SEISMIC QUALIFICATION OF THE LACBWR OVERHEAD WATER STORAGE TANK FOR THE SYSTEMATIC EVALUATION PROGRAM

Submitted to

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1.0 INTRODUCTION

In support of the Systematic Evaluation Program (SEP) at Dairyland Power Cooperative's LaCrosse Boiling Water Reactor (LACBWR), Impell Corporation has evaluated the response of the Overhead Water Storage Tank (OHST) to the postulated Safe Shutdown Earthquake (SSE). This evaluation was performed for Dairyland to demonstrate the conformance of the OHST to the SEP seismic review requirements.

The SEP, currently being conducted by the United States Nuclear Regulatory Commission (NRC), was instituted for the purpose of generating a current documented basis for the safety of older nuclear reactors, those which received their construction permits between 1956 and 1967. In particular, the seismic review requirements have established the acceptance criteria, including the recommended load combinations, analysis methods, and stress allowables for the reevaluation of equipment such as the OHST.

Impell has evaluated the seismic response of the OHST using an approach which addresses three critical areas. These include the use of SEP site specific SSE seismic input motion, the consideration of the appropriate dynamic properties of the fluid/tank system, and the effects of seismically induced tank loads on the overall stability of the LACBWR reactor containment vessel head, which is the OHST supporting structure.

The approach has conservatively estimated the seismic response of the fluid/tank system using first principals, accepted standard methodologies, and formulations including M. A. Haroun's investigation into the dynamic behavior of flexible liquid storage tanks. (Reference [1]) It has shown that the OHST meets the SEP seismic review requirements in the event of the postulated SSE.

This report describes the methodology used in the seismic evaluation of the LACBWR OHST. It also provides a summary of the results of the evaluation.

2.0 SYSTEM DESCRIPTION

2.1 OHST Design

The LACBWR OHST is a semi-ellipsoidal shell which is suspended from the reactor containment vessel head. The tank is 36 feet in diameter with a maximum depth of 9 feet (Figure 1). It is constructed of 3/8 inch carbon-silicon steel plate with an ASTM designation in the range of A201B to A300. For the purposes of this evaluation the plate material has conservatively been assumed to have a minimum yield strength of 30 ksi and a minimum ultimate tensile strength of 55 ksi.

The OHST is water filled to a maximum depth of 8 feet, 11.25 inches. The volume of the tank is essentially clear with the exception of a 36 inch diameter access tunnel (man-hole) at its center. The tunnel rises the entire height of the tank to a point just above the water line.

The OHST is suspended from the reactor containment vessel head roughly 6 feet 1 inches from its apex. The tank and the vessel head are joined by a full penetration single V weld around the entire circumference.

2.2 Loading

The LACBWR OHST is designed for the following loading conditions:

a. Gravity - The weight of the OHST and the weight of the water in the tank produces membrane stresses in the tank as well as reaction loads at the tank support.

b. Thermal - Expansion, as a result of high temperatures, would induce stresses in the OHST as well as the containment vessel head. However, these stresses are secondary (self-relieving) and since temperatures in excess of 300°F would not occur under design basis accident conditions at the tank elevation this load case has not been included in this evaluation.

c. SSE Inertia - The postulated SSE event induces inertial loads on the OHST, producing tank membrane stresses and tank support reaction loads.

d. Dynamic Fluid Pressure - The fluid mass has wave properties which are a function of the tank geometry as well as fluid/structure interaction. The seismic excitation of the fluid/tank system can generate waves resulting in dynamic fluid pressures on the tank called "sloshing" loads. The sloshing loads produce tank stresses and support reaction loads.

3.0 METHODOLOGY

To date, cylindrical geometries have been the primary focus of studies to determine the effects of seismic motion on liquid filled tanks. As a result, the majority of the closed form solutions used to predict the response of liquid filled tanks to earthquake motion apply directly to these geometries.

Therefore, the Dairyland OHST seismic response was determined using an equivalent right circular cylinder model and the findings of this research. The cylindrical model (Figure 2) has the same volume, height/radius, and thickness/radius ratios as the Dairyland OHST.

