Evaluation of WWER 440/213 Containment Compartments for NPP Mochovec

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ABSTRACT
In the frame of the safety improvement program for NPP Mochovec, Slovakia, the maximum pressure difference loads and temperatures acting on the containment compartments were evaluated and the structural design verified (1).

The structural re-evaluation was performed considering the maximum pressure difference loads, the pertinent thermal effects and the local impacts due to pipe rupture, jet and whip forces. A large degree of self-relieving thermal stress at the operational and accidental conditions due to cracking of concrete and time-dependent effects was considered.

An increased safety level compared to the original design requirements was considered. It was found that the containment design is adequate for the stipulated accidental conditions including local effects due to postulated pipe ruptures.

1 INTRODUCTION

The main building of each twin unit WWER-440/213 is designed as a rectangular, mixed reinforced concrete and steel structure. The load bearing and stiffening members comprise walls and floor slabs. Up to the elevation +18.90 m, the structure of the main building represents a monolithic concrete block structure. Above +18.90 m, the main building is subdivided into two structures, the bubbler condenser tower and the main steel structure for the reactor hall covering the reactor pressure vessel.

The foundation is situated approximately -8.0 m below plant grade. The reactor building and the bubbler condenser tower for both units are founded on a common foundation slab which has a thickness of $d = 1.50$ m. The unit dimensions in plan are approximately $72.0 \times 52.0$ m and $42.0 \times 24.0$ m respectively. The total heights of the building is about 58.0 m.

The subsoil of the foundation slab consists of a semi-rock material andesite agglomeration with tuff compound. The modulus of deformation is $E_0 = 100$ MN/m$^2$ and the Poisson's ratio is $\nu = 0.25$. The allowable soil pressure at $-8.30$ m according to STN 731001 is $p = 0.82$ MN/m$^2$. A modulus of subgrade reaction of $c = 100$ MN/m$^2$ was assumed in the calculation.

The hermetic zone located between levels $+6.00$ m to $+18.90$ m comprises the steam generator boxes (SG) with the primary piping system, the SG drive compartments and the compartments for the main circulation pumps. The compartments for the hydroaccumulators and the pressurizer are located in the corners of the reactor building up to level $+26.50$ m.

A corridor connects the reactor compartment system and the bubbler condenser tower. The bubbler condenser between $+6.00$ m - $+50.60$ m measuring in plane $34.0 \times 7.25$ m con-
sists of tray chambers on twelve levels in which up to 9 x 17 = .53 interconnected trays with borated water of temperature 40-60°C are located. The initial water depth in a tray is approximately 0.5 m, total water inventory is approximately 1.25 m³.

All containment walls are made of reinforced concrete, the outer walls have a thickness of 1.50 m. The thickness of the internal compartment walls and slabs vary between 50 and 100 cm. The containment structures were erected using concrete class B30 and the reinforcing steel 10425 (f_y = 410 MPa) according to STN 731201. The reinforcing steel 10216 complemented by gussets from structural steel were used for the construction of welded spatial trusswork with the integrated liner, so-called "armoblocks". The reinforcing steel works as a shear reinforcement.

The containment including the bubbler condenser system provides approximately 48 000 m³ of free air volume. The outer boundaries of the containment are hermetically closed against atmosphere. This hermetic area has to remain gas-tight and integral also during design base accident conditions comprising large break loss of coolant accident (LB LOCA) including main coolant circulation line rupture and different high energy pipe ruptures.

2 DESIGN LOADS

The containment evaluation was performed using the following design loads:

Dead and Live Load
The dead weight of concrete structures was calculated using the true thickness of slabs, walls, secondary concrete, screed, etc., according to the execution drawings. Long-term live load was taken into account using a uniform distributed load of p = 5 kN/m² on the slabs as a minimum. Heavy components were considered by their operational weight, distributed to the directly loaded nodal points. The weight of smaller components is covered by the a.m. uniform live load.

