Strategy for development of nuclear fuel for NPP with VVER

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TRADITIONAL INTERNATIONAL NUCLEAR CONFERENCE
BULGARIAN NUCLEAR ENERGY – NATIONAL, REGIONAL AND WORLD ENERGY SECURITY
5th June – 7th June, 2019, Varna
The main objectives of evolution of nuclear fuel - meeting the increasing demands of Consumers in terms of improving the economic efficiency, safety and operational reliability of fuel and fuel cycles while ensuring an adequate level of reliability and safety of nuclear power plants in general.

The main objectives for TVEL

- Increased operational reliability
- Increase of FA “energy storage capacity”
- Improvement of structural and fuel materials
- Justification of unit operation in load follow modes
- Monitoring the operation of nuclear fuel at NPPs
- Extended use of RT fuel
- Development and extended use of ATF
Nuclear fuel for VVER-440

Second generation fuel
Fuel pellet 7.6/1.2 mm
Fuel cycle – 5 years at the operation at 1471 MW (therm.) power (107%).
Burnup- 57 MW·day/kgU.
Operation in a power maneuvering mode.

Fuel of generation 2+
Fuel pellet 7.8/0 mm
Fuel cycle – 5 years at the operation at 1540 MW (therm.) (110%).
Burnup - 65 MW·day/kgU
Operation in a power maneuvering mode.
Operation started 2014 at Dukovany NPP

Third generation fuel
Fuel pellet 7.8/0 mm
Shroudless
Fuel cycle – 6 years at the operation
Burnup- 65 MW·day/kgU
Operation in a power maneuvering mode.
Pilot operation since 2010 at unit 4 Kola NPP. In 2016 the 2nd batch was loaded
Transition to full reload batch -2020 (plan)

Prospective design
Possible:
1. 2nd Generation fuel with “slim” fuel rods 8,9 mm (Loviisa NPP, Paks NPP).
Status: contracts signed
2. 3rd Generation fuel with “wide” angle piece (Dukovany NPP).
Status: based on feasibility studies offers for Customers are provided
Nuclear fuel for VVER-440
2nd Generation fuel with fuel rods OD 8.9 mm

2nd Generation fuel with fuel rods OD 8.9 mm – SR (Slim Rod)
Fuel pellet OD – 7.6 mm (solid design).
Fuel rod cladding OD/ID - 8.9 mm/7.73 mm.
Requirements to fuel cycle:
Lovisa NPP – to maintain reactor power and fuel cycle length with decrease in reload batch enrichment.
Paks NPP – to reduce the number of FAs in reload batch keeping the fuel cycle length.

<table>
<thead>
<tr>
<th></th>
<th>Paks NPP</th>
<th>Lovisa NPP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel cycle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current 15th months fuel cycle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New 15th months fuel cycle (fuel rod OD 8.9 mm, solid pellet)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current 12th month fuel cycle (fuel rod OD 9.1 mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New 12th month fuel cycle (fuel rod OD 8.9 mm, solid pellet)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of fresh FAs in reload batch</td>
<td>102</td>
<td>96</td>
</tr>
<tr>
<td>Average enrichment of reload batch, %</td>
<td>4.64</td>
<td>4.70</td>
</tr>
<tr>
<td>Fuel cycle length, EFPD</td>
<td>425</td>
<td>428.1</td>
</tr>
<tr>
<td>Natural uranium consumption, t/year</td>
<td>89.0</td>
<td>87.0</td>
</tr>
</tbody>
</table>
## Nuclear fuel for VVER-440
### 3rd Generation for Dukovany NPP

Comparison of equilibrium fuel cycles based on 2nd Generation fuel Gd-2M+ with 3rd Generation fuel RK-3+ for Dukovany NPP