To demonstrate that the use of this equivalent geometry was a conservative approach, a comparison of the dynamic properties of ellipsoidal and cylindrical shells was performed. This comparison identified which types of cylindrical shell response were not representative of the ellipsoidal shell response. Individual modes of response were identified and compensations were made to the calculations to insure conservative results using the cylindrical models.

The dynamic behavior of the OHST when subjected to seismic loads was evaluated using a method developed by M. A. Haroun and outlined in "Vibration Studies and Tests of Liquid Storage Tanks" (Reference [1]). This method uses a mechanical model (Figure 2) which accounts for the principal modes of response to the earthquake motion. These include the consideration of tank wall flexibility, tank rigid mass contribution, and liquid-tank shell coupling. This method enables the use of closed form solutions for the evaluation of the seismic response of the tank.

The seismic forces and their lines of action were generated for the OHST mechanical model. These forces included the contribution of the fluid/tank rigid mass, the fluid/tank flexible mass, and the liquid sloshing mass. These forces were combined with the deadweight forces on the tank. The resulting combined forces were used to calculate the maximum stresses in the weld at the attachment of

the OHST to the containment vessel head as well as the maximum membrane stresses in the OHST. These maximum stresses were then compared to the SEP acceptance criteria allowable stresses. Potential circumferential wrinkling of the OHST at the attachment to the vessel head was also evaluated.

Finally, the reactor containment vessel head was evaluated using shell stability analysis procedures (Reference [2]).

4.0 PARAMETRIC CONSIDERATIONS

It is necessary to determine and properly superpose the water filled storage tank modes of vibration to predict its seismic response. So that this could be done using accepted design procedures and closed form solutions, a right circular cylinder mechanical model (Figure 2) was developed as previously discussed. The parameters of the model were selected to provide an accurate representation of the response of the actual Dairyland ellipsoidal tank to ensure that the calculated response was realistic yet conservative. A comparison was made of the primary modes of response to seismic excitation of the actual ellipsoidal shell and the equivalent model (Figure 3). A summary of the findings is presented in the following sections.

4.1 Free Lateral/Vertical Vibrations

The free lateral vibration modes of the OHST can generally be classified as cos (θ) type modes (Figure 3a) and cos (nθ) type modes (Figure 3b). For tall cylindrical tanks the cos (θ) type modes are essentially beam flexural modes. These modes are strongly excited by the earthquake motion. For the ellipsoidal OHST however, neither the cos (θ) modes nor the cos (nθ) modes are purely flexural. Instead they are coupled flexural and extensional modes. It has been shown that deep spherical shells possess flexural modes which are very similar to the higher circumferential modes of cylindrical shells (Reference [5]).

For the equivalent cylindrical model of the OHST the fundamental frequency of lateral vibration is 32 hz. Due to the modal coupling previously discussed the actual OHST would be expected to exhibit a significantly higher fundamental frequency of vibration. Also, due to the fluid mass distribution in the OHST, the line of action of the flexible impulsive force would be expected to occur much closer to the support location.

For vertical excitation the cylindrical model does not realistically predict OHST response. Instead, the fundamental frequency is calculated by using the more conservative of two bounding models: a thin spherical shell (upper bound) and a thin circular flat plate (lower bound).

4.2 Sloshing

It is clear that the acoustic frequencies of the cylindrical shell are not representative of the ellipsoidal frequencies. Instead, the fundamental wave or sloshing frequency was determined using a more precise formula for a shallow circular basin with a parabolic bottom from Reference [5].

The calculated frequency was 1.33 hz. Since this frequency is on the flexible side of the response spectral peak, and higher order sloshing modes may fall within the peak, the peak spectral acceleration was used to determine the convective response of the sloshing modes.

5.0 SEISMIC RESPONSE

The seismic response of the OHST was evaluated using the mechanical model shown in Figure 2, and the methodology developed by Haroun (Reference [1]). This approach enabled the consideration of the significant free lateral vibration modes of the fluid/tank system. The response modes which may be excited by earthquake motion, and which were discussed in Section 4.0, are: 1) the response caused by a portion of the liquid mass accelerating in phase with the rigid tank mass, i.e. the rigid acceleration, 2) the response caused by the relative acceleration of a portion of the tank and fluid mass, due to shell deformation, i.e. the flexible acceleration, and 3) the 'convective' response resulting from a portion of the liquid accelerating out of phase with the tank, i.e. sloshing.

