Accident Pressure Analysis for a Reinforced Concrete Containment with Steel Liner

Ovidiu Coman1), Daniela Coman2), Florin Kope1)

1) Stevenson and Associates, Ltd., Romania
2) Center of Technology and Engineering for Nuclear Projects, Romania

ABSTRACT

This analysis study is intended to use modern modeling and analysis techniques and current ASME BPVC Section III Div. 2 subsection CC [1] acceptance criteria to evaluate the pressure capacity, corresponding to a new target design accident pressure of 60 psi, of the containment and to meet the applicable load combination. The original design accident pressure is 55 psi. A coupled field non-linear analysis, which considers simultaneously the accident temperature and pressure load curves, was conducted. Stresses re-distribution due to the membrane and bending stiffness changes and cracked concrete conditions were considered. The increase of containment design pressure capacity from 55 psi to 60 psi, with about 9% was possible due to reduction of the liner contact pressure based on nonlinear incremental pressure and temperature analysis results.

KEY WORDS:
Containment, accident pressure, non-linear analysis, liner contact-pressure, coupled field, ASME BPVC Section III Div. 2 subsection CC.

INTRODUCTION

The reinforced concrete containment structure is composed of a base mat, a vertical cylinder and a hemispherical dome (Figure 1). The inside radius of the concrete cylindrical shell and dome is 67'-6". The cylinder wall is 4'-6" thick, while the dome is 2'-6" thick. The base mat has a diameter of 155 feet and is 10 feet thick. It bears directly on bedrock with a central reactor vessel pit projecting into the bedrock. The inside surface of the containment is completely lined with steel plate. The base slab liner is protected by two feet of concrete.
MODELING ASSUMPTIONS AND EVALUATION CRITERIA

The design basis analysis is performed using axial symmetric models for containment shell and dome and 3D shell model for the base mat. Both types of models include the entire reactor building. The reason for using the 3D shell model is that the base mat lift-off (which controls the base mat design) for non-symmetric loads cannot be modeled using an axial symmetric model with harmonic loads since this analysis requires a non-linear iterative solution.

For containment shell and dome, the seismic response is obtained using axial symmetric shell models which allows harmonic loads. For the base slab, first it was necessary to determine the seismic loads as a result of interaction with external containment wall and internal structures. The reaction forces corresponding to OBE and SSE, vertical and horizontal components were transformed in seismic loads distributed along the junction circle between the crane wall and base mat, and containment cylinder wall and base mat respectively. This loads were used in the 3D shell model considering the base mat lift-off.

A group of three models were developed for evaluation of the liner-induced pressure due to the effect of accident temperature. The first model considers elastic interaction between the liner and containment concrete wall and dome when the liner is loaded with the accident temperature. The second model considers the non-linear behavior of the reinforced concrete containment loaded with dead weight and incremental pressure up to failure. The third model considers the non-linear interaction between liner and reinforced concrete cylinder when both incremental temperature and pressure are considered (coupled field analysis). The correlation between the accident pressure and temperature is presented in Figure 2. The evaluation criteria are based on ACI 349, Code Requirements for Nuclear Safety Related Concrete Structures and 1995 ASME BPVC, Section III Division 2, Code for Concrete Reactor Vessels and Containment.

PRELIMINARY ANALYSIS RESULTS

Preliminary analysis has been performed for the following reasons:
- validation of the analysis models
- evaluation of the new target accident pressure

These results have been produced using the axial symmetric model (with and without base mat lift-off) and the M3DS three-dimensional model for dead weight and internal pressure of: 1.0 \( P_a \), 1.15 \( P_a \), 1.25 \( P_a \), and 1.5 \( P_a \), where \( P_a = 60 \text{ psi} \) and for 55 psi, also.

The comparison between results from the M3DS (Figure 3) - three dimensional and axial symmetric model (Figure 4) indicates a good agreement with the original analysis results (test condition: \( D + 1.15 \ P_a, P_v=55 \text{ psi} \)). The result of these comparisons validates both the 3D and axial symmetric models and the original design pressure analysis results.

