VVER 1000 containment behavior under severe accident loading

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ABSTRACT

VVER-1000 containment capability evaluation in the presence of slow pressure rise and probability distribution of containment failure pressure was developed in the framework of level 2 Probabilistic Safety Assessment (PSA) for Balakovo Nuclear Power Plant (unit 4). Assessments included axisymmetric finite element model development, penetration and leakage analysis, critical failure mode definition and expert evaluation of variability in resulting failure pressure.

1. INTRODUCTION

Level 2 Probabilistic Safety Assessment considers various accident scenario inside containment which may be result of core melt in reactor pressure vessel. Among these scenario, the group with overpressure failures of containment deserves careful investigation as the catastrophic failure of this structure leads to serious radiological consequences for population and environment.

Containment capability evaluation for VVER-1000 unit (Balakovo NPP, unit 4) has been performed in the framework of TACIS 91 (Technical Assistance to Commonwealth of Independent States) project 3.1 by expert group included participants from different companies involved in the project (AEP (Russia), Belgatom (Belgium), NNC (U.K.)). The procedures previously developed for Western PWR containments were adapted and applied to assess the ultimate behavior of prestressed concrete containment of standard VVER-1000 unit and to develop failure probability function of pressure which was needed for overall probabilistic safety assessment of the plant. Important issue of the study was definition of containment failure mode (the leakage or catastrophic failure) as it concerns the further estimation of frequency and content of radiological release into environment.

2. BRIEF DESCRIPTION OF CONTAINMENT

VVER-1000 containment is the complex structure designed to provide the tightness and isolation of reactor and its essential systems in normal operation and under accident conditions. The containment consists of prestressed reinforced concrete vessel covered by steel liner over inner surface. General view of Balakovo containment is given in Fig. 1.
Figure 1 Containment building of Balakovo NPP

Reinforced concrete vessel includes the following components:

- cylinder of 22.5 m inner radius with wall thickness of 1.2 m;
- dome having shape of hemispheric sector of 35 m radius with wall thickness of 1.1 m;
- basemat supported by foundation structures of containment building below the pressure boundary;
- massive reinforced concrete support ring which is an intermediate structure between the cylinder and dome.

The cylinder wall thickness increases near juncture with basemat and support ring.

Containment vessel is made of B30 normal weight concrete (compressive strength is 30 MPa) reinforced over inner and outer side with steel bars (rebars) in meridional and hoop direction.

The cylinder also contains the openings for airlocks and penetrations and Π-shaped boron solution sump with rectangular main equipment hatch are available in basemat.

The ability of concrete shell to withstand internal pressure load is ensured by prestressing system which in normal operation maintains biaxial compression in the vessel. It is supposed that during accident the pressure increase will decompress concrete containment and prevent early cracking due to tensile stresses.

Prestressing system is composed of tendons arranged in polyethylene ducts, support anchorage devices and equipment for tensioning of tendons (hydraulic jacks are arranged in support ring). The number of tendons in cylinder and in the dome are 96 and 36 respectively. Distinctive feature of prestressing system is its helicoidal arrangement over containment (see Fig. 2) Each tendon is composed of two branches divided by U-turns arranged in the basemat and comprises 450 steel wires of 5 mm diameter. Mean values of yield and ultimate strength
of tendon are 1189 MPa and 1387 MPa respectively. The terminal ends of tendons are fixed in the support ring. Layout of prestressing system is shown in Fig.2.

Figure 2 Layout of prestressing system

Leaktight steel liner of 8 mm (yield strength 246 MPa) is attached to inner side of the vessel. The liner is welded to steel angles which are anchored in concrete. The essential function of the liner is to ensure the tightness of containment volume. Containment pressure boundary lined by steel plates includes the inner surfaces of cylinder and dome, the basemat with the boron sump walls.

Containment is enveloped by auxiliary building and is rested on reinforced concrete foundation structure containing equipment of safety systems.

3. DEVELOPMENT OF CONTAINMENT MODEL

Development of containment model comprised the following steps:
- Preliminary estimation of containment capability using simple relations and handmade calculations;
- Development of global axisymmetric finite element model of containment and nonlinear analysis of the model in the presence of pressure increase up to ultimate value;
- Deterministic check that all components of containment pressure boundary (penetrations, hatches, sump) are able to withstand the ultimate pressure obtained at previous step;
- Leakage analysis to estimate potential for early leakage due to strain concentration.

This is important issue for definition of containment failure mode as the leakage is able to arrest the further pressure increase and resulting consequences of accident shall differ from those for global rupture.

