COMPOSITE CONTAINMENT FOR NUCLEAR POWER

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SUMMARY

Fundamentally, a nuclear reactor containment structure provides three major functions; namely, (1), to withstand loads due to pressure and temperature increase due to Design Basis Accident (DBA) (2), to withstand environmental loads such as seismic, tornado and normal loads, and (3) act as a radiation shield.

Conventional design practise is to employ either a steel vessel and concrete shield building or a steel lined concrete structure.

This paper deals with a new concept in which a steel liner is employed which carries much of the primary membrane loads. This type of structure is similar in some aspects to the previously described systems:

a) A mat, lined with a thin plate on its top surface, is similar to concrete containment.
b) A cylinder and hemispherical dome, made up of steel plate and concrete, is about 2.5 feet thick (the minimum required for radiation shielding). Although the steel plate and concrete are in contact, as in concrete containment, the steel plate in composite containment is much thicker than the liner. However, the thickness is less than that required for a steel vessel. The only significant reinforcement in the concrete is hoop re-bars in the cylindrical portion which are placed near the outside surface. The reinforcement will act compositely with the steel plate in carrying hoop forces.

The governing equations have been derived accounting for the fact that the stresses in the steel liner are calculated in accordance with the shell equations for hoop and meridional strains and temperature and the fact that the reinforcing bars respond as linear members. Because of composite behavior hoop and meridional membrane strain compatibility is maintained between the steel liner and the reinforcing bars.

Similarly the equations for calculating the discontinuity moments and shears in the liner have been derived considering the fact that the reinforcing bars participate with the steel liner in structural response.

The response of composite containment to DBA is one in which the proportion of membrane forces carried in the steel liner and the reinforced concrete vary depending upon the internal pressure and temperature. When peak pressure is reached and liner temperature is relatively low, the membrane forces are carried by the steel plate and the reinforcing bars roughly in proportion to the projected areas. On the other hand, when the peak liner temperature is reached the liner will be much hotter than the re-bar. Based upon the elastic and thermal properties the difference in membrane stress between the steel liner and the reinforcing bars will be such that the portion of membrane load carried by the reinforcing bars will be increased.

In summary a concept is presented which offers two main advantages over present practise; namely reduction of materials and therefore reduced capital cost and even more significantly a shortened construction schedule which will permit more flexibility in overall plant construction schedule and will benefit the cash flow situation.

1. Introduction

The primary function of containment structure or vessel for a nuclear power plant is to remain leak-tight under internal pressure and temperature increases caused by the design basis accident, DBA, while at the same time being subjected to other loading such as seismic loads, dead and live load and other local loads arising from such effects as flying missiles, varying temperatures, and geometrical discontinuities. The containment structure or vessel may also provide for radiation shielding.

Heretofore, containment structures have either been steel vessels or steel-lined concrete containments. The present technology has been summarized in reference [1]. The strength member for a steel vessel is the steel material itself. The strength members for the concrete containment are embedded reinforcing bars or prestressing tendons, with the liner serving as the leak-tight membrane. In concrete applications the liner is considered to carry no loads and because of high internal temperatures may actually impose load upon the concrete strength members.

The concept described herein is based upon the composite behavior of the two structural elements. This is achieved by selecting a steel vessel of greater thickness than usually selected for steel liners, and surrounding it with concrete. This selection results in a much different structural response than achieved by either a steel vessel or a steel-lined concrete containment. Now the steel portion carries a considerable portion of the required loading. This departs from the previous applications where the steel carries all the imposed loads or is assumed to carry none of the imposed loads.

This concept is applicable to all nuclear power plant systems: e.g. LWR, LMFBR, HTGR, & HWR.

