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Assessment of ultimate load capacity of inner containment for Indian PHWRs

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ABSTRACT: The adequacy of Indian PHWR containment design to withstand severe accident loads through a finite element software ULCA is demonstrated before the model test may be taken up. The test is aimed to validate the software for ultimate load capacity evaluation. This will bridge the gap between theoretical prediction and experimental demonstration.

1 INTRODUCTION

Public acceptance of a nuclear power programme can be improved by providing assurance for all possible perceived risk concerns. Improvement in engineered safety features and demonstration of safe technology based on probabilistic approach have not fully overcome the psychological barrier in the minds of public. Conclusions based on comprehensive research and development programme on nuclear reactor containments could be one area of meaningful assurance to public with regard to safety even in a beyond design basis accident. A reactor containment is the ultimate physical barrier to prevent the release of radioactive material from reactor core to environment in case of design basis and severe accidents. Hence its ultimate load carrying capacity must be evaluated analytically and accuracy of this prediction must be demonstrated experimentally.

Indian Pressurised Heavy Water Reactors (PHWRs) of 220 MWe and 500 MWe design have some inherrent safety features with large volume of containment, low volumetric power density, low temperature heat sink, low excess reactivity and long prompt neutron life time. Hence global threat to containment is not likely even for many postulated accidents under severe accident category. A research and development programme is under way in India to determine the ultimate structural capacity of PHWR containments by analysis and verify the results by experiment. In this programme participation from national laboratories and academic institutes has also been encouraged.

The PHWR containment is designed to cope up with a design pressure which is the maximum pressure arising from either a main steam line break (MSLB) or loss of coolant accident

(LOCA). Main functional requirements of containment under the above design basis accident (DBA) is to achieve the following:

Complete isolation of plant from external atmosphere
Minimise ground level leakage to zero
Provide radiation shielding
Eliminate active components in so far as working of energy management feature is concerned.

The above safety and reliability goals of PHWR system have been arrived by defence in depth approach at various levels with sound design, high quality construction and provision of effective systems to mitigate the consequences of DBA. However the demand for higher standards of safety has emerged in PHWR design specially after TMI-2 and Chernobyl accidents. Safety related studies and management of severe accident constitute part of the defence in depth concept to maintain the safety of a PHWR plant and to protect the public and plant workers from exposure to radioactivities resulting from severe accidents.

The containment design in PHWR systems meets the requirement of prestressed reactor vessel design as per ASME Section III Division 2 and a factor of safety of 2 on design pressure is ensured. In the case of severe accidents where loading on the containment may exceed even above margin, the containment functional performance is required to achieve the following:

Through thickness cracking in membrane region with a slow and gradual burst kind of failure mode such that structural integrity of containment is maintained and leak before break is demonstrated.

Relatively larger time spans to limit the consequences compared to time required for containment pressure build up and release of radioactivity within containment atmosphere. This will enable the engineered safety systems or natural deposition process to bring down the level of radiological consequences to a lower level. Also a shielding cover of containment is retained.

Minimise the leakage at ground level and accidental release is completely ruled out which is likely to pose a global threat.

In the present programme a finite element software ULCA (Ultimate Load Capacity Assessment) is developed which is in use to establish the margin against burst type of failure. This code will be used to compare the experimental model test results and all the possible failure modes and constitutive laws applicable for prestressed and reinforced concrete containment will be validated on the model. With this excercise the ultimate load capacity of protoype containments can be predicted analytically with higher confidence. The present paper describes some salient features of code ULCA and an analyis is presented for a typical PHWR inner prestressed concrete containment. These pretest results demonstrate the adequacy of containment design to mitigate the consequences of severe accidents.

2. FEATURES OF FINITE ELEMENT CODE ULCA

A three dimensional finite element computer code ULCA (Ultimate Load Capacity Assessment) was developed under this programme. In order to estimate the ultimate load capacity the geometric and material nonlinearity of global concrete structure and elastoplastic behaviour of steel tendons must be accounted. The present finite element code ULCA adopts degenerate concept of formulating general isoparametric shell elements using selective integration scheme based on the concepts developed by Hinton et al 1985. In this code a layered approach with single mid point integration scheme is adopted for each layer which takes into account the nonlinear stress profile in thickness direction and the material properties may be modelled as discontinuous function of thickness. This layered approach has been used to represent the different concrete layers, thus it is possible to simulate progressive cracking through the shell thickness. The reinforcing steel is represented as a smeared layer of equivalent thickness with uniaxial strength and rigidity, thus global anisotropic behaviour of shell and material nonlinearity in steel tendons is accounted. Various constitutive material models are employed to represent compressive behaviour. A dual criteria for yielding and crushing in terms of stresses and strains is considered which is complemented with a tension cut off representation. Pre stressing loads due to steel rebars is taken care as initial stress in form of concentrated load, body weight or equivalent pressure load.

