Experimental verification of FA for WWER-1000. Investigations of TVS - 2M.

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Summary

During development of TVS-2M design for WWER-1000 and within the scope of its pre-reactor verification there was performed a complex of bench tests of FA for operational impacts. These tests were carried out with the use of the full-scale non-irradiated FA dummy and the models of units. The present report presents the methods and the results of tests of the full-scale dummy for static concentrated loads, impact of thermal cycling and vibration under separate and simultaneous impact of the listed loads. The results of tests carried out indicate that the solutions implemented in TVS-2M, first of all, a rigid welded skeleton, provide much higher resistance to distortion due to thermomechanical loads in comparison with zirconium AFA of the previous generation. This work was organized JSC TVEL.

1. Program and scope of FA experimental verification

One of the stages of verification of new FA designs is carrying out the complex of experimental investigations with the use of the units models and full-scale FA dummies on the experimental facilities of the Manufacturer of fuel (JSC NCCP) and WWER RP Designer (OKB "Gidropress"). As a rule, the program of bench tests of FA dummies includes the investigations listed in Table 1.

Table 1

Type of tests	Object of tests	Conditions	Impacts simulated	Parameters determined
1. Investigations of local characteristics of interaction of fuel rods and GC with SG	Models of units and FA fragments	In air, T=20 °C	Lateral, longitudinal forces and moments affecting fuel rods and GC	Rigidity of cells in turning fuel rods and GC, lateral forces of pushing fuel rods and GC through SG
2. Static tests	Full-scale FA dummy	In air, T=20, 320 °C	Lateral forces and torques	Dummy rigidity in bowing and torsion
3. Hydrotests	Full-scale FA dummy	In water with standard flow rate through FA, T=80, 320 °C	Coolant flow rate, pressure	Pressure loss coefficient of FA and its components
4. Operational-life proof during 1500 hours	Full-scale FA dummy	In water with standard temperature, pressure, chemistry, flow rate	Temperature, medium, coolant flow rate, pressure, pressure pulsation	Presence or absence of damaged FAs, normal operability of CPS CR
5. Thermomechanical tests	Full-scale FA dummy	In air, T=80-320 °C	Thermal cycling, lateral forces, thermogradients, vibration	Sensitivity to thermal cycling
6. Modal analysis	Full-scale dummy and FA fragments	In air, T=20 °C	Vibration	Frequencies, modes, natural oscillations damping factors, transfer characteristics

Bench tests of FA dummies permit to obtain quantitative assessments of dummy sensitivity to the simulated impacts, to study an influence of operational factors on them (for example, an influence of temperature and vibration on bowing rigidity) and design features of dummies investigated. The results of bench tests are used both for FA verification (for example, results of operational-life proof) and optimization of the design of separate units and as initial data for calculational justification.

Experimental work begin at the Manufacturer of fuel (NCCP) with investigation of local characteristics of interaction of fuel rods and GC with SG, the results of which were presented at the conferences/1, 2/. Local characteristics of interaction of fuel rods and GC with SG are used for comparative analysis of various design versions and are applied as initial data of computer codes for calculating the FA response to force, thermomechanical and vibration impacts.

Then during assembling of the experimental FA dummy the static tests at first of the skeleton consisting of GC and SG without fuel rods and then of FA dummy are carried out for lateral bowing by the concentrated force. Experimental investigations continue on the experimental facility of WWER RP Designer in OKB “Gidropress”, where hydraulic, operational-life proof, static, thermomechanical tests and modal analysis of the dummy are carried out. During these tests various types of operational impacts onto FA are simulated: hydraulic, temperature, mechanical, vibrating, chemical.

During hydrotests the pressure loss coefficients of FA and its components are determined by the measured value of pressure drop. The tests are carried out in the hydraulic channel with a geometry simulating the reactor geometry with variation of the value of coolant flow rate through FA. The results of hydrotests are necessary for evaluating the influence of design features on the pressure loss coefficient of the tested dummy. On the basis of these results a thermohydraulic calculation of the whole core is carried out and a conclusion concerning a permissibility of applying the FA of such design in the reactor from the viewpoint of thermohydraulic characteristics is drawn.

The necessary condition of FA verification is keeping strength and stability of FA during operational-life proof in which an integrated impact of practically all kinds of operational loads, with the exception of radiation, is simulated. Operational-life proof is carried out with the use of FA dummies assembled with CPS CR. During tests the number of CPS CR motions and drops, exceeding the maximum number within the whole FA operating life, is provided. The criteria of FA operability in the reactor is non-exceeding of design values of CPS CR drop time and absence of damages (distortions, wear) to dummy units and components.

Methods and results of static and thermomechanical tests will be considered in the subsequent chapters using a full-scale non-irradiated TVS - 2M dummy as an example.

