DESIGN AND FABRICATION OF NUCLEAR FUEL FOR WWER AND RBMK REACTORS

Workshop on “Modelling and Quality Control for Advanced and Innovative Fuel Technologies”
14-25 November 2005
The Abdu Salam International Centre for Theoretical Physics, Trieste, Italy
Presented by V. Onufriev - consultant
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FIG. 2. WWER-1000 fuel assembly. Dimensions are in mm.
Principal Design of a LWR Fuel Element

- UO$_2$ Fuel Pellet
- Annular Gap
- Helium Gas Plenum
- Expansion Spring
- Zr-1%Nb or 635 Alloy Cladding
### VVER design data

<table>
<thead>
<tr>
<th></th>
<th>Mashinostroitelny zavod</th>
<th>Westinghouse</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>VVER 440 Serial</td>
<td>VVER 440 U-Gd Fuel</td>
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<tr>
<td>Assembly geometry</td>
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<td>No of rods per assembly</td>
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<td>127</td>
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<td>- Fuelled</td>
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</tr>
<tr>
<td>- Unfuelled</td>
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<tr>
<td>Rod length (mm)</td>
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<td>Rod outside diameter (mm)</td>
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<td>Pellet length (mm)</td>
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<td>7.57</td>
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<td>Pellet density (g/cm³ or TD)</td>
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<td>Average linear fuel rating (kW/m)</td>
<td>12.96</td>
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<tr>
<td>Peak linear fuel rating (kW/m)</td>
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<tr>
<td>Maximum fuel temperature (°C)</td>
<td>1500</td>
<td>1500</td>
</tr>
<tr>
<td>Clad material</td>
<td>Zr1%Nb</td>
<td>Zr1%Nb</td>
</tr>
<tr>
<td>Clad thickness (mm)</td>
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<td>0.63</td>
</tr>
<tr>
<td>Average clad temperature (°C)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Maximum clad temperature (°C)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Grid material</td>
<td>Zr1%Nb</td>
<td>Zr1%Nb</td>
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<tr>
<td>Average discharge burnup (MWd/kgU)</td>
<td>42</td>
<td>-</td>
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<tr>
<td>Maximum assembly burnup (MWd/kgU)</td>
<td>&gt;50</td>
<td>53</td>
</tr>
</tbody>
</table>

¹Fuel assembly design with removable fuel rods. ²Control fuel assembly (contains six Hf slices). ³Zr1%Nb, Zr1%Nb1.3%Sn0.3%Fe. Hex=Hexagonal.
Basic WWER fuel design data (from “Design and performance of WWER Fuel”, IAEA TRS 379, 1996)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>WWER-440</th>
<th>WWER-1000</th>
</tr>
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<tbody>
<tr>
<td>Assembly length (m)</td>
<td>3.22</td>
<td>4.655</td>
</tr>
<tr>
<td>Number of fuel rods in assembly</td>
<td>126</td>
<td>312</td>
</tr>
<tr>
<td>Length of fuel rod (m)</td>
<td>2.85</td>
<td>3.84</td>
</tr>
<tr>
<td>Length of fuel stack (m)</td>
<td>2.42</td>
<td>3.53</td>
</tr>
<tr>
<td>Fuel cladding outside diameter (mm)</td>
<td>9.1</td>
<td>9.1</td>
</tr>
<tr>
<td>Fuel cladding inside diameter (mm)</td>
<td>7.72</td>
<td>7.72</td>
</tr>
<tr>
<td>Fuel cladding wall thickness (mm)</td>
<td>0.65</td>
<td>0.65</td>
</tr>
<tr>
<td>$\text{UO}_2$ pellet outside diameter (mm)</td>
<td>7.57</td>
<td>7.57</td>
</tr>
<tr>
<td>$\text{UO}_2$ pellet inside diameter (mm)</td>
<td>1.4−1.6</td>
<td>2.2−2.4</td>
</tr>
<tr>
<td>$\text{UO}_2$-cladding radial gap (mm)</td>
<td>0.075−0.13</td>
<td>0.075−0.13</td>
</tr>
<tr>
<td>$\text{UO}_2$ pellet shape</td>
<td>plain cylinder</td>
<td>chamfered</td>
</tr>
<tr>
<td>$\text{UO}_2$ pellet length (mm)</td>
<td>9−12</td>
<td>9−12</td>
</tr>
<tr>
<td>$\text{UO}_2$ pellet density (g/cm$^3$)</td>
<td>10.4−10.8</td>
<td>10.4−10.8*</td>
</tr>
<tr>
<td>$\text{UO}_2$ pellet grain size (mm)</td>
<td>10−15 $\mu$m</td>
<td>10−25 $\mu$m</td>
</tr>
<tr>
<td>$\text{UO}_2$ pellet densification, diametral (%)</td>
<td>0.4 max</td>
<td>0.4 max</td>
</tr>
<tr>
<td>Helium filling pressure (MPa)</td>
<td>0.5−0.6</td>
<td>2−2.5</td>
</tr>
<tr>
<td>Gas plenum volume (cm$^3$)</td>
<td>4</td>
<td>11.4</td>
</tr>
<tr>
<td>Total rod internal free volume (cm$^3$)</td>
<td>8.3</td>
<td>32</td>
</tr>
<tr>
<td>Fuel rod pitch (triangular) (mm)</td>
<td>12.2</td>
<td>12.75</td>
</tr>
<tr>
<td>Number of spacer grids</td>
<td>11</td>
<td>15</td>
</tr>
<tr>
<td>Fuel assembly width (mm)</td>
<td>144.2</td>
<td>234</td>
</tr>
<tr>
<td>Weight of uranium/rod (kg)</td>
<td>0.95</td>
<td>1.46</td>
</tr>
<tr>
<td>Weight of uranium/assembly (kg)</td>
<td>119.7</td>
<td>430</td>
</tr>
</tbody>
</table>

