PREVENTION OF EARLY CONTAINMENT MELT-THROUGH DURING SEVERE ACCIDENT OF LIGHT WATER REACTOR VVER-1000 V320 AT UNITS 5&6 OF NPP KOZLODUY

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Outline

- Brief Description of the KNPP Site
- Features of Units 5&6 of KNPP against SA
- Brief history of the problem
- Vulnerability of VVER-1000 V320 Design during ex-vessel phase of severe accident
- Engineering solution to prevent early containment melt-through during SA
  - Thermo-mechanical analyses
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Brief Description of the KNPP Site

- Units 1&2 – VVER-440: under decommissioning
- Units 3&4 – VVER-440: closed, last FA will be unloaded from SFP in mid of 2012
- Unit 5&6 – VVER-1000, V320 (commercial operation in 1987/1991)
- Wet SFS
- Dry SFS
Features of Units 5&6 of KNPP against SA

Each Unit has:

- Filtered Vent System
- PARs
- 1 additional 6kV 2 MW DG (mainly for the SG feedwater and Primary makeup systems)
- Additional alternative SG feedwater system powered by MDG
- PAMS (1st seismic category I&C)
- In-core water level and temperature (up to 1200 °C) measurement system
- Thermal sensors (up to 1300 °C) on RPV outer wall
- Improved capacity of batteries (10-12h)
- Common MDG 6 kV, 1.2 MW
- Emergency Response Centre (ERC) equipped to withstand 24 hours, own DG, filters, food etc.

Planned: two 0.4 kV MDG; Alternative feedwater system + additional PARs - to be taken from the closed units (3&4), what was recognized as a best practice during the stress-tests review; SF water levele and temperature measurement system; 2nd off-site ERC is going to be built.
BRIEF HISTORY OF THE PROBLEM

- In 2004-2005 PHARE Project BG.01.10.01 “Phenomena investigation and development of severe accident management guidelines for NPP Kozloduy”

- A vulnerability of VVER-1000 V320 type reactors was discovered, consisting in potential for early containment melt-through (early bypass) during the ex-vessel phase of severe accident.

- In 2008 an investigation was initiated by NPP Kozloduy to find a solution for prevention of early containment bypass during SA

- In 2011 the project was finished and specific engineering solution was proposed and adopted as work design to resolve the issue
Vulnerability of VVER-1000 Design during ex-vessel phase due to molten core-concrete interaction

- If vessel failure is not prevented, the melt will discharge and spread over the cavity floor. The spreading will be stopped temporarily by the door and the cavity walls. After that the melt will interact with the concrete axially and radially.

- Due to the radial ablation the melt will reach to first ring of IC channels in \(~45\) min. and within few hours will penetrate in the premise below, what is defined as early containment bypass (melt-through).

- Above results come from improved CORCONE calculations.
Vulnerability of VVER-1000 Design during ex-vessel phase of SA due to MCCI (2)

(1) Ionization chamber (IC) channel
(2) Containment wall
(3) Reactor pit
(4) Premise of the mechanisms for lifting IC

Layout of Ionization chamber (IC) channels in the concrete around the reactor pit

Layout of premises inside and outside the containment of VVER-1000 Design
Engineering solution for plugging IC channels

The plug (4) is designed to be made of TiC:
\[ T_m^{\text{TiC}} = 3170^\circ C \]
\[ \rho^{\text{TiC}} = 4930 \text{ kg/m}^3 \]

The ball (5) is designed to be made WC:
\[ T_m^{\text{WC}} = 2870^\circ C \]
\[ \rho = 15800 \text{ kg/m}^3 \]

For comparison:
\[ T_m^{\text{UO}_2} = 2837^\circ C \]
\[ \rho^{\text{UO}_2} = 8740 \text{ kg/m}^3 \]
Thermo-mechanical analyses

- Thermo-mechanical analyses were done by simulation of the process of penetrating of melt in IC channels.
- Finite-element models (FEM) were built, which included the proposed plugging devices and the adjacent parts – the steel tubes, concrete of the containment wall, the biological shield below the plugs and the penetrating melt itself.
- The CAD-CAM package of NISA II – DISPLAY III code was used to perform the FEM calculations by applying the updated HEAT-III module for phase transition and radiation heat transfer.
Thermo-mechanical analyses (cont’d)

Temperature development for period $0 \div 86400$ s for 14 characteristic nods

General FEM of Plugging device of IC channel

FEM mesh with location of 14 characteristic nods
Thermo-mechanical analyses (cont’d)

Statements:

1. The analysis of the results shown that the thermal stability of all parts of the proposed device and adjacent components is guaranteed.

2. The biological shield (insert) made in the original design from Teflon has a minimal margin to its melting point ($T_S \approx 327 \, ^\circ C$) and has to be replaced.

3. Teflon to be replaced by concrete

Temperature distribution at 1923 s
EXPERIMENTAL WORK
Cold and Hot experiments

1. Cold experiment

The device was modeled in scale $M=1:1$, the plug and plugging ball made by steel, embedded in a steel tube as the largest type channel and with a real IC powering cable.