As input to the mechanical model the participation of the fluid and tank mass in each of the response modes was determined. The participation of the fluid mass in the rigid and flexible response in the lateral directions was determined using the relations developed by Haroun Figures 21c and 21e (Reference [1]). The participation of the tank steel mass, which is only a small component of the total mass, was conservatively assumed to be 100 percent in both the flexible and rigid lateral response. In the vertical direction, since there is essentially no wave motion, 100 percent of the fluid and tank mass was considered to act in the tank flexible response.

The third mode, sloshing, is purely a lateral response. Rather than use the convective mass participation relations developed by Haroun for cylindrical tanks, 100 percent mass participation was used for the Dairyland OHST. This was done to effectively consider the ellipsoidal tank geometry. To maintain its lowest energy potential the liquid motion will tend to be out of phase with the tank motion. For this type of geometry this requires a higher fluid mass participation at a lower fundamental frequency than for the cylindrical tank.

5.0 SEISMIC RESPONSE

The input motion to the mechanical model was determined from the "LACBWR Containment Building Seismic/Analysis Report"(Reference [3]). The accelerations for the rigid mass response were taken as the rigid spectral acceleration (ZPA). The flexible and sloshing mass accelerations were selected on the basis of the fundamental modal frequencies as discussed in Section 4.0.

The line of action of each of the resulting dynamic forces was determined from Haroun Figures 21d and 21f (Reference [1]). The response of the LACBWR OHST was calculated using the fundamental equations of motion, the equivalent masses, and the appropriate spectral accelerations . Since, in general, the maximum value of the convective and impulsive forces do not occur at the same time, the maximum value of the tank support shear and moment can be estimated using the square-root-sum-of-the-squares of the individual response components.

SHEAR: $$\left|Q\right|_{MAX} = \left[(M_s a_s)^2 + (M_f a_f)^2 + ((M_r - M_f) a_r)^2\right]^{1/2}$$

MOMENT: $$\left|M\right|_{MAX} = \left[(M_s a_s H_s)^2 + (M_f a_f H_f)^2 + ((M_r H_r - M_f H_f) a_r)^2\right]^{1/2}$$

Where:

M_s, a_s, H_s = sloshing mass, acceleration, and distance from support

M_f, a_f, H_f = flexible mass, acceleration, and distance from support

M_r, a_r, H_r = rigid mass, acceleration, and distance from support

5.0 SEISMIC RESPONSE

A summary of the parameters used to calculate the fluid/tank response is given in Table 1.

The loads resulting from the tank seismic response were then combined with the deadweight loads. The resulting forces were used to calculate the maximum stresses in the weld at the attachment of the OHST to the containment vessel head. The maximum membrane stresses in the OHST were calculated. The critical acceleration to cause circumferential wrinkling of the tank was determined using the methodology developed by Steele and Ranjan (Reference [4]). A summary of the stress results is provided in Table 2.

6.0 CONTAINMENT VESSEL HEAD BUCKLING

For columns and flat plates, the classical small deflection theory is in close agreement with actual buckling loads. As a result theoretical buckling loads can confidently be used as the basis for design allowables. This is not true for the design of shell structures. The buckling load for some types of shells may be significantly less than the theoretical buckling load. Additionally, there is extreme scatter in the test data for the buckling of shells. The scatter results may range to 500 percent and the average buckling load may be one eighth of the theoretical buckling load (Reference [2]). This is the result of numerous variables such as manufacturing tolerances, end restraints, and external disturbances.

The statistical reduction of actual test data has proven to be a useful method of determining the shell design allowable buckling load. This method was used to qualify the Dairyland reactor containment vessel head for the effects of the OHST seismically induced loads.

The statistically reduced buckling data used was provided in Reference 2. Due to limited results of test data for hemispherical shells, an equivalent conical shell model was used to determine the buckling load.

First a comparison was made between the linear compressive membrane stresses induced in the hemispherical and conical shells by the same type of loading. In both models the resisting membrane stresses in the portion of the vessel head above the OHST attachment were conservatively neglected. The vessel head was treated as an open shell with the top edge at the OHST attachment. This is the location where the OHST seismic reaction loads were applied.