* 10.4−10.7 g/cm$^3$ since January 1995.
Basic design features of WWER reactor/fuel

**Reactor Type:** LW cooled, water moderated, FAs – hexagonal shape

**Fuel Reload Type:** During refuelling outages

**Fuel:** UO$_2$ or (U+Gd)O$_2$ enriched to:

- WWER-440 - 3.8% (4-5 years) or 4.2% for the 2$^{nd}$ generation (5 years); Gd rods have lower enrichment level
- WWER-1000 – 3.8-4.3% (4 years) and 4.9% for perspective 5 years residence time; about Gd rods-see slide Number 56
- Fuel pellets – with central hole, trend for hole diameter decrease

**Tendency:** Increase of enrichment, burnup, duration of the single fuel cycle and total residence time; decrease of FA consumption

**Coolant Condition:** Non-boiling, 12.5 (440) and 16.0 MPa (WWER-1000)

**Clad Operational Mode:** Free Standing, ~0.5 (~2.0) MPa He inner pressure for WWER-440(1000)

**Tendency:** Change for E635 alloy as cladding and SG material
RBMK-1000 Fuel Assembly Design
### RBMK design data

<table>
<thead>
<tr>
<th>Assembly geometry</th>
<th>RBMK-1000</th>
<th>RBMK-1500</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UO₂+Er (2.6% U²³⁵)</td>
<td>UO₂+Er (2.8% U²³⁵)</td>
</tr>
<tr>
<td>No of rods per assembly</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>Circular array</td>
<td>Circular array</td>
</tr>
<tr>
<td>Fired</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>Unfired</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Overall assembly length (mm)</td>
<td>10014</td>
<td>10014</td>
</tr>
<tr>
<td>Overall assembly width (mm)</td>
<td>79</td>
<td>79</td>
</tr>
<tr>
<td>Rod length (mm)</td>
<td>3640</td>
<td>3640</td>
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<tr>
<td>Rod outside diameter (mm)</td>
<td>13.63</td>
<td>13.63</td>
</tr>
<tr>
<td>Pellet length (mm)</td>
<td>12.15</td>
<td>12.15</td>
</tr>
<tr>
<td>Pellet outside diameter (mm)</td>
<td>11.48</td>
<td>11.48</td>
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<td>Pellet density (g/cm³ or TD)</td>
<td>10.4-10.7</td>
<td>10.4-10.7</td>
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<tr>
<td>Average linear fuel rating (kW/m)</td>
<td>15.3</td>
<td>15.3</td>
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<tr>
<td>Peak linear fuel rating (kW/m)</td>
<td>35.0</td>
<td>35.0</td>
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<tr>
<td>Clad material</td>
<td>Zr1%Nb</td>
<td>Zr1%Nb</td>
</tr>
<tr>
<td>Clad thickness (mm)</td>
<td>0.86</td>
<td>0.86</td>
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<tr>
<td>Maximum clad temperature (°C)</td>
<td>350</td>
<td>350</td>
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<tr>
<td>Grid material</td>
<td>Zr1%Nb</td>
<td>Zr1%Nb</td>
</tr>
<tr>
<td>Average discharge burnup (MWd/kgU)</td>
<td>25.8</td>
<td>30</td>
</tr>
<tr>
<td>Maximum assembly burnup (MWd/kgU)</td>
<td>29.6</td>
<td>34.5</td>
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</table>
Basic design features of RBMK reactor/fuel

**Reactor Type:** LW cooled, graphite moderated, FAs in vertical pressure tubes

**Fuel Reload Type:** On-power

**Fuel:** (U+0.5% Er)O$_2$ enriched to 2.6%

**Burnup, MWd/kg U:** 27

**FA consumption per year:** 311

**Tendency:** Increase of Er content, enrichment and burnup, decrease of FA consumption

**Coolant Condition:** Boiling, up to 20% steam at outlet, 7 MPa, presence of free oxygen, possibility of nodular/crevice corrosion

