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Structural investigation on the potential leakage spots of a VVER-440/V213 NPP containment

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ABSTRACT: The rectangular and circular hatches, large diameter pipe penetrations and the wall liner have been identified as potential leakage spots of the VVER-440/V213 type containment. The structural performance of the selected components has been investigated for the loads acting after LBLOCA with no condensation in the bubbler condenser. The properties of the sealing material of the hatches has been tested. The calculations demonstrate that these components can withstand the assumed beyond design base loads without increasing leakage.

INTRODUCTION

The containment behaviour of the VVER-440/V213 units under different internal and external events has been widely investigated in the last years. The investigation includes structural analysis of the containment under conditions of design base loss of coolant accidents (LOCA) and beyond design base LOCA assuming that the pressure suppression system efficiency is below design value. The results of these investigations made for NPP Paks were reported on the previous SMIRT conferences [1].

The VVER-440/V213 reinforced concrete containment design differs essentially from the usual PWR one. The VVER-440/V213 confinement is a set of interconnected and sealed box-like compartments designed to keep leakage less than 14.7%/day at 0.25 MPa. The annual tests of containment at the NPP Paks units show a maximal leak rate of 9%/day (with 2% accuracy). This leakage is caused by local imperfections of the sealing of pressurised boundary, and most of them could be identified and avoided during annual outages.

One of the basic question of recent investigations is the leak tightness of the confinement being the last barrier limiting the radioactive releases in case of LOCA. The tightness of the structural elements with large leaking potential (doors, hatches, penetrations) and the leak tightness of the stainless steel liner are of great importance. The behaviour of these structural components under different LOCA condition is not known. The objective of this work was to investigate the structural performance of the selected components for the loads acting after large break loss of coolant accident (LBLOCA) with no condensation in the bubbler condenser. The preliminary results of this investigation were reported in [2].

IDENTIFICATION OF THE POSSIBLE LEAKAGE SPOTS

The confinement walls, floors and ceilings are sealed by a 6 mm thick stainless steel liner plates that are either attached to or embedded within the concrete walls, floors, and ceilings. The edges of the plates are carefully welded together, and there is a detection system to monitor leaks. The three-dimensional finite element calculation of the reactor building indicate that the most demanded place for the lining is the corner of the bubbler tower. This part of the liner has been selected for the evaluation.

There are several other structural components for the sealing the compartment boundary such as

- hermetic cap located over the reactor shaft,
- 5 hermetic doors ,
- 20 hatch covers over the steam generator and pump compartment in the 18.9 m level operating floor providing access to the main circulating pumps and steam generators,
- the sluice gate between the reactor shaft and spent fuel storage pond,
- different pipe and cable penetrations through the confinement wall (191 large diameter and 1289 small size penetrations).

Based on the judgement the largest size rectangular and circular hatch, and main steam pipe penetration have been chosen for the evaluation. The basic design features of these components are summarised below.

The hatch covers are rectangular and circular shape and different size. There are two aspects of the selection: size, and the position of the hatch on the floor slab. For the analysis the largest circular (radius 1780 mm, and 160 mm thick) and rectangular (size 3660x1560 mm, and 260 mm thick) covers have been selected. They are nearly in the middle of a large slab with 6 m span which may have large deformation under internal pressure load. The cover caps were made from steel plates. The steel plates are fixed to the opening boundaries by means of wedging. There are 12 wedges for both rectangular and circular cover plates. The hatch hold-down devices are anchored into the 1.5 m thick reinforced concrete slab by means of deformed bars. The distances between the hold-down points vary in the interval of 0.78-0.93 m. The leak tightness is achieved by two 16x22 mm sealing strips placed in two parallel channels (8x44 mm) along the cap edges. The sealing strips are compressed by the self weight of the caps and by the wedging. The material of the sealing strips is Silopren HV 3/622.

The main steam line penetration (type T617) is of 760 mm diameter. The penetration mounted into the housing which is anchored into the reinforced concrete wall of confinement. The penetration itself consists of inner pipe (steam line of 4.4 MPa pressure) an outer tube and a stiffening ring between the two tubes. The outer tube fixed into the housing and welded together with the liner. There are four steam line penetrations through the confinement wall. For the analysis that penetration has been selected, where the acting moments and the relative displacements re the largest as defined from the overall 3-dimensional calculation of the confinement.