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2nd Generation fuel Gd-2M+</th>
<th>3rd Generation fuel RK-3+ fuel cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reference</td>
<td>Alternative</td>
</tr>
<tr>
<td>Rated reactor thermal power, MW</td>
<td>1485</td>
<td>1475</td>
</tr>
<tr>
<td>Number of fresh FAs for reload batch by types, pcs.</td>
<td>66</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>12 FA 4,38% /</td>
<td>12 FA 4,76% /</td>
</tr>
<tr>
<td></td>
<td>54 RK 4,76%</td>
<td>78 RK 4,73%</td>
</tr>
<tr>
<td></td>
<td>66</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>6 FA 4,38% /</td>
<td>60 RK 4,40%</td>
</tr>
<tr>
<td>Fuel cycle length (coast-down), EFPD</td>
<td>322 (0)</td>
<td>450 (41)</td>
</tr>
<tr>
<td></td>
<td>335 (36)</td>
<td></td>
</tr>
<tr>
<td>Maximum fuel assembly burnup, MW*day/kgU</td>
<td>55,9</td>
<td>61,7</td>
</tr>
<tr>
<td></td>
<td>56,0</td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>FA design</td>
<td>Average fuel enrichment, % $^{235}\text{U}$</td>
</tr>
<tr>
<td>----</td>
<td>--------------------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>1</td>
<td>RK-2 (9,1/7,6/1,2)</td>
<td>4.77</td>
</tr>
<tr>
<td>2</td>
<td>RK-2+ (9,1/7,8/0,0)</td>
<td>4.73</td>
</tr>
<tr>
<td>3</td>
<td>RK-2 (9,1/7,6/1,2)</td>
<td>4.64</td>
</tr>
<tr>
<td>4</td>
<td>RK-3 (9,1/7,8/0,0)</td>
<td>4.87</td>
</tr>
<tr>
<td>5</td>
<td>RK-2 SR (8,9/7,6/0,0)</td>
<td>4.73</td>
</tr>
<tr>
<td>6</td>
<td>RK3+SR (8,9/7,6/0,0)</td>
<td>4.73</td>
</tr>
</tbody>
</table>
2nd Generation fuel

- Preparation of materials to substantiate the performance of fuel rods and fuel tags in the modes of basic and maneuverable operation, as well as safe behavior in design basis accidents as part of the introduction of new fuel at the Mochovtse NPP and the Bohunice NPP.
- Development of a justification for the introduction of fuel with fuel rods with a diameter of 8.9 mm at Paks NPP and Loviisa NPP. Manufacturing and conducting hydraulic and life tests RK and TVS models.
- A set of studies to justify the use of the alloy Э125 о.ч. on the basis of spongy zirconium as a material for covers of working VVER-440 cassettes.

3rd Generation fuel

- Development of documentation for the start of commercial operation of the third-generation cassettes and the introduction of control over local parameters on blocks 3-4 of the Kola NPP.
- Development of substantiating materials for the introduction of RK-3 + at Dukovany NPP.
**Nuclear fuel for VVER-1000**  
**FA of 4\(^{th}\) Generation**

### Main features of FA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TVSA-PLUS</th>
<th>TVS-2M</th>
<th>TVSA-12</th>
<th>TVS-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel column height, mm</td>
<td>3680</td>
<td>3680</td>
<td>3530</td>
<td>3680</td>
</tr>
<tr>
<td>Number of SG, pcs</td>
<td>15</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Distance between SG, mm</td>
<td>255</td>
<td>340</td>
<td>340</td>
<td>340</td>
</tr>
<tr>
<td>Fuel pellet dimension, mm</td>
<td>7,6/1,2</td>
<td>7,6/1,2</td>
<td>7,8/0</td>
<td>7,8/0</td>
</tr>
<tr>
<td>(\text{UO}_2) mass, kg</td>
<td>527,0</td>
<td>527,0</td>
<td>545,2</td>
<td>568,4</td>
</tr>
<tr>
<td>Antivibration grid and debris filter</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

Fuel rods with solid pellets of OD 7.8 mm showed performance as follows:
- Operated ~ 65 000 fuel rods;
- Maximum fuel rod burnup 67 MW*day/kgU;
- Experimental justification of fuel rods in DBA RIA, LOCA and RAMP carried out.
- Fuel rod and FA design developed and approved by scientific committee of Rosatom