**Clad Operational Mode:** Free Standing, 0.5 MPa He inner pressure

**Tendency:** Change for E635 alloy as cladding and SG material

**Pressure Tube Material:** E125 Alloy (Zr-2.5%Nb) in annealed condition
### Separation Technologies in the World

<table>
<thead>
<tr>
<th>Method</th>
<th>Operator(s)</th>
</tr>
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<tbody>
<tr>
<td>Gaseous diffusion</td>
<td>USEC (USA)</td>
</tr>
<tr>
<td></td>
<td>Eurodif (France)</td>
</tr>
<tr>
<td>SSF=1.0043</td>
<td>CNNC (China)</td>
</tr>
<tr>
<td>Gas centrifuge</td>
<td>Rosatom (Russia)</td>
</tr>
<tr>
<td>SSF=1.25</td>
<td>JNFL (Japan)</td>
</tr>
<tr>
<td></td>
<td>INB (Brazil)</td>
</tr>
<tr>
<td></td>
<td>Kahuta (Pakistan)</td>
</tr>
<tr>
<td></td>
<td>CNNNC (China)</td>
</tr>
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</table>

*Under implementation:*
Gas centrifuges of the 7th generation
- Urenco, Rosatom, JNFL, USEC, COGEMA

*Under research with insignificant financing:*
Atomic vapor laser isotope separation
- USEC / LLL - “SILEX” (USA)
- CEA - “SILVA” (France)
- Laser-J (Japan)

Molecular laser isotope separation
- SSL - “SILEX” (Australia)
Type and capacity of operational enrichment plants worldwide (IAEA NFCIS data, status as of Dec. 2003)

<table>
<thead>
<tr>
<th>Facility Name</th>
<th>Country</th>
<th>Type</th>
<th>Capacity, MTSWU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paducah/USEC</td>
<td>USA</td>
<td>D</td>
<td>11300</td>
</tr>
<tr>
<td>Eurodif</td>
<td>France</td>
<td>D</td>
<td>10800</td>
</tr>
<tr>
<td>Ekaterinburg/Rosatom</td>
<td>Russia</td>
<td>C</td>
<td>7000</td>
</tr>
<tr>
<td>Siberian Chemical Combine/Rosatom</td>
<td>Russia</td>
<td>C</td>
<td>4000</td>
</tr>
<tr>
<td>Urenco Capenhurst</td>
<td>UK</td>
<td>C</td>
<td>2300</td>
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<td>Urenco Nederland</td>
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<td>Germany</td>
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<td>1800</td>
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<td>JNFL Rokkasho</td>
<td>Japan</td>
<td>C</td>
<td>1050</td>
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<tr>
<td>Angarsk/Rosatom</td>
<td>Russia</td>
<td>C</td>
<td>1000</td>
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<tr>
<td>Krasnoyarsk/Rosatom</td>
<td>Russia</td>
<td>C</td>
<td>1000</td>
</tr>
<tr>
<td>Lanzhou 1</td>
<td>China</td>
<td>D</td>
<td>900</td>
</tr>
<tr>
<td>Shaanxi</td>
<td>China</td>
<td>C</td>
<td>200</td>
</tr>
<tr>
<td>Kahuta</td>
<td>Pakistan</td>
<td>C</td>
<td>5</td>
</tr>
<tr>
<td>(INB Resende)</td>
<td>Brazil</td>
<td>C</td>
<td>Start</td>
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</tbody>
</table>

C-Centrifuge; D-Diffusion
Enrichment services in Russia - Rosatom operates 4 plants with 13000 MTSWU/a capacity, see below photo of centrifuges in a shop of Krasnoyarsk.
JSC TVEL is a manufacturer and supplier of Russian nuclear fuel – (1)

Development, manufacture, licensing and supply of WWER and RBMK fuels to Russian and foreign customers are done by the Joint Stock Company TVEL (JSC TVEL). JSC TVEL brings together enterprises, engaged in all areas of the nuclear fuel cycle and structurally operates as a Corporation. TVEL Corporation is an industrial commercial entity comprising JSC TVEL being the main company and its subsidiaries and affiliates. Apart of the above-mentioned services, TVEL Corporation provides scientific monitoring of fuel operation, including warranty on operation of reactor cores at NPPs.
JSC TVEL is a manufacturer and supplier of Russian nuclear fuel – (2)

