DEVELOPMENT OF TVSA VVER-1000 FUEL

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Introduction

The TVSA fuel assemblies with a rigid angle-piece skeleton operate at 21 VVER-1000 units of Kalinin NPP, and Ukrainian, and Czech and Bulgarian NPPs. The total of more than 6,000 TVSA fuel assemblies have been fabricated. High lifetime performance has been achieved, namely, the maximum FA burnup is 65 MW·day/kgU; maximum fuel rod burnup is 72 MW·day/kgU; the lifetime is 50,000 EFPH.

The TVSA fuel assembly is being improved to enhance its technical and economic performance and competitiveness of the Russian fuel for the VVER-1000 reactor:

- Reliability and safety are being enhanced; repairability is being ensured.
- High burnup levels in fuel are being ensured.
- The uranium content in FAs is being increased.
- The operational life is being extended.
- Thermal-technical characteristics of FAs are being improved.

The basic TVSA fuel assembly design evolved into the TVSA-PLUS with the fuel column elongated by 150 mm. The TVSA-PLUS fuel assembly has been in operation since 2010 at Kalinin NPP power units; an eighteen-month cycle is implemented at the uprated power of 104%.

The TVSA-12PLUS fuel assembly has been developed with an elongated fuel column, optimized spacer grid positions (the spacer grid pitch is 340 mm) and with ensuring higher rigidity for the skeleton. It is provided for that fuel rods with the elevated uranium content and mixing intensifier grids will be used.

The TVSA-T is developed for VVER-1000 reactor cores at the Temelin NPP. The TVSA-T is characterized by a load-carrying skeleton formed with angle-pieces and combined spacer grids that incorporate mixer grids. The TVSA-T design won the international tender to supply fuel to the Temelin NPP in the Czech Republic, and currently Temelin NPP Unit 1 and 2 are operating with the cores fully loaded with TVSA-Ts.

The work was done under contracts with JSC TVEL.

The TVSA-12PLUS fuel assembly with the elongated fuel column and optimized spacer grid positions

The TVSA-12PLUS fuel assembly with the elongated fuel column of 3,680 mm is characterized by optimized positions of spacer grids (the spacer grid pitch is 340 mm) and increased rigidity of the skeleton.

Below are design solutions for the TVSA-12PLUS:

- 12 spacer grids 35 mm high, arch type
- Anti-vibration lower unit
- Shortened end pieces—top nozzle and bottom nozzle
- Fuel rod with the fuel column elongated by 150 mm
- Up to 4.95% ^{235}U enrichment
- Disassemblable and repairable design
- Debris filter
- Mixer grids

TVSA-12PLUS has an elevated uranium content. Mixer grids are provided for uprating the core power. The higher skeleton rigidity in TVSA-12PLUS enhances operational reliability.

A supplement for the TVSA-12PLUS design has been developed to introduce in the design a top nozzle unified with that in the TVS-2M fuel assembly. The use of the unified top nozzle is to improve technical and economic performance of the fuel assembly through:

- unifying components of the top nozzle,
- simplifying removal of the top nozzle in FA repair, which is due to the special feature of the collet joint in the unified top nozzle,
- using hold-down springs made of smaller diameter wire of 5.1 mm, which reduces stiffness of the spring block in the top nozzle and the hold-down force in the FA, while preventing the liftoff, thus decreasing the accumulated FA bend.

The TVSA-T fuel assembly for the Temelin NPP

The TVSA-T fuel assembly for VVER-1000 reactor cores at the Temelin NPP is characterized by a load-carrying skeleton formed by angle pieces and combined spacer grids that incorporate mixer grids. /1/.

The combined two-layer grid consists of a cell-type spacer grid and a strap-type mixer grid that is the same as that used in the TVSA-ALPHA fuel assembly. The two grids are placed in the same rim.

The TVSA-T design won the international tender to supply fuel to the Temelin NPP in the Czech Republic. A very important objective was achieved to expand the market of the Russian fuel for the VVER-1000 reactor. Currently, Temelin NPP Unit 1 and 2 are operating with their cores fully loaded with TVSA-Ts.

