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Design Optimization of the Primary Containment Building of a Pressurized Water Reactor

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***Abstract*—**Primary containment structure is one of the five safety layers of a nuclear facility which is needed to be designed in such a manner that it can withstand the pressure and excessive radioactivity during accidental situations. It is also necessary to ensure minimization of cost with maximum possible safety in order to make the design economically feasible and attractive. This paper attempts to identify the optimum design conditions for primary containment structure considering both mechanical and radiation safety keeping the economic aspects in mind. This work takes advantage of commercial simulation software to identify the suitable conditions without the requirement of costly experiments. Generated data may be helpful for further studies.

***Keywords*—**PWR, concrete containment, finite element approach, neutron attenuation, Von Mises Stress.

NOMENCLATURE

Notation	Details
σ	Stress on the element
φ_0	Initial radiation flux density
φ	Radiation flux density after attenuation
I_0	Initial intensity of radiation
I	Radiation intensity after attenuation
σ_a	Absorption cross section of the material
N	Atomic density of the material

I. INTRODUCTION

SAFETY has always been the major concern of a nuclear power plant in which containment plays the most important role. Containment provides biological and radiation shielding to the surroundings of a nuclear reactor. Nowadays, almost all the containments have steel liner inside the reinforced concrete structure. There have many studies regarding the effect of neutron irradiation, stresses under extreme conditions (such as natural calamities, aircraft impact, earthquake, explosion etc.) on both of the shells. But, none of the studies included both of the neutron intensity attenuation and the mechanical stress analysis. Yang [1] performed finite element stress analysis of the vertical buttresses of a nuclear containment vessel. Krieg et al. [2] analyzed the load-carrying capacity of spherical steel containment of a PWR under hydrogen detonation. Response of reinforced concrete containment structure under internal blast loading has been analyzed by Zhao et al. [3]. Lee et al. [4] presented the thermal analysis of the containment during construction under severe weather condition. Effects of long-term irradiation on the behavior of reinforced concrete members of a nuclear power plant have been studied by Park et al. [5].

This study includes both the mechanical analysis and the attenuation of thermal neutron released from the reactor core. Comparing both of these phenomena, an optimum design of the containment has been predicted.

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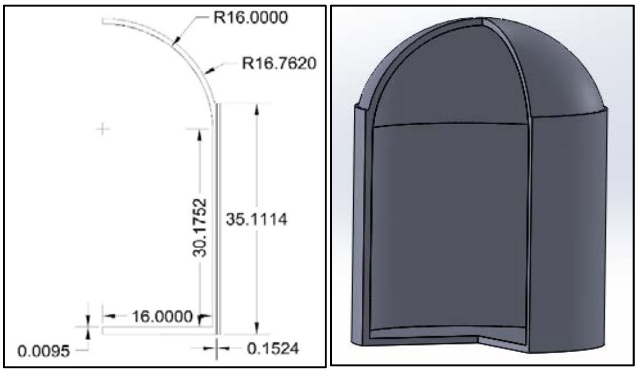
II. DESCRIPTION OF STRUCTURE

There are different design parameters for different nuclear power plants. The primary containment that we have taken as a basis of comparison in this paper has a cylindrical shape with hemispherical dome on top. The inner radius of the cylinder is 16 m, the steel liner has a thickness of 0.9525 cm, height of the inner cylinder is 30.1752 m. The thickness of the concrete layer is 1.057275 m. Vertical tendons have a diameter of 0.1524 m. The containment has 160 vertical tendons in total. The dome has thickness of 0.762 m. The containment has a total air volume of 28,230 m^3 [6]. Fig. 1 shows the different design parameters of the primary containment structure.



(a) (b)

Fig. 1 (a) Plant layout model in 2D, (b) 3D Model of the containment

In this study, the thickness of both the steel liner and the concrete layer has been varied in order to find the optimum thickness for both steel liner and concrete layer of the containment. The steel liner has been taken between the range of 9 cm and 15 cm and the concrete layer has been taken between the ranges of 0.9 m and 1.2 m.

The inner pressure in case of accident has been assumed to be 414 kPa considering that all the water inside the cooling circuits may be vaporized in case of rapid heat generation [7].