Experimental modal analysis of FA is carried out under force and kinematic excitation of vibration. With a force pattern of loading the vibration load is applied to FA components (SG, fuel rods), with the kinematic loading the vibration is transferred to FAs through the supports. By the results of the modal analysis the following modal characteristics of the whole dummy and its separate units are determined: frequencies, modes, FA oscillations damping factors. As FA is a non-linear structure, the modal analysis is carried out at various levels of vibration load. The results of the modal analysis are used both in designing new FA structures for tuning away from resonances at frequencies of exciting forces in the reactor and as initial data during calculated simulation of FA vibration response to operating impacts.

In individual cases a standard program of experimental investigations can include additional types of tests, for example, investigations of fuel rods wearing, the process of friction in the units “fuel rod - SG", core assembleability.

2. Methods and results of static tests

Static tests are carried out using test benches of NCCP and OKB "Gidropress" by general methods.

The scheme and photo of NCCP test bench with TVS-2M skeleton are presented in figure 1. The test bench represents a rigid framework inside which FA or skeleton are located vertically. The FA tail-piece is placed into seat simulating a seat in the reactor. The FA cap is fastened in clamp. The loading by longitudinal force F is performed with the help of the clamp, the unique design of which provides a reliable fastening of FA cap against displacements and skews. The loading by transverse force P on SG is performed through rigid yoke with the help of jack. The test bench structure allows to apply a lateral force to the face perpendicularly or to the SG angle. The information acquisition system created especially for the test bench services two force sensors and up to 30 displacement transducers simultaneously. Longitudinal force F and lateral force P are measured by force strain-gauge transducers. The test bench is equipped with electron-mechanical linear displacement transducers. The transducers can be placed on any component of FA structure. Tests are carried out at room temperature.

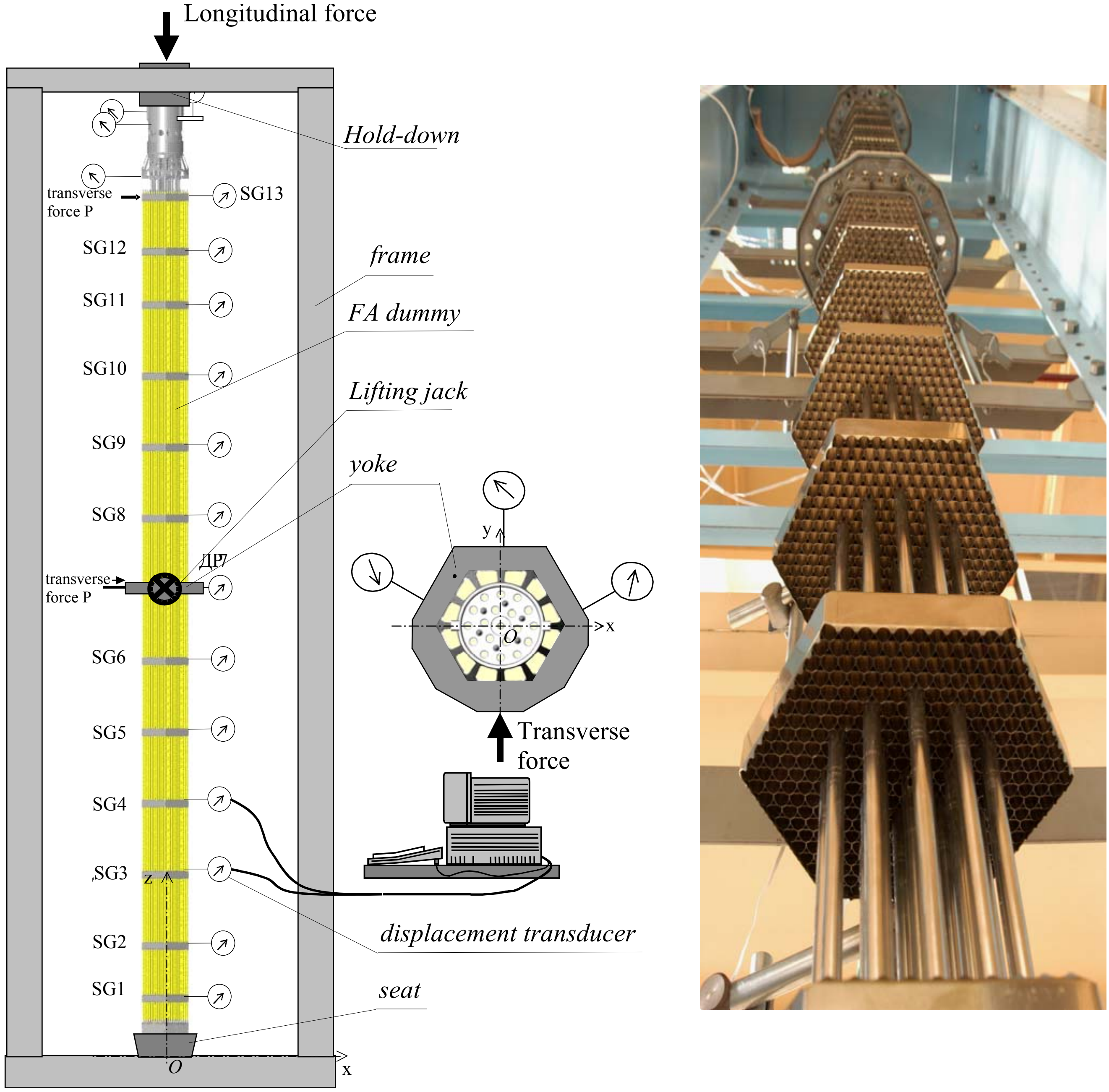


Figure 1 - Scheme of NCCP test bench for mechanical tests, arrangement of transducers and general view of TVS-2M skeleton

The test bench of OKB "Gidropress" (figure 2) is intended for carrying out static, thermomechanical tests and tests of FA dummies under conditions of temperature simulation of loss of coolant accidents.