Adjacent Structures
The loads transmitted by adjacent buildings and by the steel superstructures were considered by line loads. The lateral resistance of structures of the intermediate building was neglected.

Thermal Load
The temperatures at normal operating conditions were employed following a separate specification. The temperatures in the containment compartments vary between 40 °C and 60 °C, in the reactor hall or in the intermediate building between 20°C in winter and 32°C in summer. An external ambient temperature of -12°C in winter and +32°C in summer and a site ground temperature +10°C were used. In the calculations, the winter climate conditions were considered.

Design Basis Accident (DBA)
Based on a specific data base of the source rates and post accident procedures, thermal hydraulic analyses (3) were performed postulating
- 2A-cold-leg ruptures in SG compartments loop 1/3 and 4/6 with active and passive spraying, and
- main steam line break (including cascading break of 2-BRUA) with active spraying.

The transient pressure differences and temperatures acting on the containment compartment walls and slabs were evaluated for each particular case. The governing values result from the main coolant cold leg rupture (LB-LOCA) in the SG compartments. A maximum
peak pressure of approximately 2.16 bar was determined at about 10 s after the beginning of the accident. The duration of high pressure phase is limited to approximately 50 s for the main coolant line rupture, and to approximately 20 min for main steam line rupture. The maximum room temperatures were found between 110-120°C.

A maximum pressure difference of 117 kPa was evaluated for the wall between SG compartment and I&C Rooms (Nos. 201 to 204), max Δp of 49 and −72 kPa for the partition wall to the air traps, and Δp = 39/-13 kPa for the wall between SG and main coolant compartments.

Altogether, the results of the refined thermal-hydraulic analyses yielded pressure differences in part considerably lower than those recommended and used for the preliminary assessment. Proceeding from the results of Riskaudit (2), the predicted maximum overpressure was 170 kPa. A safety addition of 15% is included in this value. So far, the maximum overpressure resulting from the plant specific analyses was reduced by a factor of 117/170*1.15 = −0.8.

Similarly, the pressure difference acting on the partition wall to the air traps was determined to be 72 kPa. Following (2), a value of 120 kPa should be used.

Thermal Effects at Accident Conditions
With regard to the time needed for heating of concrete, a combination of the thermal effects with the maximum accident pressure is not required. The design for accident temperature and a residual accident pressure is covered by the design for maximum pressure.

3 LOAD COMBINATIONS AND ACCEPTANCE CRITERIA

Proceeding from the original design format and following the development of the European standards, the concept for the re-evaluation of the containment compartments is based on design in limit states. The partial safety factors for design loads and design resistances were adopted in compliance with the recommendations of IAEA for WWER-440/213 evaluation (4). The following load conditions and design situations were considered:

Normal Operating Conditions (NOC) or Service Conditions
comprising the combination of the permanent actions (dead load), variable actions of live load, component reactions, eventual climate actions due to snow and wind load, and the effects due to imposed deformations. The evaluation is primarily required in Serviceability Limit State (SLS).

Test Conditions (Service conditions)
comprising the combination of the permanent actions, variable actions of live load, component reactions, and the effects due to imposed deformations. The evaluation is required in SLS and Ultimate Limit State (ULS).

Design Basis Accident (DBA)
comprising the combination of the accidental pressure and thermal effects due to LOCA with the permanent and variable actions including the effects due to imposed deformations. The evaluation is required in ULS as to check the global margin of containment capacity. The relevant equation for actions is

\[ 1.0/1.35D + 1.3L + 1.35 \text{IND} + 1.35 (P_A + T_A) \]

in which

- \( D \) = dead load (permanent load)
- \( L \) = actual live load
- \( \text{IND} \) = indirect action (imposed deformations) including thermal effects at NOC

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\[ P_A, T_A = \text{pressure, temperature generated by DBA} \]
The partial safety factors are 1.5 for concrete and 1.15 for the reinforcement.

DBA (BDBA)
comprising the combination of the accidental pressure and thermal effects including eventual jet and pip whip forces or internal missiles with the a.m. permanent and variable actions.