The following general provisions were taken into account in the analysis:
• The pressure rises gradually up to the ultimate value when containment fails due to 
rupture of section components (concrete, liner, tendons). Dynamic effects which could be 
caused by such phenomena as hydrogen explosion and direct containment heating at high 
pressure vessel failure is not taken into account in present model.

• The global model of containment is axisymmetric, i.e. the load (pressure + prestress and 
dead weight) and mechanical properties of concrete, rebars and tendons do not depend on 
azimuth angle of containment axis. As an implication-large openings (penetrations, 
hatches, airlocks) are not available in the global model geometry.

• Modeling of liner’s local behavior inside irregular areas (near large penetrations, airlocks 
and hatches, the junctions of cylinder to basemat or on the dome and etc.) is performed 
based on results of global model analysis assuming that stress-strained state of global 
model is independent on the state near these areas (Saint-Venant principle).

• It was assumed that mechanical properties of reinforced concrete vessel and liner, tension 
force and mechanical properties of tendons meet requirements of design specifications, 
i.e. effects of possible reduction of tension force, corrosion and ageing are not considered 
in present study.

The main results of these studies are described below.

3.1 Development of containment finite element models

The main objectives of global finite element model were to obtain containment failure 
pressure and check results of preliminary calculations. Resulting stress-strained fields in liner 
are required as an input for leakage analysis.

As it was mentioned before the openings in containment and basemat are not available 
in the global finite element model so the concrete and liner surfaces are continuous, i.e. 
penetrations, airlocks and hatches were not taken into account because their arrangement at 
different azimuth angles of containment axis disrupts the axial symmetry of the model. 
Details of stress strained conditions in these areas were considered carrying out liner stress 
concentration analysis.

The simplified approach for modeling of reinforced concrete in the part of cracking 
evaluation was adopted (“smearing cracks” model).

Applied loads (internal pressure, dead weight, tension force in tendons) were assumed 
to be independent on azimuth of containment; in addition the pressure and prestress do not 
change with height of containment. The tension force in tendon is constant along its length 
(the friction force between the tendon and the duct was not considered).

The liner finite elements are attached to reinforced concrete vessel elements in nodal 
points of model, i.e. anchorage devices layout is not considered in the model.

The finite-element code ABAQUS was used for modeling of Balakovo containment. 
Axisymmetric four-node finite elements (rings having quadrilateral sections) were used for 
modeling of concrete. For liner modeling thin shell axisymmetric elements are available. The 
modeling of reinforcement and prestress in concrete was performed using built-in features 
available in ABAQUS.

The finite element mesh for Balakovo VVER containment is given in Fig. 3. 
A number of simplifications were introduced into the model. This concerns the helicoidal 
layout of prestressing system in cylinder which was changed for equivalent orthogonal grid of 
tendons. In dome non-axisymmetric layout of tendons (see Fig. 2) was modeled by orthogonal 
system with account for non-uniform stress distribution induced by prestress in the dome.

The boundary conditions were applied along the bottom surface of the model. The 
nodal points were fixed in both directions of degrees of freedom. This assumption was 
justified by stiffness calculation for foundation structures which showed that the basemat 
support can be considered as rigid.

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The loads were applied in the following sequence: dead weight, prestress and internal pressure history. Development of deformed state in containment is presented in Fig.3.

Figures 4,5 illustrates qualitative change of stress-strain state in tendons, concrete and liner in hoop direction of membrane area in cylinder of containment. Point 1 is initial state of containment at the moment when the pressure starts to increase. The concrete and liner are compressed. The tendons are loaded by pre-tension force. The spans 1-2 and 2-3 correspond to linear change of parameters in stress strain state. Point 2 is the zero compression in concrete at mid-height of the cylinder. Compression in concrete changes for tension and point 3 is beginning of membrane area concrete cracking. The change in stiffness of the system can be observed in change of slope in concrete and liner characteristic at point 3.

At the span 3-4 intensive cracking and stress redistribution occurs between boundary effect areas (junctions: wall-basemat, dome-cylinder) and membrane area of cylinder and dome. The most stressed area moves to membrane zone.

The span 4-5 reflects the state of containment when pressure load is carrying basically by tendons (the liner stiffness is low). The liner and tendons are still within elastic range.

After point 5 as the result of tearing in tendons, the stiffness of system drops to zero and strains in tendons and liner of membrane area quickly rise and has left approximate pressure limit-0.84 MPa. An indication of approximation to this limit is inconvergence of finite element solution. The ultimate pressure value was obtained using median values for material properties so in further it was considered as median ultimate pressure of global failure of containment.