2. Description

The concept could easily be employed for other containment geometries such as spherical shells; however, this paper will deal with the geometries which are currently the most common. The geometry of this containment concept as described herein will therefore be similar to many containment structures now being designed and built for nuclear power plants; namely a base mat, cylindrical walls and a hemisperical dome, see Figure 1. The differences in this concept from others arise from the fact that this containment concept is, structurally,neither a concrete structure nor a steel vessel. It can best be described as a steel vessel around which concrete is placed, with the entire structure supported on a concrete mat. Since the concrete is placed in intimate contact with the steel vessel, the two structural components act compositely. The fact which distinguishes this from conventional reinforced concrete containment is that the steel vessel has much greater elastic stiffness than the steel liner of the reinforced concrete containment. This fact makes it possible to reduce the elastic stiffness of the surrounding concrete in such a way that the steel vessel can carry loads instead of producing thermal loads in the concrete shell, as is the case in conventionally reinforced or prestressed concrete containment structures. The steel vessel is attached to the surrounding concrete by means of anchor studs or continuous members such as ties, angles, or channels.

There need be no major reinforcing in the concrete surrounding the steel vessel except for the hoop reinforcing bars in the cylindrical portion. The remaining reinforcement is provided for crack control and for construction purposes and therefore may be relatively

Typical Composite Containment Structure

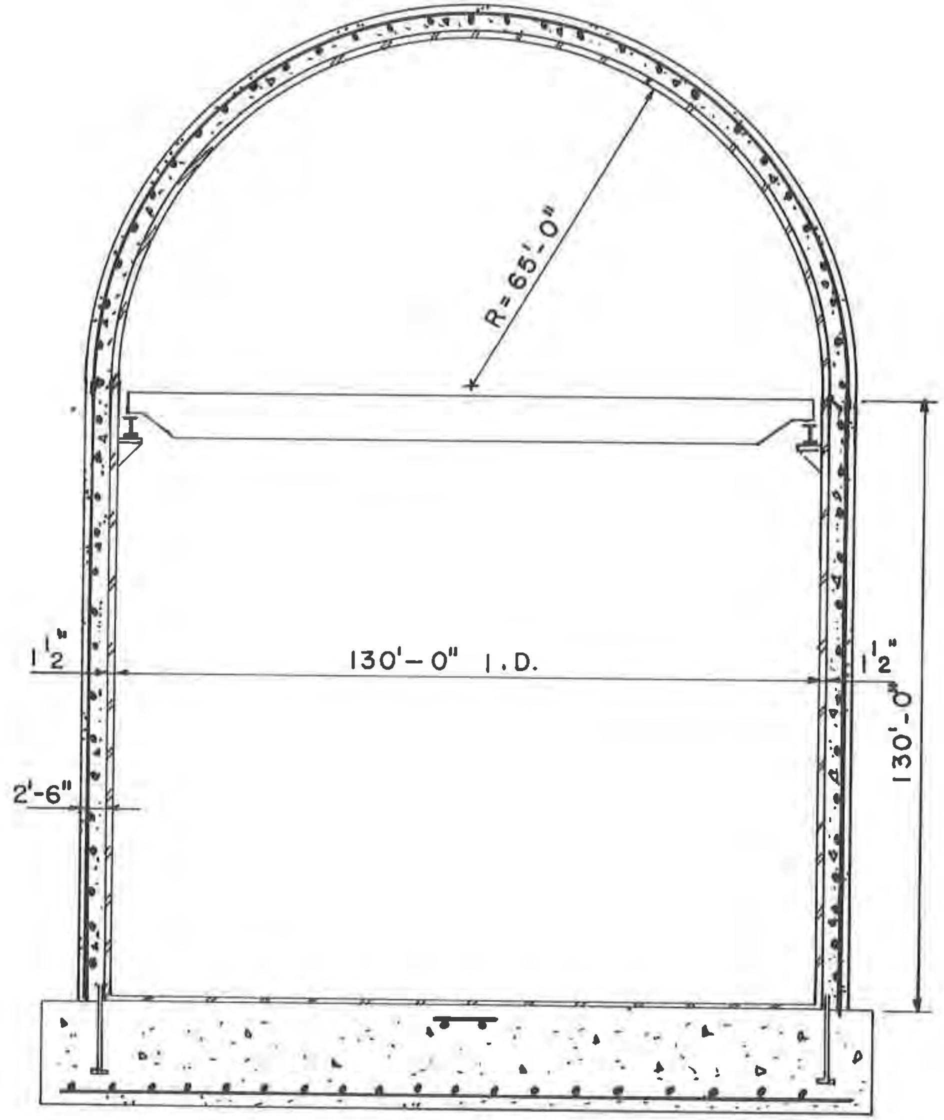

Figure 1

nominal. For particularly severe loading requirements, however, reinforcing bars may be placed to carry imposed loads in all directions.

At the base of the cylinder in the region where large discontinuity moments and shears are developed, a bond breaking membrane between the steel vessel and the surrounding concrete will eliminate the development of high composite bending stiffness, while not disturbing the composite membrane stiffness.

