NUCLEAR FUEL for NPPs: CURRENT STATUS AND MAIN TRENDS of DEVELOPMENT

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V. Molchanov

10th International Conference on WWER Fuel Performance, Modelling and Experimental Support
07-14.09.2013, Inter-Hotel, Bulgaria
Our Goal

To supply Customer with the fuel, that ensures:

Safe and reliable operation

Economic efficiency of utilization in flexible fuel cycles
Customer’s main requirements to NF at the present stage:

1. To provide high performance of operational reliability of fuel.
2. To uprate NPP’s capacity to the level of more than 100% from the designed one.
3. To increase fuel cycle length.
4. To increase the burnup of the fuel.
5. To introduce load-follow mode at NPPs.
**NF design and fabrication technology development – the main tool of maintaining of Fuel Company competitiveness**

<table>
<thead>
<tr>
<th>Safety</th>
<th>Reliability</th>
<th>Economic efficiency</th>
<th>Competitive price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment-calculated justification of fuel behavior</td>
<td>Development of normative and methodological base</td>
<td>Increase in fuel burnup</td>
<td>Unification of fuel behavior</td>
</tr>
<tr>
<td>Development of NF calculation codes and design methodologies</td>
<td>Development of QMS</td>
<td>Increase in fuel lifetime</td>
<td>Improvement of conversion, enrichment and fabrication technologies</td>
</tr>
<tr>
<td>Development of innovative fuel types and design materials</td>
<td>Development of FA and fuel rod designs</td>
<td>Increase in fuel cycle length</td>
<td></td>
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<td></td>
<td>Development of fuel and design materials</td>
<td>To ensure load-follow modes of reactor’s operation</td>
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<tr>
<td></td>
<td></td>
<td>Justification of NF operability under conditions of uprated capacity of reactor</td>
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</tbody>
</table>
Nuclear fuel reliability increase

- FA geometrical stability increase
  Application of FA with rigid skeleton
- Improvement of protection from damage by foreign objects in coolant
  Implementation of anti-debris filters (ADF)
- Improving vibration resistance
- Implementation of anti-vibration grids (AVG)
- Improvement of thermal technical reliability
  Mixing grid implementation (MG)
- Fuel - cladding interaction preventing, lower GPD output
- Increase of ave. grain size of fuel
- Improvement of corrosion resistance and resistance to radiation impact
  Implementation of new design materials
NF economic efficiency improvement

- Fuel burnup increase
- Fuel lifetime increase
- Creation of conditions for reactors’ thermal power increase
- Ensuring of NF operability under load-follow modes
**VVER-440 Nuclear Fuel**

**FA of the second generation**
**Enrichment 4.87% Fuel pellet 7.6/1.2**
- Kola NPP since 2010;
- Mohovce NPP since 2011;
- Bogunice NPP since 2012.

**RK-3 of third generation**
**Enrichment 4.87% Fuel pellet 7.8/0**
- at Kola NPP since 2010.

**FA of the second generation with intensification tabs on SG**
- Lovliša NPP since 2012.

**Units thermal power uprate on the base FA of the 2nd generation**
- Kola NPP (Units 3,4) – 107%;
- Mohovce NPP – 107%;
- Bogunice NPP – 107%;
- Dukovany NPP – 105%;
- Paks NPP – 108%;
- Lovliša NPP – 109%.

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**Burnup, MW-day/kgU**
- PK-1: 45
- PK-2: 57
- PK-3: 65

**Number of FA for reload batch, pcs.**
- PK-1: 84
- PK-2: 68
- PK-3: 60

**Uranium consumption, kg/MW-day**
- PK-1: 0.209
- PK-2: 0.184
- PK-3: 0.180

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VVER-440 Nuclear Fuel

Second generation fuel
   Enrichment 4.76%
   Pellet 7.8/0 мм

Fuel cycle - 6-year when operating at 1485 MWt (thermal).
Type of fuel rod bundle – profiled, U-Gd.
Number of fuelling cassettes – 60
Burnup- 65 MW day/kgU per fuel rod
Operation in load-follow mode.

*Technical documents set to substantiate the project of introduction at Dukovany NPP, Czechia, is developed.*

*Expected effect of introduction* – lower number of cassettes for reloading ~7% compared with second generation fuel cassettes with fuel 4.87% and pellet 7.6/1.2 мм.
RK-3 design – without the shroud tube, skeleton formed by angels and tubes. Mass of UO2 - 132 kg (increased by 4.5%). Fuel rod pitch in the bundle increased from 12,3 to 12,6 mm. Fuel cycle – 6 x 1 year. **The expected benefit of RK-3 implementation** – increase in fuel consumption efficiency about 10% as compare to FA of the second generation.

