APPLYING RISK-INFORMED APPROACHES TO OPTIMIZE KOZLODUY NPP UNITS 5&6 OPERATION
Introduction

Risk Engineering Ltd. has realized a package of measures intended to optimize the operation, technical service and repair of Kozloduy NPP Units 5 and 6 aiming to increase capacity factor and as a result to bring the technological regulations for safe operation in compliance with the latest international criteria.

The program for optimization of the operation, technical service and repair consisted of the following tasks:

- Modifications of non-destructive control program;
- Scope and frequency of technical service and repair;
- Scope and frequency of testing;
- Assessment of the rest lifetime of the equipment of the safety systems and systems important to safety;
- Development of a risk monitoring program.
A Risk-informed Non-Destructive Inspection Program has been elaborated to modify the in-service inspection periodicity and scope in order to:

• Enhance or maintain the safety level of Core Damage Frequency (CDF) / Large Early Release Frequency (LERF)
• Enhance the reliability of High Safety Significant Components (HSSCs)
• Reduce the number of non-destructive tests
• Reduce the personnel exposure
• Economic benefits
Scope Definition

➢ Overall Scope
  ▪ All pipelines belonging to Class 1, 2, and 3 according to ASME Part XI
  ▪ Piping systems modeled in the PSA
  ▪ Fluid systems from the rest of the plant, defined as significant in terms of risk
  ▪ Systems within the scope of the current in-service inspection program, which are defined as significant in terms of risk
  ▪ The systems included in the program are subject to review and coordination

➢ Partial scope
  ▪ Defined piping class or selected systems
<table>
<thead>
<tr>
<th>Technological designation</th>
<th>Name</th>
<th>Justification for the inclusion in the program</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA</td>
<td>Main Steam Line System</td>
<td>Great impact on the annual planned outage</td>
</tr>
<tr>
<td>RL</td>
<td>Steam Generator Main Feedwater System</td>
<td>Great impact on the annual planned outage</td>
</tr>
<tr>
<td>TK</td>
<td>Primary Feed and Bleed System</td>
<td>Great impact on the annual planned outage and reducing the personnel exposure</td>
</tr>
<tr>
<td>TQ2</td>
<td>Emergency Core Cooling System - Low Pressure</td>
<td>Great impact on the annual planned outage</td>
</tr>
<tr>
<td>YA</td>
<td>Primary Circulation Pipelines</td>
<td>Great impact on the annual planned outage</td>
</tr>
<tr>
<td>YT</td>
<td>Emergency Core Cooling System - passive part</td>
<td>The system has average impact on the annual planned outage and is monitored more frequently than other systems with similar impact</td>
</tr>
<tr>
<td>YP</td>
<td>Primary pressure compensation system</td>
<td>Great impact on the annual planned outage</td>
</tr>
</tbody>
</table>
The segments definition is based on the following:

- Pipelines rupture leading to equal effects for the Unit (MLOCA, loss of TQ2 train 1, loss of the Boron Acid Emergency Reserve Tank, compromising the containment integrity, etc.)
- Pipeline sections in which the flow is separated or joined
- Part of the pipeline which can be isolated after rupture (Check Valves, Motor Operated Valves (MOV), Air Operated Valves (AOV)), with no credit to Manual Valves
- Changes to pipeline diameter
- Pipelines expected to have equal probability of failure, based on the physical properties thereof

The segments definition is done in parallel with establishing the direct effects

The segments are defined within the frames of each system
Segments and Effects Definition (2)

- Establishing of effects
  - Direct effects - those related to the loss of medium through the rupture point
  - Indirect effects – spatial effects related to pipeline rupture (floods, spraying, fast leakage, pipe whip, high moisture and temperature level)
  - The effects are determined for each segment with and without operator actions
  - The direct and indirect effects are determined independently, but are grouped on a later stage
Determine the Pipeline Failure Probability

- The necessary number of calculations is determined by Win-SRRA program
- All data sources are gathered
- The pipeline degradation mechanisms are defined
- Input forms for the Win-SRRA program are elaborated
- Calculations by the Win-SRRA program
- Review and documentation of results
Grouping of PSA calculations

In order to reduce the number of PSA calculations, the equal effects are grouped and for them a single PSA calculation is done.