The elimination of large discontinuity moments and shears at the base of the cylinder also eliminates these discontinuity moments and shears being transferred to the base mat.

The base may be either the steel-lined reinforced concrete mat or the steel ellipsoidal shell commonly employed for steel containment vessels. In either case the major loading on the base is internal pressure load, which is carried by membrane forces for the steel ellipsoidal shell or by bending moments for the mat.

3. Derivation of Equations

3.1 Membrane Forces

For the steel vessel, the following equations apply for meridional forces, hoop forces, and tangential shear, respectively:

$$N_\phi' = \frac{Et'}{1-\nu^2}\left[\varepsilon_\phi - \alpha\delta T' + \nu(\varepsilon_\theta - \alpha\delta T')\right] \qquad (1)$$

$$N_\theta' = \frac{Et'}{1-\nu^2}\left[\varepsilon_\theta - \alpha\delta T' + \nu(\varepsilon_\phi - \alpha\delta T')\right] \qquad (2)$$

$$N_{\phi\theta}' = \frac{Et'}{2(1+\nu)}\ \gamma_{\phi\theta} \qquad (3)$$

where ν is Poisson's ratio, E is Young's Modulus for steel, t' thickness of steel vessel, N_ϕ', N_θ' and $N_{\phi\theta}'$ are membrane meridional, hoop, and shear forces in the steel vessel, respectively, α is the coefficient of thermal expansion for steel, $\delta T'$ is the temperature increase in the steel vessel during DBA, and ε_ϕ, ε_θ, and $\gamma_{\phi\theta}$ are membrane meridional, hoop, and shear strains, respectively.

For the surrounding reinforced concrete, the following equations apply for meridional and hoop forces, respectively:

$$N_\phi'' = Et'''(\varepsilon_\phi - \alpha\delta T'') \qquad (4)$$

$$N_\theta'' = Et''(\varepsilon_\theta - \alpha\delta T'') \qquad (5)$$

where t'' and t''' are the areas per unit length of hoop and meridional reinforcing bars, respectively, and $\delta T''$ is the temperature change in the reinforcement during DBA.

The following total composite membrane meridional and hoop forces are:

$$N_\phi = N_\phi' + N_\phi'' \qquad (6)$$

$$N_\theta = N_\theta' + N_\theta'' \qquad (7)$$

where N_ϕ and N_θ are the total membrane forces acting on the composite structure in meridional and hoop direction, respectively.

