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# ULTIMATE LOAD CAPACITY OF CONTAINMENT STRUCTURE OF VVER AT KUDANKULAM, INDIA

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## ABSTRACT

Nuclear safety regulations in India require assessment of containment structure for Ultimate Load Capacity (ULC) for internal pressure. The Russian Federation designed VVER 1000 reactor building constructed at Kudankulam (KKNPP) was assessed for ULC of its primary containment. The reactor building consists of a pre-stressed concrete primary containment and a reinforced concrete secondary containment built over a large cellular foundation structure consisting of containment base slab connected to the mat foundation through a number of reinforced concrete cross walls and intermediate slabs. The evaluation was carried out using a numerical model of the complete structure by non-linear Finite Element Method using ABAQUS software. The ULC value was established based on criteria specified in USNRC RG 1.216. The structural response was studied using the patterns observed in deformations, stresses & strains with rise in internal pressure. It is noted that structural response in general areas of the containment is linear till twice the design pressure ($P_d$). The start of yielding of reinforcing bars in the general area of the wall is noted at a pressure of 2.80 $P_d$. The ULC pressure is estimated as 3.0 $P_d$. Based on the study, it is concluded that structural capacity for pressure load of the steel lined pre-stressed concrete containment of KKNPP satisfies the Indian regulatory requirement.

## INTRODUCTION

Atomic Energy Regulatory Board (AERB) is empowered to publish safety codes/standards/guides to ensure nuclear safety in India. AERB safety code on design (AERB/NPP-PHWR/SC/D, 2009) requires the containment to be designed taking into account all identified design basis accident scenarios as the containment structure is the last engineered barrier against release of radioactivity into public domain. In addition, features for mitigating consequences of severe accidents need to be provided. One of the recommendations stemming from this requirement is evaluation of ULC of the containment structure considering pressure load. Elaborating the above requirement, AERB safety guide (AERB/NPP-PHWR/SG/D-21, 2007) requires that the structural integrity of the containment structure including major appurtenances against collapse should be demonstrated by calculating ULC considering both pressure and temperature loads. AERB stipulates that ULC of a containment structure should not be less than the maximum peak pressure calculated for potential severe accidents or two times the design pressure, whichever is higher.

Kudankulam NPP, which is located at Kudankulam village in Tirunelveli district of Tamil Nadu, India, has adopted a double containment philosophy with a pre-stressed concrete inner containment structure and a reinforced concrete outer containment structure, both resting over a cellular raft (foundation system consisting of thick base slab connected to a mat foundation through a number of reinforced concrete cross walls). To arrive at the actual margin over the design pressure, it was necessary to carry out structural analysis to evaluate the ULC of primary containment structure.

The objective of the study is to estimate the ULC of primary containment structure for internal pressure as a part of safety assessment of the containment structure. In addition to ULC, behaviour of containment is evaluated with respect to various parameters termed as performance indicators, such as occurrence of first crack, reinforcement yield, and tendon yield etc., based on defined criteria as per International practices.

Estimation of ULC of primary containment is carried out considering increased internal pressure loads. As the containment structures of KKNPP rest on a cellular foundation system as described above, pressurization of containment hermetic zone cause deformations in the non-hermetic foundation system also. The numerical model was prepared considering this portion also. Besides, the influence of large appurtenances such as air locks on the ULC is also investigated. In the ULC estimation, failure is accounted only in concrete cross-sections of containment and not in steel appurtenances connected to it. Appurtenances are analyzed separately and are estimated to possess higher strength than concrete. Hence failure of concrete cross-sections will precede the failure of these appurtenances.

## CONTAINMENT STRUCTURE OF KKNPP 1&2

KKNPP-1&2 primary containment comprises of a pre-stressed concrete cylindrical structure capped with a hemi-spherical dome. It has a carbon steel liner on the inner surface. It has three leak tight locks, which are the Transport Air Lock (TAL), the Main Air Lock (MAL) and the Emergency Air Lock (EAL) placed on circular openings in the cylindrical wall. TAL opening is the largest; whereas MAL and EAL openings are of the same size.

The primary containment structure along with the associated containment slab forms the hermetic boundary. The basement portion which lies below the containment slab is a non-hermetic zone. This area houses different components of active process safety systems. The non-hermetic basement portion and the containment bottom slab are connected to each other by a number of cross walls and slabs. This structural arrangement leads to a cellular behaviour of the foundation mat- containment base slab system along with vertical cross-walls.

