Loss of Cooling Accidents Modelling in At-reactor Spent Fuel Pool of VVER-1200

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**Development of VVER Technology**

**Further enhancement of NPP safety** - taking into account the lessons learned on severe accident (SA) management in the light of the “Fukushima Daiichi” accident.

**VVER-1200** reactors of AES-2006 project are referred to the *generation 3+* in which the latest achievements were implemented meeting the post-Fukushima requirements.

<table>
<thead>
<tr>
<th>Ostrovets NPP in Belarus</th>
<th>Hanhikivi-1 NPP in Finland</th>
<th>Paks-2 NPP in Hungary</th>
</tr>
</thead>
</table>

**Kurchatov Institute** - responsible organization in Russia for scientific support of new NPP project development and enhancing nuclear safety including issue of severe accident in the spent fuel pool (SFP). Main activities: Scientific and technical support of NPP operation at phases: designing, commissioning, operation and decommissioning.
Single section SFP of the NPP with VVER-1200 reactor. It is concrete compartment of rectangular shape with metal stainless steel liner (side wall thickness - 3 mm and bottom thickness - 6 mm).

The total water volume during the fuel storage in the SFP is about 1200 m$^3$.

SFP is equipped with fuel close packed storage racks. **Total capacity** of the SFP is 732 cells for fuel assemblies. Each fuel assembly is placed into the vertical hexagonal shroud made of borated stainless steel with a thickness of 6 mm.
Accident Scenarios, Progression and Phenomena

**Accidents Scenarios in the SFP:**
- Loss-of coolant accident with fast drainage of the SFP water;
- Loss-of cooling accident with slow uncovery of the FAs by gradual water evaporation and boil-off.

**Accident progression:**
- Loss of cooling function → water heat-up and boiling, water level lowering;
- Fuel uncovery → fuel heat-up and failure and fission product release;
- Severe fuel damage → oxidation in air + steam, hydrogen generation, severe fuel failure;
- Recovery → water level recovery, quenching.

**Accident phenomenology:**
- Thermal-hydraulics;
- Fuel behaviour;
- Fuel assembly and rack degradation;
- Molten corium concrete interaction (MCCI);
- Criticality;
- Fission product release and transport.

**References:**
The occurrence of the accident in the SFP will differ from analogous accident in the RPV for several key parameters, affecting the speed of the accident and the consequences:

✓ There is much more water in the SFP than in the RPV;
✓ There are more FAs in the SFP with significantly varying distribution of the residual heat per FA than in the RPV;
✓ Total power of the decay heat may be less than in the RPV;
✓ During the uncover and following oxidation of the rods cladding it is necessary to consider the presence of air, which can significantly accelerate the oxidation of the cladding;
✓ The presence of air also accelerates the degradation of nuclear fuel and may increase the release of ruthenium and other less volatile fission products;
✓ Radiation heat transfer takes place in a more complex geometry than in the RPV (each FA is placed into borated steel pipe);
✓ Accident occurs at low atmospheric pressure.

Accident conditions vs. normal operation:
The heat removal from the SFP by conduction through the side walls and the floor of the pool, and by radiation, convection and evaporation from the pool surface is not significant under normal conditions. But in case of accident with loss of cooling, when the pool water temperature increases, the above mentioned phenomena should be taken into account.
Initial Data and Computational Tools

➢ **Type of reactor:** VVER-1200 (AES-2006 Project).

➢ **Accident scenario:** Loss-of cooling accident.
(SBO + generators failure, which excludes water supply to the SFP by basis safety systems).

➢ **SFP loading:**
- 163 - FAs with 3 days storage time (full core unloading);
- 42 - FAs with 30 days storage time;
- 42 x 10 - FAs with 1-10 years storage time (10 FAs groups).

➢ **Total decay heat:** 14.18 MW
(max number of FAs in the SFP and max residual heat - corresponds to emergency full core unloading to the SFP after 30 days NPP operation for 12 months fuel cycle).

➢ **Initial water level:**
- 16.3 m above the SFP bottom (corresponds to fuel reloading)
- 11.0 m above the top of the fuel racks

➢ **Computational tools:**

1. **SOCRAT** - System of SA codes (Russia, IBRAE + NRC KI + etc.)
2. **ANGAR** - Containment code (Russia, AEP)
3. **HEFEST-ULR** - Core-catcher modeling (Russia, NRC KI)
4. **MAVR-TA** - FP release modeling (Russia, NRC KI)
5. **SAPHIR-2006** - Nuclear criticality (Russia, NRC KI)
## Fuel Loading and Decay Heat of the FAs Groups in SFP