Substituting equations (1) and (4) into equation (6);

$$N_\phi = \frac{Et'}{1-\nu^2}\,\varepsilon_\phi - \frac{Et'}{1-\nu^2}\,\alpha\,\delta T' + \frac{\nu Et'}{1-\nu^2}\,\varepsilon_\theta - \frac{\nu Et'}{1-\nu^2}\,\alpha\delta T' \tag{8}$$

$$+ Et'''\,\varepsilon_\phi - Et'''\,\alpha\delta\,T''$$

and combining term;

$$N_\phi = E\left[\varepsilon_\phi\left[\left(\frac{t'}{1-\nu^2} + t'''\right)\right] + \varepsilon_\theta\,\frac{\nu t'}{1-\nu^2} - \alpha\left(\frac{t'}{1-\nu^{\,2}}\,\delta T' + t'''\,\delta T''\right) - \frac{t'\nu}{1-\nu^{\,2}}\,\alpha\delta T'\right] \tag{9}$$

Substituting equations (2) and (5) into equation (6);

$$\frac{N_\theta}{E} = \varepsilon_\theta\left(\frac{t'}{1-\nu^2} + t''\right) + \varepsilon_\phi\,\frac{\nu t'}{1-\nu^2} - \alpha\left(\frac{t'}{1-\nu^2}\,\delta T' + t''\delta T''\right) - \frac{t'\nu}{1-\nu^2}\,\alpha\delta T' \tag{10}$$

Solve equation (9) for $\varepsilon\phi$

$$\varepsilon\phi = \frac{\frac{N_\phi}{E} - \varepsilon_\theta\,\frac{\nu t'}{1-\nu^2} + \alpha\left[\frac{t'}{1-\nu}\,\delta T' + t'''\,\delta T''\right]}{\frac{t'}{1-\nu^2} + t'''}$$

and substitute into equation (10) and solve for ε_θ

$$\frac{N_\theta}{E} = \varepsilon_\theta\left(\frac{t'}{1-\nu^2} + t''\right) + \frac{\frac{\nu t'}{1-\nu^2}}{\left(\frac{t'}{1-\nu^2} + t'''\right)}\left[\frac{N_\phi}{E} - \frac{\nu t'}{(1-\nu^2)}\,\varepsilon_\theta + \alpha\left(\frac{t'}{1-\nu}\,\delta T' + t'''\,\delta T''\right)\right]$$

$$-\alpha\left(\frac{t'}{1-\nu}\,\delta T' + t''\,\delta T''\right)$$

and combining terms

$$\frac{N_\theta}{E} - \frac{N_\phi \nu t'}{E\left[t' + t'''(1-\nu^2)\right]} + \alpha\left(\frac{t'}{1-\nu}\delta T' + t''\delta T''\right) - \frac{\nu t'\,\alpha}{t' + t'''(1-\nu^2)}\left[\frac{t}{1-\nu}\,\delta T' + t'''\delta T''\right]$$

$$= \varepsilon_\theta\left[\frac{t'}{1-\nu^2} + t'' - \frac{\left[\frac{\nu t'}{1-\nu^2}\right]^2}{\frac{t'}{1-\nu^2} + t'''}\right]$$

then

$$\varepsilon_\theta = \frac{N_\theta + E\alpha\left[\frac{t'}{1-\nu}\,\delta T' + t''\,\delta T''\right] - \left[\frac{\nu t'}{t' + t'''(1-\nu^2)}\right]\left[N_\phi + E\alpha\left(\frac{t'}{1-\nu}\,\delta T' + t'''\,\delta T''\right]\right.}{E\left[\frac{t'}{(1-\nu^2)} + t'' - \nu^2\,\frac{\left(\frac{t'}{1-\nu^2}\right)^2}{\frac{t'}{1-\nu^{\,2}} + t'''}\right]} \tag{11}$$

Similarly

$$\varepsilon_\phi = \frac{N_\phi + E\alpha\left[\frac{t'}{1-\nu}\,\delta T' + t'''\,\delta T''\right] - \left[\frac{\nu t'}{t' + t''\,(1-\nu^2)}\right]\left[N_\theta + E\alpha\left(\frac{t'}{1-\nu}\,\delta T' + t''\,\delta T''\right]\right.}{E\left[\frac{t'}{1-\nu^2} + t''' - \frac{\nu^2\left(\frac{t'}{1-\nu^2}\right)^2}{\frac{t'}{1-\nu^2} + t''}\right]} \tag{12}$$

Equations 3, 11, and 12 provide information on membrane strains for which the state of stress and displacements can be found for both the steel vessel and the reinforcing bars in the concrete.

