

## Progression of Stress Development in Pressurized Containment Structures

M.A. Daye, B.L. Meyers

*Bechtel Power Corporation, 15740 Shady Grove Road, Gaithersburg, Maryland 20877-1454, U.S.A.*

### Abstract

The evaluation of BWR and PWR containment structures subjected to internal pressure is presented. Failure modes and locations, at yield and ultimate stresses for each component material are identified. Pressure levels corresponding to yield and ultimate stresses of the liner plate, reinforcing steel and stressing tendons for the dominant failure mode are established. Comparisons between the results of hand computations, using fundamental equilibrium equations, and finite element analysis are made. The results indicate close agreement between hand computations and finite element analysis.

### 1. Introduction

The containment structure is designed to house the nuclear steam supply system and limit the release of radioactive material to the environment during normal operation and in the event of accidents. The structure also provides protection to the reactor system from the effects of severe and extreme environmental loads such as tornados and external accidents. The subject of this paper is to evaluate containment structural behavior associated with accidental increase in internal pressure. Two types of concrete containments are evaluated: 1) that used to house a Boiling Water Reactor System (BWR), and 2) a Pressurized Water Reactor System (PWR).

Under internal pressure, a number of failure modes may initiate, each corresponding to a different pressure level. The evaluation identifies the location for the dominant failure mode associated with the lowest pressure level, and the stress progression at that location resulting from increased internal pressure up to the ultimate capacity.

### 2. Description of Reactor Containment Structure

In general, the containment structure for either the BWR or the PWR System consists of a flat reinforced concrete slab, an upright concrete cylinder and a concrete dome. All internal surfaces of both containment types are lined with 1/4 inch thick steel plates anchored to the concrete. The major difference between the BWR containment and the PWR containment is the reinforcing system in the cylinder and dome. Reinforced concrete is generally used for the BWR containment and prestressed concrete is generally used for the PWR containment. This difference is the result of the accident design pressure specified for each system. The accident pressure for the BWR is on the order of one to two bars,

and the accident pressure for the PWR is approximately three to five bars. Figure 1 shows the general configuration for the containments considered in this evaluation.

### 3. Failure Modes

One of the primary loadings on the containment structure is internal pressure. Failure under such loading may occur due to different types of stress (i.e., membrane, bending or shear) and at different locations in the structure. A number of such failure modes may be postulated for each containment structure. Each mode results from a different mechanism, occurs at a different pressure level and is a function of the capacity and structural configuration of the system at the critical location. In order to evaluate the capacity of a given containment, the pressure associated with each postulated failure mode is determined. The failure mode occurring at the lowest pressure level is considered to be the governing failure mode.

Although the containments for the BWR and PWR systems are somewhat different in design and pressure capacities, experience has shown that under the combination of dead load and internal pressure, failure modes develop which are similar in nature and at approximately the same locations. Therefore, both containment systems are investigated for similar failure modes listed in Table I.

All failure modes are evaluated by equating the maximum force a section can sustain at a specified stress level to the force developed as the result of internal pressure. The force on the section due to internal pressure is computed using mechanics of materials and thin shell theories. A closed form solution was developed for each failure mode by directly relating internal pressure to section capacity. Formulae developed for the postulated failure modes are shown in Table I. Failure in the BWR reinforced concrete containment is assumed to occur when the stress in the reinforcing steel has reached its specified yield limit. The PWR prestressed concrete containments are assumed to fail when either the reinforcing steel or the prestressing tendons reach the specified yield limit, whichever occurs first. The computed pressure capacity corresponding to each failure mode for both containment types are given in Table II. Section properties used in this analysis are given in Figure 1 and Table III.

It can be seen from the pressure values given in Table II that the lowest pressure capacity in each case corresponds to the cylinder failure mode due to membrane force in the hoop direction. Therefore, this mode is considered as the dominant mode.

### 4. Component Stress Levels Versus Internal Pressure

The state of stress for the dominant failure mode can be investigated by relating the pressure capacity and critical stresses in the liner plate, reinforcing steel and prestressing tendons. Such comparisons are made for the conditions listed in Table IV.

The actual yield stress for the reinforcing steel is based on the average of test results for the steel used in construction of the containments.

The pressure and stress levels are computed utilizing the closed form solution corresponding to the dominant failure mode (Equation 1 in Table I). The results are given in Table IV.