Also, TVEL Corporation manufactures and supplies fuel for fast reactors, PWRs, research reactors, nuclear powered ships and submarines. In 2004, Corporation TVEL supplied fuel to about 80 power reactors worldwide in 13 countries accounting for 17% of world total. In 2004 fuel was supplied for initial cores of new WWER-1000 reactors including Kalinin Unit 3 (Russia), Tianwan Unit 1 (China), Khmelnitski Unit 2 and Rovno Unit 4 (Ukraine). In co-operation with FRAMATOME ANP, Corporation TVEL manufactures and supplies PWR fuel for power reactors to Netherlands, Switzerland and Sweden.
FUEL FABRICATION IN THE WORLD-MERGING FUEL VENDORS

- 4 biggest fuel vendors for LWR in the world:
  - BNFL-Westinghouse-ABB plus EFG (W-Atom) in April 2000,
  - Framatome-Siemens (Framatome-ANP) in July 2000,
  - GE-Hitachi-Toshiba in 2000,
  - JSC TVEL in 1996 (present share=17%)
- Plus several national LWR fuel fabricators with smaller capacities (Brazil, China, India, Japan, Korea)
TVEL Corporation enterprises (nuclear fuel component)

- JSC Mashinostroitelny zavod (Electrostal, Moscow region) - powder, pellets, rods, FAs for WWERs, RBMKs, BN, submarines

- JSC Novosibirsk Chemical Concentrates Plant (Novosibirsk) – powder, pellets, rods, FAs for WWERs, RRs

- JSC Chepetsk Mechanical Plant (Glazov, Udmurt Republic) – Zr alloy components
JSC Ulba Metallurgical Plant (Ust-Kamenogorskk, Kazakhstan)

- TVEL Corporation partner, also through JSC JV UKR TVS (Russia+Ukraine+Kazakhstan)

- Ulba plant produces powder and pellets for Novosibirsk plant and RBMK repU pellets for Electrostal plant

- Main areas of JSC JV UKR TVS activity: improvement and development of nuclear fuel production in Ukraine, Russia and Kazakhstan, creation and development of new industrial and technological ties between the enterprises of Ukraine, Russia and Kazakhstan; provision of Ukrainian NPPs with nuclear fuel.
QA/QC and Quality Management Systems certification

• TVEL Corporation obtained certificate of Quality Management System compliance with ISO 9001 (version 2001) after auditing by TUV (Germany) in December 2004

• Electrostal, Novosibirsk and Glazov plants passed through the same procedure in 2003-04 and received certificate of Quality Management System compliance with ISO 9001 (version 2000) and Ecology Management certificate ISO 14001

• QA/QC Systems of Electrostal, Novosibirsk and Glazov plants were audited and certified by TUV (Germany) as complying to the ISO 9001 (versions 1997 and 2000)
Alternative WWER Fuel Suppliers

- WWER-440 fuel alternative supplier is BNFL of BNFL-W-ABB Group. Fuel was/is supplied as partial reload batch fuel to Paks and Loviisa NPPs.
- W of BNFL-W-ABB Group supplies WWER-1000 fuel to Temelin NPP, Czech Republic. Corporation TVEL is an alternative supplier in this case.
- W of BNFL-W-ABB Group delivered in the 2\textsuperscript{nd} quarter 2005 six WWER-1000 FAs to the South-Ukranian NPP, Unit 3 as a trial. If it is OK, 42 more FAs will be delivered in 2006-07.
Westinghouse

Typical VVER-1000 fuel assembly (UO₂ fuel)

- Hold-down spring plunger
- Removable top nozzle
- Zircaloy shroud tube
- Zircaloy spacer grid
- Bottom nozzle
- Plenum spring
- Natural/depleted/OPF UO₂ axial blanket
- UO₂ + Gd₂O₃ neutron absorber, (in selected rods)
- Enriched UO₂ fuel pellets
- Water rod
- Debris filter plate
- Low pressure drop Zirc-4 mid grid with mixing vanes
- Zirc-4 cladding
- Zirconium diboride integral fuel bundle absorber
- Inconel bottom grid
- Removable top nozzle
- Natural uranium axial blanket
Major Stages in WWER/RBMK Fuel Fabrication

- Conversion of UF₆ gas into UO₂ powder (Dry-gas flame or Wet-ADU route)
- The uranyl-nitrate fusion cake from RT-1 plant serves as raw material for fabrication of the RepU fuel pellets for RBMKs and test FAs for WWERs (ADU process)
- pellet fabrication (powder preparation, pressing, sintering, grinding, drying, inspection)
- Rod assembling components (claddings, plugs, springs,..)
- FA assembling components (rods, CRs, SGs, top and bottom nozzles, guide tubes, filters,..)
Uranium Oxide Fuel Manufacture
Convert UF₆ to UO₂
Dry Route-Principal chemical reactions

\[ \text{UF}_6 + 2 \text{H}_2\text{O} \rightarrow \text{UO}_2\text{F}_2 + 4 \text{HF} \text{ (Hydrolysis)} \]
\[ \text{UO}_2\text{F}_2 + \text{H}_2 \rightarrow \text{UO}_2 + 2\text{HF} \text{ (Reduction)} \]