It was observed that the most severe load combination is \( D+1.5 \ P_a + TL \). Also, the reinforcement hoop membrane stress for elevations 44 (cylindrical wall) and 115 (dome) are controlling the design. Table 1 shows these results including the reinforcement hoop membrane stress. It was concluded that the liner contact pressure contribution is
significant. Based on these conclusions, the first priority was given for the best estimation of the liner contact pressure by means of non-linear analysis technique.

Table 1. D + 1.5 P, Uplift = Yes, Primary

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<td>3.86</td>
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</tr>
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<td>6</td>
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<td>166.71</td>
<td>415.0</td>
<td>0.59</td>
<td>3.40</td>
<td>414.0</td>
<td>3.06</td>
<td>43.23</td>
</tr>
</tbody>
</table>

Figure 3 - M3DS 3D shell model

Figure 4 - M2DN Axial Symmetric model
LINER CONTACT PRESSURE ANALYSIS RESULTS

In order to understand the reinforced concrete behavior under internal pressure loading, the M2DN - axial symmetric model was used in a non-linear analysis. Reinforced concrete non-linear material properties have been used including concrete crack capability. The base mat lift-off was considered. This model was analyzed for dead weight and incremental internal pressure (load step=0.1 psi) up to 110 psi. Liner and temperature effect were not considered for this model due to convergence difficulties. Figure 4 shows the deformed shape corresponding to 110 psi. Figure 6 shows the displacement diagram (10 time units corresponds to 1 psi). The displacement diagram shows the following:

- the cracks in concrete develop from 30 psi and the membrane stiffness is reduced about 3-4 times
- the base slab uplift starts at 43 psi internal pressure
- the reinforcement general yield starts for pressure greater than 103 psi.

The results of this analysis show the reduction of stiffness, the radial and vertical displacement variations versus internal pressure and provide reinforcement stresses and strains data for each load step.

Analytical Solution for Evaluation of the Liner Contact Pressure

Description of the Problem:

A long cylinder, free at both ends, is composed of two different materials; the first material extends radially between radii \( r_1 \) and \( r_2 \), and the second one between \( r_2 \) and \( r_3 \). The first cylinder is loaded with a uniform temperature field, \( T \). A contact pressure, \( p \), will be developed between the two cylinders due to restrain of thermal expansion. The basic problem is to determine this contact pressure. The material properties of the first cylinder are \( E_s, \nu_s, \alpha_s \) (elasticity modulus, Poisson coefficient, thermal dilatation coefficient), and the material properties of the second cylinder are \( E_c, \nu_c, \alpha_c = 0 \).

The following figure shows the two cylinders:

![Figure 5 – Problem Description](image)

Solution of the Problem:

The following notation was used:

- \( \sigma_r \) - radial stress
- \( \sigma_h \) - hoop stress
- \( \sigma_z \) - meridional stress (along the cylinder generators)
- \( u(r) \) - radial displacement
- \( \varepsilon_z \) - meridional tensile strain

According to the equations from the 3D elasticity theory (applied to the axial symmetric case of the problem) we have the following solutions:

- for the internal cylinder

\[
\sigma_r = \frac{p r_1^2 - r_2^2}{r^2 \left( r_2^2 - r_1^2 \right)} - \frac{p r_2^2}{r^2 - r_1^2} \quad (1)
\]
\[ \sigma_h = \frac{p r_1^2 r_2^2}{r^2 (r_2^2 - r_1^2)} - \frac{p r_2^2}{r_2^2 - r_1^2} \]  
\[ \sigma_z = E_s (e_s - \alpha_s T) - 2\nu_s \frac{p r_2^2}{r_2^2 - r_1^2} \]  
\[ u(r) = r \left[ (1 + \nu_s) \mu_s T - \nu_s e_s \right] - \frac{r}{E_s} \left[ \left( 1 - \nu_s - 2\nu_s^2 \right) \frac{p r_2^2}{r_2^2 - r_1^2} + (1 + \nu_s) \frac{p r_1^2 r_2^2}{r_2^2 - r_1^2} \right] \]  
- for the external cylinder
\[ \sigma_r = \frac{p r_2^2 r_3^2}{r^2 (r_3^2 - r_2^2)} - \frac{p r_2^2}{r_3^2 - r_2^2} \]  
\[ \sigma_h = \frac{p r_2^2 r_3^2}{r^2 (r_3^2 - r_2^2)} - \frac{p r_2^2}{r_3^2 - r_2^2} \]  
\[ \sigma_z = E_c \varepsilon_s + 2\nu_c \frac{p r_2^2}{r_3^2 - r_2^2} \]  
\[ u(r) = -r \nu_c \varepsilon_s + \frac{r}{E_c} \left[ \left( 1 - \nu_c - 2\nu_c^2 \right) \frac{p r_2^2}{r_2^2 - r_1^2} + (1 + \nu_c) \frac{p r_1^2 r_2^2}{r_2^2 - r_1^2} \right] \]  