Pre-stressing system of Freyssinet, France is used for the pre-stressing the containment. . Pre-stressing is achieved by using 55C15 type tendons arranged in an orthogonal pattern. 53 horizontal tendons are placed in the cylindrical wall and 15 tendons are placed in dome area. Thickness of containment is uniform 1.2m in cylinder as well as dome portion, whereas the thickness is 1.85m in the pilasters areas where the horizontal tendons are anchored. 60 vertical tendons are placed as inverted U-shape circular in cylinder and in two mutually perpendicular directions in dome. The pre-stressing tendons are deviated around the openings of the three air locks along their trajectories with smooth radii of curvature to avoid high force concentrations near the openings.

Non-hermetic part of the reactor building is a rigid concrete box structure consisting of a bottom reinforced concrete foundation raft, rigid internal cross walls, an intermediate slab, and a reinforced concrete slab which acts as the bottom boundary of the hermetic region. Above this slab, annexe structures are attached to opposite sides of outer containment. Outer/secondary containment (OC) is a reinforced concrete structure capped with a hemi-spherical dome. The rib walls supporting a tertiary dome shaped covering for the Passive Heat Removal System (PHRS) are placed on the outer side of OC dome. These structures and the hemispherical dome of the OC are also of reinforced concrete.

The inner/primary containment is designed for 0.40 MPa accident over pressure which is the design pressure, ($P_d$). The design also considers a test pressure ($P_t$) of 0.46 MPa, which is 15% more than $P_d$ to account for effect of liner thrust on account of temperature load. The containment and its details are described in AERB technical report (2014).

## FINITE ELEMENT MODEL

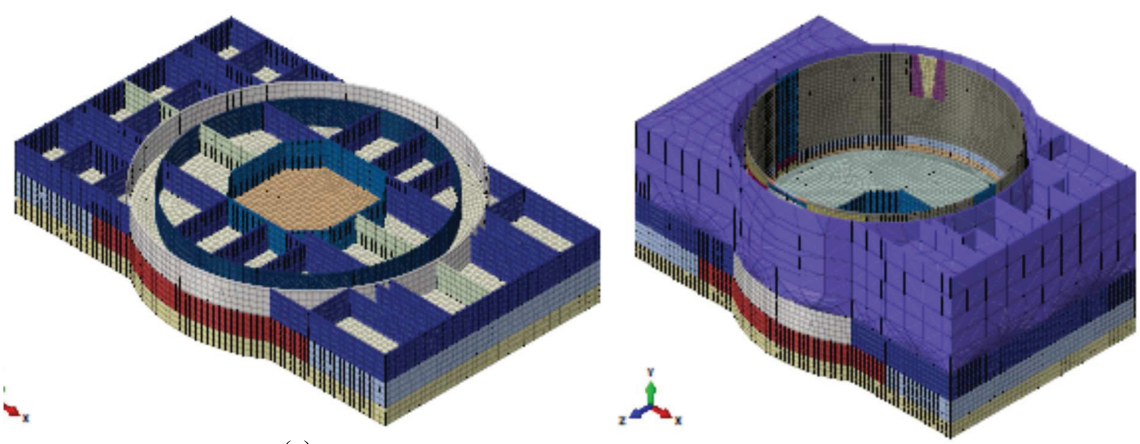
Finite element model used for analysis includes the pre-stressed concrete inner containment, the reinforced concrete outer containment, non-hermetic cellular foundation system, PHRS gallery and annex structures connected to the containment building.

The geometric model of the containment is developed based on gross cross section details taken from design drawings. The containment is modelled as a shell structure along its centre line. The cellular basement of the reactor building, i.e., the non-hermetic region, is also modelled using shell elements along the centre line of slabs and walls. OC wall including dome, PHRS circular gallery and annex parts present on two opposite sides of the outer containment are also integrated into the Finite Element (FE) model. The FE model as well as analysis is done using ABAQUS (2013).