5. Closed Form Solution Versus Finite Elements Results

In order to determine the validity of the results obtained using the closed form solution, a comparison between these results and results obtained from computer finite element analyses were performed. The available computer results are in the form of reinforcing steel stresses and associated pressure levels. Since the design pressure for each containment is different, comparisons were made for sets of pressure levels associated with each containment. The results shown in Table V indicate a very close agreement between the two approaches.

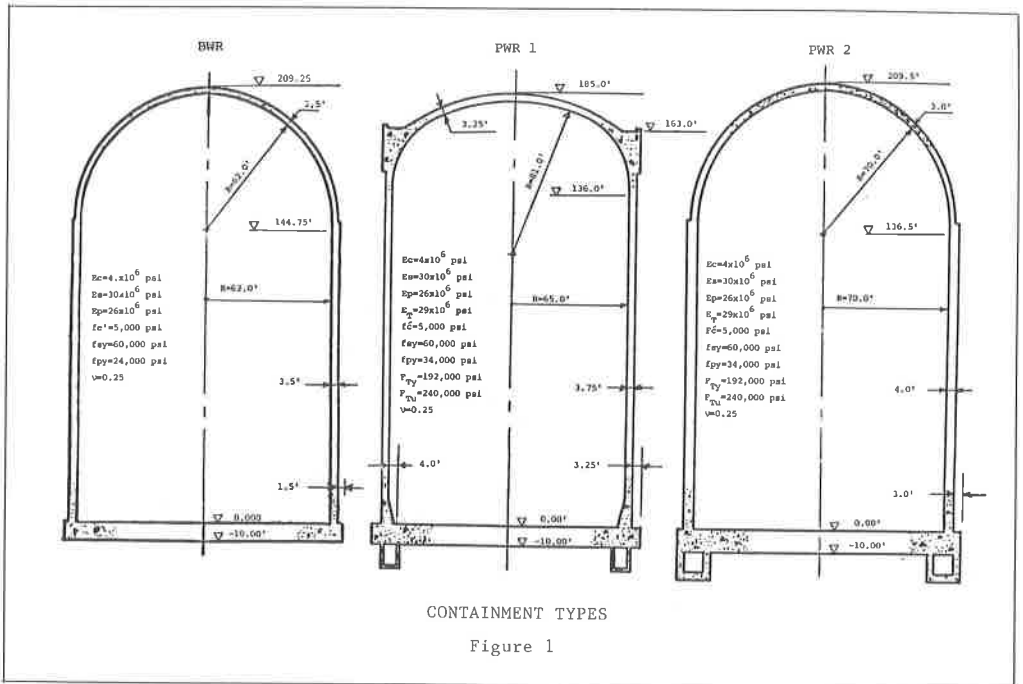
6. Conclusions

Three typical concrete containment structures were investigated using simple closed form solutions to determine their behavior under internal pressure. These solutions were compared to computer finite element analyses. The agreement was excellent.

The evaluation indicates that the dominate mode of failure under internal pressure is a membrane failure in the hoop direction of the upright cylinder. The ultimate capacity of each containment is about three times its design capacity based on minimum allowable material stress. If actual material properties are used, ultimate capacity can generally be increased.

The strains developed at the ultimate pressure capacity of the containment are within the strain limits of the liner plate material. Thus, significant leakage is not expected to develop during the short period the structure is subjected to accidental internal pressure increase.

The paper has demonstrated that expected structural behavior of containment structures can be accurately predicted using simple hand calculations.



LIST OF NOTATIONS

Gross area of considered section in in<sup>2</sup> (for unit width of 1 inch (Ag=t))

Ag	Inside, outside and diagonal reinforcing steel areas in in <sup>2</sup> /in
As, As', Ad	Area of liner plate in in <sup>2</sup> /in
Ap	Area of prestressing tendon in in <sup>2</sup> /in
At	Concrete section depth to tension steel in inches
d	Concrete section depth to compression steel in inches
d'	Modulus of elasticity for concrete, reinforcing steel, liner plate, and prestressing tendons respectively in psi
Ec, Es, Ep, Et	Reinforcing steel and liner plate stresses respectively in psi
fs, fp	Specified concrete compressive strength in psi
f'c	Specified yield stresses for reinforcing steel and liner plate respectively in psi
fsy, fpy	Initial effective stress in prestressing tendons in psi
Fi	Stress in prestressing tendon in psi
Ft	Specified yield and ultimate stresses for prestressing tendons in psi
F <sub>Ty</sub> , F <sub>Tu</sub>	Stress on section due to dead weight of structure above in psi
LD	Containment internal pressure in psi
P	Equivalent external pressure on containment cylinder and dome applied by the prestressing tendons in psi
Pi	Containment ultimate pressure capacity in psi
Pu	Radius from center of personnel lock to edge of opening in inches
Z	Radius from center of personnel lock to section considered in inches
Z <sub>1</sub>	Inside radius of cylinder or dome in inches
R	Radius from center to outer edge of basement in inches
R'	Radius from center of basement to section considered in inches
RI	Spacing between shear reinforcement steel in inches
s	Total thickness of concrete dome, cylinder or basement in inches
t	Strain on section from position at zero load in in/in
ε	Strain on section due to deadload and prestressing force at P=0. in in/in
ε <sub>1</sub>	Poisson ratio for concrete
v	