The tensile behaviour of concrete is an important aspect for containment ultimate load capacity evaluation. This is investigated through smeared crack representation in finite element model. The response of concrete under tensile stresses is assumed to be linear elastic until the fracture surface is reached. Cracks are assumed to form in planes perpendicular to the direction of maximum principal tensile stress as soon as the stress reaches the specified concrete tensile strength. Due to bond effect cracked concrete carries between cracks a certain amount of tensile force normal to the cracked plane. The concrete adheres to the reinforcing bars and contributes to the overall stiffness of structure. The tension stiffening parameters generated experimentally in terms of ficticious elasticity modulus and maximum strain sustainable in tension is used in the present code. The details of the formulation and code validation are given by Gupta et al [1993].

3. PHWR CONTAINMENT STRUCTURAL FEATURES

PHWR containment design (fig. 1) is based on double containment philosophy. The inner containment wall (ICW) and roof slab are of pre stressed concrete which have the primary load resisting and containment function in case of accidental release of radioactive mixture of air/steam at high pressure and temperature. The outer containment is of reinforced concrete which completely encloses the inner containment forming an annular secondary space. Any radioactive leakage passing through the inner containment is trapped in this annular space and is pumped out to pass through the scrubbers before being released to atmosphere in a controlled manner. The annular space is permanently maintained at negative pressure in order to completely eliminate the net direct leakage to out side. The design pressure for inner containment is 122.625 kPa and design pressure of outer containment is 6.867 kPa. The outer containment wall (OCW) has a ultimate load capacity of 46.7 kPa as demonstrated in an earlier SMiRT paper by Singh et al [1993]. In this paper we present our results of analysis for inner containment and an ultimate load capacity of 282.04 kPa (2.3 times DBA pressure) is demonstrated. In view of the double barrier and structural failure of both ICW and OCW in membrane region catastrophic failure is not expected in case of severe accident. Moreover the response of both ICW and OCW will be gradual and structural integrity of both walls will be maintained. Thus it is ensured that leakage to ground level will be limited to the minimum extent.

4. ULTIMATE LOAD CAPACITY EVALUATION

A typical PHWR inner containment is analysed for its ultimate load carrying capacity. The general cross section of containment is shown in fig.1. The inner diameter of ICW is 39.62m. The ICW is generally 0.61m thick. The annular gap between ICW and OCW is 2.0m wide with OCW of 0.61m thickness. The outer diameter of containment is thus 46.06m. Both the walls are connected to the base raft at El - 87.3m. The finished ground level is at El -100.0m. The soffit of inner containment is roofed over by containment slab of total thickness of 2.75 m which also forms floor slab for steam generators at El-126.28 m. The containment slab is grid slab having bottom slab as prestressed concrete and top slab as reinforced concrete. The top slab is connected with bottom slab with ribs spanning in two directions. For bottom slab M35 grade of concrete is used and for top slab and webs M 20 grade concrete is used. The containment slab is connected to ICW and OCW. The OCW continues up to El 146.87m from where outer dome springs up reaching elevation 154.615 m. The outer dome is 130 mm thick. The aim of this analysis is to predict ultimate pressure for inner containment wall which is prestressed. As in the present work the emphasis is on global analysis hence no openings have been modelled. Detailed local analyses to ensure integrity near openings such as main air lock and piping penetrations is planned to be studied separately. In the present model the cellular slab is represented with only bottom prestressed slab with a prestress load of 100 T/m in radial direction.The aim here is to check the IC wall ultimate load capacity. It is shown by preliminary calculations that roof slab remains within elastic limit for a large pressure and ICW is designed to burst in gradual manner. Hence this assumption in modelling is justified. However a separate detail study has been planned to check the effect of discontinuity region between ICW and roof slab on the ultimate load capacity in a more realistic manner. The ICW is divided into six concrete layers and reinforcement is modelled with four smeared steel layers. The ICW is prestressed and the prestressing axial bars are anchored at the base raft. The reinforcement in ICW is uniform from El- 100.0 to El- 123.48m. Thus four smeared steel layers are outer and inner face hoop and longitudinal bars respectively. The base of ICW consists of heavy reinforcement upto EL- 87.6m. The prestressing load through axial tendons in ICW is 120 Tons per cable which are spaced 0.75 m c/c along ICW perimeter. The hoop tendons have a capacity of 200 Tons and are spaced at 0.27 m c/c along the height and are anchored at stressing ribs.

The analysis is carried out by incrementing load gradually. In the first step prestress load is applied and the resulting stresses are stored as initial stress for further analysis. The resulting stress pattern for pre stress load is shown in figs. 2-4. Subsequently internal pressure load is incremented in gradual manner to check the ultimate load capacity. Figs. 5-7 shows the stress pattern in concrete and steel layers at p (design pressure due to DBA). Stress pattern at two times design pressure (2p) is shown in fig. 8-10.Subsequent stress patterns at 2.1p, 2.2p and ultimate pressure 2.3 p are shown in figs. 11-19.