Four node composite layered shell element with reduced integration scheme (S4R) available in ABAQUS is used for finite element discretization of the primary containment structure. Three integration points are selected in the thickness direction of shell elements to capture the progress of concrete damage through the thickness of containment cross section. Element size of 0.75m was adopted for primary containment to capture the structural response. The layered shell element was chosen to optimize the modelling and analysis complexities compared to a 3D solid FE model, while maintaining the overall structural behaviour for ULC estimation.

Apart from two layers (composite layer without any separation) that simulate concrete and the steel liner in the element, the rebar and pre-stressing steel are modelled as embedded steel layers within the concrete element. The embedded layers simulate steel reinforcement and pre-stress steel as smeared steel layers with thickness equal to the ratio of steel area to steel spacing. Profile of pre-stress tendons is modelled based on their layout and relative position in the wall and dome. The deviation of tendons around all major openings is accounted in the model. This has been achieved by portioning the geometry of the containment as per tendon profile and providing average spacing in different zones along the tendon paths.

Basement part of the reactor building is not pre-stressed. The containment base slab is a composite structure with steel liner. Walls and slabs below the base slab are modelled as layered shell with reinforcing bars modelled as embedded steel layers; vide Figure 1(a). Outer containment wall and base slab extension in the annexe parts of the building are modelled using elastic shell elements, vide Figure 1(b). The material properties of these items are defined such that only the stiffness contributions of these portions are accounted in the analysis.

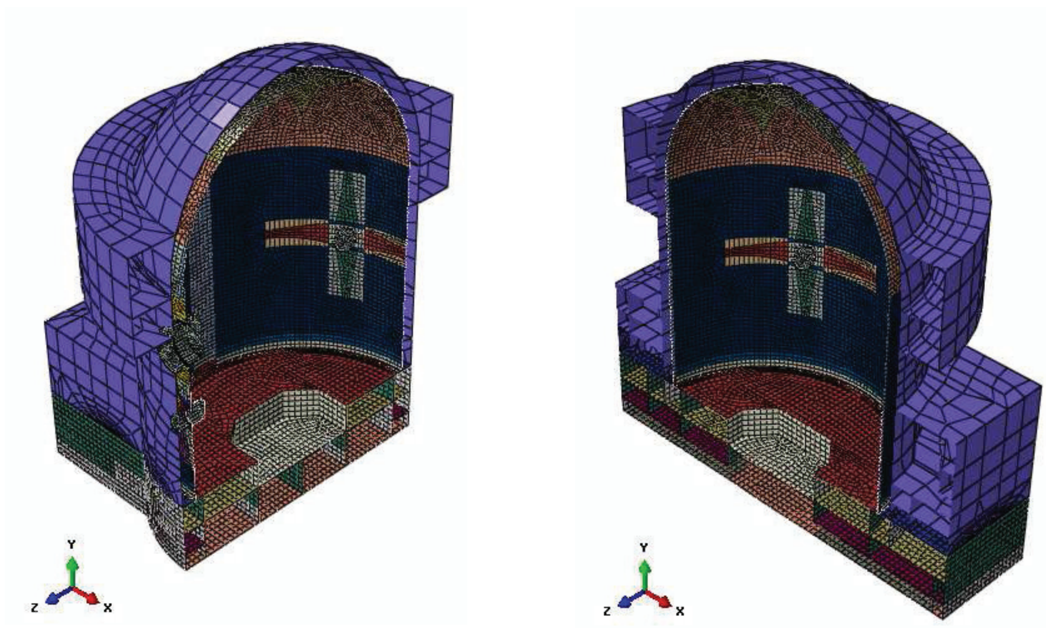


(a) (b)

Figure 1. FE Model of KKNPP containment (a) basement region and (b) annexe portions with outer containment

The three major air lock openings, i.e., TAL, MAL and EAL are included in the model. Embedded Parts (EP) around the openings are modelled using shell elements and are connected to surrounding elements by tie constraint. These EPs are considered to behave elastically irrespective of containment pressure. Airlock closures are tied to the containment structure to make all the active degrees of freedom equal for these pair of surfaces and thus accounts for load transfer between the wall and the closures when internal pressure is applied on the surface of the closures.

To accommodate the differences in section properties such as value of section thickness, rebar and pre-stress steel areas/rebar spacing in the FE model, a total of 64 cross sections are defined and locations having same section properties are grouped together. A total of 80 different regions/zones have been developed in the FE model. The containment structure is monolithically connected to the top of the hermetic slab. Outer containment and annex parts of the building are modelled using a single section property and hence are assigned to a single zone/region. Brief illustration, sectional view of the different regions and FE model of the reactor building is indicated in Figure 2.