The test bench includes the following systems and devices:

- a column with devices for fastening, longitudinal compression and lateral loading the dummy
- coolant circulation system – a heat-resistant fan, pipelines with gate valves, electric heaters, a column;
- coolant heating system – electric furnaces, electric heating of pipelines, voltage converter, switching and protective accessories;
- vibration excitation and control system;
- automatic measuring system;
- automatic process control system

Static tests carried out using the test bench include tests for lateral bowing and torsion by the concentrated force and the moment. Tests are carried out at 20 and 320 °C.

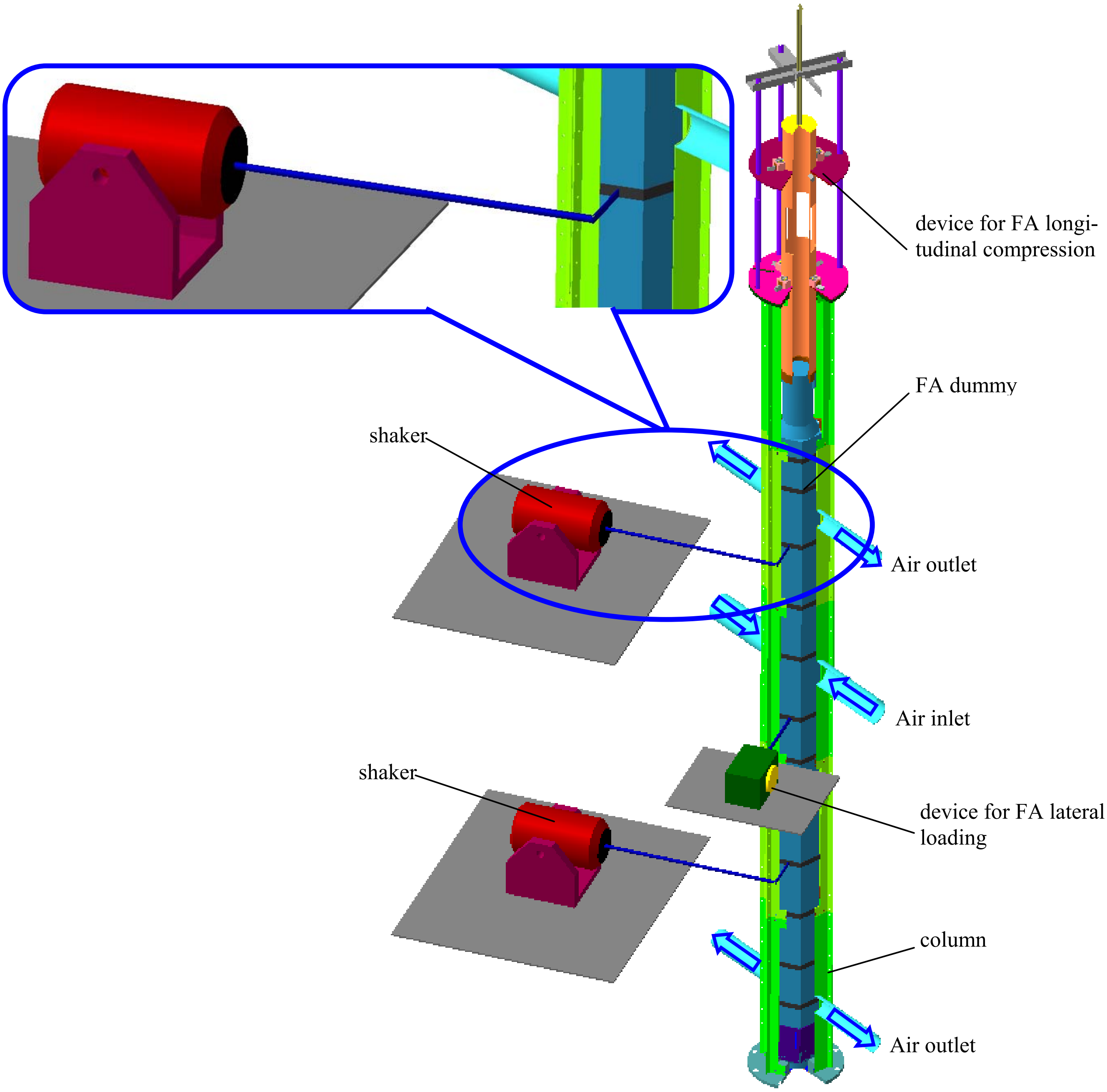


Figure 2 – Scheme of OKB “Gidropress” test bench

The FA rigidity is traditionally evaluated under lateral bowing at the level of the middle SG. Figures 3 and 4 present characteristics of TVS-2M dummy and skeleton under applying loads to SG7. These characteristics were determined using NCCP test bench. The regression equations at the sections shall be considered adequate – determinancy factor is R^2>0,98.