The containment performance in DBA case and severe accident case is described in a chronological manner in table 1 which is self explanatory. It may be noted that servicibility criteria of inner containment is maintained at twice the DBA pressure. Cracking starts at 2.1 p and pressure relief to annular volume will be initiated. Even in case of station black out condition when the vacuum in the annular space is not available the radioactive products will be deposited in this space as OCW ultimate pressure is 46.7 KPa as demonstrated by Singh et al[1993]. The structural integrity of ICW is maintained up to 2.3 times DBA pressure and failure is in membrane region. The load deflection curve in membrane region is shown in fig. 20 and deflection profile along height at ultimate load (2.3 DBA pressure) is shown in fig 21 which shows that failure is gradual.

5 CONCLUSIONS

The 220 MWe Indian PHWR containment design is capable of withstanding severe accident loads and even under worst postulated hypothetical circumstances the two shielding covers of inner containment and outer containment are available to limit the exposure to plant personnel and public. Further work to evaluate the containment design near opening is under progress to establish the margins through local and global analyses.These pre test results will be verified in a 1:8 size model experiment for new 500 MWe PHWR containment design and computer code ULCA will be validated to predict the ultimate load capacity of new PHWR and Advanced Heavy Water Reactor containments with higher confidence levels.

REFERENCES

1. Hinton E., Owen DRJ (1985) 'Finite Element Software for Plates and Shells' -Pineridge Press Limited, UK.

2. Gupta A., Singh R.K., Kushwaha H.S., Mahajan S.C., Kakodkar A.,(1993)'Ultimate Load Capacity Assessment of Reinforced Concrete Shell Structures, BARC/1993/E/036 - BARC Report.

3. Singh R.K., Gupta A., Kushwaha H.S., Mahajan S.C., and Kakodkar A. (1993) 'Ultimate Load Capacity Assessment of Indian PHWRs - Some Pre Test Results'. U02/5 SMiRT XII Conf., Stuttgart, Elsevier Publishers, Amsterdam.

TABLE-1

Containment Performance in Design Basis and Severe Accidents

Load Case	Observations	Comments
1)Prestress Load (po) (figs.2-4)	Stresses within elastic limit. At base wall junction in outer cover surface cracks appear due to discontntinuity. No cracking or yielding of concrete or steel noticed at ICW slab junction.	Servicibility criteria is met as cover cracks at base wall junction are of initial flaw size which are taken care by epoxy paint for leakage control.
2) Prestress Load (po) + design basis accident pressure (p) (figs.5-7)	Stresses within elastic limit. Compressive stresses in concrete and steel in membrane region retained. Surface cracks at base wall junction due to po remain stable.	Servicibility criteria is met.
3) po + 1.2p	Stresses within elastic limit. Compressive stresses in concrete in membrane region. Axial tendons under minor tension, hoop tendons remain in compression surface cracks at base wall junction due to po remain stable.	Servicibility criteria is met.
4) po + 1.4p	Stresses within elastic limit. Axial membrane stresses tensile and hoop membrane almost becomes zero in concrete. Hoop tendons remain under small compression and axial tendons show minor tension. Surface cracks at base wall junction due to po remain stable.	Servicibility criteria is met.
5) po + 1.6p	Stresses within elastic limit. Concrete and steel membrane stresses become tensile. Surface cracks at base wall junction due to po. close due to opposite nature of discontinuity stresses. No crack noticed in other regions.	Servicibility criteria is met.
6) po + 1.8p	Stresses within elastic limit. Concrete and steel membrane stresses are tensile. No cracks noticed.	Servicibility criteria is met.

7) po + 2p (fig. 8-10)	Stresses within elastic limit. Concrete and steel membrane stresses are tensile. Surface cracks in outer cover of ICW noticed between EL-120.98m to EL-118.75m at ICW slab junction.	Since crack initiation in cover is on outer layer of ICW and slab junction, servicibility criteria is met.
8) po + 2.1p (fig. 11-13)	More cracks appear at slab ICW junction and some of the cracks extend to core region. Between EL-118.75m to EL-95.60 m all layers of concrete crack. Below this level between EL-95.60m and 89.90m cover and a part of concrete core cracks. At base wall junction new surface cracks appear at inner cover of concrete. No yielding in rebars is noticed. Structural integrity is maintained.	Leakage rate to annulus between primary and secondary containment will be more than the specified value of 0.1% per hr. However increased ground level activity will give early warning to plant personnel. Pressure reduction in primary containment will be initiated.
9) po + 2.2p (fig. 14-16)	Hoop concrete stresses in membrane region are fully relaxed. Local dilation causes bending axial stresses in concrete and steel. Hoop tendons carry full tension load and minor yielding is initiated in these rebars in membrane region. New cracks in inner cover and core region noticed at ICW and slab junction between EL-124.09m to 120.98m. Inner cover surface cracks at base wall junction remain stable. Structural integrity is maintained.	Due to through thickness cracks in entire membrane region leakage from primary containment to secondary containment will result in pressure relief. This permits some time for fission products to plate out.
10) po + 2.3p (fig. 17-19)	The numerical model shows compressive axial and hoop membrane stresses in concrete. Axial tendons show bending behaviour with small tension yielding. Hoop tendons show significant yielding in membrane tension, (but within ultimate tensile strength of steel) small yielding in axial rebars noticed in slab and ICW junction along with on set of compressive plastic deformation in concrete at this location. Structural integrity is maintained.	The failure mode demonstrates significant leak before break. The structural integrity of primary containment is maintained which will act as shielding cover.