The lateral and vertical components of the seismically induced reactions at the OHST attachment to the reactor containment vessel head were calculated to be 1761 kips and 656 kips respectively. It was determined that the most critical component of loading with respect to the stability of the vessel head was the 656 kip vertical load since it induces the highest compressive membrane stresses at the point of the load application.

6.0 CONTAINMENT VESSEL HEAD BUCKLING

A unit axial load was applied to both the cone model and the actual hemispherical model to determine if a reduction factor should be used with the empirical cone data. The maximum circumferential membrane stresses and the comparable longitudinal inplane stresses were calculated for both models. A reduction factor of 0.50 was conservatively applied to the cone data based on this comparison.

The buckling stresses were determined for the cone model subjected to axial load, the vertical component of the seismic load, and bending due to the lateral component of the seismic load. The internal pressure of the containment vessel, which significantly enhances the stability of the vessel head, was conservatively neglected.

The results, shown in Table 3, indicate that even using the conservative reduction of the empirical cone data, the OHST induced loads on the reactor containment vessel head are well below the critical buckling loads. Also, the maximum compressive stresses due to axial compression and bending are not coincident, lending to an even larger buckling factor of safety.

7.0 DISCUSSION AND CONCLUSIONS

The results of this evaluation of the seismic response of the Dairyland LACBWR OHST clearly demonstrate that the tank meets SEP acceptance criteria for the postulated SSE event. Also, the results have shown that the OHST seismic reaction loads on the reactor containmnet vessel head will not induce buckling of the head.

The approach used in the evaluation of the OHST and the vessel head has conservatively considered all aspects of dynamic response to the seismic motion. In particular, the tank wall flexibility, the liquid-shell coupling, and the appropriate seismic input motion were included in the evaluation.

Clearly the LACBWR OHST has significant margin in its seismic design. This margin will ensure that the tank and supporting containment vessel head will maintain their integrity and continue to function properly during and after the postulated SSE event.

8.0 REFERENCES

1. M. A. Haroun, "Vibration Studies and Tests of Liquid Storage Tanks" Earthquake Engineering and Structural Dynamics, Vol. II, 179-206, 1983.

2. E. H. Baker, et al, "Shell Analysis Manual", NASA Report NASA CR-912, North American Aviation, Inc., Ca., April 1968.

3. NRC Letter LS05-83-10-041, Crutchfield (NRC) to Linder (DPC), "Transmittal of LACBWR Containment Building Seismic/Analysis Report".

4. C. R. Steele and G. V. Ranjan "Effect of Stiffening Rings on the Design of Torispherical Heads", Pressure Vessel Design, American Society of Mechanical Engineers, PVP-Vol. 57, 1982.

5. Blevins, R. D., "Formulas for Natural Frequency and Mode Shape", Van Nostrand Reinhold Company, 1979.

Table 1

Summary of OHST Seismic Response

RESPONSE	DIRECTION	MASS (lb sec^2/ft)	Acceleration(g)	Line of Action (ft)
Rigid	X (Lateral)	4731	0.45	$H_r = 3.65$
	Y (Lateral)	4731	0.40	$H_r = 3.65$
	Z (Vertical)	-	-	-
Flexible	X (Lateral)	4496	0.48	$H_f = 3.58$
	Y (Lateral)	4496	0.46	$H_f = 3.58$
	Z (Vertical)	12,730	0.60	Tank. Polar Axis
Sloshing	X (Lateral)	11,763	3.43	$H_s = 3.35$
	Y (Lateral)	11,763	3.13	$H_s = 3.35$
	Z (Vertical)	-	-	-

Table 2

a) Summary of OHST Stress Results

Component	Allowable	Stress Component	Magnitude	Stress Ratio
Support Weldment	4.50 k/in	Resultant Shear	1.75 k/in	0.39
Tank Steel	30 ksi	Circumferential (Hoop) Membrane	11.2 ksi	0.37
Tank Steel	30 ksi	Meridional Membrane	11.2 ksi	0.37

b) Circumferential Tank Buckling

Critical Acceleration	Calculated Acceleration	Ratio
20.4g	5.0g	0.24

Table 3

Summary of OHST Induced Buckling Loads

Vessel Head Buckling Loads		Actual OHST Induced Loads		Interaction
Axial (kips)	Moment (ft-kips)	Axial (kips)	Moment (ft-kips)	
6930	88,500	656	5,900	0.16*

*Note: SEP seismic review requirements state that this ratio may not exceed 0.67.