Pilot batch operation (12 FAs) started at Kola NPP Unit 4 in 2010. Results are positive. Extension of RK-3 usage at Kola NPP is expected in 2017 after transition to core control by local parameters in 2015.
### VVER-440 Nuclear Fuel
#### Stages of development

<table>
<thead>
<tr>
<th>years</th>
<th>before 1998</th>
<th>after 1998</th>
<th>after 2003</th>
<th>after 2010</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FA type</strong></td>
<td>Regular RK, with shroud</td>
<td>Regular RK, with shroud</td>
<td>2-nd generation RK, with shroud</td>
<td>2-nd / 3-d generation RK</td>
</tr>
<tr>
<td><strong>Fuel rod bundle type</strong></td>
<td>Nonprofiled</td>
<td>Profiled</td>
<td>Profiled, UGd</td>
<td>Profiled, UGd</td>
</tr>
<tr>
<td><strong>Fuelling enrichment, % U$^{235}$</strong></td>
<td>3.60</td>
<td>3.82</td>
<td>4.25 / 4.38</td>
<td>до 4.87</td>
</tr>
<tr>
<td><strong>Fuelling FA, pcs.</strong></td>
<td>105</td>
<td>84</td>
<td>66</td>
<td>60</td>
</tr>
<tr>
<td><strong>Burnup, MW·day / kgU</strong></td>
<td>36</td>
<td>45</td>
<td>57</td>
<td>65</td>
</tr>
<tr>
<td><strong>Fuel cycle</strong></td>
<td>3-year</td>
<td>4-year</td>
<td>5-year</td>
<td>6-year</td>
</tr>
<tr>
<td><strong>Natural U consumption, kg /MW·day</strong></td>
<td>0.256</td>
<td>0.209</td>
<td>0.184</td>
<td>0.180</td>
</tr>
</tbody>
</table>
TVSA-PLUS (TBCA-12PLUS in 2014) and TVS-2M have identical techno-economic characteristics which provide:

- capability to increase reactor thermal power up to 104% of nominal
- 18 months fuel cycle (reload batch of 66 pcs.)
- fuel rod burnup - 72 MW·day/kgU
- capability to operate in load-follow modes (100-75-100% Ne)
- protection from foreign materials
- capability for repair at NPP site
Main solutions
✓ compatibility with VV6 fuel
✓ 8 combined grids (SG+MG)
✓ fuel column 3680 mm high (blankets 2×150 mm)
✓ fuel pellet 7.6/1.2 mm
✓ mass of UO₂ in cassette 524.1 kg
✓ burnup per fuel rod 72 MW day/kgU

Start of TVSA-T operation:
➢ at unit №1 – 2010
➢ At unit №2 – 2011

Stages of development
Power increase to 104% (TVSA-T basic design)
FA design optimization (12 SG; pellet 7.8/0 mm)
Fuel cycle optimization
Nuclear Fuel for VVER-1000
TVSA-12

- TVSA-12 design
  - 12 SG 35 mm height
  - fuel column length 3530 mm
  - fuel pellet Ø7,8/0 mm
- Geometrical, thermal-hydraulic, neutron-physics and thermal-mechanical compatibility with TVSA is provided
- 12 pilot TVSA-12 were loaded at Kalinin-1 in 2011. Results of operation is positive
- 2013 - justification and licensing in Ukraine.
- Delivery of the first batch of TVSA-12 at Rovno-4 in 2014

<table>
<thead>
<tr>
<th>FA type</th>
<th>TVSA</th>
<th>TVSA-12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydraulic loss coefficient for FA with DF</td>
<td>12,1</td>
<td>12,5</td>
</tr>
<tr>
<td>Number of SG / height of SG (mm)</td>
<td>15 / 20</td>
<td>12 / 35</td>
</tr>
<tr>
<td>Skeleton bowing rigidity, H/мм</td>
<td>55</td>
<td>61,5</td>
</tr>
</tbody>
</table>
# VVER-1000 Nuclear Fuel Stages of development