The outer pressure is taken to be that of the atmosphere. The tendons are approximated by replacing them with a cylindrical steel shell having the same area as well as area moment of inertial. This reduces the accuracy, but it is negligible compared to the reduction of computational complications in the simulation model. Commercial simulation software has been used to generate the stress analysis data throughout the steel liner and concrete structure.

III. Mathematical Modeling

A. Mechanical Stress Analysis

Since the thickness of the steel liner and concrete structure of the containment vessel is very small compared to the inner diameter of the structure, it can be considered as a thin walled cylinder in its cylindrical portion, and the tangential stress can be calculated to be:

$$\sigma = \frac{P \times D}{2t}$$

Since the longitudinal stress is smaller than the transverse stress, it is of lesser importance. In this study, the Von Mises stress, which is the resultant of both the principal normal stresses, has been considered for the analysis in order to ensure higher factor of safety for design.

1. Neutron Attenuation Point of View

Not only mechanical integrity of the structure but also the capacity to attenuate radiation intensity is to be considered in order to design a containment structure so that protection from radiation may be ensured. Radiation intensity is attenuated according to the following formula:

$$I = I_o e^{-\sigma N x}$$

High density aggregates (such as barite, magnetite and hematite aggregates) are used to absorb the gamma radiation as well as neutron of various energies [8].

IV. Finite Element Modeling

On the basis of symmetrical condition of the geometry,2D axis-symmetric model of Fig. 1 (a) is implemented on COMSOL Multiphysics. For physics-controlled mesh and normal element size, number of domain elements varies from 85405 to 47496 depending on the case study. All the elements are taken to be triangular in shape. The base of the concrete section is defined as fixed-end condition. Top of the spherical dome is defined as axial-symmetric condition. The inner pressure is set to be 414 kPa which is the design pressure of this containment. These boundary conditions are specified in Fig. 2.

The mesh element size is selected depending on the physics of the analysis. The mesh elements are triangular in shape as it gives the most accurate results for stress analysis related models. Fig. 3 shows the mesh modeling of the containment structure at the two locations of the structure that the paper has investigated with highest importance.