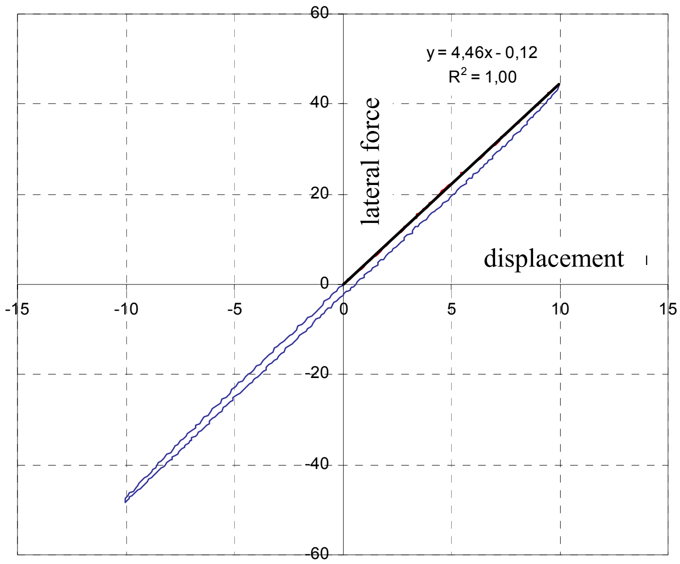


Figure 3 - Lateral displacement of TVS-2M skeleton SG7 under bowing

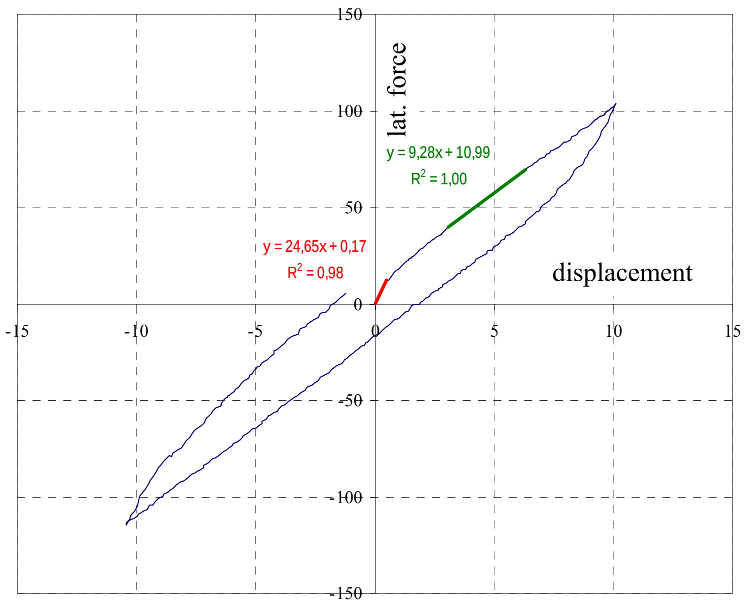


Figure 4 - Lateral displacement of TVS-2M dummy SG7 under bowing

The characteristics obtained under welded skeleton bowing up to 10 mm have the view of a direct line – rigidity is constant both during a forward and reverse motion. The hysteresis is practically absent.

The characteristics obtained under dummies bowing have always some sections on which the rigidity significantly differs. The rigidity on the initial section, during displacements up to ~1 mm, is summarized from the rigidity of the skeleton and the fuel rod bundle which are stationary relative to SG cells due to friction. After overcoming the static friction forces in pairs "fuel rod – SG cell" the dummies rigidity falls. Hysteresis of dummy characteristics is explained by a presence of friction.

Tests with a sequential loading of the skeleton or FA by the lateral load, applied to various SGs over the fuel assembly height, and also the obtaining as complete information as possible on bowing of the fuel assembly along the length for the assigned load in order to build a sufficiently representative bent FA axis are important for verification of computer codes.

Figure 5 presents a curve of TVS-2M dummy bowing. The data of bowing measurements are marked by points. The arrows show SGs to which the lateral force was applied.