(a) (b)

Figure 2. Finite Element Model of KKNPP containment (a) section through shorter axis, (b) section through longer axis, i.e. through annex buildings

## MATERIAL CONSTITUTIVE MODELS

Concrete Damage Plasticity (CDP) model [ABAQUS (2012)] is used to model concrete material behaviour, whereas metal plasticity models are used for the steel liner, steel rebars and pre-stressing steel.

### *Concrete*

The basic properties of concrete that are adopted for the simulation are furnished in Table-1. The main failure mechanisms assumed in the CDP model are tensile cracking and compressive crushing of the concrete material. The inelastic region of the stress-strain curve in compression is derived using equations of the Hsu & Hsu model as reported by Wahalathantri, B. L. et al (2011), which is capable of simulating non-linear behaviour of reinforced concrete elements. This model provides stress-strain relationship under uni-axial compression. A linear stress-strain relationship is assumed up to 50% of the ultimate compressive strength ($\sigma_{cu}$) in the ascending portion. For concrete stress-strain relation in tension, linear softening is assumed from peak tensile capacity to its 10% value for a strain of 0.1%. This is modified version of model proposed by Wahalathantri, B. L. et al (2011), where tri-linear softening curve is modified as linear. This tension model of concrete keeps the post-crack energy minimum to minimize its influence in ULC. The stress-strain curves for concrete in compression and tension derived using these models are given in Figure-2.

**Table-1: Basic properties of concrete**

| Property of concrete | Hermetic region | Non-hermetic region (basement) |
|---|---|---|
| Cube compressive strength (MPa) | 50 | 30 |
| Modulus of elasticity (Pa) | $3.9 \times 10^{10}$ | $2.3 \times 10^{10}$ |
| Poisson's ratio | 0.2 | 0.2 |
| Split tensile strength (MPa) | 3.48 | 2.73 |

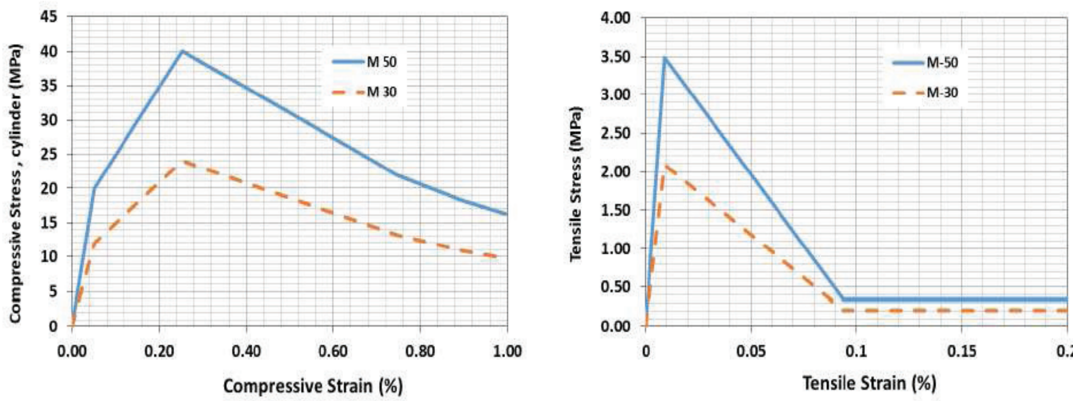



Figure 3. Stress-Strain curve of concrete in compression and tension for hermetic and non-hermetic regions of the model

***Steel***

Metal plasticity model has been used to simulate non-linear material property for the pre-stressing steel, reinforcing bars and liner. Steel grade Fe500 ($f_y$= 500MPa) is used as reinforcing steel and steel with breaking stress of 1.86 GPa is used as pre-stressing steel. Carbon steel having yield strength of 240 MPa is used as the hermetic steel liner material.