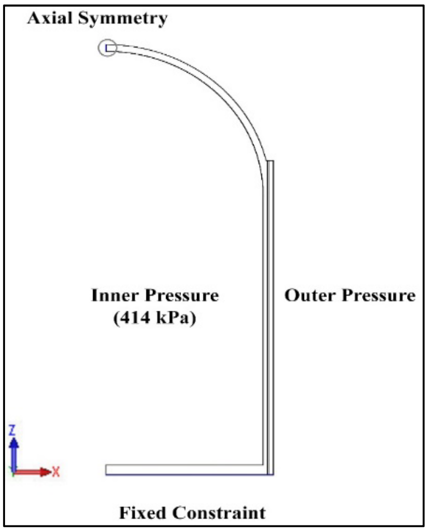


Fig. 2 Loading and boundary conditions

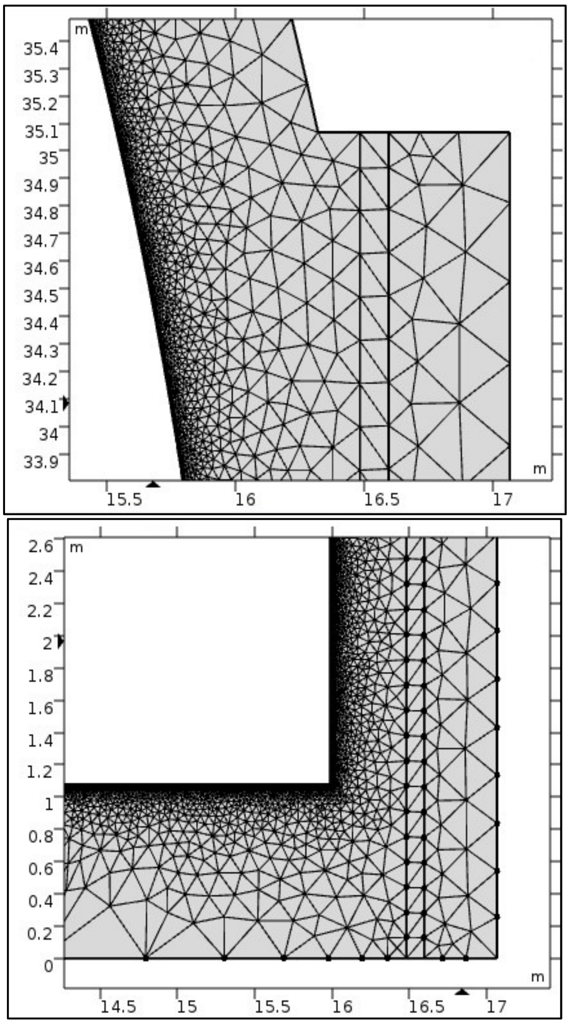


Fig. 3 Mesh modeling of containment wall along with steel liner and tendon

V. Results and Discussion

The simulated datasets obtained from the stress analysis of the structural components considering different design parameters are shown in Fig. 4.

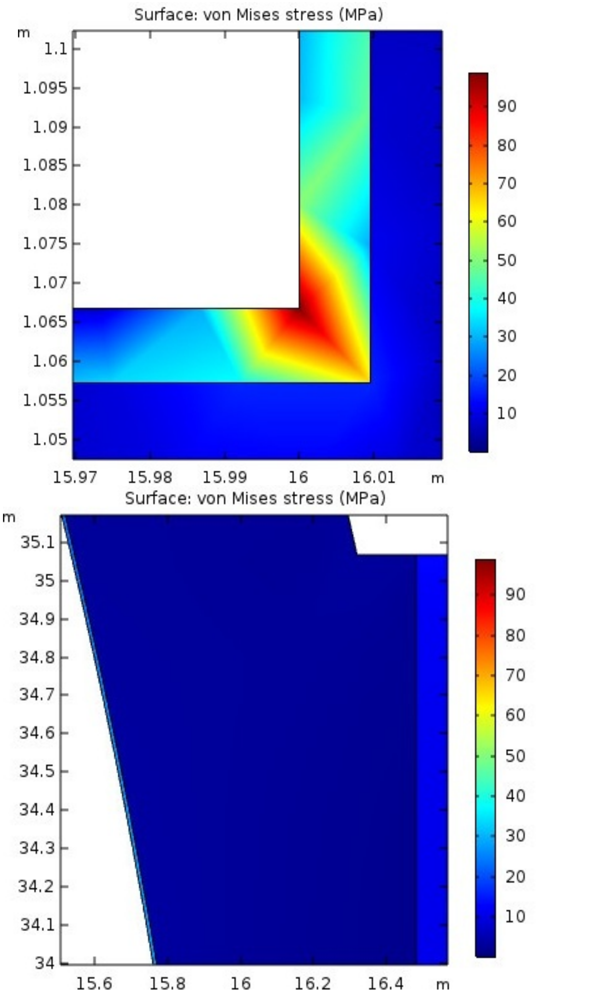


Fig. 4 Stress distribution in the wall of reactor containment building (RCB)

The datasets indicate that, for none of the design conditions, the Von Mises stress is higher than the maximum compressive strength of steel and concrete at any location. The variations of maximum Von Mises stress with variation of thickness steel liner and thickness of concrete layer are shown in Fig. 5.

Fig. 6 shows neutron intensity reduction with the increase of thickness of concrete and steel liner. Keeping in mind that this calculation is provided for the extreme case where the reactor vessel provides no attenuation to the neutron and there is no attenuation due to the tendons inside the containment structure, 98.5% attenuation (from this chart) may be considered safe enough.

Maximum deformation of the containment is presented on Fig. 7 for several thickness combinations of concrete and steel liner. The obtained data indicate that deformation is less than 2.8 mm for all the design cases.

The price of nuclear grade steel and concrete is variable in international market and it is very difficult to estimate the exact cost of the structure for a specific design. The approximate total costs for different combinations are shown in Table I.