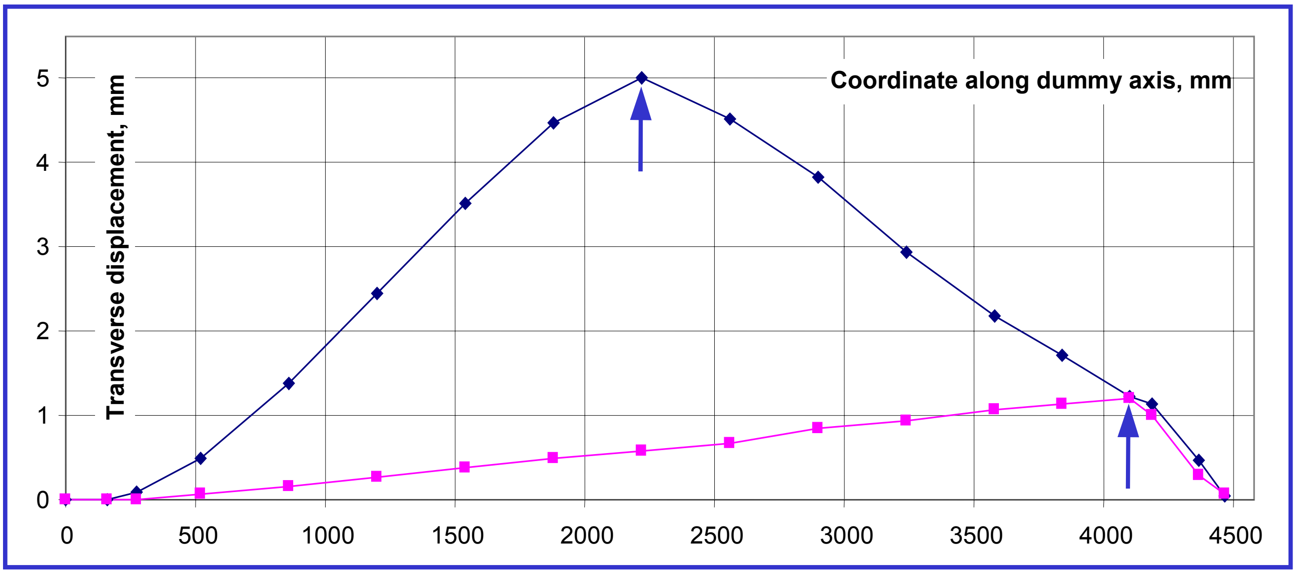


Figure 5 – Bowings of TVS-2M dummy

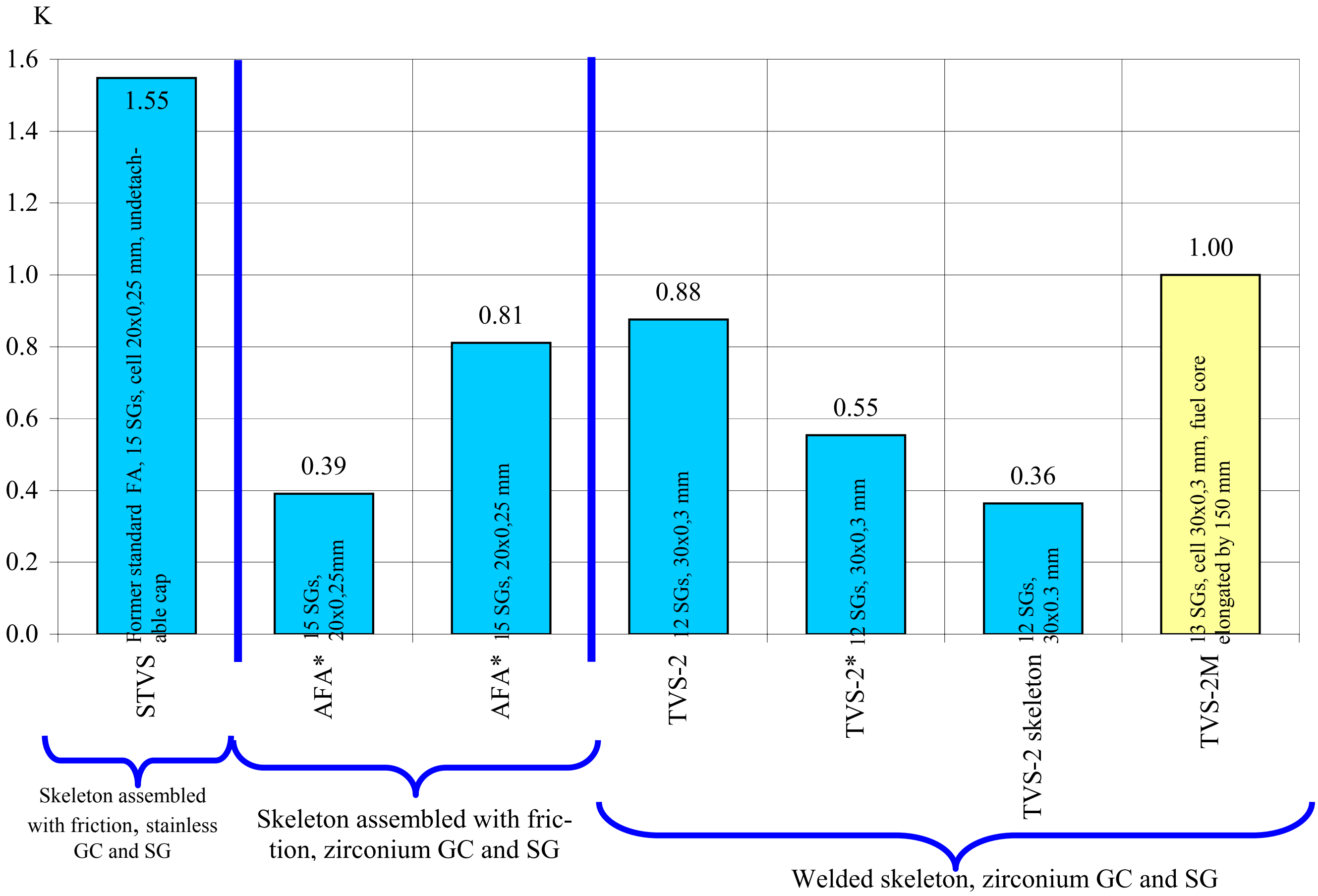
Characteristics of TVS-2M dummy under longitudinal-lateral bowing, obtained during tests at OKB "Gidropress" test bench under similar conditions with allowance for errors of measurements coincide with the results obtained at NCCP test bench.