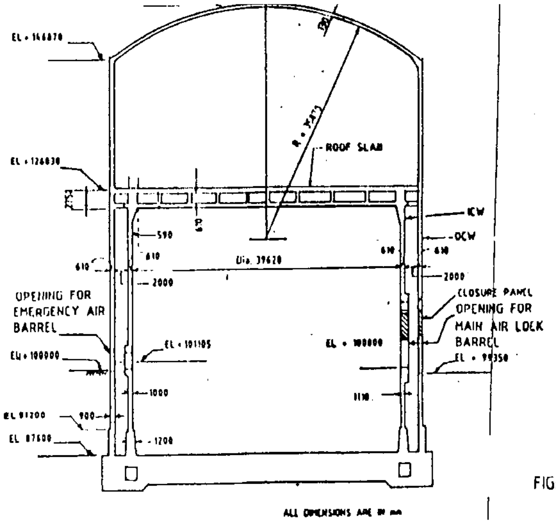


FIG: 1 220 MWe INDIAN PHWR CONTAINMENT SCHEMATIC

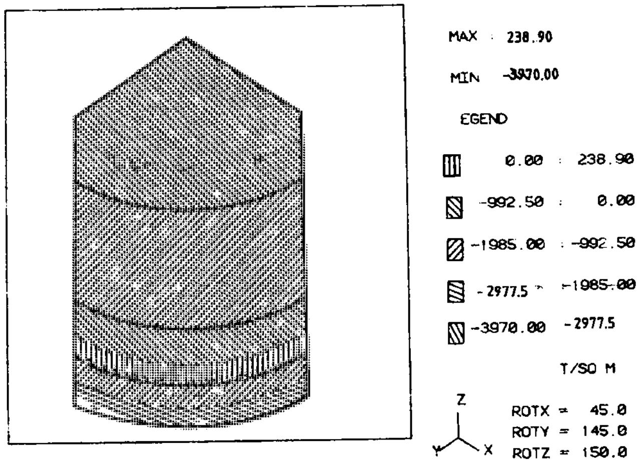


FIG:4 PHWR ICW.STEEL HOOP STRESS (TOP LAYER) AT PRESTRESS(Po)

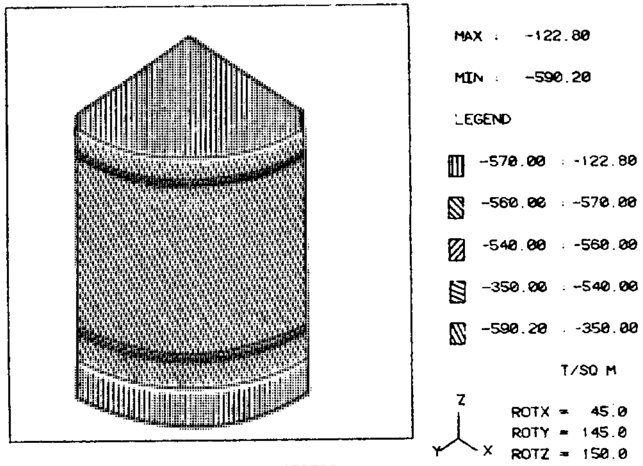


FIG:2 PHWR ICW.CONCRETE HOOP STRESS (TOP LAYER) AT PRESTRESS(Po)

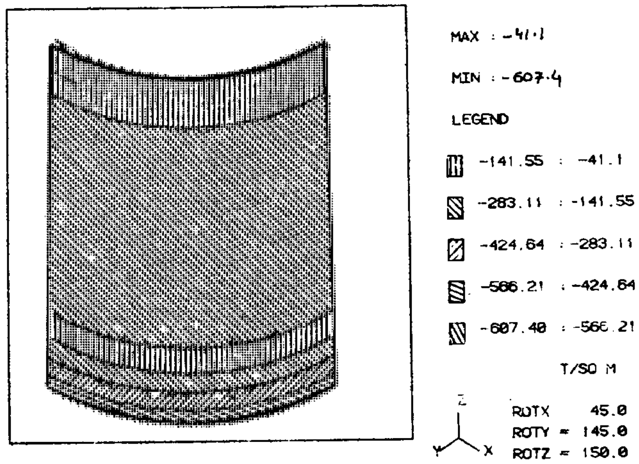


FIG:3 PHWR ICW.CONCRETE AXIAL STRESS (TOP LAYER) AT PRESTRESS (Po)