SL-2 (Extreme environmental conditions)
comprising the combination of the design earthquake with the a.m. permanent and variable actions.

With regard to the status of the plant completion, it is not necessary to evaluate all load combinations, such as those related to the erection conditions. Focusing on the safety issue containment CO4, the evaluation of the containment compartment structures could be limited to the accident load combinations comprising DBA events. However, as the stipulated DBA loading can only occur after the plant has been in operation, the evaluation of normal operation conditions was performed in a first step.

4 CALCULATION MODEL

In view of the general shape complexity of the hermetic zone a three-dimensional finite element model of the whole reinforcement concrete structure was developed to perform the design checks. As can be seen from Figures 1 and 2 the model comprises the essential structural members of the confinement, i.e. slabs and walls forming the hermetic zone, the important floors and the foundation slab, outer and inner walls including cylindrical structures for the reactor pit and for steam generator compartments as well as three corner-compartments. All plate members are modeled considering their true thickness taken from the drawings. The interaction between the structure and the soil is considered using a subgrade reaction modulus.

The complete finite element model to be used in the analysis consists of approximately 4400 nodal points and 5400 elements. The calculation was performed using the computer code TRIMAS (5).

5 CALCULATION METHOD

Imposed Deformations and Concrete Cracking
a) Effects of imposed deformations at NOC were considered using the compatibility of deformations with the crack behavior. The evaluation is based on so-called cracking forces of a section taking into account the existing reinforcement ratio, diameter and spacing of rebars as well as the mean values of crack width and spacing, and sufficiently approximate estimate values of the effective tensile strength for concrete. In doing so, a reduction due to time-dependent effects, such as creep, was not utilized in check for NOC.

b) The evaluation was performed in SLS. As the stresses remain restricted, an explicit check for ULS could be omitted in most of the cases. The effective tensile stress effect of concrete B30 considering the self-equilibrating stresses was assumed to be \(-1.0 \text{ MPa}\) for concentric tension and \(-1.2 \text{ MPa}\) for flexural tension.

It was shown that the temperature increase at the operating conditions is safely covered by controlled crack propagation and the corresponding forces basically remain in limit of cracking forces.
Creep and Shrinkage
Reflecting the actual age of the containment structures, the effective residual creep and shrinkage values were estimated and an average modulus of deformability \( E_{ef,c} = E_{ef}/(1+\psi t) \) determined. The concrete behavior at increased temperatures and the influence of the increased temperature on creep was considered according to Schneider and Budelmann (6, 7).

Using effective moduli of deformability for the determination of stresses due to imposed deformations in non-cracked concrete, a sufficient approximate estimate yields the following reductions of the thermal constraint:
- about 60% considering the age of structures at begin of normal operation,
- about 70% considering the increased creep due to increased containment temperatures during NOC and the thermal degradation of concrete after the first heating.

The short-term thermal effects due to accident temperature need not be combined with the maximum accident pressure. As the stiffness degradation due to time-dependent and thermal effects is approximately 70%, it can be concluded that the increase of the accident temperature constraint force has been compensated by the stiffness reduction. Thus, the design for accident temperature and the remaining accident pressure is covered by design for maximum accident pressure.

6 RESULTS AND CONCLUSIONS
The evaluation of containment compartments for service (normal operation) conditions comprising the combination of the permanent actions (dead load), variable actions of live load, component reactions, and the effects due to imposed deformation was performed in serviceability limit state (SLS). With regard to the restricted steel stresses in SLS, a check in ultimate limit state (ULS) could be dispensed.

The evaluation for DBA conditions comprising the combination of the accident pressure and thermal effects with the permanent and variable actions including the effects due to imposed deformation was performed in ULS for bending and longitudinal force as well as for shear. The global margin of compartments capability was checked using a partial safety factor 1.35 for accident load and 1.5 or 1.15 for concrete and steel as to demonstrate an acceptable safety level at DBA conditions.