Investigations of influence of such operational factors, as temperature, vibration and decrease in tightness between fuel rods and SG cells, occurring due to relaxation of stresses in the cells and fuel rods radiation growth, on FA characteristics under longitudinal-lateral bowing were also carried out at OKB "Gidropress" test bench.

At operating temperature of 320 °C the rigidity of TVS-2M dummy is lower by 18 % than at 20 °C. Decrease in rigidity of the other dummies tested earlier at operating temperature was of about the same value and was caused by a decrease in the modulus of elasticity of FA structural materials.

Excitation of FA broadband vibration within the range from 0 up to 100 Hz as well as at the determinate frequencies of 9, 16,5 and 99 Hz being frequencies of exciting forces in the reactor leads to a decrease in bowing rigidity by the value from 3 up to 8 %.

Experimental assessment of rigidities of sheathless FA dummies in terms of TVS-2M rigidity are presented in figures 6 and 7. Rigidity was determined for the similar value of FA bowing equal to 5 mm as a ratio of the lateral force applied to SG, being average over the height, to its displacement. Figure 6 presents the bowing rigidities of FAs of various structures beginning with designs of 80th years, which were obtained at OKB "Gidropress" test bench, figure 7 presents the rigidities of FAs, produced at the Manufacturer at present - the values of rigidities were obtained at NCCP test bench. Introduction of FA designs with rigid welded skeleton (TVS-2 and TVS-2M) permitted to increase the bowing rigidity in comparison with FA of the previous generation – AFA in "fresh" state and especially during simulation of the "burnt out" state. The skeleton rigidity of TVS-2 and TVS-2M amounts to 0,36-0,56 from the rigidity of "fresh" FA that provides more than a triple margin to a loss of stability even without a supporting effect of the fuel rod bundle.



* - simulation of "burnt-out" state by increasing the diameter of cells to generation of clearance between fuel rod and cell

Figure 6 – Relative bowing rigidities of dummies (results of OKB "Gidropress")