<table>
<thead>
<tr>
<th>Storage time</th>
<th>FAs number</th>
<th>Decay heat of the FAs group, kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 days</td>
<td>163</td>
<td>12 425</td>
</tr>
<tr>
<td>30 days</td>
<td>42</td>
<td>884</td>
</tr>
<tr>
<td>1 year</td>
<td>42</td>
<td>254</td>
</tr>
<tr>
<td>2 years</td>
<td>42</td>
<td>147</td>
</tr>
<tr>
<td>3 years</td>
<td>42</td>
<td>99.5</td>
</tr>
<tr>
<td>4 years</td>
<td>42</td>
<td>75.3</td>
</tr>
<tr>
<td>5 years</td>
<td>42</td>
<td>62.1</td>
</tr>
<tr>
<td>6 years</td>
<td>42</td>
<td>54.2</td>
</tr>
<tr>
<td>7 years</td>
<td>42</td>
<td>49.2</td>
</tr>
<tr>
<td>8 years</td>
<td>42</td>
<td>45.8</td>
</tr>
<tr>
<td>9 years</td>
<td>42</td>
<td>43.3</td>
</tr>
<tr>
<td>10 years</td>
<td>42</td>
<td>41.3</td>
</tr>
<tr>
<td>Total</td>
<td>625</td>
<td>14 182</td>
</tr>
</tbody>
</table>

Emergency core unloading to the SFP after 30 days NPP operation (for 12 months fuel cycle)
System Of Codes for Realistic Assessment of Severe Accidents

Developers: IBRAE RAN, AEP, SPbAES, Kurchatov Institute, VNIIEF, IPPE, EREC.

Main SOCRAT Modules:

- RATEG  - primary and secondary thermal hydraulics
- SVECHA - core degradation
- HEFEST  - thermal physics of corium and thermal mechanics of RPV
- TOCHKA - point neutron kinetics
- BONUS   - FP accumulation in fuel
- RELEASE - FP release from fuel in gas gap
- MFPR_MELT - FP release from the corium
- GAPREL - FP release from the gas gap
- PROFIT - FP behavior in the primary circuit
- CONTFP - FP behavior in containment volumes
- RACHIM - activity and heat generation by FP
- VAPEX-M  - fuel-coolant interaction

+ Material Properties Database
SOCRAT System of SA Codes

- Oxidation, melting and displacement of the core elements
- FP release in primary side
- FP release in gas gap
- Core degradation, hydrogen generation
- Clad deformation and rupture
- FP inventory
- Melt-water interaction
- Melt behavior in reactor vessel
- Neutron kinetics
- FP release from melt
- FP behavior in primary side
- Heat-hydraulics in secondary side
- Heat-hydraulics in primary side
- Thermal-hydraulics in containment
- FP behavior in containment
- Hydrogen safety in containment
- FP leak in environment
- Melt behavior in core catcher
- MCC1
ANGAR Code

**ANGAR code** is a lumped-parameter containment code for integral analysis of the thermal hydraulics and the distribution of steam, hydrogen, and other non-condensable gases in the NPP containment compartments.

**Developer:** AEP

ANGAR code can be applied for:
- containment analyses and for monitoring of DBAs as well as severe accidents;
- modelling the temperature state of construction structures and technological equipment during the short-term as well as slow long-term processes of accident scenarios.
- Simulation of active and passive safety systems, including the passive heat removal system and passive autocatalytic hydrogen recombiners.

**Main phenomena** modeled by ANGAR code:
- pressure and temperature change during the course of an accident;
- heat and mass transfer to the structure;
- natural and force convection flows gas diffusion between adjacent zones;
- distribution of the gases in containment compartments;
- stratification of the light gases in containment;
- hydrogen removal by recombination (PAR modeling);
- effects of spraying.
HEFEST-ULR Code

The HEFEST-ULR code is intended for modelling of corium localization and cooling in the core catcher

Developer: Kurchatov Institute (Russia)

Main phenomena modeled by HEFEST-ULR code:

✓ 2-D axial symmetric conductivity;
✓ Volumetric heat decay;
✓ Melting of the sacrificial material and mixing with the corium;
✓ Thermal ablation of the concrete (MCCI);
✓ Chemical reactions between the sacrificial materials and the corium;
✓ Molten pool formation and stratification;
✓ Convective heat transfer between the layers of the molten materials;
✓ Crust formation;
✓ Radiation heat transfer from the upper surface of the molten pull;
✓ External water cooling of the core catcher vessel.
Nodalization Scheme for SOCRAT Code

- 12 representative heat elements for each FAs group with time storage from 3 days to 10 years
- 2 heat elements for concrete walls
- 3 cameras
- main channels
- bypass channels
- 2 boundary conditions (wall, atmosphere)
Nodalization Scheme for ANGAR Code

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of compartments</td>
<td>33</td>
</tr>
<tr>
<td>Connections</td>
<td>111</td>
</tr>
<tr>
<td>Number of walls</td>
<td>248</td>
</tr>
<tr>
<td>Total walls surface</td>
<td>~25000 m²</td>
</tr>
<tr>
<td>Containment volume</td>
<td>~73000 m³</td>
</tr>
<tr>
<td>Annulus space walls surface</td>
<td>1000 m²</td>
</tr>
<tr>
<td>Volume of annulus space</td>
<td>~25000 m³</td>
</tr>
</tbody>
</table>
Nodalization Scheme for HEFEST-ULR Code

Calculation scheme of the SFP bottom region for HEFEST-ULR code

- Axisymmetric geometry of SFP
- Spatial mesh step: 0.0025 m
- Total number of meshes: 27 360