Eq. (1) ... (8) do not completely solve the problem unless \( p \) and \( \varepsilon_s \) are known. These unknown values are determined when imposing the following conditions:

1. The axial tensile force is zero (the cylinder is practically free at both ends).
2. The displacement \( u(r) \) is the same at the interface between the two cylinders.

The first condition can be written as:
\[ \int_{r_1}^{r_2} r \sigma_x dr + \int_{r_1}^{r_2} r \sigma_x dr \]  
and the second:
\[ u(r) \bigg|_{r=r_2} \text{ (from Eq. (4))} = u(r) \bigg|_{r=r_2} \text{ (from Eq. (8))} \]

Taking into account Eq. (3), (4), (7), (8), the two Eq. (9) and (10) lead to the following system of equations:
\[ \varepsilon_s \left( 1 + \frac{E_s r_3^2}{E_s r_2^2 - r_1^2} \right) - \frac{2\nu_s (\nu_s - \nu_c) r_2^2}{E_s (r_2^2 - r_1^2)} = \alpha_s T \]  
\[ \varepsilon_s (\nu_s - \nu_c) + p \left[ \frac{(1 - \nu_s - 2\nu_s^2) r_2^2}{E_s (r_2^2 - r_1^2)} + (1 + \nu_c) \frac{r_2^2}{E_s (r_2^2 - r_1^2)} \right] = (1 + \nu_s) \mu_s T \]

We define:
\[ \beta = \left( \frac{r_1}{r_2} \right)^2 \gamma = \left( \frac{r_1}{r_2} \right)^2 \lambda = \frac{E_s}{E_s} \frac{\gamma - 1}{1 - \beta} \]  
\[ A = (1 + \nu_s) \left( 1 + \lambda \right) - (\nu_s - \nu_c) \]  
\[ B = 2(\nu_s - \nu_c)^2 + \frac{4 + \lambda}{\lambda} \left[ \left( 1 - \nu_s - 2\nu_s^2 \right) + (1 + \nu_c) \right] + \left[ \left( 1 - \nu_s - 2\nu_s^2 \right) + (1 + \nu_c) \right] \]

The solution of system (11) leads to the following relation for the contact pressure:
\[ p = E_s \alpha_s T (1 - \beta) \frac{A}{B} \]
Numerical results:

The following data, specific to the containment structure, has been considered:

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Liner</th>
<th>Concrete</th>
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</thead>
<tbody>
<tr>
<td>$r_1 = 67.46875'$</td>
<td>$E_s = 4.176 \times 10^6$ kp/ft$^2$</td>
<td>$E_c = 4.5 \times 10^5$ kp/ft$^2$</td>
</tr>
<tr>
<td>$r_2 = 67.50'$</td>
<td>$\nu_s = 0.30$</td>
<td>$\nu_c = 0.15$</td>
</tr>
<tr>
<td>$r_2 = 72.00'$</td>
<td>$\alpha_s = 6.50 \times 10^{-6}$ 1/°F</td>
<td>$\alpha_c = 0$</td>
</tr>
<tr>
<td></td>
<td>$T = 283.75 - 70 = 213.75 \degree$ F</td>
<td></td>
</tr>
</tbody>
</table>

The contact pressure was computed for ten cases - for $E_c^{(k)} = E_c/k$ where $k=3,4$, corresponding to cracked condition, according to Eq. (15). The results are the following (psi):

- $p_3 = 22.494$
- $p_4 = 21.379$

The main conclusion is that it is necessary to perform a non-linear analysis with both incremental temperature and pressure. This analysis considers as an initial strain and stress conditions the results of the current load step for the next load step together with non-linear behavior of the concrete material and reinforcement steel.