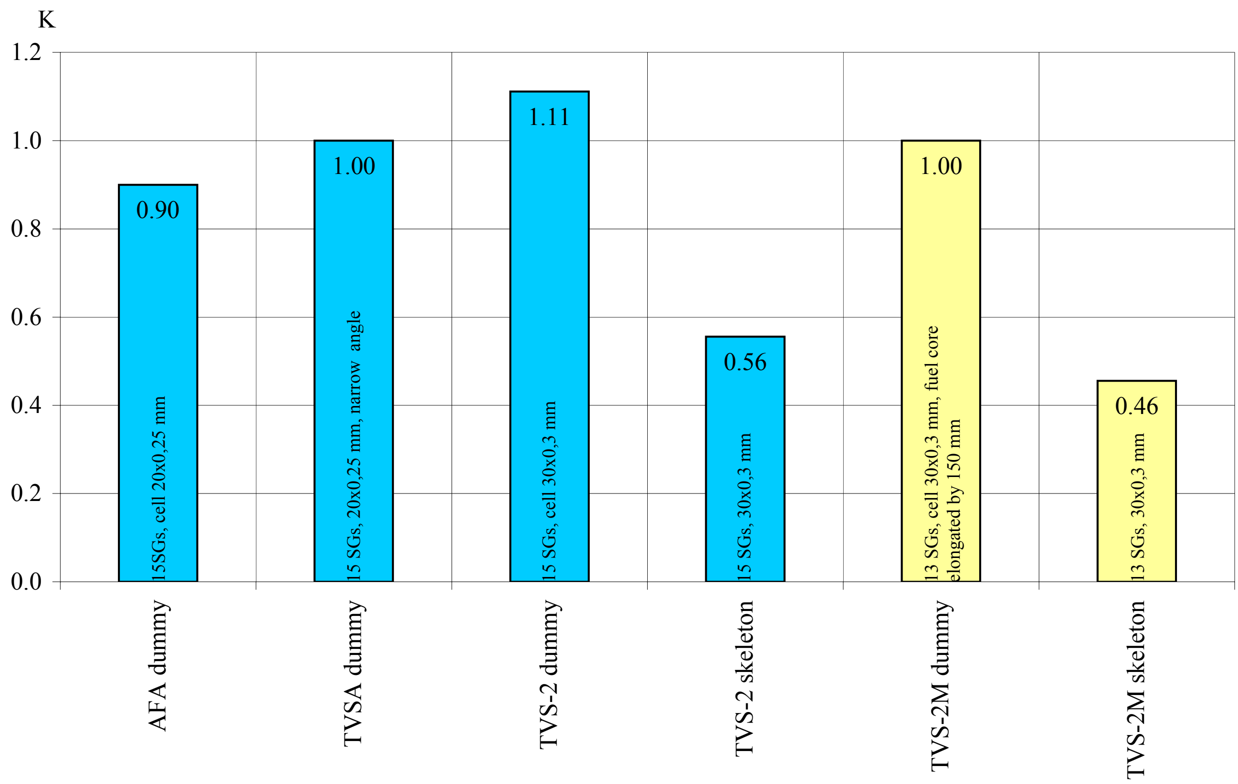


Figure 7 - Rigidity of FAs of various designs by the results of tests at NCCP test bench

3. Methods and results of thermomechanical tests

Tests for thermal cycling were carried out at the test bench (figure 2). Each cycle included dummy heat-up up to operating temperature of 320 °C and cooldown up to 80 °C with holding at maximum and minimum temperatures within 1 hour. Heat-up and cooldown rates corresponded to standard ones.

As a result of a difference between thermal coefficients of expansion of the test bench column materials and FA (in reactor – reactor vessel and FA) a cyclic change of the longitudinal force, acting onto FA, which caused lateral distortions of the dummy, took place. During tests temperatures of FA components by 63 measuring channels, a lateral bowing at 7 levels over FA height, a longitudinal compression of FA and a force of longitudinal compression were recorded. By the results of tests the dependences of TVS-2M lateral bowing on temperature and a force of longitudinal compression were obtained and a residual dummy bowing and its sensitivity to thermal cycling were determined.

Figure 8 shows dependences of average temperature, compression and lateral bowing of TVS-2M on time during tests. Dependences of lateral bowing have a periodic component changing synchronously with temperature. Peak-to-peak amplitude of the periodic component does not exceed 3,5 mm. An aperiodic component (cumulative bowing) does not exceed 0,2 mm that is comparable with an error of measurements.

WWER-1500 FA dummy of the close design was used for thermocyclic tests with the impact of the lateral concentrated force of 0,1 kN and vibration with parameters typical for the operating WWER-1000 reactor: frequencies 9 and 99 Hz and amplitude of 1-2 m/s^2. The impact of the lateral concentrated force without vibration resulted in the occurrence of the lateral bowing with the value up to 1,2 mm, under simultaneous impact of thermal cycling, the concentrated force and vibration the maximum cumulative FA bowing was equal to 2,2 mm. The increment of the cumulative bowing under impact of the concentrated force and vibration occurred only during the first cycle of heat-up - cooldown, and in the subsequent cycles it stopped.

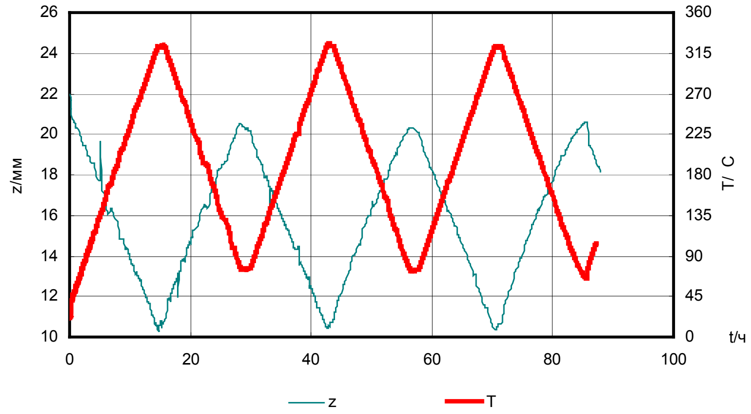
Such character of distortion under thermal cycling is peculiar to FA dummies with rigid skeleton while with TVS-prototypes (zirconium AFA with skeleton assembled with friction and earlier STVS with SG and GC of stainless steel) the cumulative bowing increased from cycle to cycle and by the end of tests it could reach the values up to 10 mm. Thus, the results of the carried out thermomechanical tests of TVS-2M dummy confirmed its higher resistance to the applied impacts.