Total Reaction:
\[ \text{UF}_6 + 2 \text{H}_2\text{O} + \text{H}_2 \rightarrow \text{UO}_2 + 6 \text{HF} \]
Conversion of UF₆ to UO₂

**Wet Routes**

**Ammonium Diuranate (ADU)**
- UF₆ Vapour
- Steam (200°C)
- UO₂F₂ plus HF
- Add, Stir Ammonia, Dilute Nitric Acid (60°C)
- ADU Precipitate
- Filter/Wash (Ammonia)/Dry
- UO₃
- Reduce by adding H₂ (820°C)
- UO₂

**Ammonium Uranyl Carbonate (AUC)**
- UF₆ Vapour
- Add Water, Ammonia, CO₂ (50°C)
- AUC Precipitate slurry
- Filter/Wash/Dry
- AUC cake
- Fluid Bed Reaction Chamber
- Steam, H₂, N₂ (500°C)
- UO₂
Uranium Oxide Fuel Manufacture

Convert UF$_6$ to UO$_2$

Flame Reactor - Principal scheme, not specific to Electrostal plant,
Uranium Oxide Fuel Manufacture

Convert UF₆ to UO₂

Dry Route-Principal scheme, not specific to Electrostal plant

Dry Route Rotary Kiln
Screw Blender

Condition, Lubricate
PROCESS OF UO₂ POWDERS PRODUCTION-


- UF₆
- ²³⁵U ≤ 5.0%

Al(NO₃)₃ → hydrolysis

Extraction – Re-extraction

Ammonium poliuranate precipitation

Filtration

Drying, Thermal decomposition

Homogenization

Reduction

H₂

NH₄OH

TBP
Conversion of UF$_6$ to AUC

NH$_3$ CO$_2$ Supply

UF$_6$ Evaporation

Reaction Tank

Portable Filter for AUC Collection

Off Gas

To AU UO$_2$ Conversion
Conversion of AUC to UO₂ Powder

- Fluidized Bed
- Stabilisation
- Storage Container
- Homogenizer (~2tU)
- To Pelletizing
<table>
<thead>
<tr>
<th>Parameter</th>
<th>ADU</th>
<th>AUC</th>
<th>Dry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific surface area, m²/g</td>
<td>2.5-6.0</td>
<td>3.6-6.0</td>
<td>2.1-3.0</td>
</tr>
<tr>
<td>Bulk density, g/cm³</td>
<td>1.5-2.0</td>
<td>2.0-2.3</td>
<td>0.7-1.0</td>
</tr>
<tr>
<td>Pack density, g/cm³</td>
<td>2.4-2.8</td>
<td>2.6-3.0</td>
<td>1.5-1.9</td>
</tr>
<tr>
<td>Flowability</td>
<td>Bad</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>O/U ratio</td>
<td>2.03-2.17</td>
<td>2.0-2.16</td>
<td>2.05-2.12</td>
</tr>
<tr>
<td>Impurity content, ppm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>30-50</td>
<td>30-70</td>
<td>≤100</td>
</tr>
<tr>
<td>C</td>
<td>40-200</td>
<td>120</td>
<td>40</td>
</tr>
<tr>
<td>Fe</td>
<td>≤70</td>
<td>10-20</td>
<td>10-50</td>
</tr>
<tr>
<td>Cr</td>
<td>40</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>Ni</td>
<td>30-40</td>
<td>10</td>
<td>6-10</td>
</tr>
<tr>
<td>Mn</td>
<td>5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>V</td>
<td>10</td>
<td>10</td>
<td>1</td>
</tr>
</tbody>
</table>
Pellet Manufacturing

From Conversion
- Homogenizer
- Rotary Press
- Sintering Boats

235U In-line Instrumentation

To Sintering and Grinding
Sintering and Grinding of Pellets

- Sintering Furnace
- From Green Pellet Pressing
- Grinding
- Storage
- Inspection (Visual Surface)
Technological scheme of WWER-1000 pellet fabrication in 1990’s (Y. Bibilashvili, V. Onufriev, Lecture at the Training Course on Fuel QA/QC, Saclay, 1992)
UMP - Nuclear Fuel Pellets Process flow sheet

1. UO₂
2. U₃O₈
3. Er₂O₃
4. Gd₂O₃

**Sieving**

**Prepressing**

**Mixing with a binder**

**PVA**

**Blending**

**Sieving**

**Pressing**

**Sintering**

**Grinding**

**UO₂ Pellets**

**Sieving**

**Mixing with a lubricant**

**Zn Stearat**
PORE MICROSTRUCTURE OF UO₂ PELLETS

PORE DISTRIBUTION BY SIZE

1 – monomodal pore distribution;
2 – bimodal pore distribution

addition of pore-forming agent
0.1 wt.%

addition of pore-forming agent
0.5 wt.%

addition of pore-forming agent
1.0 wt.%
PELLET MICROSTRUCTURE OPTIMIZATION (TECDOC-1416)