The top of the reactor shaft is sealed by a steel cap, which is part of the hermetic boundary. Based on engineering judgement the spherical cap with oversized hold-down system seem to be not critical. The sluice between the reactor shaft and spent fuel pond is not critical because there is a plate mounted with bolts and sealed by silicon resin parallel with the sluice as a redundant pressure boundary. This is a modification realised at NPP Paks.

ANALYSES

The selected structural components have been analysed using rational finite element models, which include the reinforced concrete structure (floor slab or wall), the liner, anchorage of steel parts, and the sealing.

The first question is the mechanical behaviour of the selected components under accident condition, whether the liner and its fixes, the pipe penetration and its fixes, the cover plates and their hold-down devices can withstand the internal pressure loads without damages resulting in enhanced leakage.

The second question is the performance of sealing. It is important to obtain the relative displacement between the steel cover edge and the cover support seat in the reinforced concrete floor slab, i.e. the compression of the sealing strip along the cover edges.

The structural components considered are mounted on the place under cold and non stressed conditions. The internal pressure will deform of the reinforced concrete floor slabs, walls, etc. which act as a deformation of the fixing boundary. The bending stiffness even in the case of cover plates is 1:100 of the reinforced concrete bending stiffness. The deformation of the compartment floors and walls was taken from the 3-dimensional overall calculation of the containment performed for the same internal pressure load.

Loads

The conditions (pressure and temperature distribution versus time) in different parts of the containment has been calculated for the cases of loss of coolant accidents and also main steam line break. The calculation has been performed for the design conditions as well as beyond design base cases assuming reduced condensing capacity of the bubbler condenser (100, 75, 50, 25 and 0 % of the design condensing capacity). The maximum pressure obtained in the case of the main stream line break, slightly less for the large break LOCA. The peak pressure in both cases is lower than the design value of 0.25 MPa. The reduction of the bubbler condenser capacity increases of the maximum pressure up to 0.395 MPa which is a conservative assumption.

The load combination consists of dead load, live load and accidental load, i.e. an internal overpressure 150 kPa in as designed LOCA case, and 295 kPa in the beyond design base LOCA case.

The dead load is applied as a distributed load q= 24.97 kN/m^2 for rectangular, and q=13.52 kN/m^2 for the circular cover plate respectively. A 0.9 coefficient is applied for the dead load because it is acting against the internal pressure.

Rectangular hatch

The steel cap is a plate supported along the edge except of the hold-down wedges which act as fix points and are under the influence of the internal pressure, self weight and the action of compressed sealing strips, the last being negligible in case of large overpressure. The cap may be considered as a free edge plate fixed at certain points only.

The cover plate has been modelled by 288 rectangular elements taking into account the position of the hold-down wedging. In fact the 260 mm thick cover is composed by two 130 mm thick steel plates mounted together on the edges to allow the lifting of the cover as a single plate, but this mounting do not eliminate the slipping of the plates relative each other. In the calculation a single plate with 163.8 mm thickness has been considered as an equivalent to the coupled two plates. There are 5 nodal points between the hold-down points which allows to obtain the deformation of the edges.

The bending under distributed loads is defining the stresses in the plate and the stresses due to normal forces are negligible even in the vicinity of hold-down points. The maximum moment 83.40 kNm/m and the corresponding edge stress is 14.8 MPa. The strength of the rectangular cover plate was found sufficient. The maximum edge differential displacement between the hold-down points was 0.055 mm.

Circular hatch

The circular steel cover plate has been modelled by 304 elements. There are 7 nodal points between the hold-down points which allows to obtain the deformation of the edges. The modelling and the calculation are similar to the rectangular hatch cover case.

The maximum moment edge stress 58.1 MPa. The strength of the circular cover plate was found sufficient. The maximum edge differential displacement between the hold-down point was 0.165 mm.

Hatch hold-down

The shear resistance of the steel wedging pin should be checked. The largest reaction force acting is of 276.5 kN and the corresponding shear stress τ=92.17 MPa. The shear stress in the in the hold-down bolts is τ=41.06 MPa. The strength of the hold-down wedging was found sufficient for the loads applied.

The pull-out of the hold-down bolts has been examined. The maximum forces acting on one bolt are 622 kN and 717 kN in the rectangular and circular hatch covers respectively. The anchorage of the bolt into the floor slab can withstand this loads.

The largest total displacement of the hold-down wedging and anchorage bolts was found equal to 1.552 mm (circular cover).

