TVSA-T fuel assembly for “Temelin” NPP. Main results of design and safety analyses. Trends of development

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INTRODUCTION

◆ TVSA is a fuel assembly with rigid skeleton formed by 6 angle pieces and SG is successfully operated at 17 VVER-1000 power units of Kalinin NPP, as well as, at the Ukraine and Bulgaria NPPs

◆ Within the contract for fuel supply for “Temelin” NPP, TVSA-T fuel assembly was developed based on proven solutions confirmed by operation of TVSA modifications during 4-6 years and by the results of post-irradiation examination

◆ TVSA-T design is characterized by using of combined spacer grids (SG+MG) and by fuel column elongation by 150 mm

◆ A set of analyses and experiments was performed to validate TVSA-T design, including thermohydraulic tests, validation of critical heat flux correlation for TVSA-T, integrated mechanical, vibration and lifetime tests

◆ TVSA-T design was successfully licensed in SONS. Now the TVSA-T core in operation at “Temelin” NPP unit 1.
TVSA-T DESIGN BASIS

- Operational reliability and safety of fuel in view of operation conditions as per operator requirements
- Compatibility with reference fuel, in-reactor structures and “Temelin” NPP equipment
- Elimination of fuel rod fretting damage
- Bending resistance – sufficient stiffness of FA design (sags in homogeneous core ≤ 6 mm)
- Effective fuel consumption with high burnup to 72 MW·day/kgU, flexible fuel cycle
- Structure dismountability to ensure leaky fuel rod replacement
TVSA-T DESIGN DECISIONS

- 6 angle pieces
- 6 combined SG
- Lower antivibration assembly
- Fuel rods with increased uranium content and fuel column elongated by 150 mm
- Enrichment for U235 – up to 4.95%
- Design dismountability and maintainability
- Debris filter
- Application of mixing grids - heat exchange intensifiers (MG)
◆ The combined two-level SG consists of cell-type SG and mixing grid TVSA-ALFA in a single shell
◆ MG is a plate-type grid with flow deflectors (vanes) without fuel rod spacing
◆ The combined SGs ensure:
  - Decrease of temperature gradient over TVSA cross section and local steam content
  - Increase of DNBR

*MG application permits to increase core power and power peaking factors*
TOP NOZZLE

Top nozzle consists of:
- upper shell;
- spacer skeleton;
- spring assembly;
- connecting elements

The top nozzle is fixed to guide thimbles by collets.
Bottom nozzle consists of:
- casing;
- support ribs;
- locking element.

The nozzle includes debris filter catching particles above 2 mm.
### MAIN CHARACTERISTICS OF TVSA-T CORE

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum core power</td>
<td>3030 MW</td>
</tr>
<tr>
<td>Fuel column height</td>
<td>3680 mm</td>
</tr>
<tr>
<td>Fuel rod outer diameter / fuel rod pitch</td>
<td>9.1 / 12.75 mm</td>
</tr>
<tr>
<td>Maximum relative rating of fuel rod</td>
<td>1.63</td>
</tr>
<tr>
<td>Maximum relative rating of FA</td>
<td>1.45</td>
</tr>
<tr>
<td>Average linear loading of fuel rod</td>
<td>156.3 W/cm</td>
</tr>
<tr>
<td>Maximum linear loading of fuel rod at the height of 0.5 Hcore / at the height of 0.8 Hcore</td>
<td>448 / 375 W/cm</td>
</tr>
<tr>
<td>Fuel rod maximum burnup</td>
<td>72 MW day/kgU</td>
</tr>
<tr>
<td>Reference fuel cycle</td>
<td>5x320 EPPD</td>
</tr>
</tbody>
</table>

- TVSA-T characteristics ensure operation in the conditions of flexible fuel cycle with reduced neutron leak and possibility to change lifetime duration within 230-500 EPPD
- TVSA-T reference fuel cycle is five-year cycle with 36 makeup FAs, duration is 320 EPPD
MAIN EXPERIMENTS TO VALIDATE THE MECHANICAL DESIGN

- Mechanical tests of FA components, fragments and mockups to determine bending and torsion stiffness, load bearing capacity and stability
- Study of seismic stability and loading during LOCA
- Vibration tests of 3-span fragment in transverse-longitudinal coolant flow
- Tests for RCCA drop
- Life tests of full-scale TVSA-T mockup under actual coolant parameters
- Transport tests of full-scale FA mockup

