MARK III Containment Vessel/Annulus Concrete Design

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SUMMARY

Recently, engineers have been considering the significant dynamic impact of safety/relief valve (S/RV) discharge loads on the containment structures, safety related equipment, and piping systems in boiler water reactor nuclear power plants. For a plant in the construction stage, extensive modifications will be made to qualify these new loads. The lower portion of the containment vessel serves as a suppression pool pressure boundary and is designed to sustain the effects of postulated loss of coolant accidents, seismic occurrences, S/RV discharge loads, and other effects. Extremely high spectral peak accelerations of the free-standing steel containment vessel can be obtained during the air clearing process of the S/RV discharge. Parametric studies indicated that a substantial reduction in response can be obtained by increasing the stiffness of the steel containment vessel in the lower area. A concrete backing configuration in the suppression pool area of Mark III Containment is proposed in this paper. A composite action is assumed between the steel containment vessel shell and the concrete section.

The system is physically separated from the shield building. This approach warrants an early erection of the shield building and a late installation of piping systems in the containment vessel suppression pool area. Finite element analyses are performed by using ASHSD2 and EASE2 computer codes. The results of the analyses have shown the proposed stress criteria are satisfied. The approach presented is justified to be a workable system for a new plant design.

1.0 INTRODUCTION

Boiler water reactor nuclear power plants are equipped with safety/relief valves (S/RV) in the nuclear steam supply system to protect against overpressurization. S/RV discharge loads occur during the actuation of the S/RV. These loads are expressed in terms of a pulsating pressure originating at the ends of the S/RV discharge lines and impinging on the suppression pool boundary.

Prior to the lifting of a relief valve, the downstream piping between the S/RV discharge and the water surface is filled with air. The discharge piping terminates in the suppression pool with the water level inside the pipe at the same level as the water level in the suppression pool. When a relief valve lifts, the effluent reactor steam causes a rapid pressure buildup in the discharge pipe. This rapid compression of the column of air in the pipe causes a subsequent acceleration of the water slug in the submerged portion of the pipe. As the highly compressed air exits, it immediately begins to expand to the lower receiver pressure, displacing the water and propagating a pressure disturbance throughout the suppression pool. The air bubble-water mass system is capable of oscillating until all the air has left the pipe and is fully expanded. The sequence of expansion and contraction is repeated with identifiable frequencies until the bubbles reach the pool surface.

A typical section view of General Electric Company, BWR Mark III containment nuclear power plant is shown on Figure 1. A standard Mark III containment design also uses quenchers to minimize suppression pool boundary loads resulting from the S/RV discharge air clearing phenomena. A Mark III S/RV discharge line and quencher in the suppression pool is shown on Figure 2. S/RV discharge piping routed to the suppression pool is arranged for uniform distribution of air clearing loads as well as pool thermal mixing.

The number of S/RVs that will open during a reactor pressure transient could be from 1 to 19 valves. This can be shown for situations where various reactor power levels are assumed when the transient event is initiated. Therefore, the pool boundary structures must be able to withstand any number of valves discharging at a given moment. The S/RV discharge loads on structures can be evaluated for asymmetrical and symmetrical cases. In both cases, dynamic effects can generate significant structural responses for the entire reactor building in the horizontal and the vertical directions. The responses result either from directly applied pressure field or from base excitation of the soil-structure interaction caused by the loads acting on the mat. An idealized quencher bubble pressure oscillation forcing function is shown on Figure 3.

2.0 DESIGN OPTIONS

Critical motions are generated in the lower portion of the containment vessel where the S/RV loads are directly applied. Parametric studies indicated that increasing the stiffness of the containment in the suppression pool area can reduce the responses of the structures. The following three options were discussed by Goozman and Jan.[1]

(1) Adding steel stiffeners to the steel containment shell.

(2) Steel or concrete bracing of the steel containment against the shield building.

(3) Filling the annulus between the steel containment and shield building with concrete.

For a new plant design, adding steel stiffeners to increase the containment shell stiffness is not very attractive, since insufficient dynamic response reduction can be obtained. In addition to the rather expensive operations of welding, fabrication, and erection, the embedment design is not a simple task.