![Figure 3 Finite element mesh of containment and development of deformed state](image)

- a) prestress in normal operation, b) intermediate state, c) ultimate state
Figure 4 Stress development in containment components at mid-height of cylinder
a) tendons, b) concrete

Figure 5 Parameters of deformed state-a) displacement at the top of the dome b) strain in liner at mid-height of cylinder

Results of finite element analysis were found to be in good correlation with the results of preliminary study.

3D-model of equipment hatch arranged in the bottom of the basemat was developed (see Fig 6) to analyze the local stress-strain state of concrete and liner. Internal pressure, self weight, and static boundary conditions simulate the loads applied to the model. Analysis of results has shown elastic behavior of equipment hatch up to the ultimate containment pressure.

Figure 6 Equipment hatch finite element mesh
3.2 Leakage and penetration analysis.

At this step the liner behavior near large opening (penetrations, airlocks, hatches) and junction points was studied.

Analysis include the following steps:
- evaluation of stress-strain state at discontinuities;
- derivation of ultimate pressure in containment resulting in rupture of liner at discontinuity;
- estimation of leakage rate;
- estimation of pressure value and potential for regime of leakage from containment to stop further pressure increase.

For estimation of stress concentration at discontinuities the methodology of Electric Power Research Institute (EPRI) detailed in the report "Criteria and Guidelines for Predicting of containment leakages" [Ref. 1] was applied. Input data for analysis are results of stress-strained state calculation in the liner away from discontinuities, obtained from axisymmetric finite element model.

The strain concentration factor was applied to global parameters of stress-strain state to take into account distinctive features of strain fields near discontinuities.

The local strain was obtained as

$$\varepsilon_p = K \alpha \beta \varepsilon_{global}$$

(1)

where $K$ is strain concentration factor depending on concentrator $\alpha$ is strain localization factor given for localization of strain peaks based on experiment and analysis results $\beta$ is biaxiality coefficient which take into account biaxial strain state in the liner $\varepsilon_{global}$ is the global strain in characteristic direction for the discontinuity. It is obtained from finite element analysis.

EPRI report contains the data on various strain concentrators based on results of experiment and analysis. These data were used for evaluation of strain concentration.

Evaluations covered various areas of discontinuities including wall-basemat junction, areas of main airlock and other large penetrations. Stress analysis of liner near steam penetration (most stressed region of liner) showed that liner remains elastic during pressure increase up to beginning of plastic tearing in tendons. Plastic tearing in liner starts when plastic deformation in tendons has been developed up to certain value and result in decrease of whole system stiffness.

Thus the liner failure is strongly correlated of capacity of tendons just prior to rupture of containment section. So the failure mode with early leakage of containment and further pressure increase of pressure was not observed.

The ability of the pressure boundary components (penetrations, hatches, sump) to withstand the ultimate pressure was confirmed by deterministic analysis of simplified models.

3.3 Probabilistic analysis

The objective of this part of study was to define parameters of cumulative containment failure probability function depending on internal pressure.

Ultimate pressure of containment failure was assumed to be lognormal distributed random value and ultimate containment pressure of global failure obtained at earlier steps was assumed to be median.

The random value of ultimate pressure may be expressed as

$$\overline{P} = P_m \tilde{\varepsilon}_c$$

(2)

where $P_m$ is median ultimate pressure 0.84 MPa derived at previous studies.

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\( \varepsilon_c \) is lognormal distributed random value with unit median and lognormal standard deviation \( \beta \).

The standard deviation \( \beta = 0.22 \) is estimated based on results of similar studies performed for prestressed concrete containments of Western and U.S. PWR-type reactors with account for expert judgments.

Two sources of variability considered are variability due to imperfection of containment model and small deviation of geometry during on-site construction and variability in mechanical properties of containment components (parameters of concrete failure surface, ultimate and yield strength of rebars, liner and tendons). The composite \( \beta \) value was obtained as square root from sum of squares for each source of variability.

The cumulative probability distribution function for ultimate pressure is given in Fig 7.

![Cumulative failure probability function of pressure](image)

Figure 7 Cumulative failure probability function of pressure

4. CONCLUSION

The model of VVER-1000 containment behavior under severe accident loading was developed in the framework of level 2 PSA for Balakovo NPP unit 4. As the results critical failure mode of containment and qualitative assessment of behavior under accidents with overpressure is determined. Cumulative containment failure probability function of the pressure required for safety assessment of the unit was derived. The study showed that prestressing system of containment is the essential component of the structure which bound capability of containment. In future studies it is planned to estimate the reliability of this system based on on-site information and analysis of statistic over standard units with VVER-1000 reactor.

5. REFERENCES