Selection of replacing components

Changes to the PSA model

- Three types of effects which determine the changes to PSA model (IE, mitigating systems and a combination of both)

Calculation of CDF and LERF
Risk Assessment

- Assessment of the significance of each segment with regards to the risk
  - PSA model of the plant for defining the CDF/CDP and LERF/LERP;
  - Pipes failure probabilities obtained through the Win-SRRA program;
  - Test intervals

- Criteria for risk significance assessment
  - High safety significance – $RRW \geq 1.005$;
  - Average safety significance – $1.001 \leq RRW < 1.005$;
  - Low safety significance – $RRW < 1.005$

RRW - Risk Reduction Worth
Risk Assessment (2)

Risk Assessment
- Impact
- RRW
- RAW
- Indirect effects

Failure Probability
- Mechanism
- Probability
- Base

Other Concerns
- Containment behavior
- External events
- Risk at shutdown and low power operation
- Other scenarios
- Operational/maintenance experience/
- Design bases/Defense in-depth
- Other deterministic concerns

Expert Team

Segments with low and with high safety significance
Structural Elements Selection

- The place of the segment in the structural elements matrix shall be found
- The zones with 100% control over the highly significant segments shall be defined
- Statistical evaluation (Perdue model) shall be done
- The interface between the necessary tests and the extended in-service inspection program (if such) shall be determined
- The locations to be inspected shall be selected
- The methods and inspection intervals shall be determined
## Structural Elements Selection (2)

<table>
<thead>
<tr>
<th>High Failure Importance (HFI)</th>
<th>Low Failure Importance (LFI)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>REGION 3</strong></td>
<td><strong>REGION 4</strong></td>
</tr>
<tr>
<td>Unit 5 – 48 segments</td>
<td>Unit 5 – 797 segments</td>
</tr>
<tr>
<td>Unit 6 – 64 segments</td>
<td>Unit 6 – 785 segments</td>
</tr>
<tr>
<td><strong>REGION 1</strong></td>
<td><strong>REGION 2</strong></td>
</tr>
<tr>
<td>Unit 5 – 36 segments</td>
<td>Unit 5 – 83 segments</td>
</tr>
<tr>
<td>Unit 6 – 36 segments</td>
<td>Unit 6 – 83 segments</td>
</tr>
</tbody>
</table>

**Low Safety Significance (LSS)** | **High Safety Significance (HSS)**
## Structural Elements Number

<table>
<thead>
<tr>
<th>System</th>
<th>Unit 5</th>
<th>Unit 6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ongoing Non-Destructive Inspection Program</td>
<td>Risk-informed Non-Destructive Inspection Program</td>
</tr>
<tr>
<td>RA</td>
<td>113 40 125 40</td>
<td></td>
</tr>
<tr>
<td>RL</td>
<td>207 34 196 34</td>
<td></td>
</tr>
<tr>
<td>TK</td>
<td>475 35 466 35</td>
<td></td>
</tr>
<tr>
<td>TQ2</td>
<td>816 52 751 50</td>
<td></td>
</tr>
<tr>
<td>YA</td>
<td>105 44 117 56</td>
<td></td>
</tr>
<tr>
<td>YP</td>
<td>238 28 230 29</td>
<td></td>
</tr>
<tr>
<td>YT</td>
<td>237 6 217 6</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2191 239 2102 250</td>
<td></td>
</tr>
</tbody>
</table>
The program applicability related to the ongoing non-destructive inspection program shall be defined.

The program shall be presented for approval and the required documentation shall be elaborated.

A feedback process shall be developed to enable changes in the program.
Program Implementation (2)

Periodic update

- Changes of the plant
  Design characteristics
- Changes of the plant
  Operating procedures
- Changes of the plant
  Equipment
- Results from risk informed
  Non-destructive control
- Failures data from
  Plant operation
- Corrective actions
  From the programme
- Changes in PSA model

Determination of scope / systems and segments

Forced update

- Large PSA changes
- Large events
- In the plant

Program implementation
The risk parameters of the risk-informed program shall be juxtaposed to those of the ongoing non-destructive inspection program:

- CDF without operator’s actions
- CDF with operator’s actions
- LERF without operator’s actions
- LERF with operator’s actions

Evaluation of the dominant contributors
Cost-Effectiveness Analysis

➢ The cost-effectiveness analysis is performed by using two methods:
  • Method 1 – the average currents method;
  • Method 2 - Monte Carlo simulation method.
Software Products

- RI-ISI – software developed by Westinghouse
- WinSRRA – software for pipelines structural reliability assessment developed by Westinghouse
- @Risk – used for analysis of uncertainties; generating full range of results on the risk for each segment
- Microsoft Excel – forms developed by Westinghouse are used for the Perdue model
Conclusions and Results

- Acceptable negligible risk increase
- Non-destructive inspection’s scope reduction for all systems
- Non-destructive inspection’s time period reduction
- Significant cost reduction for performing non-destructive inspection