Table 1  
CLOSED FORM EQUATIONS FOR FAILURE MODES

1. Cylinder failure due to membrane force in hoop direction	$P = \frac{R}{s} \left\{ (As+As'+Ad) Es \epsilon + (Ag Ec \epsilon) + Ap Ep \epsilon + A_m E_m' (\epsilon+\epsilon_1) + A_m E_1 \right\}$ $\epsilon = \frac{Es}{Es} = \frac{EP - F_i}{E_t} - \epsilon_1, \quad \begin{matrix} C Es < Epy \\ C Ep < Epy \\ C E_m < E_m' \end{matrix} \quad \begin{matrix} FI \\ FI \\ FI \end{matrix} \begin{matrix} P \\ P \\ P \end{matrix} \begin{matrix} \epsilon \\ \epsilon \\ \epsilon \end{matrix} \begin{matrix} EC \\ EC \\ EC \end{matrix}$
2. Basement failure due to radial moment near cylinder base	$P = \frac{32}{R^2} \left\{ As fs (s-d') + Ap Ep (t-d') \right\}$
3. Dome failure due to membrane force at 45° above spring line	$P = \frac{R}{s} \left\{ (As+As') Es \epsilon + (Ag Ec \epsilon) + Ap Ep \epsilon + A_m E_m' (\epsilon+\epsilon_1) + A_m E_1 \right\}$
4. Cylinder failure due to shear near personnel lock	$P = \frac{4\sqrt{f'c} d - 4B}{2k_1 + 500 Ag} \sqrt{f'c} d \left\{ \frac{Av f_{sy} d}{s t^2 / 2t_1} \right\} + \frac{Av f_{sy} d}{s t^2 / 2t_1}$
5. Cylinder failure due to shear at base	$P = 4(1+LD/500) \sqrt{f'c} d - \frac{4R/2}{500 Ag} \sqrt{f'c} d \left\{ \frac{Av f_{sy} d}{s \sqrt{Rt} / \sqrt{3(1-\nu^2)}} \right\} + \frac{Av f_{sy} d}{s \sqrt{Rt} / \sqrt{3(1-\nu^2)}} + P_i$ $P_i = F_i A_m / R$
6. Cylinder failure due to membrane force in meridional direction near spring line	$P = \frac{R}{s} \left\{ (As+As'+Ad) Es \epsilon + (Ag Ec \epsilon) + Ap Ep \epsilon + A_m E_m' (\epsilon+\epsilon_1) + A_m E_1 \right\}, \quad \epsilon_1 = c_1 + \frac{LD}{2C}$
7. Cylinder failure due to meridional moment at base	$P = \frac{2\sqrt{3(1-\nu^2)}}{R} \left\{ C_s \left( d - \frac{s}{2} \right) + C_s (d - d') \right\} + P_i, \quad P_i = F_i A_m / R$ $C_s = \left\{ fs - f'c - \frac{Es}{EC} \right\} \left( LD - \frac{PR}{2C} \right) As'$ $C_c = As fs + Ap fp + \left\{ \frac{Es}{EC} As + \frac{Ep}{EC} Ap \right\} \left( LD - \frac{PR}{2C} \right) - C_s$ $\# = \frac{C_c}{f'c - \left( LD - \frac{PR}{2C} \right)}$

\*The term (Ag Ec ε) is used only when concrete is in compression  
\*\*Applicable to failure modes 3, 4, and 6

Table II  
CONTAINMENT PRESSURE CAPACITIES  
AT YIELD OF FAILURE MODES

Containment Type	Failure Mode						
	1	2	3	4	5	6	7
BWR	55	83	63	78	79	80	81
PWR 1	127	140	271*	681	168	154	167
PWR 2	138*	140	156*	528	149	161*	163