Characteristics of TVSA-T ensure operation under flexible fuel cycle conditions with reduced neutron leaks and with a possibility of varying the cycle duration in the range 230–500 EFPD. A five-year fuel cycle (5×1 year) has been introduced in Temelin NPP Unit 1 and 2 with 36 makeup FAs. This fuel cycle has the duration of 320 EFPD with elevated power peaking factors K_r^{max} =1.63, K_Q^{max}=1.45. The results of TVSA-T operation in Temelin NPP power units are positive.

Successful operation of TVSA-Ts, considering the Kalinin NPP experience, has created prerequisites to uprate the power of Temelin NPP units to 104% (to 3,120 MW) as part of economically efficient five-year fuel cycle. The power uprate to 104% has been validated for Temelin NPP Unit 1 and 2.

In 2011 and 2012, according to the operating program, post-irradiation examinations have been carried out on pilot TVSA-Ts in Temelin NPP units, in particular, visual inspection, measurement of twisting and bending, measurement of FA lengths. The post-irradiation examinations of TVSA-Ts are conducted in the Temelin NPP inspection and repair facility retrofitted by OKBM.

Results of the TVSA-T post-irradiation examinations are positive. It has been shown that the angle-piece skeleton is in the normal condition, and geometrical characteristics of TVSA-T are preserved—the bend of fuel assemblies after the second year in operation was 1.4–4.5; the twist was below the predicted value of one degree. The growth of fuel rods and the change in the TVSA-T length are below the design values.

TVSA inspection and repair facility

A first in Russia facility has been developed that is designed for repair and non-destructive testing of fuel assemblies in the NPP fuel cooling pool during scheduled-preventive repair periods. The facility enables fulfilling the following tasks:

- repair leaky TVSAs to bring them back to the core for afterburning
- repair leaky spent TVSAs, which facilitates resolving the problem of long-term spent fuel storage
- obtain real-time information about TVSA condition in and after operation, including visual inspection, monitoring bending and twisting, monitoring the size across the flats

The TVSA inspection and repair facility in Kalinin NPP Unit 1 has undergone acceptance testing. In 2012, in the inspection and repair facility, activities have been performed to remove and reinstall the TVSA top nozzle.

Main areas for development

Increasing the uranium content in fuel rods

In order to implement advanced economically effective fuel cycles, to uprate the power and enhance fuel utilization, fuel rods are used having a higher uranium content and thinner cladding with a fuel pellet ∅7.8 without the central hole (Figure 1).

Higher-uranium-content fuel rods with the pellet ∅7.8 have been in successful pilot-industrial operation for five years in Kalinin NPP Unit 1 within the TVSA-ALPHA fuel assembly. The total of 139 TVSA-ALPHAs with higher-uranium-content fuel rods and operational time of 1–5 years are in Kalinin NPP Unit 1. After five years in operation, the burnup of 62.2 MW·day/kgU has been achieved in fuel assemblies; and of 67 MW·day/kgU, in fuel rods.

Three TVSA-ALPHAs with higher-uranium-content fuel rods have been equipped with mixer grids. After being in successful operation for four years these assemblies keep operating for the fifth year.

The burnup characteristics of TVSA-ALPHA with higher-uranium-content fuel rods after being in operation for 4 and 5 years

Number of FAs	Time in operation, year	Burnup, MW·day/kgU
20	4	45-54.1
3	5	58-62.2