FIGURE 1

LACBWR OVERHEAD WATER STORAGE TANK
AXISYMMETRIC SECTION

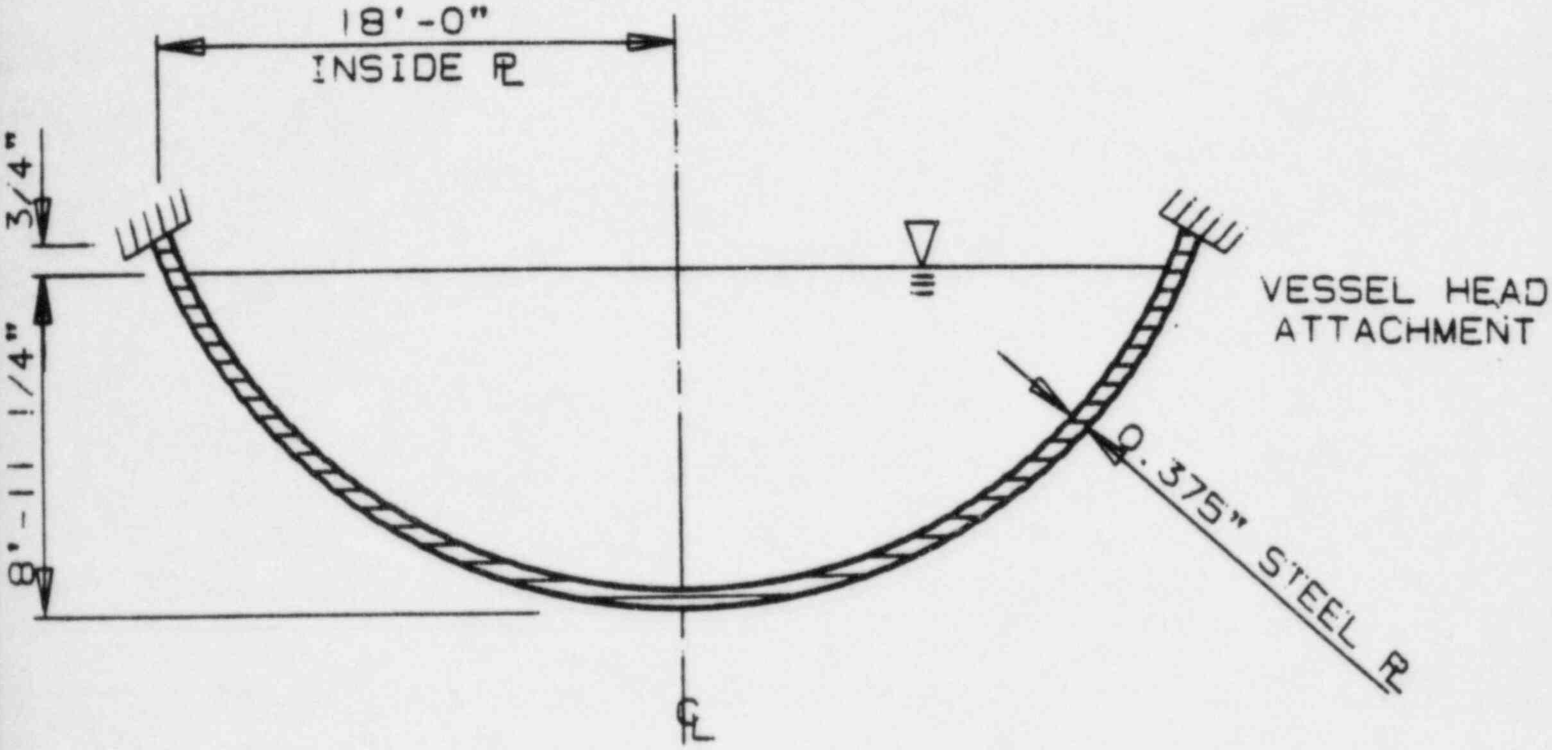
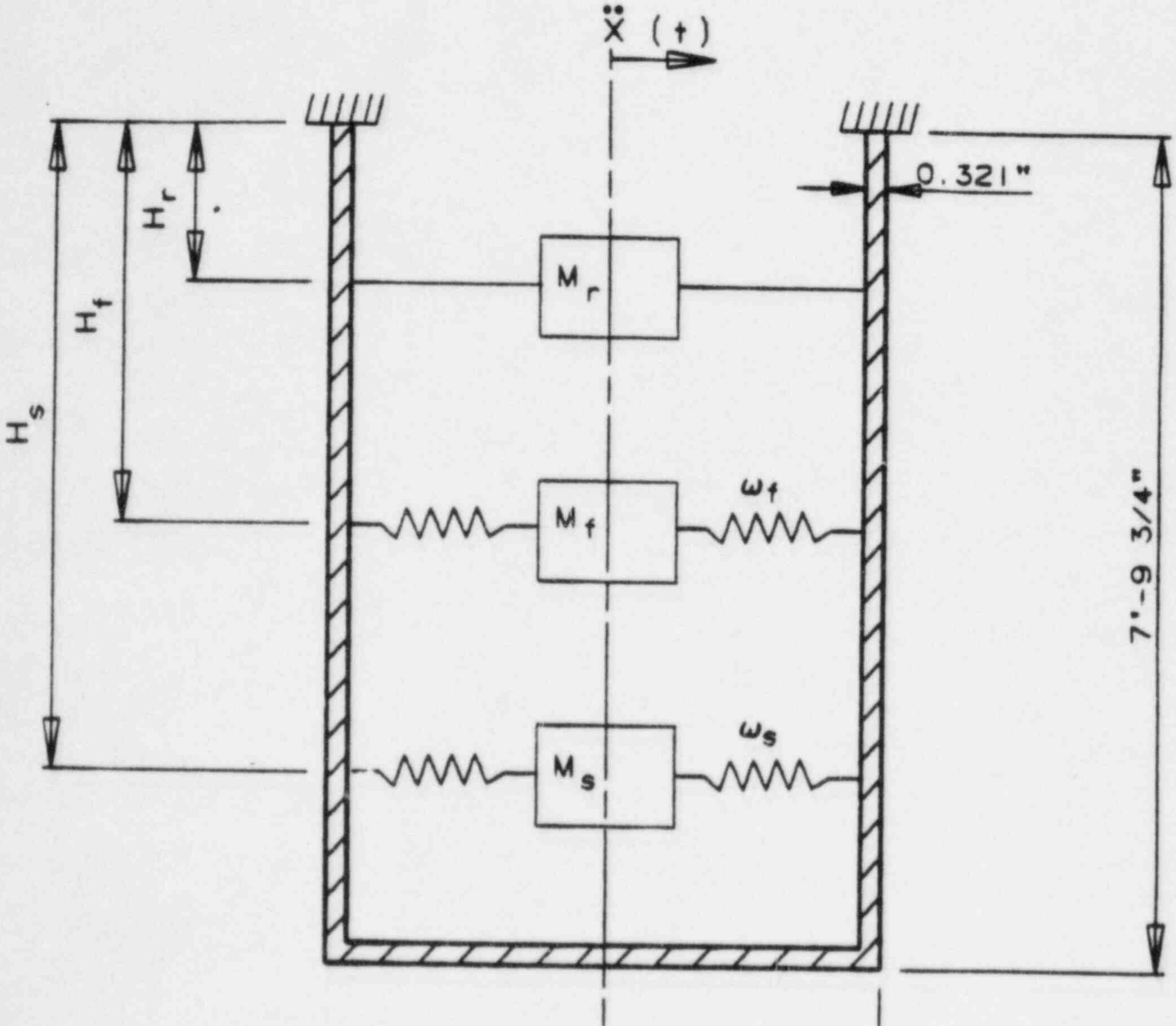