3.2 Discontinuity Moments and Shears in the Steel Vessel

Through the use of a bond breaker composite bending stiffness is eliminated at the base of the cylinder while maintaining membrane composite action. The shell equations are similar to those found in a standard text except that the contribution of the hoop reinforcing bars is accounted for. The resulting peak bending stress in the steel shell of a composite structure will be considerably less than for a steel containment vessel designed to carry the full internal pressure load. The equations for the discontinuity moment and shear at the base of cylindrical steel vessel are presented.

Assuming that the surrounding reinforced concrete is only reinforced in a significant quantity in the hoop direction of the cylinder, the bending stiffness in the Meridional direction of the concrete is minimal and may be neglected.

The basic shell equations are:

$$M_\phi = D \frac{d^2w}{dx^2}$$

and

$$D \frac{d^4w}{dx^4} + \frac{E(t'+t'')}{r^2} w = z$$

where M is meridional moment in steel vessel, w is the radial displacement in steel vessel, D is flexural rigidity of the steel vessel, z is the normal force per unit area of steel vessel and r is the radius of steel vessel.

simplifying

$$\frac{d^4w}{dx^4} + 4U^4 w = v$$

where

$$U^4 = \frac{3(1-\nu^2)(t'+t'')}{r^2 t'^3} \quad \text{and} \quad v = \frac{z(12)(1-\nu^2)}{Et'^3}$$

If z=0 and M_ϕ and Q_ϕ are the base meridional moment and radial shear respectively, then solving for w

$$w = \frac{e^{-Ux}}{2U^3D} \left[UM_{\phi o} (\sin Ux - \cos Ux) - Q_{\phi o} \cos Ux \right]$$

Solving for M and Q we have:

$$M_{\phi o} = 2U^2Dw$$

$$Q_{\phi o} = -4U^3Dw$$

where $M_{\phi o}$ is the meridional discontinuity moment at the base of the steel cylinder, $Q_{\phi o}$ is the radial discontinuity shear at the base of the steel cylinder, and w is the radial displacement in cylinder away from the discontinuity.

4. Illustrative Example

This example will be an analysis of membrane forces at a section in the cylinder above the discontinuity region.

4.1 Design Parameters

Consider Containment Structures with hemispherical dome and loading as follows:

Diameter of Cylinder	130'-0"
Height of Cylinder	130'-0"
Steel Cylinder thickness	1½"
Steel Dome thickness	1"
Concrete cylinder thickness	2'-6"
Concrete dome thickness	2'-0"
Hoop Re-bar	#18 @ 8" o.c.
DBA peak pressure	60 psig
DBA peak temperature	260 F
SSE peak ground acceleration	0.2 g
OBE peak ground acceleration	0.1 g

For purposes of this example, only nominal reinforcing is placed in the vertical direction in concrete cylinder and the dome and is therefore ignored. Therefore, t' is 1.5 inches, t'' is 0.5 inches, t''' is 0.0, T' is 150 F, and T'' is 0.0.

Equations 11 and 12 become for this example:

$$\varepsilon_\theta = \frac{N_\theta + 42.4125 - 0.15N_\phi}{58{,}000} \tag{15}$$

$$\varepsilon_\phi = \frac{N_\phi + 44.253 - 0.113136\, N_\theta}{43{,}7461} \tag{16}$$

Load Combinations

I DL + 1.5P + T

II DL + 1.5P

III DL + 1.25P + 1.25 E + T

IV DL + 1.25P + 1.25 E

V DL + P + E_s + T

VI DL + P + E_s

VII DL + P + E_O + T

VIII DL + P + E_O

IX DL + T

where DL represents dead load, P represents internal pressure, T represents temperature effects, E_O represents operating basis earthquake loads, and E_s represents safe shutdown earthquake loads.