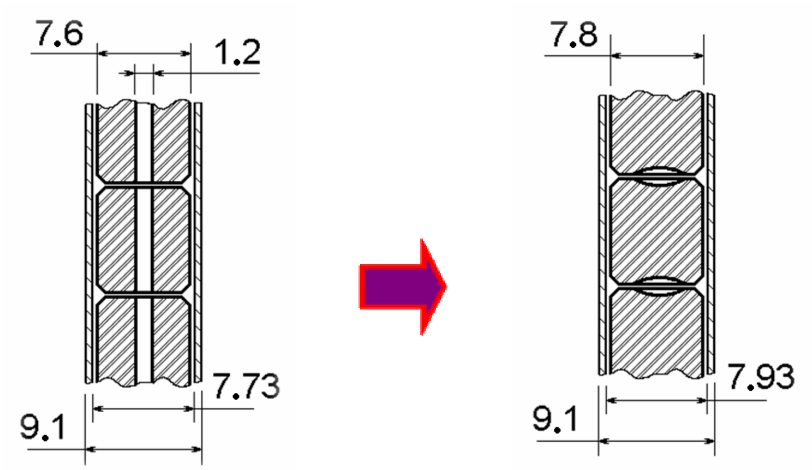

Figure 1 – Fuel rod design development to increase the fuel loading

Optimizing the hold-down force

Excess hold-down forces in the FA have an effect upon shape changes in TVSA, bending accumulation in fuel assemblies in operation, and upon interaction forces between FAs.

Measures intended to prevent the excess hold-down forces in the FA in order to improve the thermal-mechanics of the assembly and reduce FA bending in the core include the following:

- Optimizing the spring block in the TVSA top nozzle—hold-down springs made of the wire ∅5.1 mm instead of ∅5.6 mm reduce rigidity of the spring block in the top nozzle by ~20% and decrease the FA hold-down force in the critical modes.
- A probabilistic approach is used to take into account uncertainties in determining the minimum hold-down force that prevents the FA from lifting.
- Lugs are upgraded on the protective tube block in power units such that the required hold down force is ensured for TVSAs in the core and they are prevented from lifting.

Validating the mixer grid effectiveness

Mixing heat-transfer intensifier grids enable equalization of temperatures, reduced local void fractions, enhanced operational reliability, and increased thermal-technical margins.

The TVSA mixer grid design is a strap-type grid that has flow mixing vanes and does not function as a spacer for fuel rods (Figure 2).

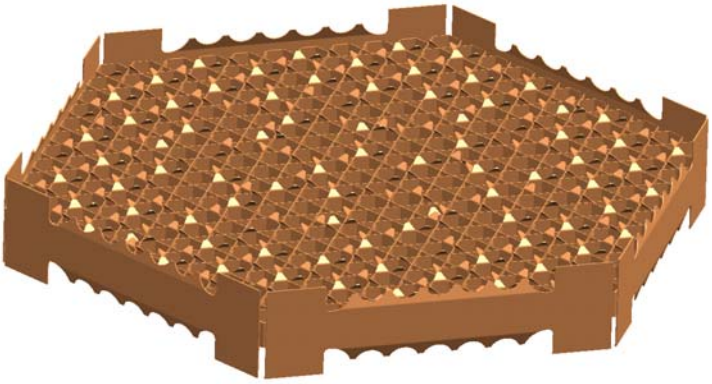

Figure 2 – Mixing intensifier grid

Thermal-hydraulic validation of the mixer grid for TVSA-ALPHA and TVSA-T was jointly carried out by OKBM, IPPE and NNSTU and included the following /2-4/:

– hydraulic testing of fragments and a full-size mockup

– studying the mixing properties on large-scale 57-, 61- and 94-rod models using the propane tracer methods at NNSTU

– studying thermal-hydraulics and departure from nucleate boiling on 19-rod models at OKBM and IPPE

– validation of the critical heat flux correlation for TVSA with mixer grids; verifying in the KANAL thermal-hydraulic sub-channel code

Optimization studies and investigations have been carried out to enhance effectiveness of mixer grids, in particular, dimensions, inclination angle, and positions of flow mixing vanes have been optimized.

A more effective mixer grid has been developed with flow-mixing vanes placed according to the so-called row-by-row “cross-flow” pattern.

A set of experimental studies on thermal-hydraulic characteristics and departure from nucleate boiling has been accomplished in the thermal-physical test facility with 19-rod models of TVSAs having mixer grids placed according to the “cross-flow” pattern including models with a standard sub-channel and guide thimble, radial and axial power profiles, various locations of mixer grids (~1,200 modes).