- Extension of the campaign duration by 8%  
- Decrease in number of reload batch FA by 10%  
- Decrease in reload batch’s enrichment by 0.25%  
- Decrease in neutron flux on reactor vessel
Plans-2019. Nuclear fuel for VVER-1000/1200

- Justification of the safety of the transfer of the Novovoronezh NPP-2 (VVER-1200) from the four-year to the 18-month fuel cycle.
- Development of the substantiation of the performance of a fuel element of VVER-1200 in maneuverable operating conditions in a flexible fuel cycle of 12-18 months.
- Development of fuel justification materials for the Hanhikivi NPP (VVER-1200).
- Development of fuel justification materials for the Hanhikivi NPP (VVER-1200).
Completion of pilot operation of TVSA-12PLUS at unit No. 3 of KlnAES. Preparing a decision on transferring all KlnAES units to TVSA-12PLUS loading.

Development of technical project TVSA with demountable design. Test the full-scale mockup. The TVSA design with fuel rods without fixation in the support grid will allow:

- provide maintainability of TVSA;
- greatly simplify the manufacturing technology of the lower support assembly and assembly of a bundle of fuel elements;
- improve thermomechanical behavior of fuel assembly.

Development of an 18-month fuel cycle based on TVS-4 with uranium regenerate.
**High enrichment fuel for VVER-1000/VVER-1200**

### Scenario of using increased enrichment fuel for 18 months fuel cycle

<table>
<thead>
<tr>
<th>FA</th>
<th>Fresh FA</th>
<th>Burned FA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of FA in reload batch</td>
<td>Average enrichment $^{235}$U, %</td>
</tr>
<tr>
<td>VVER-1000 usual enrichment</td>
<td>73(72)</td>
<td>4,6</td>
</tr>
<tr>
<td>VVER-1000 increased enrichment</td>
<td>61(60)</td>
<td>5,45</td>
</tr>
</tbody>
</table>

### Scenario of using increased enrichment fuel for 24 months fuel cycle

<table>
<thead>
<tr>
<th>TBC</th>
<th>Fresh FA</th>
<th>Burned FA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of FA in reload batch</td>
<td>Average enrichment $^{235}$U, %</td>
</tr>
<tr>
<td>VVER-1200 usual enrichment</td>
<td>108</td>
<td>4,7</td>
</tr>
<tr>
<td>VVER-1200 increased enrichment</td>
<td>82(81)</td>
<td>5,86</td>
</tr>
<tr>
<td></td>
<td>73 (72)</td>
<td>6,3</td>
</tr>
</tbody>
</table>

### Main milestones of Program for increased enrichment

1. Feasibility studies for using of increased enrichment for VVER-1000.
2. Justification of using of increased enrichment for VVER-1000.
4. Manufacturing of pilot batch, operation in VVER-1000, post-irradiation examination
5. Feasibility studies for using of increased enrichment for VVER-1000/1200/1300
MAIN ADVANTAGES

- REDUCTION of hydrogen production in accident conditions;
- REDUCTION of peak temperatures in accident conditions;
- HIGH corrosion-resistance under operation parameters as well as coolant boiling;
- EXCLUSION of hydrogen absorption during normal operation;
- MINIMAL impact on fuel enrichment and reactor physics;
- INCREASED resistance to debris damage.
**42XHM alloy**

**MAIN ADVANTAGES:**
- EXCLUSION of Zirconium-steam reaction;
- HIGH corrosion-resistance under operation parameters as well as coolant boiling;
- HIGH long ductility under irradiation;
- INCREASE of the parameters of the primary circuit;

42XHM alloy is widely used as cladding material for fuel rods of transport reactors, in this conditions, damages of claddings produced from 42XHM alloy have not been occurred. In respect to VVER reactors, 42XHM alloy is used in absorption rods claddings.