MICROSTRUCTURE OF UO₂ PELLETS

Pellet of “pure” UO₂

Pellet of UO₂ alloyed with aluminum silicate admixture
PELLET MICROSTRUCTURE OPTIMIZATION (TECDOC-1416)

GRAIN MICROSTRUCTURE OF UO₂ PELLET

Pellet with bimodal structure

Pellet with monomodal structure
(G ~ 23 µm)

Pellet with monomodal structure
(G ~ 90 µm)

GRAIN SIZE DISTRIBUTION IN PELLET

1 – Pellet with bimodal structure;

2 – Pellet with monomodal structure
PELLET MICROSTRUCTURE OPTIMIZATION (TECDOC-1416)

MICROSTRUCTURE OF
URANIUM-GADOLINIUM FUEL

Non-optimized pellet

Pellet with aluminum silicate admixture

Pellet alloyed with aluminum silicate admixture and optimized by addition of gadolinium
THE USE OF HIGHLY ACTIVE UO₂ POWDERS with SAV=6-8 m²/g

PELLETS’ SHRINKAGE RATE DURING SINTERING

1 – curvature of shrinkage of pellet from “usual” UO₂ powder;
2 - curvature of shrinkage of pellet from highly active UO₂ powder;
3 – curvature of pellet heating

GRAIN MICROSTRUCTURE OF UO₂ PELLETS

1 – pellet from “usual” UO₂ powder;
2 – pellet from highly active UO₂ powder
PLASTIC PROPERTIES OF FUEL PELLETS
(TECDOC-1416)

Correlation of fuel pellets creep rate in the function of inverse temperature under the strain of 30 MPa

1 – fuel pellet from “pure” UO₂ (average grain size 13 µm);
2 - fuel pellet from UO₂ alloyed with aluminum silicate admixture (admixture concentration 0.0050 wt. %, average grain size 25 µm);
3 - fuel pellet from UO₂ with bimodal microstructure alloyed with aluminum silicate admixture (admixture concentration 0.0030 wt %, average grain size 20 µm);
4 – fuel pellet from UO₂ alloyed with aluminum silicate admixture (admixture concentration 0.010 wt %, average grain size 30 µm);
5 – fuel pellet from UO₂ alloyed with aluminum silicate admixture (admixture concentration 0.025 wt %, average grain size 30 µm);
## Characterization of Specimens Studied


<table>
<thead>
<tr>
<th>Composition</th>
<th>Density, g/cm³</th>
<th>Grain size, µm</th>
<th>O/Me ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>UO₂</strong></td>
<td>10.4</td>
<td>11</td>
<td>2.0015</td>
</tr>
<tr>
<td><strong>UO₂+ Mullite 0.25% mass (2SiO₂ Al₂O₃)+ Nb₂O₅ 0.1% mass</strong></td>
<td>10.4</td>
<td>16</td>
<td>2.0032</td>
</tr>
</tbody>
</table>
Creep rate of standard and modified UO$_2$ vs. reversed temperature:

- - standard pellets

- - modified UO$_2$ at stresses 10, 20, 30 and 40 MPa, respectively
OPTIMIZED TECHNOLOGIES OF FUEL PELLETS PRODUCTION AT ULBA PLANT ENSURE (IAEA-TECDOC 1416):

- the level of open porosity not higher than 0.3% while preserving the high level of pore structure uniformity;

- regulation of pellet density and pore distribution by size: from monomodal distribution with average pore sizes about 1.5÷3.5 μm to bimodal distribution with average pore size of small pores about 1÷3 μm and the average size of large pores about 10÷50 μm;

- regulation of the average grain size and grain distribution by sizes within wide ranges: from bimodal structure with the grain size of 1÷3 μm of fine-grain phase and 10÷30 μm of coarse-grain phase to homogeneous monomodal structure with the average grain size about 20÷50 μm. At the summary boron equivalent of alloyed pellets not exceed 1.0 μg/gU;

- the alternative method of grain size increase up to 25÷30 μm that is the use of highly active UO₂ powders in the production of pellets;

- high plastic properties of pellets.
Summary on fuel pellet optimization

- Increase of dioxide grain size and hot plasticity by alloying with $2\text{SiO}_2\cdot\text{Al}_2\text{O}_3$, sometimes also with and $\text{Nb}_2\text{O}_5$, use of powders with high Surface Area Value and controlled grain boundary porosity
- Possibility for different pore size and grain size distributions, e.g. mono-modal, bi-modal
- Decreasing diameter of the inner pellet hole for WWERs from 2.4 mm to 1.2-1.6 mm, and not excluded in future-up to 0 mm. Availability of facets.
- Implementation of U-Gd and U-Er Integrated Fuel Burnable Absorbers in WWERs and RBMKs, respectively
Specific features of RepU (Reprocessed U) pellet fabrication for RBMKs and WWERs at Ulba plant—Proselkov V., et al, IAEA-TECDOC 1416, p. 69