Conclusion

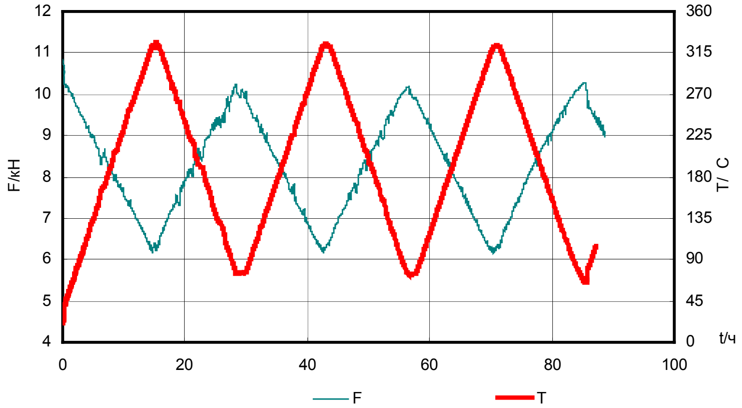
In carrying out bench tests of full-scale dummies for justification of FA designs with welded rigid skeleton, that is TVS-2M and WWER-1500 FA, there were developed and introduced new methods of static and thermomechanical tests for:

- lateral bowing by static concentrated force under conditions of FA vibration;
- torsion by concentrated moment;
- thermocyclic tests under conditions of impact of the lateral concentrated force and vibration.

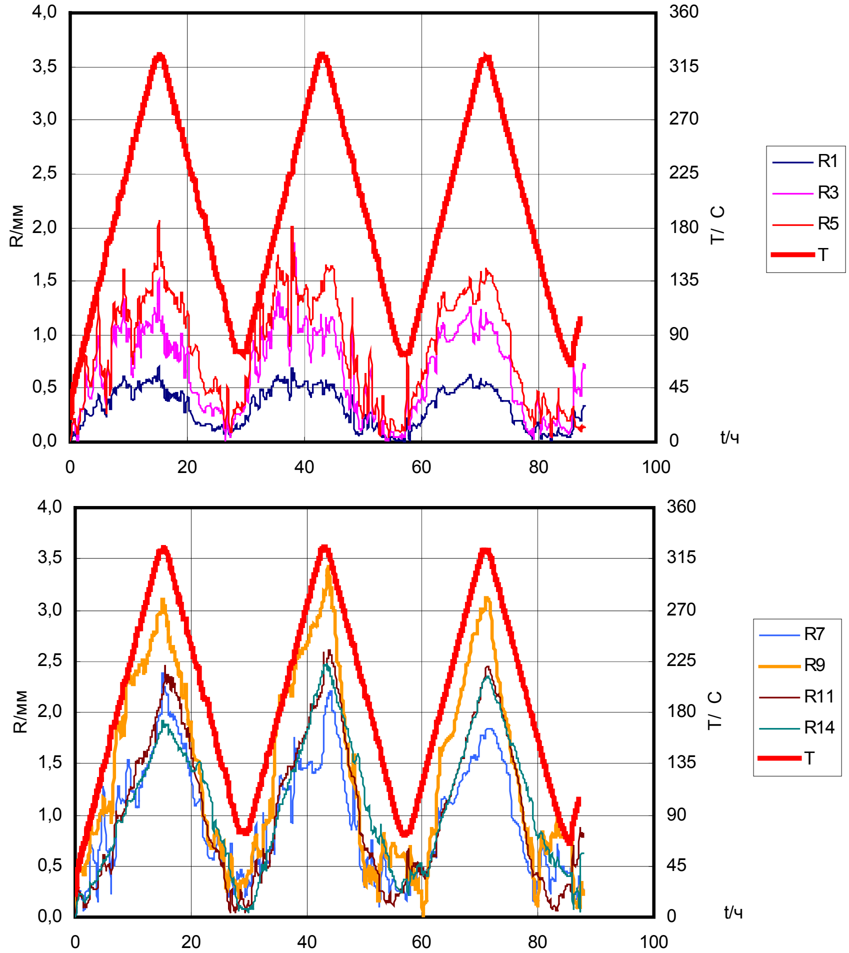
The results of static and thermomechanical tests of TVS-2M dummy indicate that structural innovations realized in TVS-2M, first of all, rigid welded skeleton, led to increase in resistance to the simulated force, thermomechanical and vibration impacts in comparison with dummy-prototypes.



Longitudinal compression (z) and average temperature (T) versus time (t)



Force of longitudinal compression (F) and average temperature (T) versus time (t)



Lateral displacements of FA components (R) and average temperature (T) versus time (t)

Figure 8

List of abbreviations accepted

WWER	-	water-cooled water-moderated power reactor
SG	-	spacing grid
GC	-	guiding channel
SFA	-	former standard fuel assembly
FA	-	fuel assembly
TVS-2	-	fuel assembly with rigid skeleton
TVS-2M	-	modernized fuel assembly with rigid skeleton
AFA	-	advanced fuel assembly
F	-	longitudinal force of compression, N
K	-	dimensionless bowing rigidity
R	-	FA lateral bowing , mm
R1…R14	-	FA lateral bowing at different levels, mm
T	-	temperature, °C
t	-	time, s
z	-	longitudinal compression, mm

References

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2. A.Enin, V.Rozhkov, M.Shustov, A.Ustimenko. Experimental Study of New Generation WWER-1000 Fuel Assemblies at JSC NCCP, 18th International Conference on Structural Mechanics in Reactor Technology (SMiRT 18), Beijing, China, August 7-12, 2005