4. 2 Membrane Forces (k/in)

	D	DL	E	E_s
N	19.5	6.2	4.4	8.8
N	39.0	-	-	-
N	-	-	3.4	6.8

4. 3 Discussion of Results

The results of a conceptual design are given in Table I using the load combinations which will be controlling the design of the main structural components. For the load combinations certain loads have been neglected which would not have a significant affect upon

Summary of Results

Load Combination	N_ϕ k/in	N_θ k/in	$N_{\phi\theta}$ k/in	ΔT °F	ϵ_θ in/inx10^{-3}	ϵ_ϕ	N_θ' k/in	N_θ'' k/in	N_ϕ k/in	σ_θ' ksi	σ_θ'' ksi	σ_ϕ' ksi	Tangential Shear Stress ksi
I	23.0	58.5	0	150	1.6804	1.3860	34.1	24.4	23.0	22.7	48.8	15.3	-
II	23.0	58.5	0	0	.9491	.3745	44.7	13.8	23.0	29.8	27.6	15.3	-
III	18.2	48.75	0	150	1.5247	1.3015	26.6	22.1	18.2	17.7	44.1	12.1	-
IV	18.2	48.75	4.25	0	.7934	.2900	37.2	11.5	18.2	24.8	23.0	12.1	2.8
V	22.1	39.0	6.8	150	1.3465	1.4159	19.5	19.5	22.1	13.0	39.0	14.7	4.5
VI	22.1	39.0	6.8	0	.6153	.4043	30.1	8.9	22.1	20.1	17.8	14.7	4.5
VII	17.7	39.0	3.4	150	1.3579	1.3153	19.3	19.7	17.7	12.9	39.4	11.8	2.3
VIII	17.7	39.0	3.4	0	.6266	.3037	29.9	9.1	17.7	19.9	18.2	11.8	2.3
IX	-6.2	0	0	150	.7473	.8670	-10.9	10.8	-6.3	-7.2	+21.6	-4.2	-

Table I

the overall strength requirements.

Load Combinations I through VI are representative of the controlling loading combinations in reference 2 while Load Combinations VII and VIII are representative of the controlling Load Combinations in reference 3 .

Load Combination IX represents a DBA in which the temperature of the steel increases but no internal pressure develops. As can be seen, the compressive stresses in the vessel are rather low because the reinforced concrete does not significantly restrain thermal growth.

A review of Table 1 indicates that the maximum stress in the hoop reinforcing bars is 46 ksi, a stress well below 0.9 f_y for reinforcing bars with a yield stress f_y, of 60 ksi. The maximum stress in the steel vessel occurs in Load Combination II and is 29.8 ksi. This stress is well below the yield stress of ASME SA-299 and SA-537 Class 1 and 2. For SA-299; f_y=40 ksi, f_u=75 ksi, and f_a=20.6 ksi, where f_u is the ultimate stress and f_a is the allowable stress, and f_y is the yield stress as given in reference 4. Inasmuch as Load Combinations I through VI are factored load combinations, the stress of 29.8 is well below 0.9 f_y.

For Load Combinations VII the maximum stress in the hoop reinforcing bars is 36.6 ksi which is above 0.5 f_y; however, the hoop stress in the steel vessel is only 13.8 ksi which equals 0.345 f_y and 0.67 f_a. For Load Combination VIII the maximum stress in the hoop reinforcing bars is only 19.6 ksi while the hoop stress, meridional stress, and shear stress in the steel vessel is 19.6, 11.8, and 2.3 ksi, respectively; resulting in a principal tensile stress of 20.1 ksi which is less than the design stress intensity value S_m equal is 20.6 ksi listed in Table I-10.1 in reference 4 .

Load Combination IX is included to cover the effect on an increase in temperature within containment without pressure increase. The resulting compressive stresses are low. Stability is maintained by steel anchorage of the steel vessel to the concrete.