**BOUNDARY CONDITIONS**

For KKNPP, the hermetic containment rests on the non-hermetic supporting structures. The outer containment and annex structures of reactor building are also interconnected to the hermetic containment. The entire structural system rests on the foundation mat supported on soil/rock foundation medium. The entire structural system is modelled in the study. The soil/rock foundation medium is represented by spring elements modelled at the bottom of raft to simulate soil-structure interaction. Translational tension-compression soil springs are assumed in three orthogonal directions. The spring constants are used as reported in AERB technical report (2014). The airlocks and closures for the air locks are modelled separately and connected using tie constraint to the containment structure.

**LOADING**

Permanent loads acting on the containment are the dead load and pre-stressing load. Additionally, rise in internal pressure occurs during accident conditions. Static non-linear analysis for estimation of ULC is carried out using three load steps. Pre-stressing load is applied in the 1st load step as an initial stress in the tendons. Pre-stressing load is considered after accounting for all losses for a containment design life of 40 years. Different effective pre-stress forces are estimated and applied in hoop as well as meridian direction and applied accordingly. Dead load on account of self-weight including super imposed load on account of internal structures is applied in the 2nd load step and internal pressure load is applied in the 3rd load step. Internal pressure load is applied in smaller sub-steps and increased linearly till failure criteria for ULC is reached.

## ASSUMPTIONS IN THE FE MODEL

Following assumptions are made in the present study:

a) As shell element FE model is adopted, shear reinforcement placed across the concrete section could not be accounted. However, its effect on ULC is not expected to be significant as the failure is governed mainly by direct tension.
b) Individual pre-stressing tendons are not modeled; they are idealized as smeared layers based on their spacing and position from centre line of the containment cross section thickness. Therefore, variation of pre-stress force in each tendon cannot be accounted and thus average pre-stressing force in typical hoop and meridian type is used as input for modelling the pre-stressing loads.
c) Liner is considered integrally attached to the concrete section.

## FAILURE CRITERIA

ULC is defined as a measure of safety margin above the design pressure, $P_d$. As per USNRC Standard Review Plan (SRP) 3.8.1, NUREG-800 (2013), which refers to USNRC RG-1.216 (2010), for cylindrical pre-stressed concrete containments, the pressure capacity may be estimated based on satisfying both of the following strain limits: (a) a total tensile average strain in tendons away from discontinuities (e.g., hoop tendons in a cylinder) of 0.8 %, which includes the strains in the tendons before pressurization and the additional straining from pressurization; and (b) a global free-field strain for the other materials that contribute to resist the internal pressure (i.e., steel liner, if considered, and reinforcing bars) of 0.4 %. In the present study, hoop strain in reinforcement and liner will be same due to strain compatibility resulting from the assumption of integral behaviour. Also, the liner is not designed to function as a pressure resisting member but to ensure leak tightness. Hence ultimate capacity will be estimated considering the pressure at which both the criteria, i.e., (a) total strain in hoop pre-stressing tendon away from discontinuities reach 0.8% and (b) a global free-field strain for hoop rebar reaches 0.4%.

## RESULTS AND DISCUSSIONS

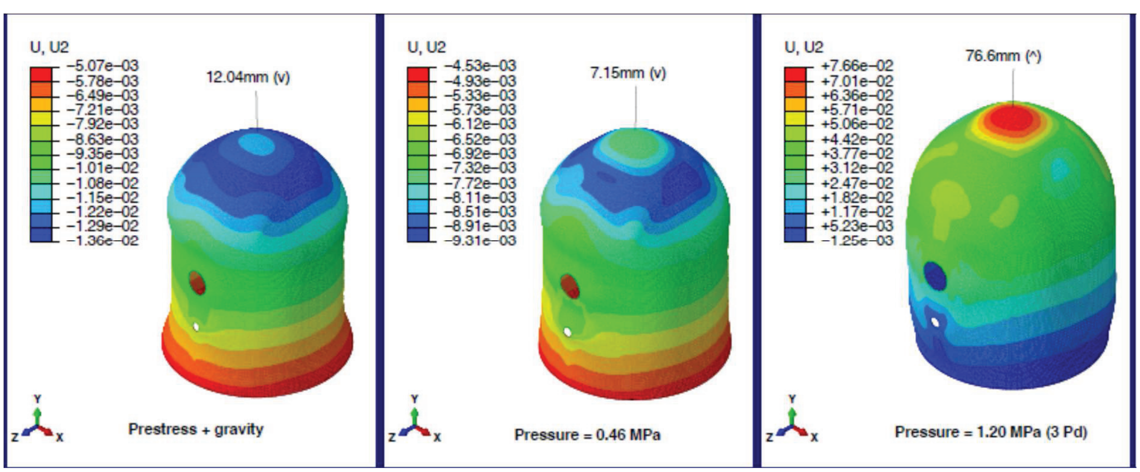



Figure 4. Vertical deformation contours of containment at different pressure load steps