*To validate TVSA-T, the results of TVSA designs and its modifications test results were also used*
THERMOHYDRAULIC TESTS

- Hydraulic tests of FA fragments and mockups including testing of two full-scale TVSA-T mockups at OKBM RGS and LKP Skoda test facilities under actual coolant parameters
- Testing of debris filter to determine hydraulic loss and effectiveness of debris entrapping
- Investigations of local flow hydrodynamics using 57-rod TVSA model
- Investigations and optimization of mixing grids
- Investigations of thermohydraulic characteristics and CHF on 19-rod TVSA models at two thermophysical tests facilities in OKBM and IPPE
- Validation of DNB correlation for TVSA-T
CHF COMPARISON FOR TVSA-T MODELS WITH CALCULATION USING CORRELATION CRT-1
MAIN ACTIVITIES FOR TVSA-T DESIGN

TVSA-T design was validated by OKBM together with RRC “Kurchatov Institute”, VNIINM and IPPE

Main activities for the design included the following:

- Design methodologies as per Customer requirements
- Development of the neutronic part of the design
- Development of the thermohydraulic part of the design
- Fuel rod and gadolinium fuel rod design development
- FA mechanical design development
- TVSA-T design validation by experiments
- Provision of TVSA-T compatibility with “Temelin” NPP design
- Development of safety analysis report (Chapter 4 and 15 SAR)

The design was validated, and the accidents were analyzed using the procedures based on VVER safety validation methodology applied in Russia, Rostekhnadzor regulatory documentation in view of Czech regulatory documentation requirements fulfillment

The computer codes certified it Rostekhnadzor and licensed in Czech regulatory body were used for design validation
COMPUTER CODES FOR MECHANICS, THERMOHYDRAULICS AND SAFETY ANALYSES

**Thermomechanical Analysis**

- **ANSYS**
  - FA stress-strained state analysis.
  - Static and cyclic strength validation

**Thermohydraulic Analysis**

- **KANAL**
  - FA and core subchannel thermohydraulic analysis

**Safety Analysis in Accidents**

- **Non LOCA (RIA, LOFA)**
  - TIGR
  - 3-D neutron kinetics model and subchannel TH model

- **LOCA**
  - RELAP5/MOD3.2
  - Best estimate integral thermohydraulic code

- **RAPTA-5**
  - Fuel rod analysis in accidents
SAFETY ANALYSIS

- Analysis of acceptance criteria sensitivity for main parameters and substantiation of selection of conservative initial state and normal operation system actuation scenario
- Safety analysis at PRPS operation
- Safety analysis when PRPS fails and DPS operates
- The analysis of LOCA was performed in co-operation with UJV Rez
LIST OF CRITERIA (CONDITION I - IV)

- Departure from nuclear boiling ratio
- Maximum temperature of fuel rod cladding
- Equivalent oxidation level of fuel rod cladding
- Oxidized zirconium quantity
- Maximum temperature of fuel
- Maximum average-radial enthalpy of fuel
- Number of leaky fuel rods
- Pressure in reactor plant circuits

The analysis results confirm that the design criteria are satisfied during operation of TVSA-T fuel loadings in “Temelin” NPP core in Condition I - IV
Validation of CHF and heat exchange coefficients correlation as a part of subchannel code KANAL, used in the design, based on the results of experiments with TVSA-T models

Revising of engineering coefficients for power peaking factors and coolant heating factor

Statistical recording of local parameters deviations ($\Delta q$, $\Delta h$, $\Delta corr$) at DNBR calculation based on provision of one-sided confidence probability of 95%

DNBR calculation for Condition II-IV is similar to Condition I with application of hot assembly subchannel model in TIGR-1 code

This approach is implemented in TVSA-T design and “Temelin” safety analysis
TVSA-T DESIGN DEVELOPMENT LINE

- Reduction in consumption of materials and fabrication labor input
- Improved fuel handling conditions (refueling rate, SPR duration)
- Skeleton bending stiffness enhancement
- MG optimized design

TVSA-T

2 SG
6 CSG (SG+MG)

8 SG
3 MG

TVSA-T2

510x6=3060
SG and CSG pitch

255
MIXING GRID OPTIMIZATION

- Optimization developments and studies were performed to improve MG effectiveness – optimization of dimension, inclination and location of deflectors. MG was optimized with deflector location as per by-row cross flow scheme.
- Optimized MG is characterized by higher mixing efficiency and CHF increase.
- Positive experience of twist-type MG of TVSA operated at Kalinin NPP during two fuel load.