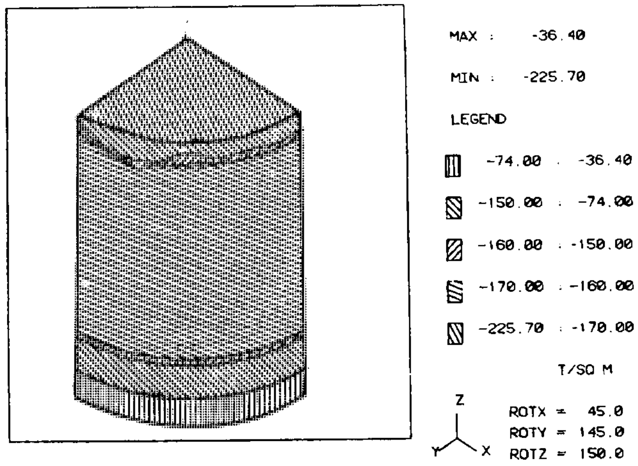


FIG:5 PHWR ICW.CONCRETE HOOP STRESS (TOP LAYER) AT Po + P(DBA)

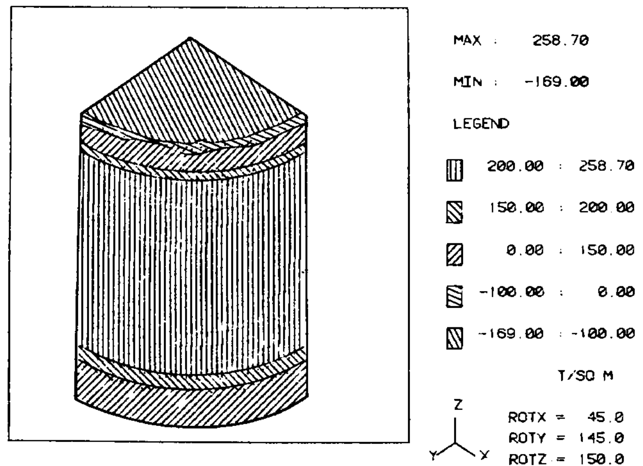


FIG:8 PHWR ICW.CONCRETE HOOP STRESS (TOP LAYER) AT Po + 2P(DBA)

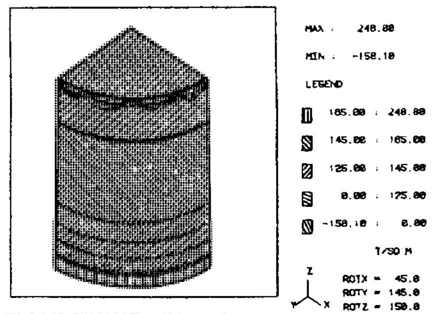


FIG:9 PHWR ICW.CONCRETE AXIAL STRESS (TOP LAYER) AT Po + 2P(DBA)

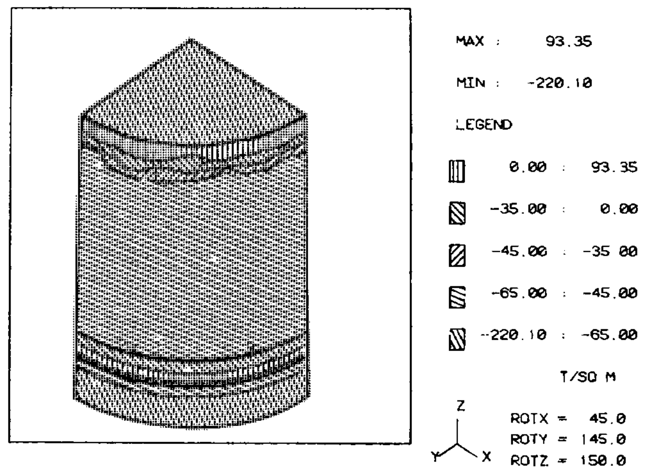


FIG:6 PHWR ICW.CONCRETE AXIAL STRESS (TOP LAYER) AT Po + P(DBA)

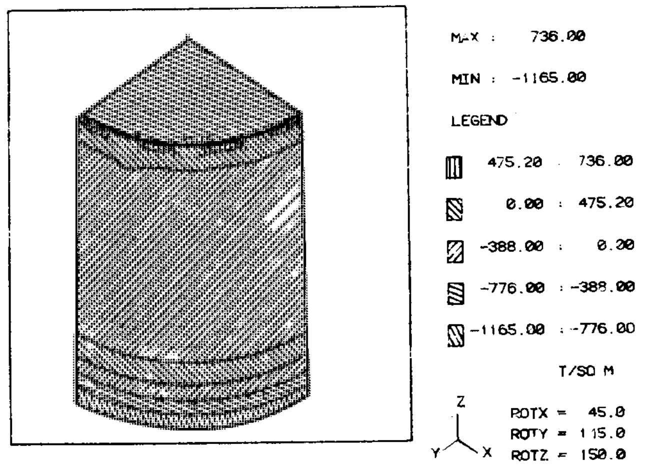


FIG:7 PHWR ICW.STEEL HOOP STRESS (TOP LAYER) AT Po + P(DBA)