Vertical displacement at crown of the dome has been plotted over the range of applied pressure. The dome crown undergoes a downward deflection of 12.04 mm due to application of pre-stress and gravity loads. Under internal pressure of 0.46 MPa (which is the test pressure), the vertical deflection of dome crown is noted to be 7.15mm in downward direction. This indicates that the upward deflection due to internal pressure of 0.46 MPa is 4.89mm. This value is comparable to 5.0mm deflection measured at the dome crown during pre-commissioning containment test of KKNPP - 1. At pressure of $3.0P_d$, the upward deflection observed at dome crown is 76.6mm. Figure 4 shows the contour plots of vertical deformation of containment structure alone at different pressure load steps.

***Performance Indicators in Hermetic Region (Containment)***

To have a global perspective on the performance of the structure, pressures corresponding to important changes in structural behaviour are represented through performance indicators. Table 2 shows the key performance indicators in hermetic region.

**Table 2: Performance indicators in hermetic region (containment)**

| **Performance Indicators** | **Pressure at Milestone, ($P_d$)** |
|---|---|
| Neutralization of pre-stress force in Cylinder | 1.47 |
| Neutralization of pre-stress force in Dome | 2.00 |
| Rebar yielding in general area | 2.80 |
| Rebar yielding at discontinuity (near opening) | 2.50 |
| Yielding of pre-stressing tendon in general area | 3.00 |
| Yielding of pre-stressing tendon at discontinuity | 2.50 |
| Initiation of liner yield in general area | 2.50 |
| Initiation of liner yield at discontinuity | 2.00 |

***Performance Indicators in Non-Hermetic Region (Basement)***

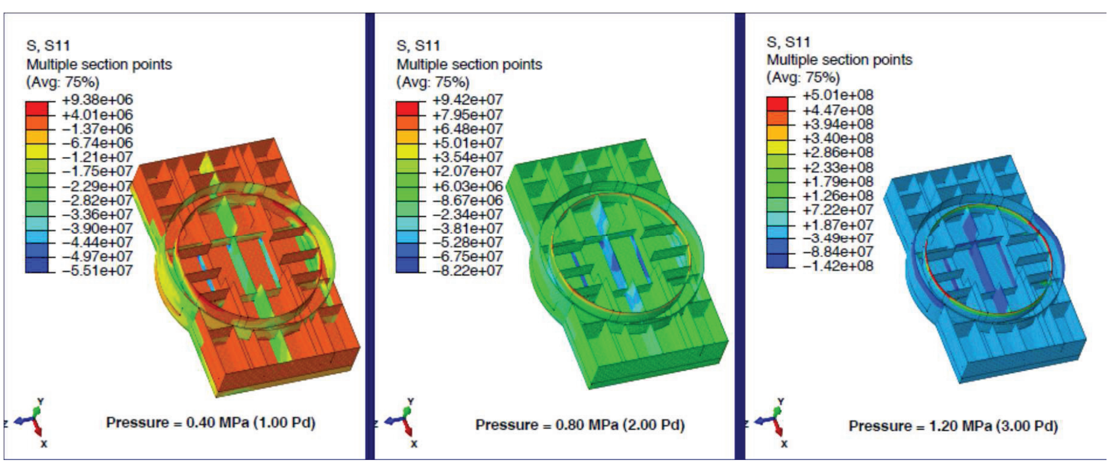



Figure 5. Stress contour of horizontal reinforcing bars of non-hermetic/basement walls at different factors above design pressures $P_d$

The main objective is to assess the structural integrity of basement with respect to containment failure. No significant rebar yielding in basement slab is observed, whereas rebar yielding is initiated in inner wall of stressing gallery at onset of containment failure. Figure 5 depicts the stress contours of rebars in non-hermetic walls.