Using analytical relations, the obtained equivalent pressure is 21.37 psi for DT=213.75 °F, fact which confirms the F.E linear analysis results. For an equivalent pressure of 23, psi the liner compression hoop stress reaches the yield limit. The elastic linear analysis fails to capture the phenomenon that a portion of the thermal strains is balanced by the internal pressure effect. The 21-22 psi value does not consider this effect. Even if the concrete elasticity modulus is reduced, this results in only a minor reduction of the contact pressure using elastic analysis.

The M2DNR model was used in order to capture the liner - containment wall interaction under both temperature and pressure incremental loads. M2DNR is an axial symmetric 1 ft. wall ring model: liner, reinforcement, and concrete were modeled using non-linear material properties. The model was loaded with both incremental pressure and temperature. Material non-linearity, including cracking capability, was considered. The results consist in radial displacement and hoop stress in the liner. Due to the temperature effect, the liner induces additional pressure and the concrete cracking starts from 30 psi (24 psi produced by internal pressure + 6 psi due to liner contact pressure TL), which is consistent with the results produced by M2DN model). The hoop reinforcement stresses are given in Table 1. Figure 7 shows the variation of the liner compressive hoop stress due to both temperature and pressure:

- starting with 24 psi internal pressure and corresponding temperature the concrete cracks are developed reducing the containment stiffness.
- The maximum compressive stress in liner was obtained about 55 psi and T=280 °F.
- After this pressure, the compressive stress in the liner starts to decrease.
- At 97 psi the liner hoop stress is zero because the temperature effect is balanced by the pressure effect.

<table>
<thead>
<tr>
<th>R ft</th>
<th>Elev. ft</th>
<th>Axial Stress Ksi</th>
<th>Axial Strain</th>
</tr>
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<td>1.0332</td>
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<td>66.410</td>
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<td>25.750</td>
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<tr>
<td>2.400</td>
<td>166.710</td>
<td>11.4168</td>
<td>3.94250E-04</td>
</tr>
</tbody>
</table>

Table 1. Element results for zone = RF1  non-linear analysis time=901.00, P = 90 psi
SUMMARY AND CONCLUSIONS

The containment pressure analysis results show the followings:

- The increase of containment design pressure capacity from 55 psi to 60 psi, with about 9% is possible due to reduction of the TL the liner contact pressure based on nonlinear incremental pressure + temperature
analysis results. This can be explained by the fact that the non-linear analysis considers the membrane and bending stiffness changes when the concrete is cracked. One important result from these analyses is that for a containment pressure of 90 psi the hoop reinforcement stress is close but still below 0.9f_y.

- The load combination which controls the design is D + 1.5P_a + TL (Figure 7). The seismic loads corresponding to the new seismic conditions (approximately two times greater than the original design) are not controlling the pressure capacity of the containment.
- The reinforcement tensile stress limit of 45 Ksi (0.9f_y) is reached for the hoop reinforcement in the cylindrical wall at elevation + 44 ft. and in the area of connection between the dome and cylindrical wall, Elev., 98-115. 79 ft.
- The base slab results show a higher pressure capacity. This can be explained by the fact that the effect of the internal structure, which stiffens the base slab, was considered.
- For the containment wall and dome, the temperature gradient effect increases the tensile stress for the external reinforcement layers. The membrane stress must be in equilibrium with internal pressure, so the maximum reinforcement stress for external layer exceeds 0.9f_y, but is less than f_y and the membrane stress does not exceed 0.9f_y. Obviously, the maximum reinforcement strain does not exceed 2ε_y.
- We can conclude that for the new target accident pressure P_a=60 psi, the reinforcement stresses and strains are less than the code allowable for all check points and applicable load combinations.

REFERENCES