Red color – corium melt
Blue color – air (free volume)
Grey color – concrete wall and bottom

Corium melt on the SFP concrete bottom
## Calculation Results: Chronology of Main Accident Events

<table>
<thead>
<tr>
<th>Event</th>
<th>Time, h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station blackout, accident start</td>
<td>0</td>
</tr>
<tr>
<td>Water boiling start</td>
<td>4.8</td>
</tr>
<tr>
<td>Water level in SFP reduces to the upper edge of FAs</td>
<td>45</td>
</tr>
<tr>
<td>Fuel part uncovering for the FAs with 2-10 years storage time</td>
<td>49.1</td>
</tr>
<tr>
<td>Fuel part uncovering for the FAs with 1 year storage time</td>
<td>49.9</td>
</tr>
<tr>
<td>Fuel part uncovering for the FAs with 30 days storage time</td>
<td>50.4</td>
</tr>
<tr>
<td>Fuel part uncovering for the FAs with 3 days storage time</td>
<td>51.6</td>
</tr>
<tr>
<td>Start of the hydrogen generation because of zirconium-steam reaction</td>
<td>51.5</td>
</tr>
<tr>
<td>Depressurization of the fuel rods of the FAs with 3 days storage time</td>
<td>54.7</td>
</tr>
<tr>
<td>Maximum temperature of rods claddings reaches 1473 K</td>
<td>55</td>
</tr>
<tr>
<td>Start of the melting of the FAs with 3 days storage time</td>
<td>57.3</td>
</tr>
<tr>
<td>Maximum temperature of the fuel reaches 2550 K</td>
<td>58.9</td>
</tr>
<tr>
<td>FAs collapse, materials of the FAs relocate to the SFP bottom</td>
<td>64.2</td>
</tr>
<tr>
<td>Melt-through of the SFP concrete bottom</td>
<td>73.3</td>
</tr>
<tr>
<td>End of the calculation</td>
<td>73.3</td>
</tr>
</tbody>
</table>
SOCRAT Calculation Results (T/H in SFP)

Water level in the SFP

Steam generation

Hydrogen generation

Fuel temperature along the height of the FAs with 3 days storage time

Maximum fuel temperature of all FAs groups with different storage time
SOCRAT Calculation Results (Fuel Damage)

Mass of UO$_2$ along the fuel rod height

Mass of ZrO$_2$ along the rod height

Mass of Zr along the rod height

Mass of SS along the rod height
ANGAR Calculation Results (T/H in Containment)

Pressure in the containment

Temperature of atmosphere in the dome part of the containment

VVER-1200 containment
HEFEST-ULR Calculation Results (MCCI)

Cavern form at time 66.1 h

Cavern form at time 67.5 h

Cavern form at time 70.8 h

Cavern form at time 73.3 h
HEFEST-ULR Calculation Results (MCCI)
HEFEST-ULR Calculation Results (MCCI)

Corium temperature

Corium density

Hydrogen generation (MCCI)

Total hydrogen generation (T/H + MCCI)
Measures on Accident Management

Mobile diesel-generator unit; Alternate intermediate circuit pump; Mobile fan cooling tower.
Water Supply to the SFP

Sources of the water:
- Containment tanks for the stock of borated water with a concentration of 16 gN$_3$B$_3$/kgH$_2$O with a total capacity of 2000 m$^3$;
- Two storage tanks of demineralized water with 700 m$^3$ of water each.

The possible measures for supplying water to the SFP:
- Filling the SFP with a sprinkler pump along the line: storage tank of borated water, sprinkler pump, sprinkler piping system, piping and fittings for the cooling system of SFP, piping system, wells of the reactor internals revision shaft;
- Filling the SFP with SFP cooling system pump along the line: tank-pit, pipelines of the tank-pit, SFP cooling system pump, heat exchanger, SFP;
- Filling the SFP with a pump for feeding borated water to the filters from the sump tanks;
- SFP supply from the secondary circuit make-up water system from demineralized water tanks with a pump.
A set of existing calculation codes created for analyzing accidents with reactor installations allows performing complex evaluation of the severe accidents in the SFP – from the initial event to the melt-through of the concrete pool bottom, as well as the development of accident management measures to prevent the severe phase of the accident.

However, the reactor codes do not fully take into account the specific features of the accident phenomena in the SFP. To eliminate the identified deficiencies in modelling, it is necessary to upgrade several code models. Primary among them, in our opinion, are the following:

- Upgrading of the SOCRAT code model describing the oxidation of fuel element claddings to take into account the specifics of the oxidation process in a vapor-air-hydrogen atmosphere in the SFP;
- Modernization of the SOCRAT code model (or development of a new model) describing radiation and re-radiation between the elements of the SFP to take into account the non-axisymmetric geometry of the SFP and to take into account the placement of the FAs inside the borated-steel shrouds of the fuel close packed storage racks;
- Development of a new module for the HEFEST-ULR code simulating the corium spreading along the SFP bottom.

It will be useful to organize the benchmark for SFP accident scenarios with modified codes.
Thank you for attention!