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>FA type</strong></td>
<td>TVS, TVS-M</td>
<td>AFA</td>
<td>TVSA</td>
<td>TVS-2</td>
<td>TVSA-Alpha</td>
<td>NVS-2M/TVSA-PLUS</td>
<td>TVSA-12</td>
</tr>
<tr>
<td><strong>Absorber type</strong></td>
<td>–</td>
<td>U-Gd</td>
<td>U-Gd</td>
<td>U-Gd</td>
<td>U-Gd</td>
<td>U-Gd</td>
<td>U-Gd</td>
</tr>
<tr>
<td><strong>Fuelling enrichment, % U\textsuperscript{235}</strong></td>
<td>4.31</td>
<td>3.77</td>
<td>до 4.4</td>
<td>4.26</td>
<td>4.83</td>
<td>4.88</td>
<td>4.83</td>
</tr>
<tr>
<td><strong>Number of fuelling FA</strong></td>
<td>54</td>
<td>48</td>
<td>42</td>
<td>54</td>
<td>36</td>
<td>60 – 66</td>
<td>36</td>
</tr>
<tr>
<td><strong>External diameter, мм</strong></td>
<td>7.57 / 2.3</td>
<td>7.57 / 1.5</td>
<td>7.57 / 1.4</td>
<td>7.57 / 1.4</td>
<td>7.8 / 0.0</td>
<td>7.6 / 1.2</td>
<td>7.8 / 0</td>
</tr>
<tr>
<td><strong>Fuel burnup, MW×day/kgU</strong></td>
<td>49</td>
<td>49</td>
<td>55</td>
<td>55</td>
<td>65</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td><strong>Fuel cycle</strong></td>
<td>3×1</td>
<td>3×1</td>
<td>4×(310–320)</td>
<td>3×(350–370)</td>
<td>5×(310–320)</td>
<td>3×(480–510)</td>
<td>5×(310–320)</td>
</tr>
<tr>
<td><strong>U consumption, kg/MW×day.</strong></td>
<td>0.240</td>
<td>0.205</td>
<td>0.199</td>
<td>0.210</td>
<td>0.187</td>
<td>0.230</td>
<td>0.187</td>
</tr>
</tbody>
</table>
FA of 4th generation for VVER-1000

**Stages of development**

<table>
<thead>
<tr>
<th>Stage</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design documentation</td>
<td>2012</td>
</tr>
<tr>
<td>Rosatom scientific meeting #2</td>
<td>2013</td>
</tr>
<tr>
<td>Pilot operation</td>
<td>2015</td>
</tr>
</tbody>
</table>

**TVS-2M**
- 12 SG, MG, DF,
  - Fuel column – 3680 mm,
  - Unified top nozzle

**TVSA-PLUS**
- DF,
  - Fuel column – 3680 mm

**TVSA-ALFA**
- SG, DF,
  - fuel pellet Ø7,8/0 mm

**FA of 4th generation**
- Unified top nozzle
- 12 SG, MG, DF
- Fuel column – 3680 mm
- Fuel pellet Ø7,8/0 mm
- $\text{UO}_2\text{mass}$ - 568,4 kg
- Fuel cycle 3x510 or 5x333
- increase in fuel cycle length at 8% of
  reduction in number of FA at 10%
- or decrease in reload batch enrichment at 7%
**VVER-1000 fuel cycles, thermal power 104 % $N_{\text{nom}}$**

<table>
<thead>
<tr>
<th>Fuel Cycle</th>
<th>Country/Region</th>
<th>Operation Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>TVS-2M</td>
<td>Balakovo NPP, Rostov NPP, Tyanvan NPP (planned)</td>
<td>3×18 months</td>
</tr>
<tr>
<td>TVSA-PLUS, TVSA-12PLUS</td>
<td>Kalinin NPP</td>
<td>3×18 months</td>
</tr>
<tr>
<td>TVSA-T, TVSA-12</td>
<td>Temelin NPP, NPP of Ukraine (planned), Kozloduy NPP (planned)</td>
<td>5×12 months</td>
</tr>
</tbody>
</table>
Development of Nuclear Fuel for VVER-1000/1200/1300

- Development program for Ukrainian NPP - 2012, Kozloduy – 2013

TVSA-12
Fuel pellet 7.8/0mm
Active length 3530 mm

TVSA-PLUS
TVS-2M
Fuel pellet 7.6/1.2mm
Active length 3680 mm

- Amendment to TVSA-PLUS design with 12 SG was developed – 2012
- Start of pilot operation of TVSA-12PLUS – 2014
- Implementation of TVS-2M at Tyanvan, Kudankulam and Busher NPPs

TVS-4A
TVS-4
Fuel pellet 7.8/0mm
Active length 3680 mm

- Fuel rod, U-Gd fuel rod and FA designs are developed in 2012
- Experimental justification of fuel rod design – 2012-2015
- Pilot batch delivery – 2015

TVS-2006
RP power 3200 MW
Active length 3730 mm

- The first core for unit 1 NVNPP-2 (VVER-1200) is fabricated – 2012
- Further development of FA-2006 design (mixing grids implementation, modified Zr alloys) – 2012-2015