Options 2 and 3 provide a large increase in the stiffness of the containment and a substantial reduction of the structural responses, and fluid-structure interaction effects. The jurisdictional boundaries of the ASME Boiler and Pressure Vessel Code become a major concern. The shield building has to be designed for direct pressure impingement and the lower part of the shield building needs to be upgraded to ASME Code, Section III, Division 2 design. The shield building structure may be subjected to only minor effects due to these new loads, but the high energy piping which is anchored at the middle part of the shield building will be subjected to a rather substantial increase of base motion.

3.0 SYSTEM DESCRIPTION

A different type of design approach is presented herein using reinforced concrete backing in the suppression pool area with an approximate height equal to the suppression pool depth. The area is defined as the zone in which the steel shell and the reinforced concrete backing work together to support the design loads. The configuration of the containment/annulus concrete is shown on Figure 4. The concrete backing is separated from the shield building by a 2-inch gap filled with seismic separation material. The concrete and steel containment shell are designed as a composite structure and are anchored to the foundation mat. The cylindrical steel containment shell has circumferential external stiffener rings which serve as shear transfer devices for a complete composite action.

4.0 CODE COMPLIANCE

The containment vessel, head, and any portion of the shell embedded in the concrete foundation mat or backed by reinforced concrete are designed, fabricated, erected, inspected, and tested in accordance with Subsection NE, Section III, Division 1 of the ASME Boiler and Pressure Vessel Code. The reinforced concrete backing in the suppression pool area is designed in accordance with the rules of the ASME Code, Section III, Division 2.

The ASME Code, Section III, Division 1 and Division 2 do not specifically deal with a composite concrete-steel shell configuration. Article CC-3120 of Division 2 states that, "the liner shall not be used as a strength element;" but it also states that, "the interaction of steel liner with the concrete containment be considered in determining maximum strains." It is quite clear, in Section III, Division 2, that the principal structural member is the reinforced concrete section. Ignoring the structural load carrying capacity of the thin steel shell liner will not jeopardize the accuracy of the containment analysis. However, the configuration proposed in this paper has a thick steel shell containment backed by concrete and the interaction of the steel and concrete is significant; not only in terms of strains but also the resulting stresses. The containment vessel steel is treated as an integral part of the reinforcing system for the concrete-steel shell section. The resulting stresses of the steel shell obtained from composite section analysis comply with the reinforcement stress limit requirements of Section III, Division 2 of the ASME Code. These resulting stresses are then treated as membrane stresses for the vessel steel and combined with other shell stresses, the results comply with the stress intensity limits of Section III, Division 1 of the ASME Code.

5.0 LOADS AND LOAD COMBINATIONS

The loads and load combinations for the steel containment vessel shell are developed from Article NE-3110 of Section III, Division 1 of the ASME Code and are in agreement with the provisions for NRC Regulatory Guide 1.57, "Design Limits and Loading Combinations for Metal Primary Reactor Containment System Components." The loads and load combinations specified for the design of the reinforced concrete backing are those provided by paragraph CC-3230, Table CC-3230-1, of the ASME Code, Section III, Division 2. The critical load combinations are presented on Table 1.

6.0 METHOD OF ANALYSIS

The analyses were performed using an axisymmetric finite element model and an ASHSD2 computer program for all applied loads except temperature effects. Thermal loads were analyzed using an EASE2 computer code. General descriptions of the containment vessel steel shell, the anchorage rings, and the annulus concrete section are presented as follows.

(1) ASHSD2 Computer Model. The axisymmetric ASHSD2 computer model is shown on Figure 5. The steel containment vessel and attachments are modeled as shell elements and the annulus concrete section is modeled as quadrilateral elements. Thirteen different material properties were used in the analyses. The anchorage rings are rigidly connected to the steel vessel at one end and the concrete at the other end. The concrete is connected to the steel vessel with orthotropic shell elements where the anchorage rings are located. To minimize the cost of analysis of the natural frequencies mode extraction, the effective masses for the vessel dome and the polar crane are made very small. This assumption raises the eigenvalues of the dome above the breathing modes of the lower shell without affecting the accuracy of the eigenvalues generated. These natural frequency values were used to determine the corresponding dynamic load factors for the S/RV discharge pressures, the steam condensation oscillation loads, and response spectra analysis of seismic and S/RV base excitations.