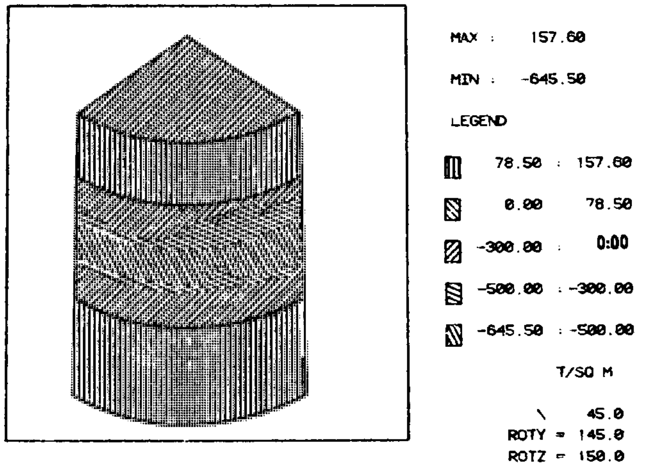


FIG:12 PHWR ICW.CONCRETE AXIAL STRESS (TOP LAYER) AT Po + 2.2P(DBA)

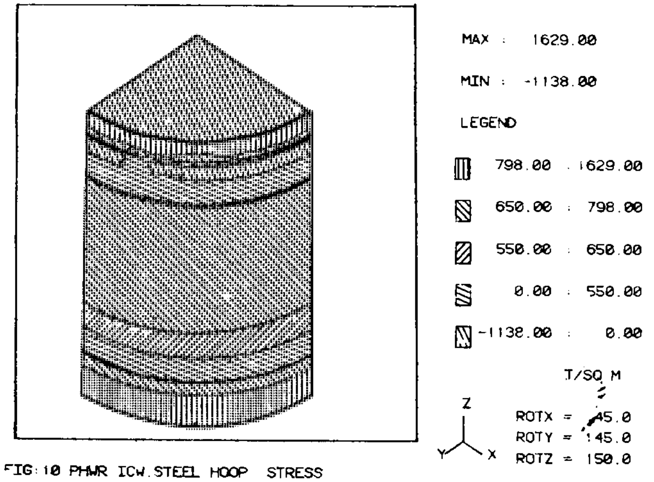


FIG:10 PHWR ICW.STEEL HOOP STRESS (TOP LAYER) AT Po + 2P(DBA)

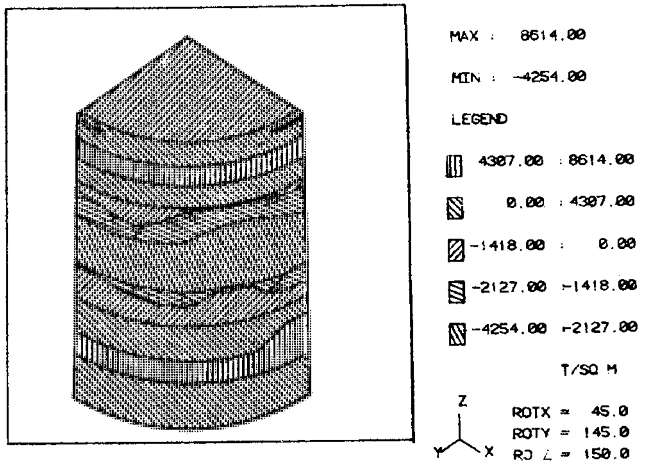


FIG:13 PHWR ICW.STEEL HOOP STRESS (TOP LAYER) AT Po + 2.2P(DBA)