TVS-TOI
RP power 3300 MW
Active length 3730 mm

- Fuel rod, U-Gd fuel rod, RCCA and FA designs are developed in 2012
- Improvement of TVS-TOI design, justification in load-follow modes 100-50-100% – 2013-2017

TVS-XXI
Enrichment up to 7% U-Er poison
New cladding and structure material

- Development of fuel rod and FA designs with enrichment up to 7% – 2012-2017
- Development of innovative materials for reactor testing – 2013-2020

Maximum FA burnup, MW-day/kgU

Fuel cycle length, EPFD
Development of NF fabrication technology

Re-equipment of metallic zirconium production

Fluoride electrolytic scheme of producing metallic Zr. powder

Introduction of chloride technology of zirconium production (Zr concentrate chlorination, cleaning of Zr from Hf, production of sponge by magnetic thermal restoration)

- Lower consumption of:
  - power – by 3.3 times;
  - chemicals – by 9.4 times

- Decreasing of:
  - personnel – by 1.4 times;
  - production areas – by 4 times

Claddings production with up the art level characteristics
- Zirconium rolling production for TVS-K and foreign customers (AECL, GNF/GE, KEPCO)
- Cost decrease because of product’s higher quality, less power consumption and labor.

Enlarged blank Ø199 mm, new technological processes with usage of:
- press of 35 MH;
- radial forging machines SKK14,10;
- rolling mill KPW 75,50,25,18 with ring calibers;
- polishing (LOESER), jet-etching;
- cladding cutting in size, laser marking.

Claddings characteristics

<table>
<thead>
<tr>
<th></th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>wall thickness, mm</td>
<td>0.63</td>
<td>0.54</td>
</tr>
<tr>
<td>diameter tolerance, mm</td>
<td>±0.04</td>
<td>±0.05</td>
</tr>
<tr>
<td>hafnium content, ppm</td>
<td>≤ 500</td>
<td>≤ 50</td>
</tr>
</tbody>
</table>

Blank: Ø109 mm
Mills HTP, HPTR
Etching in bath

Introduction of chloride technology of zirconium production (Zr concentrate chlorination, cleaning of Zr from Hf, production of sponge by magnetic thermal restoration)
Development of Nuclear Fuel fabrication technology

Section for producing uranium dioxide powder by “dry” conversion technology

Line for producing pellets

Stacker of pressed pellets in trough for sintering

Equipment for optical inspection of pellets appearance

Fuel pellets on pallets
Monitoring of NF fabrication quality and its operation

Problems being solved:

- Cooperation with Customers and NF developers
- Participation in development of nuclear fuel and starting its manufacturing
- Organization of analysis of products and elimination of nonconformancies
- Organization of control and acceptance
- Nuclear fuel operation analysis
- Customers’ claims examination organization
Indices of nuclear fuel reliability for the period of 2008 - 2013:

- for NPP with VVER-440 - $2.6 \times 10^{-6}$ 1/year (one of the best in nuclear industry)
- for NPP with VVER-1000 - $1.5 \times 10^{-5}$ 1/year
- there are no claims on FA quality from Customers
- achieved level of fuel reliability corresponds to Russian criterion, but worse as compare to worldwide practise for PWR ($10^{-6}$ 1/year)
Driving to zero failure

TVEL initiative

The nearest task

1x10^-6

The main goal

«0»

Participants of Memorandum

• Concern Rosenergoatom

Foreign Utilities

• CEZ a.s., (Czech Republic)
• NAEK Energoatom, (Ukraine)
• Kozloduy NPP, (Bulgaria)

Fuel Vendor

• TVEL

Currently within the frames of the Project:

✓ Memorandum TVEL-REA is signed
✓ 4 sided Memorandum is signed
✓ Regulation on Project activity is valid
✓ Steering Committee and Working Body are established
✓ Working Groups (WG) on design, fabrication and operation are formed
✓ Schedules of work for WG are developed
✓ Intergroup communication and information exchange on the Project are arranged

Project Stages:

Stage 1: 2013-2014
Analysis of situation and root cases of fuel failures definition

Stage 2: - 2014-2015
Development of organizational and technical actions for fuel failures elimination

Implementation and monitoring of actions at Participant’s and fuel developer’s enterprises.
Conclusion

- New FA designs
- Modern designing methods
- New automated technologies of nuclear fuel fabrication
- Driving to Zero Failure

- Increase in safety and reliability of operation
- Increase in economical efficiency of fuel utilization
- Decrease in amount of spent fuel
Thank you for attention!