Higher effectiveness of the “cross-flow”-type mixing grids was shown in terms of the mixing factor and the effect of increasing the critical heat flux compared to the earlier investigated mixer grid with mixing vanes placed according to the pattern swirling the flow around the fuel rod.

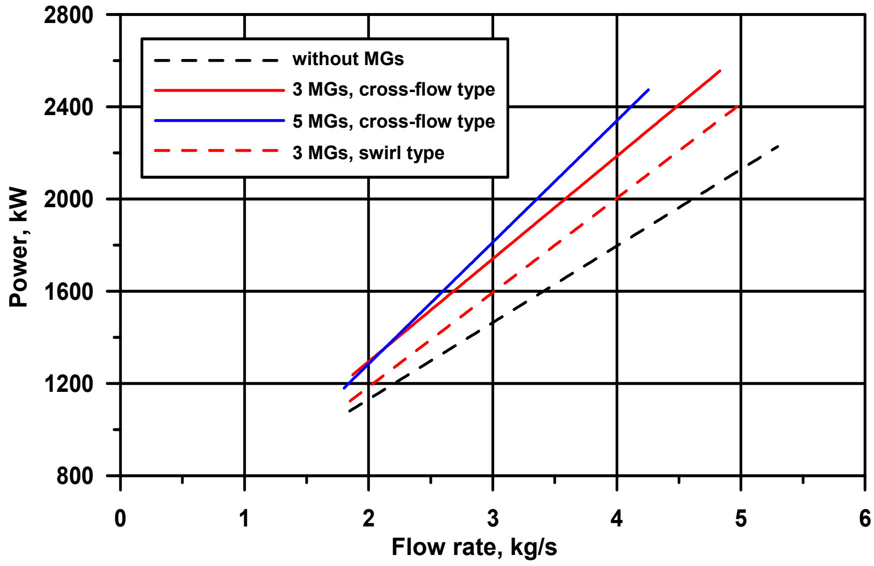

Figure 3 – Results of critical heat flux studies on the TVSA-ALPHA models with mixing grids (MG)
(P = 15.7 MPa, T_{in} = 290 °C)

Using effective mixer grids

Use of mixer grids is an important area for TVSA development. Mixer grids equalize coolant heatup, reduce local coolant void fraction, increase the DNBR, enable implementation of efficient fuel cycles with higher fuel rod power, and make it possible to uprate the core power.

Mixer grids have operated for four years in Kalinin NPP Unit 1 within TVSA-ALPHA fuel assemblies and keep operating for the fifth year.

Since 2010, TVSA-Ts with mixer grids have been operating in full core loadings at Temelin NPP Unit 1 and 2.

The effect from using mixer grids in TVSAs in the VVER-1000 reactor core is characterized by:

–maximum local coolant void fraction reduced by ~3%

–minimum DNBR increased by ~ 30%

Conclusion

1. TVSAs successfully operate at 21 VVER-1000 units of Kalinin NPP, and Ukrainian, and Czech and Bulgarian NPPs. The TVSA design is characterized by reliability, and validity of engineering solutions and lifetime characteristics. Unique TVSA performance has been achieved in terms of operating time of ~50,000 hours and fuel burnup (the maximum FA burnup is 65 MW·day/kgU; the maximum fuel rod burnup is 72 MW·day/kgU).

2. Development of TVSA aims to increase the uranium content (fuel rod with the pellet ∅7.8/0 mm), to use effective mixer grids that ensure increasing critical heat fluxes by 30%, and to implement economically effective 5×1 and 3×1.5 fuel cycles with uprated allowable fuel rod power.

3. Use of mixer grids and improved thermal-hydraulic characteristics of the TVSA angle-piece design make it possible to enhance operational reliability of the fuel, implement efficient fuel cycles with the fuel rod power uprated to Kr_{max} =1.63, reduced neutron fluence to the reactor vessel, and ensure the possibility of uprating the core power.

4. The TVSA design is characterized by high operational reliability, fuel burnup, and lifetime. This design provides competitive advantages for the Russian fuel and makes it possible to ensure high technical and economic performance for operating VVER-1000 power units and advanced VVER reactors.

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