- Fabrication of RepU fuel pellets for RBMK-1000s started in 80s.
- To check the possibility of the use of RepU fuel in WWER-440 reactors six FAs were fabricated for the experimental operation. The fuel composition was the following: U-235 –2.4%. U-236 – 0.45%. The compensation for U-236 was not carried out. The FAs with RepU were installed into the Kola NPP-Unit 1 for the 21st fuel campaign.
- The batch of WWER-1000 pellets was also produced with comp. U235 level of 4%, 18 TVSA loaded into Kalinin-2 (17th campaign).
- The analysis of experimental operation results revealed that the neutronic and thermal-physical properties of RepU fuel assemblies used in the Kola NPP practically fully corresponded to those for the normal uranium fuel assemblies.
Technological scheme of ADU-process for RepU pellet fabrication at Ulba plant- Proselkov V., et al, IAEA-TECDOC 1416, p. 69

- separate dissolving of the uranyl-nitrate fusion cake from spent WWER-440 fuel (U-235 content - 0.8 – 1.2%) and medium-enriched RepU (U-235 content - 14 - 17%) monoxide-oxide in nitric acid;
- mixing the two solutions in a ratio ensuring production of the solution with the actual U-235 content - 4.139% (for WWER-1000);
- extraction and re-extraction of the produced solution for removing impurities;
- treatment with aqueous ammonium solution for precipitation of ammonium polyuranate;
- filtration of precipitate, drying and calcination;
- reduction of uranium monoxide-oxide in hydrogen;
- specific check of U isotope’s content
View on fuel fabrication practices and plans

- Electrostal plant (~60% of fuel fabrication in Russia):
  - dry conversion was implemented in 90’s;
  - Wet route—for treatment of reused materials;
  - New 400 t/a dry conversion route powder shop was commissioned jointly with Siemens in 2003; total conversion capacity is ~1500 t/a
  - Separate lines for WWER, PWR and BWR rod fabrication in 2004;
  - Shops for fabrication of U-Gd and U-Er oxide fuels;
  - New designs for WWER and RBMK rods/assemblies.
View on fuel fabrication practices and plans

- Novosibirsk plant (~40% of fuel fabrication in Russia): :
  - Initially plant was destined for rod and FA fabrication with importing WWER-1000 pellets from Ulba plant
  - In 2001 wet conversion shop (~50 t/a) was completed for reused materials treatment;
  - In 2003 wet conversion shop (~150-200 t/a) was completed for WWER powders/pellets;
  - Dry conversion shop (450-600 t/a) is under construction
  - Separate lines for WWER, PWR and BWR rod fabrication in 2004/05;
  - New designs for WWER rods/FAs.
Zr alloy/tubing production in Russia

- Zr alloys/tubings are produced at the JSC Chepetsk Mechanical Plant, Glazov, Udmurt Republic
- Zr powder is now produced by electrolysis with subsequent iodine refining
- Zr sponge fabrication technology/equipment is in the final implementation/mounting stage
- Extraction-rectification separation of Zr and Hf allows Hf content rather lower 100 ppm in finished clads
- E-110 (Zr-1%Nb) and E635 (Zr-Sn-Nb-Fe) are present clad alloys and E-125 (Zr-2.5%Nb) is present pressure tube alloy
WWER-440 Fuel Rod Design

FUEL ROD OF WWER-440 FUEL ASSEMBLY

FUEL ROD OF WWER-440 CONTROL FUEL ASSEMBLY
## Changes in Major Parameters of WWER-440 Working Fuel Assembly

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Standard</th>
<th>Second generation fuel (U-Gd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel rod pitch in bundle, mm</td>
<td>12.2</td>
<td>12.3</td>
</tr>
<tr>
<td>Central hole diameter of fuel pellet, mm</td>
<td>1.4</td>
<td>1.2</td>
</tr>
<tr>
<td>Outer diameter of fuel rod, mm</td>
<td>9.1</td>
<td>9.07</td>
</tr>
<tr>
<td>Outer diameter of pellet, mm</td>
<td>7.57</td>
<td>7.60</td>
</tr>
<tr>
<td>Fuel column length, mm</td>
<td>2420</td>
<td>2480</td>
</tr>
<tr>
<td>Hf content of Zr materials, % mass</td>
<td>0.05</td>
<td>0.01</td>
</tr>
</tbody>
</table>

By V. Novikov, Technical Working Group on Water Reactor Fuel Performance and Technology (TWGEPT IAEA), 2005
WWER-1000 Fuel Rod Design