Use of UMo with the content of molybdenum 9 wt% additionally alloyed by Al, Sn, Si and etc as nuclear fuel

<table>
<thead>
<tr>
<th>Property</th>
<th>UO₂</th>
<th>UMo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat conductivity (500 °C), W/m·K</td>
<td>4.0</td>
<td>36.8</td>
</tr>
<tr>
<td>Uranium density, g/cm³</td>
<td>9.6</td>
<td>15.3</td>
</tr>
<tr>
<td>Melting point, °C</td>
<td>2840</td>
<td>1400</td>
</tr>
<tr>
<td>Rate of corrosion in water under 300 °C, mg/cm²·h</td>
<td>0</td>
<td>0.08</td>
</tr>
</tbody>
</table>
Two experimental FAs with samples of ATF fuel rods with VVER and PWR geometry were manufactured in 2018 and in January 2019 loaded for testing in experimental loops of MIR reactor with the corresponding water chemistry mode in order to provide experimental substantiation of the ATF technical design for VVER and PWR reactors.

Reactor tests of experimental FAs will be performed up to the burnup of \(~ 50 \text{ MW} \cdot \text{day/kgU}\).

The program provides for annual intermediate studies (visual inspection and profilometry) of experimental ATF fuel rods and the unloading of several fuel rods for post-irradiation examination.

The first phase of reactor tests and post-irradiation examination of ATF-type fuel rods will be completed in 2019.

The data obtained will be used to determine the optimal combination of fuel and cladding materials and the continuation of the next stages of justification:

- Working off technologies for manufacturing shells from alloys 42XHM and E110 with chrome plating
- Working off technologies for manufacturing U-Mo alloy tablet
- Working off technologies for manufacturing of tolerant fuel elements
- Justification of experimental-industrial operation of three combined TVS-2M with fuel rods of tolerant type in the VVER-1000 reactor of the Unit No. 2 of the Rostov NPP. Manufacturing of 3 combined TVS-2M.
- Loading of experimental FAs with separate ATF fuel rods into the power reactor of a Russian NPP.
Perspective. Accident Tolerant Fuel. Ceramic claddings (2/2)

**Benefits:**
- Dissociation temperature of SiC (~2545 °C) 2 times the shell temperature in the case of a design basis accident LOCA;
- Does not interact with water vapor until 1300 °C, the degree of corrosion of silicon carbide is orders of magnitude lower than that of zirconium;
- Thermal neutron capture cross section by silicon carbide is 25% less than that of zirconium;
- The use of silicon carbide fuel rods in VVER reactors will provide a radical increase in the radiation safety of modern nuclear power plants

**Limitations:**
- Problems with handling and using shells due to their fragility under normal conditions;
- Low creep rate of shells from SiC;
- Problems with sealing fuel rods (welding plugs and shells);
- Expensive fiber production from SiC.
2D/3D frame

Saturation, subsidence of SiC

Design of triple cladding SiC/SiC

Scheme of research works for 2017-2019 years

2017

Development of technology for the production of SiC fibers and precursors

Development of the process of obtaining experimental samples of SiC / SiC tubes by fabricating a fiber frame and its saturation with a binder

Development of technology for sealing the SiC / SiC claddings after loading of fuel pellets into the cladding tube

Carrying out of pre-reactor tests and preparing experimental samples of SiC / SiC fuel rods for reactor tests

2018

2019
Conclusions

TVEL pays great attention to the creation of new fuel compositions and to work on the improvement of zirconium materials in order to increase the reliability and safe operation of nuclear fuel in the context of increasing the burnout depth, increasing the resource and increasing power.

The machine-building equipment is constantly updated at the manufacturers of nuclear fuel, the technology for manufacturing components and fuel assemblies is being improved as a whole, and methods for controlling the quality of finished products are being improved.

Technical and economic characteristics (fuel burnup, duration of operation and fuel cycles, etc.) are at the level of global manufacturers of nuclear fuel.

TVEL provides and in the future will provide VVER reactors with only competitive and reliable Russian nuclear fuel.