Objectives of the experiment:

1. To prove that at normal operating conditions (room temperature) the plugging device will not disturb the normal movement of the IC powering cable during normal operation.

2. To prove the plugging performance of the ball.
Prevention of early containment melt-through during severe accident of VVER-1000 V320

EXPERIMENTAL WORK
Cold experiment (2)

– Two phases of the Cold experiment:

**Phase I:**
Shifting up and down the cable with the same force as it is at the Unit and measuring the effort from the ball to the cable by digital dynamometer.

**Success criterion:**
Not to exceed the calculated effort (13,9 kg) more than 10%.

**Result:** Successful

Dynamo-graphs of the cold experiment (phase 1)
The greatest peaks are related to the initial pull-up/pull-down of the cable.
EXPERIMENTAL WORK
Cold experiment (3)

Phase II:
The cable was left to fall down under its own weight through the central orifice of the plug to see whether it would squeeze through its overall length, thus imitating the cut of the cable by melt.

Success criterion
The cable must squeeze down freely through the orifice, thus been not an obstacle and allowing the ball to plug fully the orifice.

Result: Successful
EXPERIMENTAL WORK
Hot experiment

Objective of the experiment:

- To make a melt simulant with similar thermodynamic properties as the real melt, to pour down it in a steel tube with a plug (scale M=1:1) and to prove that the melt will freeze in the clearance of 2 mm between the plug and the steel tube without penetrating below the plug.

Success criterion:

- The melt, after pouring in the tube with the plug, to freeze in the clearance within the height of the plug.
EXPERIMENTAL WORK
Hot experiment (2)

- A melt simulant has been made - mixture of Al and TiC and melted in an induction furnace at T~ 700 °C. The estimated viscosity of the mixture at this temperature was in the range of $\eta=0.05-0.1$ Pa.s (close to the viscosity of corium).

- The calculated hidden heat of phase transition for Al-TiC mixture is $\Delta H_f \approx 235.2$ KJ/kg (for a mixture of 88%UO2+12%concrete is $\Delta H_f = 228\pm13$ KJ/kg).

- A flux K-Al-F was added to the simulant for better absorption (wetability) of TiC in the Aluminum. A preliminary experiment with smaller quantities was performed to prove the good mixing of TiC and Al by adding K-Al-F flux by using electron microscopy.

Micrograph of the melt simulant (zoom x400). The black spots are TiC, the white spots are Al, the grey spots are K-Al-F flux.
EXPERIMENTAL WORK
Hot experiment (3)

Performance of the hot experiment:

- The melt was poured into the tube of the model heated preliminary in a resistance furnace. It was found, after cooling down of the model and cutting the tube and the plug, that the melt was frozen in the 2 mm clearance at 20 mm below of the upper surface of the plug.

Result:

- The success criterion – successfully achieved
BNRA put the realization of the proposed design for prevention of early containment bypass during severe accident as a condition in the Licenses of the Units 5&6.

Its implementation is planned to be accomplished for both Units till the end of 2014.
CONCLUSIONS

- The implementation of the proposed engineering solution will be effective for prevention of early containment bypass of Units 5&6 of KNPP in case of severe accident.

- It could be useful for all other VVER-1000 reactors (without core catcher).
### Conclusions (cont’d)

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<thead>
<tr>
<th>Country</th>
<th>Units</th>
<th>Status</th>
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<tbody>
<tr>
<td><strong>Russia</strong></td>
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<tr>
<td>Novovrniej 5</td>
<td>1 Unit V 187</td>
<td>1 in operation</td>
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<tr>
<td>Kalinin 1,2,3,4</td>
<td>2 Units V-338, 2 Units V-320</td>
<td>3 in operation, 1 under construction</td>
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<td>Balakovo 1,2,3,4</td>
<td>4 Units V-320</td>
<td>4 in operation</td>
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<td>Volgodonsk 1,2</td>
<td>2 Units V-320</td>
<td>1 in operation, 1 under construction</td>
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<tr>
<td>Rostov-2,3,4</td>
<td>3 Units V-320</td>
<td>1 in operation, 2 under construction</td>
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<td><strong>Ukraine</strong></td>
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<tr>
<td>SU 1,2,3</td>
<td>1 Unit V-302 + 1 Unit V-338 + 1 Unit V-320</td>
<td>3 in operation</td>
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<td>Rovno 3,4</td>
<td>2 Units V-320</td>
<td>2 in operation</td>
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<td>Khmelnitsky 1,2,3,4</td>
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<td>2 in operation, 2 under construction</td>
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<td>Zaporozhe 1,2,3,4,5,6</td>
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<td><strong>Czech Republic</strong></td>
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<td>Temelin 1,2</td>
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<td><strong>Bulgaria</strong></td>
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<tr>
<td>Kozloduy 5,6</td>
<td>2 Units V-320</td>
<td>2 in operation</td>
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**Total: 32 Units (27 in operation, 5 under construction)**
The solution could be useful also for other types of reactors, that may have measurement channels in the concrete around their reactor pits.
THANK YOU FOR YOUR ATTENTION

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For detailed information – Paper #55 in Proc. of SMIRT-21