***Ultimate load capacity of containment***

Deflection pattern of the containment at MAL and in general area for different pressure load steps are plotted in Figure 6. The maximum radial deformation (~220mm) is observed near MAL during onset of containment failure ($3.0P_d$) based on strain limit in hoop pre-stressing tendon. Therefore, probable failure location could be near MAL.

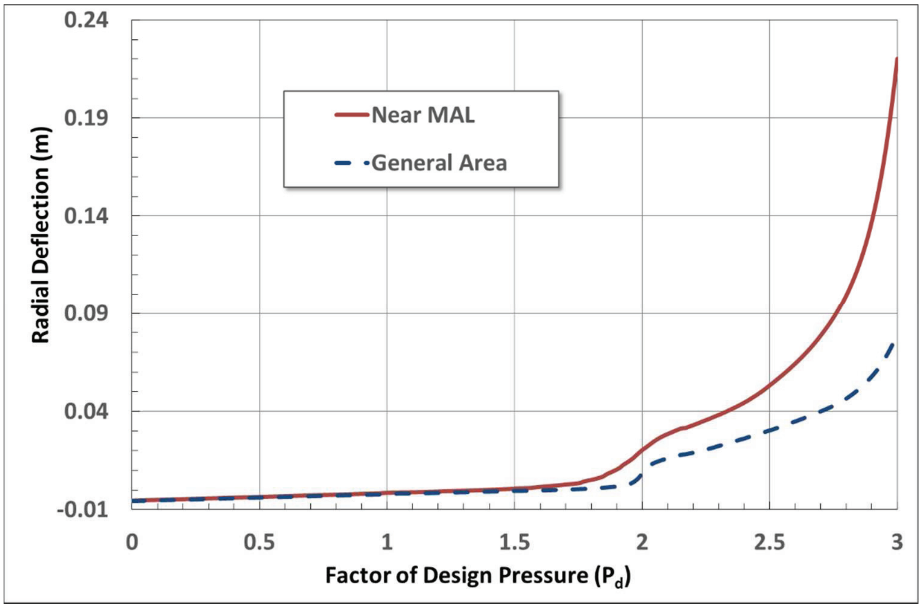



Figure 6. Deflection near MAL and in general area for different factored values of $P_d$

ULC of containment is defined based on the criteria as explained in previous section. Pressure corresponding to 0.8 % total strain in hoop pre-stressing tendon away from discontinuities is around 2.90 $P_d$ and the pressure corresponding to hoop rebar attaining a strain of 0.4 % in the same area is 3.00 $P_d$. Variation of strains in tendons and rebars in general area are illustrated in Figure 7.

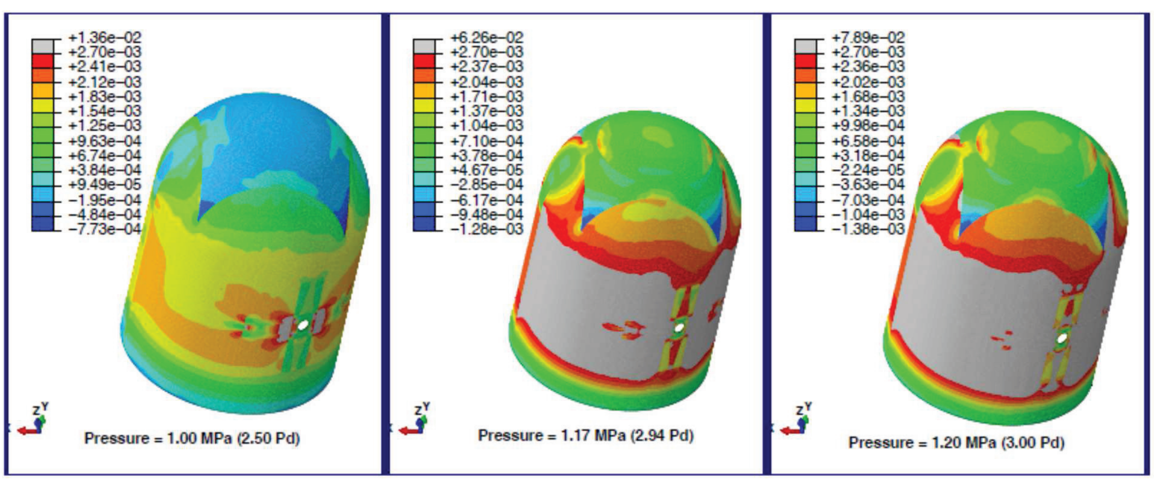



Figure 7. Strain contour in hoop pre-stressing tendons at different factors of design pressure $P_d$

Therefore, based on the criteria defined in USNRC RG 1.216, the ULC of containment is 3.0 $P_d$. Figure 8 highlights the general area where the failure criteria are reached. Failure initiates around the MAL and progresses towards the buttress zone.