Elastomer sealing

The load-compression diagram of the sealing strip material has been tested using test specimens of 100 mm length. The load-compression diagram has been obtained with two different deformation rates (0.9 mm/s and 0.1 mm/s). The diagram shows an abrupt change in the behaviour of the sealing at 7.24 mm compression when the strip fills practically the channel. This corresponds to the transition from uniaxial to triaxial stress state. The compression modulus of the sealing are 7.6 MPa and 23.62MPa in the uniaxial and triaxial stress conditions respectively. (The latter value is equal to 24.53 MPa in the first load case.) The maximum compression of the sealing is 8.3 mm. The sealing load-compression diagram is shown in Fig. 1.

The leak tightness of the sealing is defined by the largest edge displacement of the cover plate edge. This is the resulting value of the total displacement of the hold-down wedges and the anchorage bolt plus the largest edge deformation between two hold-down points. The circular hatch is the worst case considered. The resulting displacement value equals to 1.552 + 0.165=1.717 mm. This value should be less than the reversible deformation of the sealing strip, which is 3.6 mm. At the same time, the remaining compression of the strips is equal to 2.4 MPa, which is an order of magnitude higher than the internal overpressure of 0.295 MPa.

Main steam line penetration

The finite element model included a part of the confinement wall, outer tube of the penetration the inner pipe (4.4 MPa internal pressure), and a stiffening ring as well as the liner welded to the stiffening ring see Fig 2. The confinement wall has been modelled by solid elements in six layers and the penetration itself by thick shell elements. The steam line model was extended upto the first fix points.

The boundary conditions, i.e. the wall displacements have been taken from the 3-dimensional overall containment analysis. The penetration is loaded due to deformation of the wall and the housing. The calculation has been performed by COSMOS/M 385 VER 1.61 software.

The most critical place where a leakage may occur is the liner and the welding of the liner to the stiffening rings.

The maximum strains on the liner were $\varepsilon_l = 5 \cdot 10^{-5} \div 5.5 \cdot 10^{-4}$ which are less than the design value of $\varepsilon_d = 1 \cdot 10^{-3}$.

The maximal stresses in the liner were $\sigma_l = 89.6 \div 124.4$ MPa which is less than the design allowable stress $\sigma_d = 200$ MPa.

The highest stresses in the welding between the liner and the stiffening ring was 35.1 MPa which can not cause any problem.

The liner

The three-dimensional finite element calculation of the reactor building indicate that the most demanded places for the lining are the corners of the compartments. A corner formed by a floor slab and vertical wall of the bubbler tower shows largest relative displacements in the 3-dimensional overall containment calculation. The particular finite element model for the investigation of this detail consists of thick shell elements for the reinforced concrete walls. The element stiffness includes the stiffness of the liner too. The model is shown in Fig.3. The influence of the reinforced concrete cracking on the stiffness was also taken into account.

The calculations gave the highest twist rate for the weld as $6.46 \cdot 10^{-4}$ and the highest shear strain rate between reinforced concrete wall and liner $7 \cdot 10^{-7}$ which could not cause damage neither in welds nor in the fastenings of the liner. The highest normal strains in the liner are below of the values above.

CONCLUSIONS

The containment pressure boundary has been investigated. The capability of the containment walls to withstand different design base and beyond design base loads has been evaluated. The pressure load as well as the pressure differences were considered. The potential leakage spots have been identified. The strains and when appropriate the internal forces relevant for the evaluation of the selected components were determined from the 3-dimensional analysis of the overall behaviour of the containment under selected design base and beyond design base LOCA conditions.

In the case of rectangular and circular montage penetrations the leak tightness is determined by the sealing. The load-compression characteristics of the sealing strips was determined experimentally. The calculations show that no changes are to be expected in the leak tightness of both rectangular and circular montage penetrations even in the case of beyond design overpressure.

The pipe penetration analysis demonstrated that the leak tightness should be remain even if the overpressure was beyond design value. The critical area in this cease is the welding of the liner to the penetration stiffening ring. Both the strains and the stresses were found less than the allowable.

It was found in the former investigations that the containment corner is oversterssed relative to the design limits in the case of the large break LOCA. As the leak tightness is assured by the liner the behaviour of the liner was investigated in the area with maximum relative displacement between reinforced concrete wall and the liner. The influence of the cracking was taken into account too. The results show that the strain rate of the liner welds are below critical.