(2) EASE2 Model. The EASE2 computer model of the containment vessel and annulus concrete is shown on Figure 6. The model includes a slice of the structure which corresponds to a 12-inch steel vessel arc length, and consists of annulus concrete and containment vessel shell up to an elevation of 50 feet above the composite section. The steel vessel and attachments are modeled as shell elements. The concrete section is modeled as solid brick elements which are connected to the shell by beam elements. Axisymmetric boundary conditions are imposed on the entire model about its global axes. Linearly varying thermal gradients are input for all thermal load analyses.

All static, dynamic, and thermal analyses results from the computer programs were combined as described in Table I. The stress resultants were converted to the associated normal forces and flexure bending moments. The containment vessel steel shell is treated as a part of the reinforcing system when evaluating the composite action. The conventional reinforced concrete design approaches are applied to obtain the final stresses for the concrete, reinforcing bar, rings, and vessel shell. The calculated stresses are compared with code allowable stresses and satisfactory results are obtained. Table II presents the natural frequencies output from ASHSD2 computer model for tangential and radial vibratory modes.

Code allowable stresses are given in Tables III through VI.

7.0 CONCLUSION

The design and analysis are presented for a proposed configuration of BWR Mark III containment in the suppression pool area subject to S/RV discharge loads. The system uses concrete backing in the lower part of the containment vessel which is separated from the shield building. This approach reduces the containment responses to a reasonable level for design of the structure, safety related equipment, and piping systems.

The results of this analysis have shown that the stress criteria are satisfied for all components. The study did not include the effects of a containment anchor at the top of the composite section. However, when the final configuration of this joint is determined it will be necessary to consider the local stresses and provide the additional reinforcement as may be required.

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/3/ ASME Boiler & Pressure Vessel Code, Section III, Division 2, Article CC-3000, 1977 Edition with Summer 1977 addenda.

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/6/ Baker, E. H., "Structural Analysis of Shells," McGraw-Hill Book Company.

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TABLE I. LOAD COMBINATIONS FOR THE CONTAINMENT

Structural Component	Condition	Loads: Dead	Live	Pressure	Hydrostatic	Concrete Pouring	Piping Mechanical	Seismic	S/RV	Pipe Break	Thermal
Vessel Steel and Attachments	Normal Operating	X	X	X	X	X	X	X	X		X
	Long-Term Design	X	X	X	X	X	X	X	X		X
	Design with Pipe Break	X		X	X	X	X	X	X	X	X
Concrete	Service	X	X	X	X	X	X	X	X		X
	Factored Abnormal/ Severe	X	X	X	X	X	X	X	X		X
	Factored Abnormal	X	X	X	X	X	X		X		X

TABLE II. NATURAL FREQUENCIES OF THE SYSTEM

Mode No.	Natural Frequency (HZ) Tangential	Radial
M = 1	6.59	25.07
M = 2	17.84	27.29
M = 3	21.39	27.82
M = 4	22.01	28.14
M = 5	22.73	28.48

TABLE III. VESSEL STEEL SHELL AND ATTACHMENT STRESS INTENSITY LIMITS

Stress Limits	Operating Conditions	Design Condition With OBE	Design Condition With SSE
Primary Stresses			
General Membrane P_M	S_M	S_M	1.2 S_M or S_Y [2.]
Local Membrane P_L	1.5 S_M	1.5 S_M	1.85 S_M or 1.5 S_Y [2.]
Bending & Local Membrane $P_B + P_L$	1.5 S_M	1.5 S_M	1.85 S_M or 1.5 S_Y [2.]
Primary & Secondary Stresses	3 S_M	N/A	N/A

Notes: 1. S_M is 19.3 ksi for SA-516-70 at temperature of 185 F.
2. The greater of two limits govern.
3. Use 50 per cent of the values for attachment weld.

TABLE IV. ALLOWABLE STRESSES OR REINFORCING STEEL[1.] (ksi)

Load Condition	Primary Compression	Primary Tension	Primary + Secondary Compression	Primary + Secondary Tension
Service Load				
Steel Vessel	17.6	17.6	23.5	23.5
Rebar	30	30	40	40
Factored Load				
Steel Vessel	32	32	32	32
Rebar	54	54	54	54

Notes: 1. fy for steel vessel is 35.2 ksi at temperature of 185 F; fy for rebar is 60 ksi.