There are some inherent conservatisms in the method of analysis for this illustrative example. For example, a time history analysis of DBA would show that the vessel has increased in temperature when the peak internal pressure is reached and when the peak temperature increase of the liner is reached the internal pressure will be less than the peak. This changes the stress distribution for the illustrative example such that the hoop rebar stress of 48.8 ksi in Load Combination I would be reduced and hoop vessel stress of 29.8 ksi in Load Combination II would be reduced.

4.4 Comparison of Code Requirements

Because there is no code specifically governing composite containment, this example used both codes as appropriate. This has resulted in design which would have considerably greater elastic reserve than the conventional concrete containment structure designed in accordance with reference 5 .

Assuming SA-299 for the steel vessel and ASTM A615 Grade 60 reinforcing bars, the most critical factored Load Combinations in Table 1 are I and II. However, the strength requirement is only 65% of the elastic capacity of the section. This compares with the value of 90% permitted for concrete containments in reference 2 .

The strength requirement for either load combination VII or VIII is 25% of the total ultimate strength of the section. This compares to a value of 27.5% indicated in reference 4 .

4.5 Design Details

4.5.1 Cylindrical Portion

The illustrative example should be applicable for the entire cylindrical portion, except that nominal reinforcing will be placed vertically for crack control and support for hoop reinforcing bars during placement of bars and concrete.

In this example, only hoop reinforcing is considered; therefore, the total seismic force is carried by the steel vessel. Although small hoop forces are developed under a seismic loading, for purposes of this example they have been ignored. The vertical component of an earthquake has also been neglected for purposes of this example.

Under Load Combinations III through VII, the seismic interial forces of the concrete are assumed to be transferred to the steel vessel. This transfer may take place in one of two ways; one, studs welded to the vessel will transfer the inertial forces of the concrete to vessel in shear and tension; and two, the confinement of the hoop bars will cause the load to be applied to the steel vessel in bearing. Probably the more desirable method is a combination of the two methods. In any case, the full seismic load is applied to the steel vessel of this example.

The major penetrations will be at an elevation of the cylinder such that hoop reinforcing bars would be interrupted. There are two fundamental approaches. One, design the entire band as an MC steel vessel which would require a shell thickness of about 2 in. which would maintain stresses below MC allowables and would approximate the hoop strains in the composite structure above and below the elevation of major penetrations. Two, a structural ring or frame could be provided in the concrete surrounding the penetration such that the hoop bars could be anchored into the ring. Inasmuch as the vertical reinforcing bars are only nominal, no special anchorage would be required.

4.5.2 Mat

The meridional membrane force is a maximum of 15.3 k/in for factored load combinations and is 11.8 k/in under unfactored load combinations. Anchor bolts such as A490 @ 1'-6" could be provided to carry the uplift force from the cylinder into the mat. Because the discontinuity moments and shears are insignificant, top reinforcement in the mat can be relatively light.

4.5.3 Hemispherical Dome

In this illustrative example, composite response was not assumed for the dome; therefore, only nominal reinforcement is placed in dome concrete. The steel vessel carries the imposed loads including the dead load of the concrete and is designed as an MC Vessel in accordance with ASME Sec III Div. 1 Subsection NE.

The seismic forces tend to be low in the dome and, therefore, a 1" thick shell would suffice.

4.6 Material Quantities

Based upon the conceptual design, an approximate list of quantities can be made. The quantities do not include the mat and penetrations, but can serve as the basis for estimating.

Cylinder	
Steel Vessel 1½" thick	1625 Tons
Concrete 2'-6" thick	5010 c.y.
#18 hoop bars @ 8"o.c.	550 Tons
#8 vertical bars @ 12" o.c.	72 Tons
Cadweld splices	1365
Dome	
Steel vessel, 1" thick	542 Tons
Concrete (2'-0" thick)	2027 c.y.
#8 bars @ 12" o.c. E.W.	63 Tons

5. Construction Procedures

The features of this design are such that construction can be carried out in a relatively straightforward manner.