FIGURE 2

EQUIVALENT OHST MECHANICAL MODEL
AXISYMMETRIC SECTION



NOTE: RELATIVE ORIENTATION NOT NECESSARILY
REPRESENTATIVE OF TRUE LINES OF ACTION

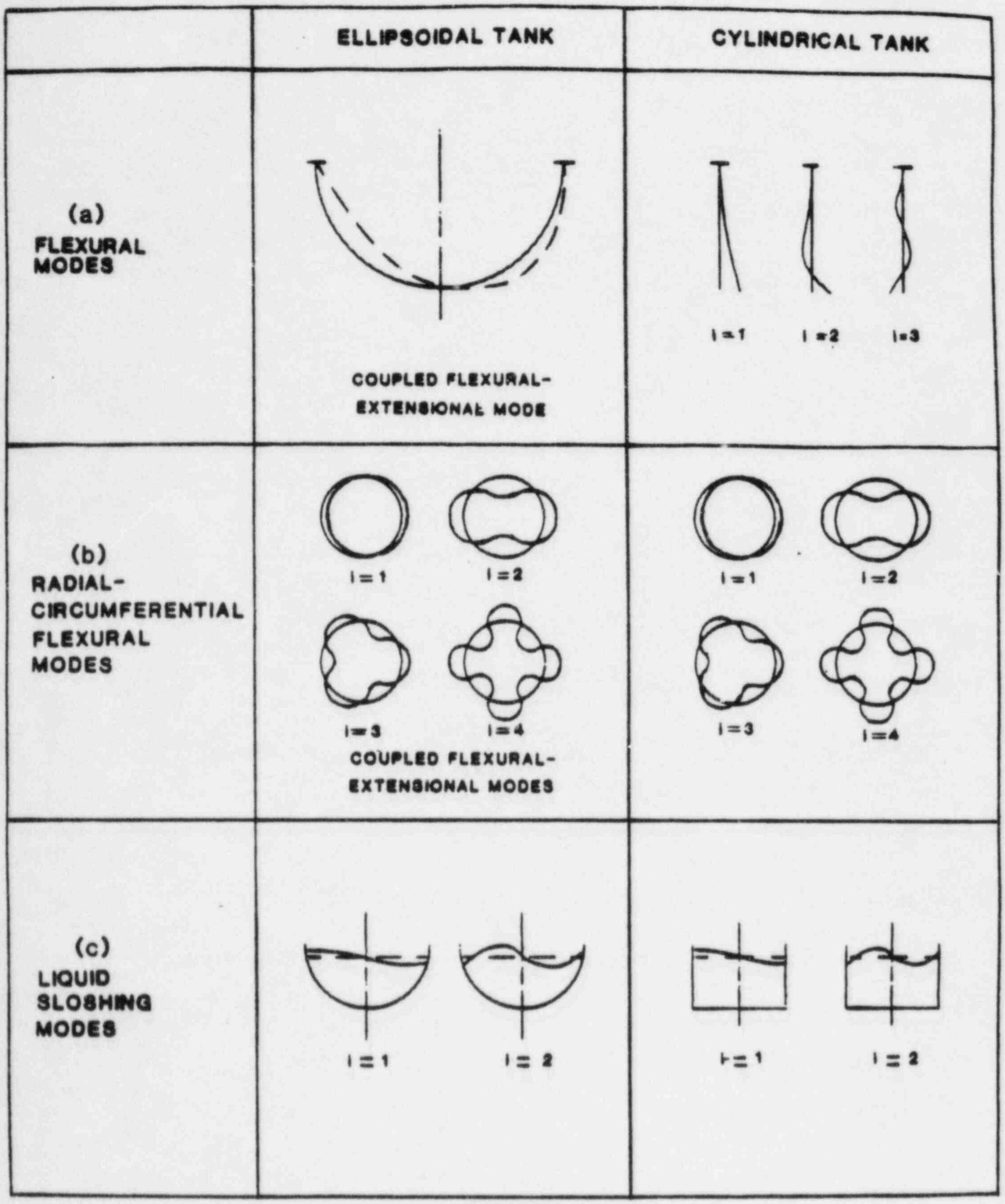


FIGURE 3
MODES OF RESPONSE
OF LIQUID FILLED TANK
GEOMETRIES