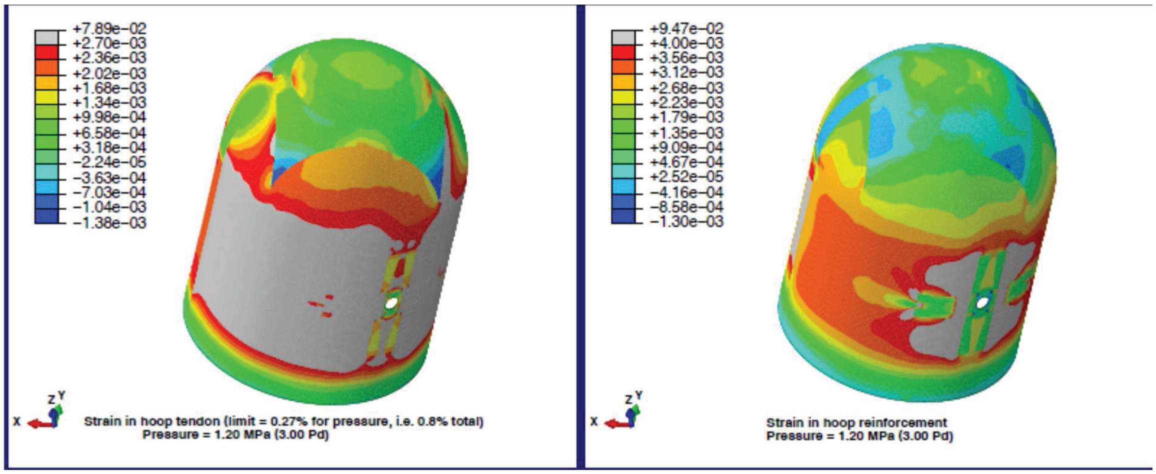



Figure 8. ULC of containment considering both the criteria for pre-stressing tendons and rebars

## CONCLUSION

Evaluation of ULC of containment structure of KKNPP-1&2 was under taken by AERB as part of its regulatory review and safety assessment. Evaluation is carried out for internal pressure load only. In addition to ULC for pressure load, behaviour of containment is evaluated with respect to various performance indicators based on defined criteria. Non-linear FE analysis of the containment structure was carried out considering non-linear material properties of concrete and steel using ABAQUS software. Pre-stressing tendons and rebar steel were modelled as embedded layers. The steel liner was modelled as an integral layer at the inner face of the concrete section.

The behaviour of containment is noted to be on expected lines as evaluated from deformation, stress and strain results. Neutralization of hoop compression in general area of the cylinder occurs at an internal pressure of 1.47 $P_d$ and in dome area at about 2.0 $P_d$. Linear structural response in general area is observed until the pressure is about 2.0 $P_d$. ULC is defined as a measure of safety margin above the design pressure, $P_d$. ULC of containment estimated based on RG 1.216 criteria is reported in earlier section. ULC pressure based on the criteria defined in RG 1.216 (2010) works out to be 3.0 $P_d$.

Containment structure of KKNPP is connected to a cellular basement forming part of the foundation of the reactor building. Pressurization of the primary containment causes deformations in the foundation portion below the containment base slab. In order to study this effect, the ULC analysis considers an integrated model of the reactor building which includes the hermetic containment, non-hermetic supporting structures, outer containment and annex structures of reactor building resting on the foundation mat supported on soil/rock strata which are represented as soil springs in the model. It is observed that the presence of basement does not significantly influence the behaviour of containment structure and reinforcing bars of slabs and walls of basement do not yield before failure of containment.

Based on results of the present study to evaluate the ULC of primary containment of KKNPP, it is concluded that the structural integrity against collapse of the steel lined pre-stressed concrete containment satisfies the requirement of 2.0 $P_d$ specified by AERB.

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