TABLE V. ALLOWABLE CONCRETE SHEAR STRESSES[1.] (ksi)

Load Condition	Primary Tangential	Primary Radial	Primary + Secondary Tangential	Primary + Secondary Radial
Service Load [2.]	0.08	0.11	0.11	0.15
Factored Load	0.16	0.22	0.16	0.22

Notes: 1. Values shown based on fc' = 4.0 ksi.
2. 50 per cent of the values given for factored primary loads, and 67 per cent of the values given for factored primary plus secondary loads.

TABLE VI. ALLOWABLE CONCRETE COMPRESSIVE STRESSES[1.]. (ksi)

Load Condition	Primary Membrane	Primary Membrane + Bending	Primary + Secondary Membrane	Primary + Secondary Membrane + Bending
Service Load [2.]	1.2	1.8	1.8	2.4
Factored Load	2.4	3.0	3.0	3.4 [3.]

Notes: 1. Values shown based on fc' = 4.0 ksi.
2. Use 1.6 ksi for load combination which includes Eo.
3. Corresponds to a limiting strain 0.002 in./in.

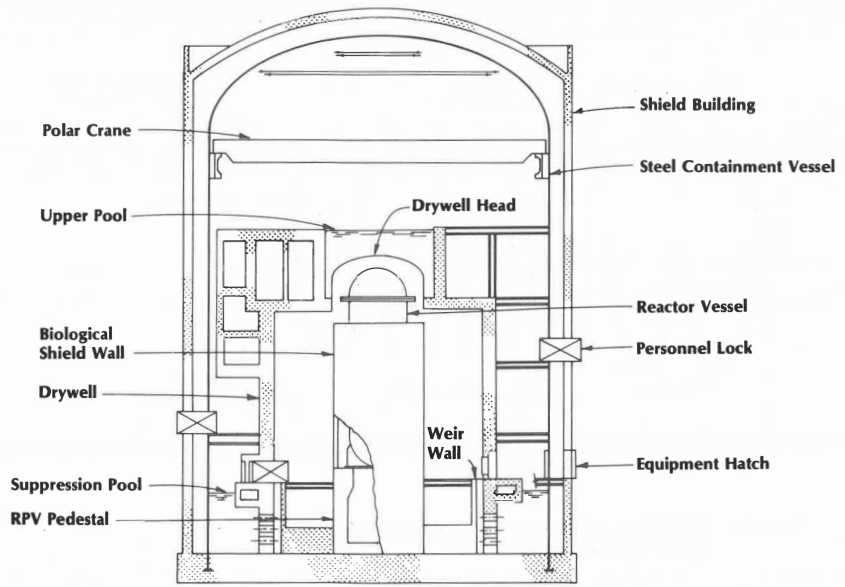

FIGURE 1. REACTOR BUILDING GENERAL ELEVATION