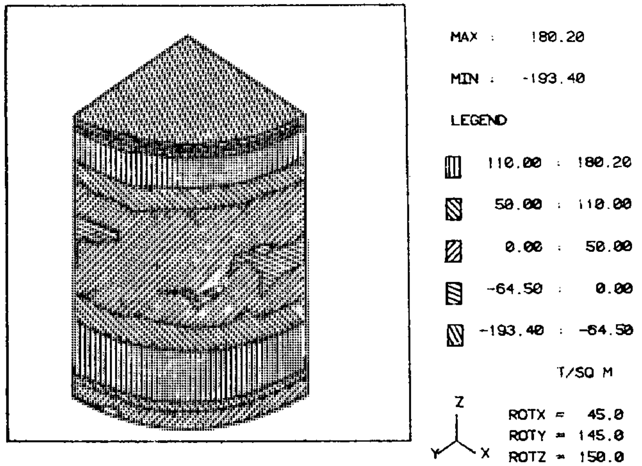
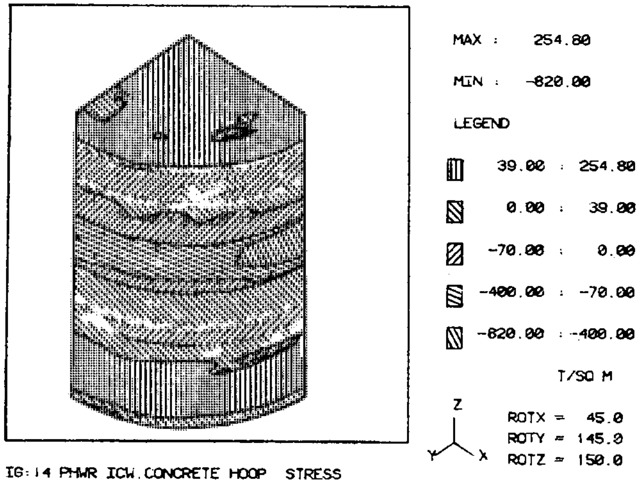


FIG:11 PHWR ICW.CONCRETE HOOP STRESS (TOP LAYER) AT Po + 2.2P(DBA)



IG:14 PHWR ICW.CONCRETE HOOP STRESS (TOP LAYER) AT Po + 2.3P(DBA)

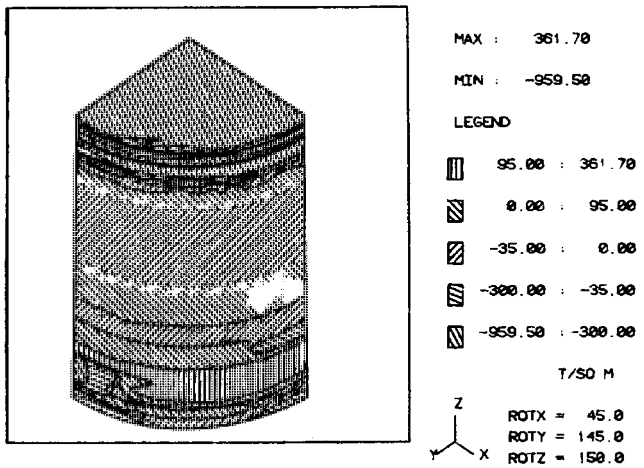


FIG:15 PHWR ICW.CONCRETE HOOP STRESS (BOTTOM LAYER) AT Po + 2.3P(DBA)

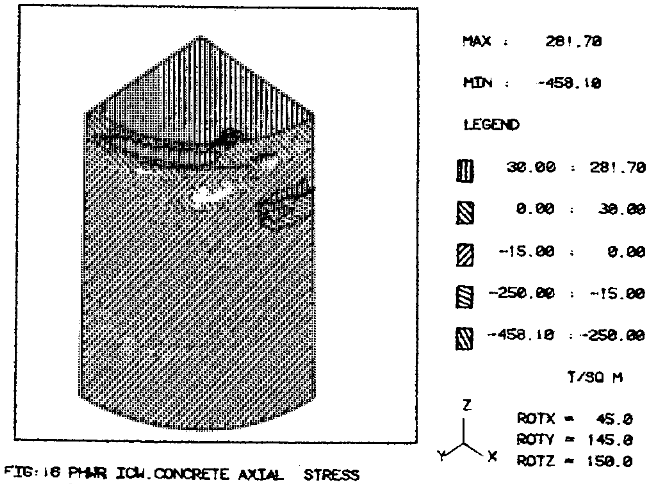


FIG:16 PHWR ICW.CONCRETE AXIAL STRESS (TOP LAYER) AT Po + 2.3P(DBA)

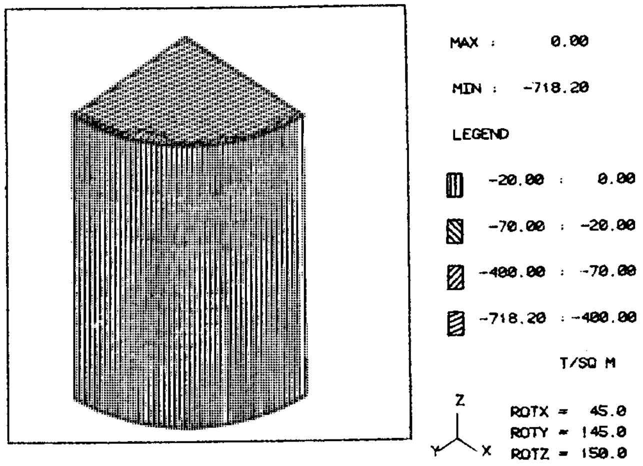


FIG:17 PHWR ICW.CONCRETE AXIAL STRESS (BOTTOM LAYER) AT Po + 2.3P(DBA)