Twist-type flow

By-row cross flow
RESULTS OF CHF INVESTIGATION OF OPTIMIZED MG

Critical power of TVSA models increased by 10-20% due to MG

P=15.7 MPa, Tin=290 °C
MAIN RESULTS OF MIXING GRID EFFICIENCY STUDY

◆ Intercell exchange increase. Decrease of temperature gradient over TVSA cross section and local steam quality by ~3%

◆ Increase of CHF and DNBR by ~15 - 30%

◆ Additional mixing grid effects:
  - weaker CHF as a function of steam quality increases DNBR in limiting modes of Condition 2
  - less influence of axial profile on CHF (form factor effect) increases DNBR in actual axial profile

◆ Possibility to increase core power and power peaking factors, implementation of effective fuel cycles with increased power in fuel rods
TVSA-12 Fuel Assembly

- SG optimized position
- Skeleton bending stiffness enhancement
- Operation reliability improvement
- Designed to operate in 5x1, 4x1 and 3x1.5 fuel cycles
- TVSA advantages application:
  - reparability
  - debris filter
  - thermocontrol tubes
  - antivibration SG
- Fuel rods with increased uranium content (thinned cladding and 7.8/0mm fuel pellet)
- High thermal performance due to MG optimization
**Thermohydraulic characteristics of TVSA allow the core uprating to 104% with fuel rod power peaking preservation $F_{\Delta h}=1.63$**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power, MW</td>
<td>3120</td>
</tr>
<tr>
<td>Inlet core temperature, °C</td>
<td>293.8</td>
</tr>
<tr>
<td>Pressure, MPa</td>
<td>15.7</td>
</tr>
<tr>
<td>Reactor flow rate, m³/h</td>
<td>82000</td>
</tr>
<tr>
<td>Average linear power, W/cm</td>
<td>162.5</td>
</tr>
<tr>
<td>Maximum relative power of fuel rods, $F_{\Delta h}$</td>
<td>1.63</td>
</tr>
<tr>
<td>Maximum linear power $q_l$, W/cm</td>
<td>448</td>
</tr>
<tr>
<td>Minimum DNBR</td>
<td>1.47</td>
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</table>
### THERMAL CHARACTERISTICS OF TVSA CORE FOR FUTURE VVER

<table>
<thead>
<tr>
<th></th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal power, MW</td>
<td>3200</td>
<td>3300</td>
</tr>
<tr>
<td>Inlet core temperature, °C</td>
<td>298.2</td>
<td>298.6</td>
</tr>
<tr>
<td>Pressure, MPa</td>
<td>16.2</td>
<td>16.2</td>
</tr>
<tr>
<td>Reactor flow rate, m³/h</td>
<td>86000</td>
<td>86000</td>
</tr>
<tr>
<td>Average linear power, W/cm</td>
<td>168.7</td>
<td>174.0</td>
</tr>
<tr>
<td>Maximum relative power of fuel rods, $F_{\Delta h}$</td>
<td>1.63</td>
<td>1.63</td>
</tr>
<tr>
<td>Maximum relative local power, $F_Q$</td>
<td>2.38</td>
<td>2.31</td>
</tr>
<tr>
<td>Maximum linear power $q_l$, W/cm</td>
<td>448</td>
<td>448</td>
</tr>
<tr>
<td>- at height of 0.5 $H_{core}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- at height of 0.8 $H_{core}$</td>
<td>370</td>
<td>380</td>
</tr>
<tr>
<td>Minimum DNBR</td>
<td>1.52</td>
<td>1.43</td>
</tr>
</tbody>
</table>

Based on the analysis results TVSA with MG for future VVER (MIR-1200) ensures necessary thermal characteristics at core power 3300 MW with increased allowable fuel rod power of $F_{\Delta h}=1.63$
CONCLUSION

◆ TVSA-T fuel assembly for “Temelin” NPP was validated. TVSA-T design is based on approved technical decisions and meets the current requirements for lifetime, operational maneuverability and safety

◆ The results of post-irradiation examination of TVSA-T operated at Kalinin NPP unit 1 during 4 years confirm the assembly operability, skeleton stiffness, TVSA-T geometric stability and normal fuel rod cladding condition

◆ Characteristics of TVSA with MG make possible core power increase up to 3300 MW according to future VVER (MIR-1200) design perspectives, providing allowable fuel rod power $F_{\Delta h} = 1.63$ (to implement effective fuel cycles)