**Ratio between the number of tests envisaged in the current Unit 5 non-destructive inspection program and in the risk-informed one**

**Ratio between the number of tests envisaged in the current Unit 6 non-destructive inspection program and in the risk-informed one**
## Conclusions and Results (2)

<table>
<thead>
<tr>
<th>System</th>
<th>Number of consequential events in the NDI program</th>
<th>Number of consequential events in Risk-informed NDI program</th>
<th>[%]</th>
<th>Number of consequential events in the NDI program</th>
<th>Number of consequential events in Risk-informed NDI program</th>
<th>[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA</td>
<td>475</td>
<td>35</td>
<td>92.63%</td>
<td>466</td>
<td>35</td>
<td>92.49%</td>
</tr>
<tr>
<td>RL</td>
<td>816</td>
<td>52</td>
<td>93.63%</td>
<td>751</td>
<td>52</td>
<td>93.08%</td>
</tr>
<tr>
<td>TK</td>
<td>113</td>
<td>40</td>
<td>64.60%</td>
<td>125</td>
<td>40</td>
<td>68.00%</td>
</tr>
<tr>
<td>TQ2</td>
<td>207</td>
<td>34</td>
<td>83.57%</td>
<td>196</td>
<td>34</td>
<td>82.65%</td>
</tr>
<tr>
<td>YA</td>
<td>105</td>
<td>28</td>
<td>73.33%</td>
<td>117</td>
<td>28</td>
<td>76.07%</td>
</tr>
<tr>
<td>YP</td>
<td>238</td>
<td>28</td>
<td>88.24%</td>
<td>230</td>
<td>29</td>
<td>87.39%</td>
</tr>
<tr>
<td>YT</td>
<td>237</td>
<td>6</td>
<td>97.47%</td>
<td>217</td>
<td>6</td>
<td>97.24%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2191</strong></td>
<td><strong>223</strong></td>
<td><strong>89.82%</strong></td>
<td><strong>2102</strong></td>
<td><strong>224</strong></td>
<td><strong>89.34%</strong></td>
</tr>
</tbody>
</table>
Risk-informed approaches were used to reduce outage lengths by:

- Moving technical service and repair, and testing activities completed during the refuelling outage to times while the plant is at power;
- Increasing the interval between technical service and testing activities;
- Reducing the number of technical service and testing activities that occur during the refuelling outage;
- Changing the type of technical service and testing activities that occur during the refuelling outage.

Reducing the outage lengths resulted in increased plant availability and power production.
An analysis of the safety systems and the systems important to safety has been completed to determine the critical elements (elements whose failure may result in violating the limits for safe operation of the system) and scope and frequency for technical service and repair were substantiated.

Once the system in the scope were defined a reliability center maintenance (RCM) approach were applied to identify the critical elements of the systems. The RCM approach includes the following steps:
• Identification of system functions and functional failures;
• Identification of component failure modes;
• Assessment of component failure probabilities;
• Identification of critical components;
• Identification of technical service activities.

Risk evaluation analysis has been performed to determine the impact of the changes on both CDF and LERF. Along with risk evaluation deterministic approach has been used to determine impact on defense-in-depth and safety margins.
As a result of risk-informed program implementation, outage time was decreased with 7 days and additional energy produced per year at the rate of 100,000 MWh.
Scope and Frequency of Testing

✓ Analysis has been performed to evaluate changes to system and component testing.
✓ The risk-informed methods were used to substantiate the change in the frequency of the tests on the safety systems and the systems important to safety and particularly the opportunities to change the conditions of the hydraulic tests on primary and secondary side.

The basic steps of the performed analysis are:
• Identification of system and component tests to be addressed (impact on power operation, potential reactor trip, length of time required for the test, impact on system availability, additional personnel exposure, releases to the environment etc.);
• Feasibility assessment and identification of test plan changes;
• Risk evaluation;
• Deterministic evaluation.
Scope and Frequency of Testing (2)

✓ Based on the consideration of limitations, changes to testing of the analyzed systems are identified. Changes to be considered include:
  • Alternate tests;
  • Test frequency;
  • Test elimination;
  • Moving test at-power operation.
✓ The impact of the changes on both CDF and LERF is determined. Each change is assessed individually and all of the changes are assessed together.
The economical impact is estimated using the following two methods:

- Monte Carlo method;
- Average flows of incomes and expenses estimation during plant life time.

- Up to 80 000 000 euro positive economical impact was calculated for Kozloduy NPP.