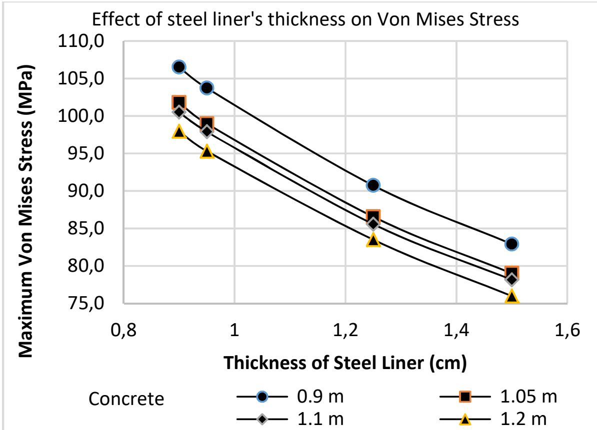


Fig. 5 Effect of steel liner's thickness on maximum Von Mises stress

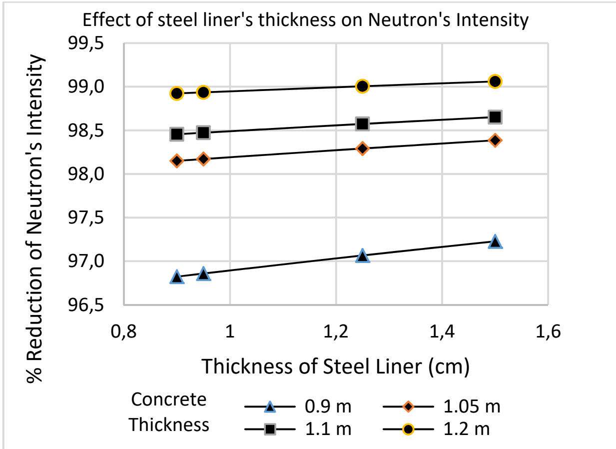


Fig. 6 Effect of steel liner's thickness on neutron's intensity

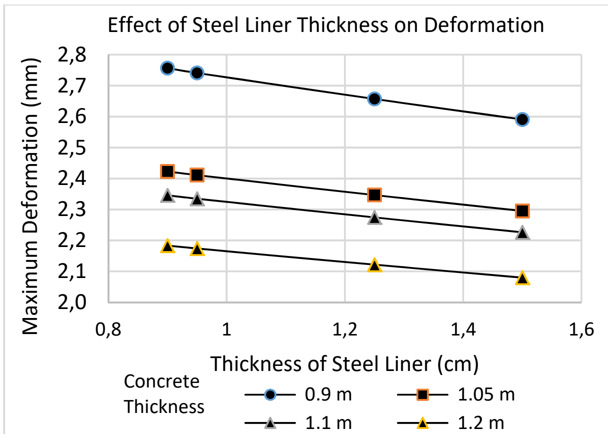


Fig. 7 Effect of steel liner's thickness on maximum deformation

The below data indicate that steel liner thickness should be 0.9 cm and concrete thickness should be 0.9 m in order to get minimum cost of the structure. However, if we consider the overall safety of the system, a relatively better option is 0.9 cm liner thickness with 1.05 m concrete thickness which will increase cost but also increase the safety features drastically.

TABLE I
TOTAL CONSTRUCTION COST OF PRIMARY CONTAINMENT FOR DIFFERENT COMBINATIONS

Liner thickness (cm)	Concrete thickness (m)	Total Cost (Million USD)
0.9	0.9	4.24
0.9	1.05	4.64
0.9	1.1	4.74
0.9	1.2	5.00
0.95	0.9	4.25
0.95	1.05	4.65
0.95	1.1	4.76
0.95	1.2	5.01
1.25	0.9	4.34
1.25	1.05	4.73
1.25	1.1	4.84
1.25	1.2	5.10
1.5	0.9	4.41
1.5	1.05	4.81
1.5	1.1	4.91
1.5	1.2	5.17

VI. CLOSING REMARKS

- From the above data and calculated values, it is evident that all the thickness of liner and concrete layer assumed in this paper may fulfill the requirements of a primary containment building for assurance of safety in case of failure.
- This study shows that thickness of the steel liner may be taken 0.9 cm, while the thickness of the concrete layer may be taken 1.05 m in order to optimize the design of the primary containment.
- This work has only considered 16 possible combinations of thicknesses of steel liner and concrete in order to get the optimum design condition. Further studies may be done to overcome the limitations of this work.

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