5.1 Foundation

If a mat is selected rather than an ellipsoidal shell base, the mat will in Many respects be similar to those in general use for reinforced or prestressed concrete containment structures. The differences lie in the design of cylinder; namely (1) high strength anchor bolts will be embedded in the concrete mat and will anchor the steel cylinder and (2) heavy reinforcement in the top of the mat caused by high discontinuity moments will not be required. These two features will facilitate construction.

The anchor bolts will be relatively few in number compared to the reinforcing bars requiring anchorage and to complexity of anchoring prestressing tendons. The reduction of top reinforcement in the mat will simplify the placement and a support of reinforcement and will facilitate the placement and vibration of fresh concrete.

5.2 Base Mat Liner and Steel Vessel

The installation of the base mat liner will be similar to that used in conventional concrete containments. The fabrication and erection of the vessel will be similar to an MC vessel. When compared to a liner, field erection may be somewhat longer due to the larger size welds; however, the heavier material will facilitate handling. The polar crane supported by the steel vessel may be set and used for construction and installation of interior structures and equipment.

5.3 Concrete Cylinder and Dome

Winches are set at the springline of the containment and are used to set reinforcement in the concrete cylinder. The winches are then used to slip form the concrete cylinder.

The concrete can either be pumped or additional winches can be used to lift concrete buckets. The use of winches eliminates the need for cranes and can be used to support moveable staging as required. The steel vessel has sufficient strength and stiffness to be used as a support for the polar crane, the loaded winches, and serve as an inner concrete form.

6. Conclusion

Composite containment offers both savings in material and reduced schedule and its adoption would help lower costs for the nuclear power plants. In the example, the resulting stresses were compared to the equivalent criteria of both concrete containment and MC vessels and found to be consistent with the intent of both governing codes. The result of this is a structure with greater safety margins than any of the conventional containment structures. A more consistent approach would be a revision of the concrete containment code.

References

1 Structural Analysis and Design of Nuclear Plant Facilities, Editing Board and Task Groups of the Committee on Nuclear Structures and Materials of the Structural Division ASCE, 1976 Draft Trial-Use and Comment.

2 ACI 359 - ASME Section III Division 2, Code for Concrete Reactor Vessels and Containments, 1975.

3 Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants, U.S. Nuclear Regulatory Commission, September, 1975.

4 ASME Boiler and Pressure Vessel Code General Requirements, Section III, Division 1, Subsection NA.

5 ASME Boiler and Pressure Vessel Code, Section III, Division 1, Class MC Components, Subsection NE.

Notation

D	$\frac{Et'^3}{12(1-\nu^2)}$, flexural rigidity of the steel vessel
DL	Dead Loads
E	Young's Modulus for steel
N_θ	applied meridional membrane force per unit length
N_θ'	meridional membrane force per unit length in steel vessel
N_θ''	hoop membrane force per unit length in reinforcing bars
$N_{\theta\phi}'$	membrane shear per unit length in steel vessel
N_ϕ	applied meridional membrane force per unit length
N_ϕ''	meridional membrane force per unit length in steel vessel
N_ϕ	meridional membrane force per unit length in reinforcing bars
P	internal pressure load
r	radius of steel vessel
T	temperature effects
U	$\frac{3(1-\nu^2)(t'+t'')}{r^2t'^3}^{\frac{1}{4}}$
v	$z\,\frac{(12)(1-\nu^2)}{Et'^3}$
w	radial displacement
α	coefficient of thermal expansion in steel
$\gamma_{\phi\theta}$	tangential shear strain
$\delta T'$	change in temperature of steel vessel
$\delta T''$	change in temperature of reinforcing bars
$\varepsilon\theta$	hoop membrane strain
$\varepsilon\phi$	meridional membrane strain
ν	Poisson's ratio