\*Tendon Yield Controls

Table III  
SECTION PROPERTIES

Containment Type	Failure Mode						
	1	2	3	4	5	6	7
BWR	As=0.333	As=0.27	As=0.068	Av=0	Av=0.0517	As=0.222	As=0.4
	As'=0.222	Ap=0.25	As'=0.222	r=60	Ag=41.75	As'=0.068	As'=0.222
	Ad=0.03	R1=708	Ap=0.25	r <sub>1</sub> =120	d=41.75	Ap=0.25	Ap=0.25
	Ap=0.25	d=95		Ag=41.75	s=12	Ad=0.03	d=32.5
	λ <sub>T</sub> =0.	d'=6		d=41.75	LD=200	LD=111	d'=8
							LD=200
PWR 1	As=0.141	As=0.22	As=0.173	Av=0.055	Av=0.0828	As=0.141	As=0.42
	As'=0.141	Ap=0.25	As'=0.083	r=64	Ag=45	As'=0.141	As'=0.4
	Ad=0.	R1=672	Ap=0.25	r <sub>1</sub> =128	d=38	Ap=0.25	Ap=0.25
	Ap=0.25	d=112	λ <sub>T</sub> =0.4217	s=11.5	s=12	λ <sub>T</sub> =0.175	t=69
	λ <sub>T</sub> =0.3939	d'=8	Fi=130,000.	Ag=45	t=45	Fi=130,000.	d=64
	Fi=120,000.		R=780	d=38	LD=202	LD=63	d'=5
				Fi=120,000.		Fi=120,000.	
				λ <sub>T</sub> =0.3939		λ <sub>T</sub> =0.3939	
PWR 2	As=0.112	As=0.483	As=0.0513	Av=0.050	Av=0.05	As=0.0183	As=0.366
	As'=0.13	Ap=0.25	As'=0.0833	r=66	Ag=48	As'=0.130	As'=0.333
	Ad=0.	R1=780	Ap=0.25	r1=115	d=40	Ap=0.25	Ap=0.28
	Ap=0.25	d=112	λ <sub>T</sub> =0.26	s=12	s=12	λ <sub>T</sub> =0.26	t=48
	λ <sub>T</sub> =0.484	d'=8	Fi=140,000.	Ag=48	t=48	Fi=133,000.	d=40
	Fi=132,000.			d=40	LD=199	LD=87	d'=4
				Fi=132,000.		Fi=132,000.	
				λ <sub>T</sub> =0.484		λ <sub>T</sub> =0.484	
							LD=200

Note: Additional parameters may be obtained from Figure 1.  
For units not shown, see List of Notations.

Table IV  
STATE OF STRESS UNDER INCREASED INTERNAL PRESSURE

Section Condition	BWR			PWR 1				PWR 2			
	P psi	f <sub>p</sub> ksi	f <sub>s</sub> ksi	P psi	f <sub>p</sub> ksi	f <sub>s</sub> ksi	F <sub>T</sub> ksi	P psi	f <sub>p</sub> ksi	f <sub>s</sub> ksi	F <sub>T</sub> ksi
Design Pressure	17	14	16	50	-2	-2	126	60	-2	-2	138
Reinforcing Steel Design Allowable Stress	32	26	30	98	26	30	157	114	26	30	170
Tendon Design Allowable Stress	-	-	-	111	34	42	168	112	24	28	168
Liner Plate Specified Yield Stress	35	24	36	115	34	47	173	124	34	39	179
Reinforcing Steel Specified Yield Stress	55	24	60	*	-	-	-	*	-	-	-
Reinforcing Steel Actual Yield Stress	65	24	72	*	-	-	-	*	-	-	-
Tendon Specified Yield Stress	-	-	-	130	34	60	192	138	34	60	192
Tendon Specified Ultimate Stress	-	-	-	154	34	60	240	166	34	60	240

$\frac{P_u}{P} = 3.8$                        $\frac{P_u}{P} = 3$                        $\frac{P_u}{P} = 2.8$

\* Tendon Yield Controls

Table V  
COMPARISON OF RESULTS  
USING CLOSED FORM SOLUTION VS. COMPUTER F.E. METHODS

BWR			PWR 1			PWR 2		
P psi	Reinf. Steel Stress, ksi		P psi	Reinf. Steel Stress, ksi		P psi	Reinf. Steel Stress, ksi	
	Formula	Computer		Formula	Computer		Formula	Computer
56	61	60	50	-1.8	-1.6	60	-2.4	-2
67	75	72	63	-0.4	-0.2	69	-1.4	-1.1
-	-	-	75	7.4	9.4	75	-0.7	-0.4
-	-	-	-	-	-	90	8	9