A sufficient capacity was determined for all compartment items as shown in Table below. However, a utilization ratio (demand vs. capacity) of nearly 100% is indicated for several items. As far as the compartments are a part of the outer hermetic zone including several „semi-accessible“ compartments, they were evaluated using the previously, conservative recommended value by Riskaudit 170 kN/m². The margin related to the plant specific results is by more than 25% higher.

In addition, the capacity of the slab of the air trap compartment has been designed for a difference pressure of \( \Delta p = 90 \) kN/m² in case of conservatively stipulated irregular pressure distribution in bubbler condenser. As the main steel beams of the bubbler condenser are well anchored into the concrete walls the stability of the partition wall between the tower shape and the air traps is adequate.

A sufficient design capacity was also checked for members affected by jet forces due to a rupture of main steel or main feed water lines. The anchorage of the whip restraints was found adequate.

Summing up, the containment compartments were found to have an adequate design margin for the conservative accidental pressure of 170 kN/m² and pertinent pressure differences acting on particular compartment members. As the pressures resulting from the plant specific, thermodynamic analyses are considerably lower, an essential safety margin is available with regard to the safety strategy in depth and when considering BDBA effects.
<table>
<thead>
<tr>
<th>Compartment / Item</th>
<th>Reinforcement Direction</th>
<th>Utilization Ratio [%] N + M</th>
<th>Utilization Ratio [%] V</th>
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<tbody>
<tr>
<td>Recirculation venting compartment</td>
<td></td>
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<tr>
<td>outer walls compartment A032 / Items W4/W21</td>
<td>Horizontal</td>
<td>(60)</td>
<td>70</td>
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<tr>
<td></td>
<td>Vertical</td>
<td>70</td>
<td>(50)</td>
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<tr>
<td>Reactor pit</td>
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<tr>
<td>outer wall of compartment A004 between levels -2.8 m and +9.0 m / Item W34</td>
<td>Horizontal</td>
<td>40</td>
<td>(30)</td>
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<tr>
<td></td>
<td>Vertical</td>
<td>(30)</td>
<td>60</td>
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<tr>
<td>I &amp; C rooms</td>
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<tr>
<td>wall between compartments A201 and A205 (A204) / Item W38</td>
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<td>80</td>
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<td></td>
<td>Vertical</td>
<td>(35)</td>
<td>80</td>
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<tr>
<td>Corridor</td>
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<tr>
<td>wall between compartments A201 and A242 / Item W24</td>
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<td>(30)</td>
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<tr>
<td></td>
<td>Vertical</td>
<td>80</td>
<td>80</td>
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<td>Rooms for SG drives and valves</td>
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<td>wall between compartments A211 and A210 / Item W19</td>
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<td></td>
<td>Vertical</td>
<td>55</td>
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<td>Bubbler condenser</td>
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<td>wall of compartment A530 / Item W1</td>
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<td>slab of compartment A530 / Item D11</td>
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<td>Compartments for hydroaccumulators and pressurizer (A525-527)</td>
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<tr>
<td>Inner walls / Items W41, 43, 45</td>
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<td>91</td>
<td>(60)</td>
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<tr>
<td></td>
<td>vertical</td>
<td>(40)</td>
<td>90</td>
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<td>Outer walls / Items W42, 44, 46</td>
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<td>(95)</td>
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<td>Slabs +26.5 m / Items S9</td>
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<td>Outer wall for SG drives (A210, A421) / Item W14</td>
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<td>Inner wall betw. SG and MCP (A201-A301) / Items W31, W32</td>
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<td></td>
<td>vertical</td>
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<td>Item W37</td>
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<td>vertical</td>
<td>95</td>
<td>50</td>
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</table>

* for Δp_{tot} = 90 kN/m²  ** for Δp_{tot} = 170/2 = 85 kN/m² and Δp_{loc} = 20 kN/m²
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Figure 1  FE Model – Elevation of Containment Compartments

Figure 2  FE Model – Inside Structures