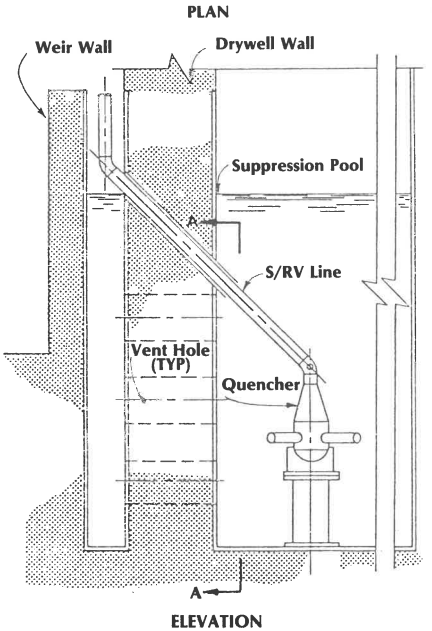

FIGURE 2. MARK III QUENCHER ARRANGEMENT

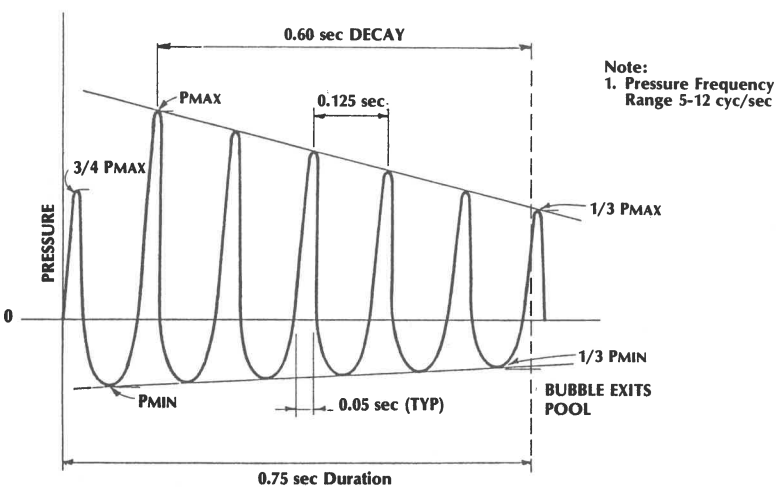

FIGURE 3. IDEALIZED QUENCHER BUBBLE PRESSURE OSCILLATION IN SUPPRESSION POOL

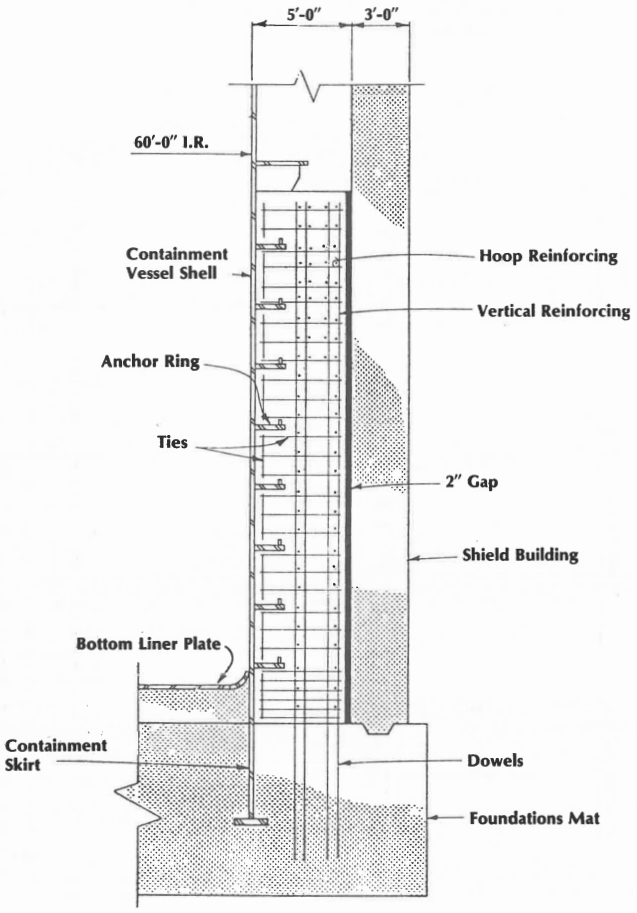

FIGURE 4. CONTAINMENT VESSEL/ANNULUS CONCRETE

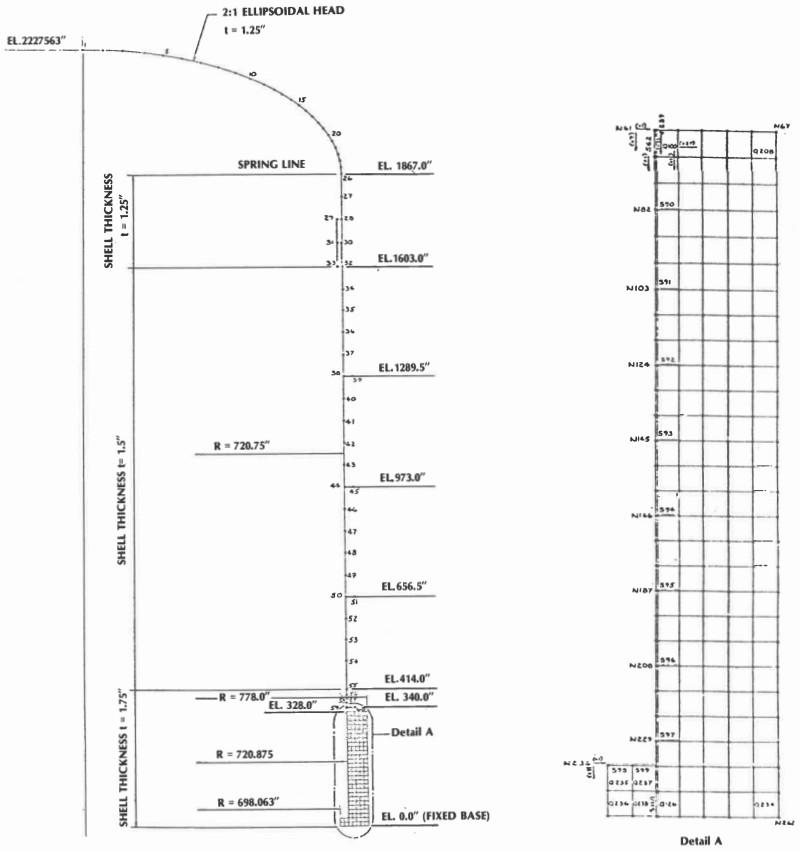

FIGURE 5. CONTAINMENT VESSEL ASH5D2 MODEL

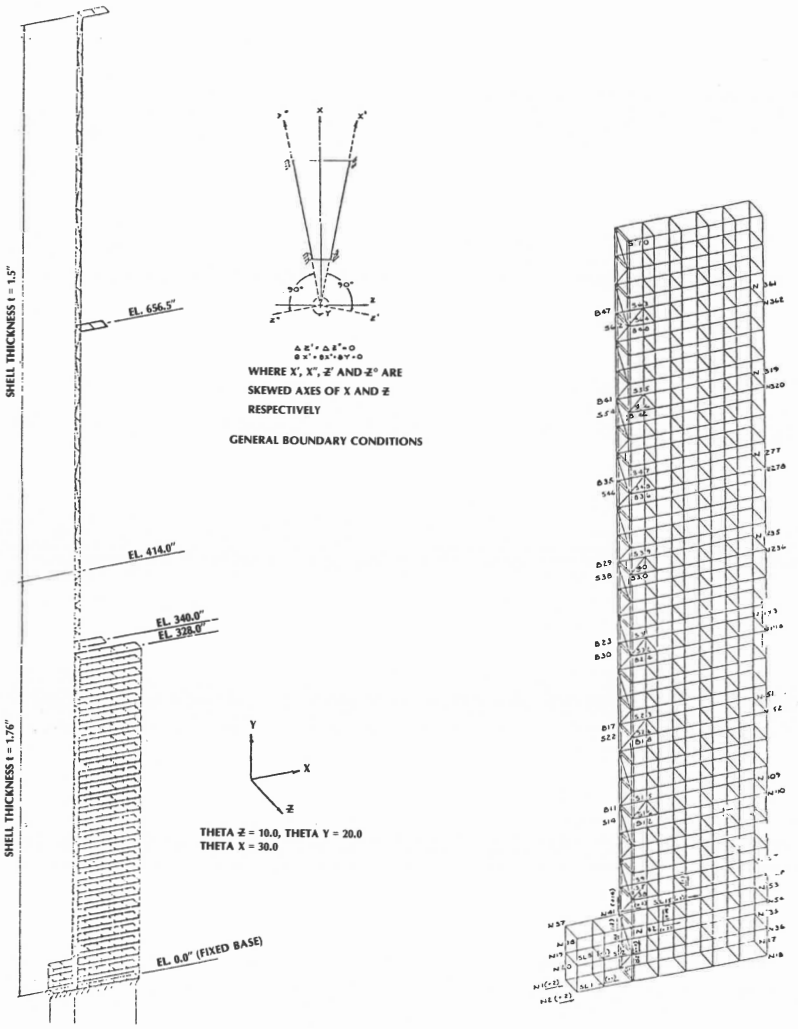

FIGURE 6. CONTAINMENT VESSEL EAST 2 MODEL