The leak tightness of the analysed main steam line penetrations seems to be assured in the case of design base and beyond design base LOCA conditions.

REFERENCES

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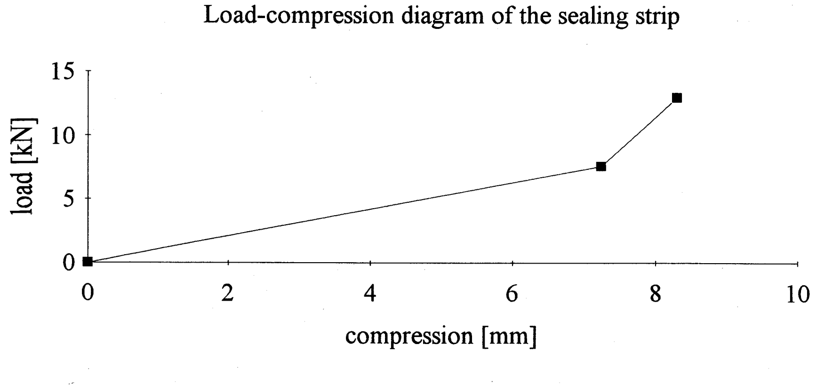

Fig. 1. Load-compression diagram of the sealing strip

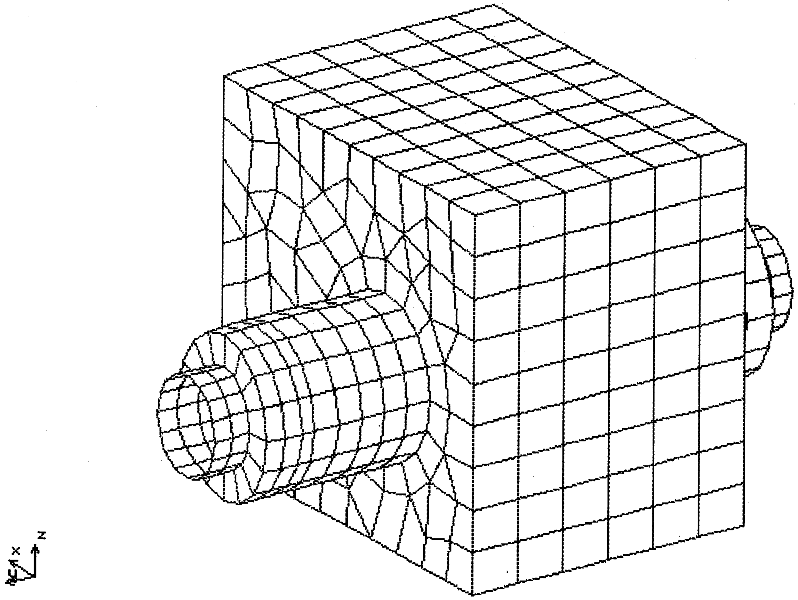

Fig. 2. Model of the main steam line penetration

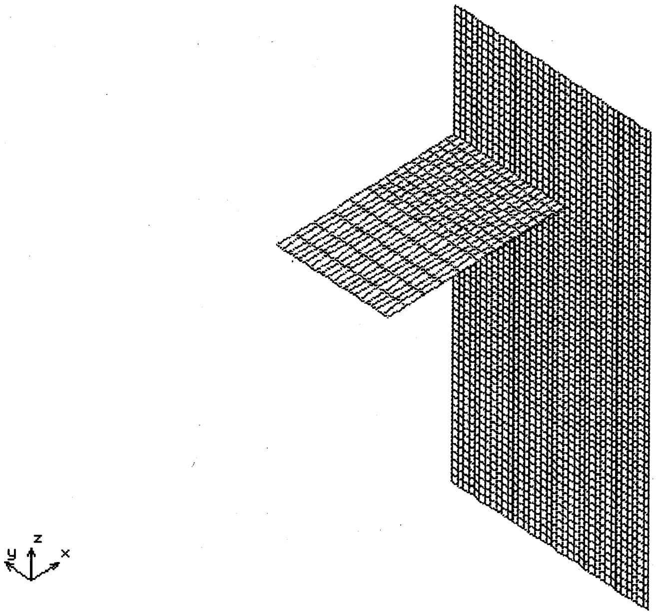

Fig. 3. Model of the critical conpartment corner