WWER-1000 fuel rod and U-Gd-fuel rod
(manufacturer - Electrostal fabrication plant)

top plug (resistance butt welding) spring cladding fuel pellet zirconium pellet (spacer) bottom plug (resistance butt welding)

255 3530 3837

WWER-1000 fuel rod and U-Gd-fuel rod
(manufacturer - Novosibirsk chemical concentrate plant)

top plug (resistance butt welding) spring cladding fuel pellet (electron-beam welding) bottom plug

255 3530 3837
Evolution of VVER-1000 FA Design

Phenomena of FA bow and Incomplete control Rod Insertion (IRI) were first observed in 1993-94 in some WWER-1000s and PWRs with long cores pushed designers to improve stiffness and rigidity of FA’s skeleton. These measures included:

- Increase of RCCA gravity weight
- More rigid Guide Tubes (thickness increase and more resistant material)
- Better rod and GT consolidation in the spacer grid (SG); new SG design
- Better fixation of the SGs on central tube, etc....

Non-FA bow related improvements included debris filters and possibility to dismantle the bundle. For WWER-1000 there were developed two novel FA designs:

- TVSA (developed by OKBM, Nizni Novgorod) and
- TVS-2 (developed by OKB “Hydropress”, Podolsk, Moscow region).
Design of TVSA

- Cap
- Angle of rigidity
- Space grid
- End piece
- U-Gd fuel rod
- Angle of rigidity
- Guide thimbles for AP

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2.2. The results of the TVSA operation in unit N1 of the Kalinin NPP.

Beginning from 2002 the core of unit 1 is fully loaded with TVSA. The result of TVSA operation in unit 1 of the Kalinin NPP:

- The core straightening is assured: the inter-assembly gaps of ~4 mm, sagging of ~4 mm, which allowed a substantially higher rate of the TVSA transfer during reloading and TPRO and the reloading time to be shortened by 4-6 days;

- The problems inherent in the Control Rod jamming dropping time and pulling forces have been obviated. The testing results are favourable;

- 12 TVSA were tested for 5 years, 2 TVSA were tested for 6 years;

- The maximal fuel burnup per TVSA is ~56 MW·day/kg U, per fuel rods is ~66 MW·day/kg U after a six year operation.

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Design of TVS-2

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In 2003 in the frame of the programme of increasing capacity factors the core of unit N1 was loaded with the first batch of TVS-2. The favourable results of the pilot operation allowed the extended loading of the unit and the introduction of TVS-2 into the other units of the Balakovo NPP.

### Table 3

<table>
<thead>
<tr>
<th>Unit N</th>
<th>Fuel load</th>
<th>Loading date</th>
<th>Quantity of TVS-2 loads</th>
<th>Mean fuel of enrichment</th>
<th>Quantity of U-Gd fuel rods/fuel enrichment / Gd₂O₃ content</th>
<th>Cycle length, eff. days</th>
<th>Burnup, MW-day/kg U</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>After 1 load.</td>
</tr>
<tr>
<td>1</td>
<td>13</td>
<td>29.03.03</td>
<td>54</td>
<td>18</td>
<td>3.53</td>
<td>9 / 3.3 / 5</td>
<td>363</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12</td>
<td>4.30</td>
<td>6 / 3.6 / 5</td>
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</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>24</td>
<td>4.30</td>
<td>9 / 3.6 / 5</td>
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</tr>
<tr>
<td></td>
<td>14</td>
<td>18.05.04</td>
<td>54</td>
<td>18</td>
<td>3.90</td>
<td>9 / 3.3 / 5</td>
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<td>36</td>
<td>4.30</td>
<td>6 / 3.6 / 5</td>
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<td>15</td>
<td>forcast</td>
<td>55</td>
<td>19</td>
<td>3.98</td>
<td>9 / 3.3 / 5</td>
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<td>24</td>
<td>4.38</td>
<td>6 / 3.6 / 5</td>
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<td></td>
<td>12</td>
<td>4.38</td>
<td>9 / 3.6 / 5</td>
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<td>13</td>
<td>27.06.04</td>
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<td>18</td>
<td>3.53</td>
<td>9 / 3.3 / 5</td>
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<td></td>
<td></td>
<td>36</td>
<td>3.90</td>
<td>9 / 3.3 / 5</td>
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<td>22.10.04</td>
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<td>18</td>
<td>3.53</td>
<td>9 / 3.3 / 5</td>
<td>351.9</td>
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<td>6 / 3.6 / 5</td>
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<tr>
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<td></td>
<td>24</td>
<td>4.30</td>
<td>9 / 3.6 / 5</td>
<td></td>
</tr>
</tbody>
</table>

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Current and scheduled use of TVS-A and TVS-2 at NPP with VVER-1000 units

By V. Novikov, Technical Working Group on Water Reactor Fuel Performance and Technology (TWGEPT IAEA), 2005