-2014 up to burn-up 51,2 MWD/kgU for 35 thousand eff. hours. The basic objective was corroboration of the results of bench operational-life proof in reactor conditions. It is confirmed that during the entire period of operation the grids maintain their shape and there is no contact with fuel rods. ADF also maintained their shape without any damage. Noticeable differences in temperature state of fuel assemblies from symmetric were not revealed.

The batch with TVS - 2M incorporating fuel rods with claddings of alloys  $\Theta$  -110M,  $\Theta$  -635M and

$\Theta$  -125 continues pilot operation at Balakovo NPP, Unit 2. The objective of tests is obtaining of the data on behaviour of the claddings with advanced combination of corrosion and strength properties in actual water-chemistry conditions. Interim visual examination of test fuel rods is carried out. Difference between appearance and radiation growth of the specified alloys is observed. Decision-making on implementation will be provided by the results of completed pilot operation and post-reactor studies.

Pilot operation of TVS - 2M with indicators of neutron and temperature measurements (NTMC) was provided at Balakovo NPP, Unit 1. In spite of limited scope of data of the results of the temperature measurements, an extended NTMC implementation is recommended. It will enable to exclude completely influence of effect of leaks through GT on indications of thermocouples and to reject using nozzles in fuel assembly caps.

### 4. Upgrade of FA - 2M for the Further Power Upgrading

According to the program of increase in energy generation all Russian power units with VVER-1000 (except for NV NPP, Unit 5) are transferred to 104 % power (3120 MW) without changing the core design. Rosenergoatom is planning to carry out pilot operation at Balakovo NPP, Unit 4, at increased power (the specific level of power will be made more precise by the test results) in 2018.

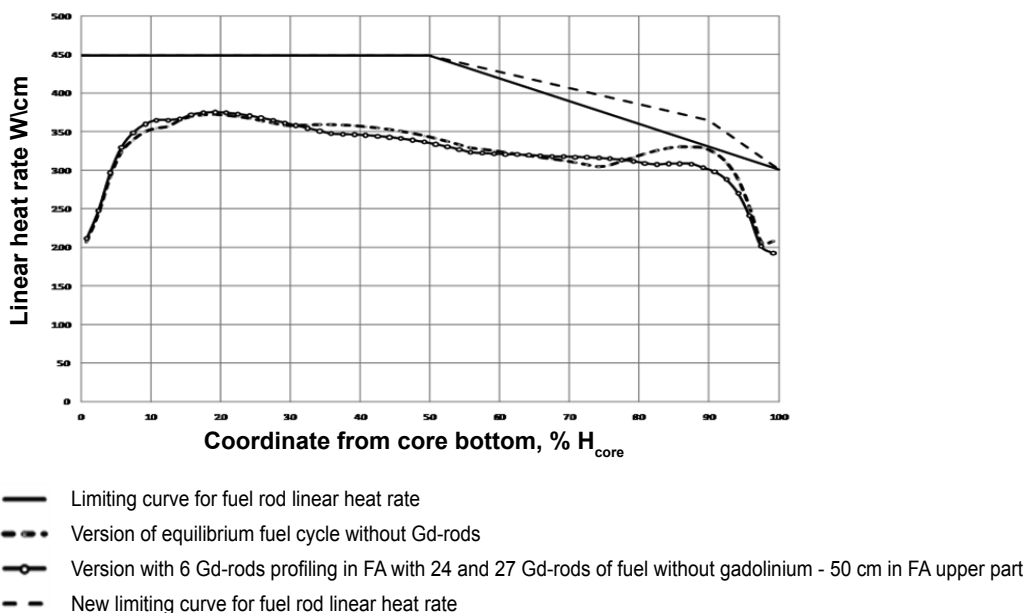


Figure 3.

With this purpose four MGs are introduced into design TVS - 2M. Their structure and arrangement in fuel rod bundle are given in /2/. A distinctive feature of these MGs and difference from all known solutions are as follows: two of them located downstream of coolant flow possess mixing properties in the area of the low steam qualities, and the two others, located upstream of the flow, intensify heat transfer in separate cells in the area of high steam qualities. These MG properties were revealed in the process of looking for versions of their design. Such combination is assumed entirely for the design of fuel assembly, and the correlation for critical heat flux is corrected for it. In 2014, after obtaining the positive results of pilot operation with pilot fuel assemblies, TVS - 2M batch with MG was loaded in Balakovo NPP, Unit 4 in the volume of complete loading. So, by 2018 the core of this Unit is possible to be completely loaded with fuel assemblies of such a type.

## 5. Profiling of Gd-fuel Rods for 18-month Fuel Cycle (FC)

Practical realization of 18-month FC has called for some structural and calculational measures pertained to the limiting curve of core axial linear heat rate established earlier. The limited burn-up due to burnable absorber - gadolinium in the upper part of the reactor core leads to the increased power at the end of cycle, and to the problem of limiting curve not to be exceeded. For solution of this problem two measures has been provided.