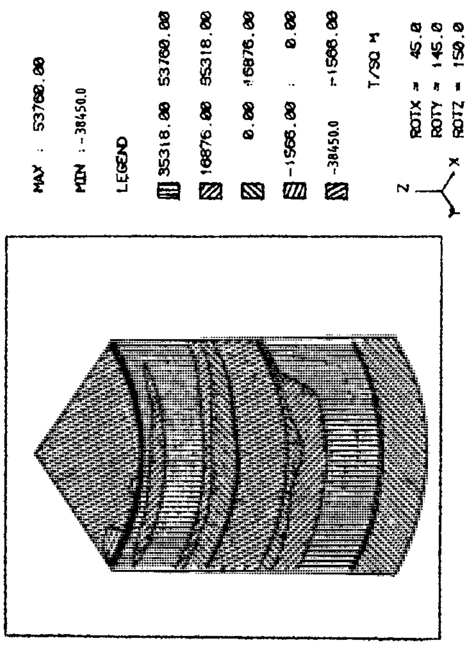


FIG:18 PHWR ICW.STEEL HOOP STRESS (TOP LAYER) AT Po + 2.3P(DBA)

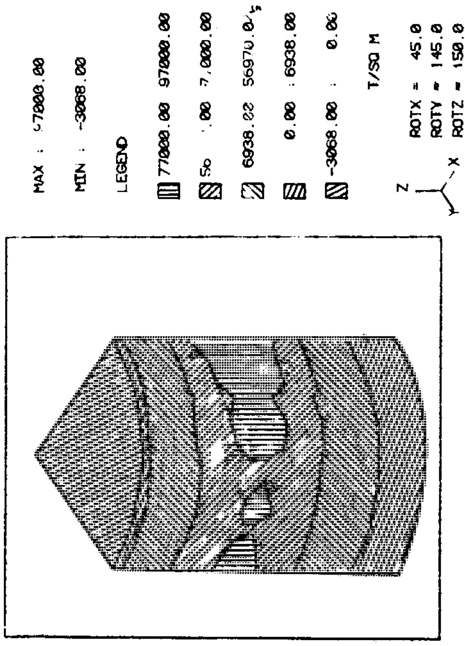


FIG:19 PHWR ICW.STEEL AXIAL STRESS (TOP LAYER) AT Po + 2.3P(DBA)

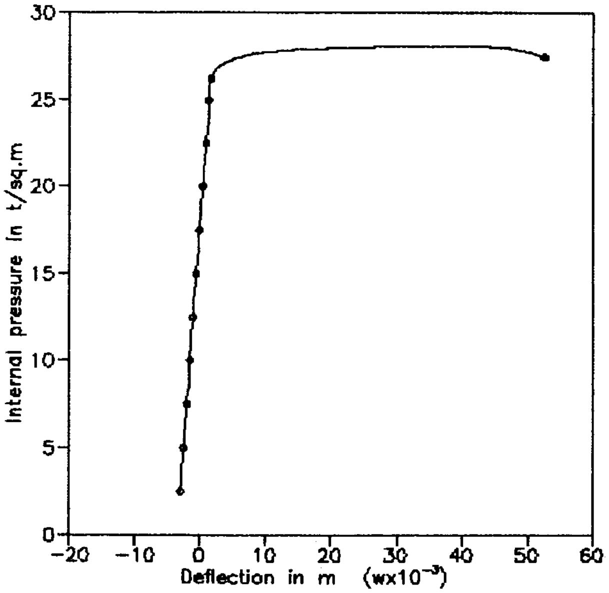


Fig. 20 Load/deflection in membrane region

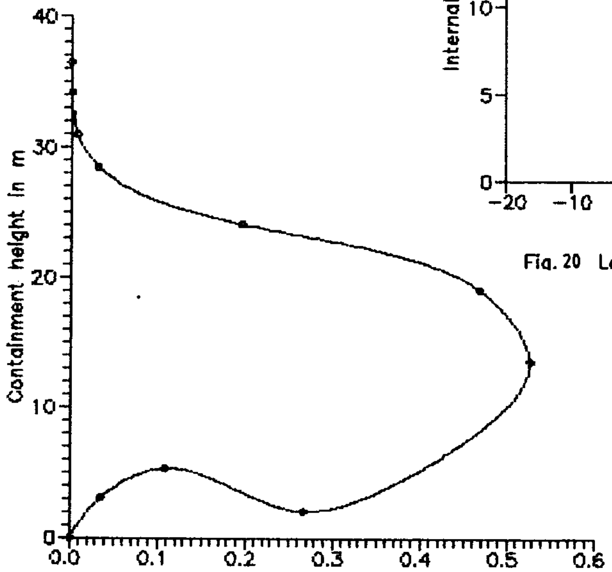


Fig.21 Deformed shape of the containment at 2.3p(DBA)