The first was involved revision and verification of a new limiting curve and the second –axial gadolinium profiling. Fig. 3 shows a new form of limiting curve and axial power distribution regarding and disregarding Gd-fuel rods. To check the effect of introduction of a new limiting curve and

gadolinium profiling, a new pilot operation of the core at Balakovo NPP, power unit 2 has been provided since 2015.

These results will also be useful for the cores of new designs where more complex profiling of gadolinium fuel rods is used.

### 5.1. Possibilities for Further Improvement of Fuel Cycle

The first possibility involves implementation of TVS - 4 design. Technical design of the core on the basis of design of TVS - 4 is developed in 2014. Difference between TVS - 4 and TVS - 2M lies only in the size of fuel pellet. TVS-4 diameter of pellet equals 7.8 mm with no central opening. Because of it, fuel mass is increased by 42 kg per fuel assembly. 18- month cycle at such loading is improved, however it is insufficient to reject unloading of fuel assemblies after two years of operation. The second possibility for essential improvement of a 18-month FC and, if necessary, for realization a 24-month FC appears at increase in initial enrichment above 5 % limit assumed now. Table 2 gives the FC main parameters for two dimensions of fuel pellet as well as RRC KI assessment of FC parameters at the increased initial enrichment.

In this case all fuel assemblies operate during three cycles that enables to increase essentially average burn-up of fuel assemblies. Increase in initial enrichment makes possible to improve also other FC versions. Either specified possibilities are now planning to realize in Russia. The first of them is close to implementation, and the second calls for fulfillment of comprehensive program of work as it covers all technological re-makings of VVER fuel fabrication. Elaboration of such a program is under way now.

**Table 2**

Ø pellets, mm	7,6 / 1,2	7,8 / 0	7,6 / 1,2 with erbium
Number of loaded FA, pcs.	66 / 67	60 / 61	~ 54
Average enrichment of make-up, % U235	4,73	4,73	5,9
Fuel cycle length, eff. days	510 / 515	512/506	510
Number of unloaded FA, pcs..			
- after the second cycle;	30	18/19	0
- after the third cycle;	36	42	~ 54
Average burn-up MWD / kgU	48,5/49,9	50,6	64

## 5.2. Possibility of FA Repair in New Designs

In principle, TVS - 2M and its further modifications have a potentiality for remote disassembly in order to replace leaky fuel rod, however, force of withdrawal of a fuel rod can reach some essential value because of necessity of deformation of the collet, fixing a fuel rod in the lower grid. Such a force can lead to failure of the fuel rod being withdrawn in case of its damages on the basis of a secondary flaw. A new FA design is developed to avoid fixing of a fuel rod in the lower grid. It will be an essentially new design feature of VVER fuel assemblies. For project AES-2006 the design of fuel repair and inspection equipment is developing in parallel. Installation of such equipment is provided in cooling pool. Repair of FA can be provided during PM. This circumstance will demand revision of all PM technology for making its realization shorter. The specified designs are dictated by foreign experience, and their realization enhances competitiveness of the Russian NPP designs as a whole. However, application of repair technology for each Customer will depend on fuel reliability parameters, therefore, a comprehensive verification of fuel, including pilot operation, shall be of top-priority.

## 6. Perfection of Absorber Element Design

The core design of VVER modern projects includes absorber elements with the combined absorber: boron carbide is in the upper part, dysprosium titanate is in lower /3/. Ratio of heights of these compositions is chosen so that the basic part is filled with more effective absorber, boron carbide being such an absorber, and the lower part, being in the area of high radiation fluxes, is filled with dysprosium titanate that practically does not swell and does not evolve gaseous products that load the absorber element clad. In new designs the core height is increased by 200 mm in comparison with the initial height. In this case, its boundaries are shifted upwards and downwards. It has led to change the absorber height. To provide unification of designs of TVS - 2M, TVS - 2006 and TVS-TOI axial dimension of the lower composition is in-

creased to 500 mm, the total height of absorber is also lengthened.

Statement of the problem on extension of service life of absorber elements and its solution are simultaneously provided in two stages. At the first stage service life will be increased to 15-20 years due to consideration of actual position of absorber in the core and increase in actual fluence. The value of permissible burn-up of absorber and permissible fluence, in terms of embitterment, to the weld and clad of an absorber element remain here as operability criteria. Post-reactor studies of fuel element are provided in order to study possibility to increase permissible irradiation of absorber and, respectively, of a clad and the weld.

To extend service life of absorber elements regrouping of absorber elements is also provided.

For further extension of service life, possibility of application of dysprosium hafnate, having longer chain of absorbing isotopes, is considered.

## 7. Conclusions

Core designs of new projects AES-2006 and VVER-TOI are based on extensive successful operational experience of the close prototype of TVS - 2M.

All improvements both of technical and economic parameters of fuel are subjected to representative examination by pilot operation at the power units with VVER-1000 being close prototypes of new designs.

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