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VERTICAL FORCES INDUCED IN A 1/5 SCALE MARK I BWR TOROIDAL WETWELL UNDER LOCA CONDITIONS*

by

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SUMMARY

During a hypothetical loss-of-coolant-accident (LOCA) in a Mark I boiling water reactor (BWR) power plant, air, followed by steam is injected into a toroidal wetwell about half-filled with water. Injection occurs below the water surface in a vertically downward direction through 0.6-m-diam open-end pipes called downcomers.

A downward load is induced on the toroidal wetwell as the water that is initially inside the downcomers is forced into the water pool below them. The magnitude of this downward load increases for about $1/4$ s, until just after gas bubbles appear in the pool. The water surface inside the toroidal wetwell then moves rapidly upward, particularly in the region adjacent to the outside of the downcomers, as water is displaced by the gas bubbles. The gas bubbles over-expand, because the flow of gases from the downcomers is not sufficient to counteract the upward displacement of the water. The direction of net load on the toroidal wetwell now shifts upward and reaches a peak of approximately half the magnitude of the maximum downward load in about $1/2$ s. The vertical load then decreases in an oscillatory manner to static conditions in about 1 s.

We designed a 1/5-scale facility to experimentally verify the predicted loading function and to study the ensuing fluid dynamics phenomena. Analytical results were used to modify the design of the experimental apparatus so that the fluid-structure interaction in the toroidal wetwell did not adversely affect measurements.

Using dimensional analysis, we developed scaling relationships that show the dimensionless groupings $F/\rho g L^3$ and $t^2 g/L$ are invariant. Here, F is force, ρ is liquid density, g is the gravitational constant, L is length, and t is time. If water is used as the working fluid in the 1/5-scale experimental apparatus, the anticipated magnitude of forces would be $1/125$ of that present in a full-scale BWR power plant and would occur in $1/\sqrt{5}$ the time.

For a structural analysis of the 1/5-scale facility, the toroidal wetwell, supports, and base structure were considered to be a spring-mass system excited by an appropriate loading function. The loading function was determined by use of the scaling relationships indicated and by anticipating full-scale BWR power plant forces. Frequency response of the toroidal wetwell was examined with finite-element computer techniques and also closed-form solutions. Required changes in the design of the experimental apparatus were incorporated so that load measurements accurately represented the loading function. Predicted vertical force-time signatures are presented.

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1. Introduction

At the request of the Water Reactor Safety Research Branch of the U.S. Nuclear Regulatory Commission, the Lawrence Livermore Laboratory has conducted 1/5-scale experiments to quantify the three-dimensional response of the pressure-suppression system in a Mark I boiling water reactor (BWR) power plant. The primary purpose of the experiments was to determine the vertical forces that occur on the suppression system during a hypothetical loss-of-coolant accident (LOCA).

A Mark I BWR power plant consists basically of (1) a light-bulb-shaped vessel called a drywell that contains the reactor pressure vessel, (2) a toroidal wetwell, a torus that is about half-filled with water and is connected to the drywell with eight vent pipes, and (3) conventional equipment associated with power conversion. The pressure-suppression system is associated with the first two items above, and these are shown in the cross-sectional view in Fig. 1. Particular dimensions are for the Peach Bottom plant [1], which we used as a reference for designing our 1/5-scale experimental facility. The Peach Bottom drywell and top half of the toroidal wetwell are initially filled with air at ambient pressure and are connected by open-flow passages. The flow passages consist of eight 2-m-diam vent pipes that connect the drywell to a 1.5-m-diam ringheader. The ringheader is formed in the shape of a torus and is positioned inside the toroidal wetwell. Ninety-six downcomers are attached to the ringheader. The downcomers are 0.6 m in diameter, are positioned in pairs along the axis of the ringheader, and have an open bottom that is submerged 1.2 m below the water surface. Spacing between downcomer pairs along the ringheader varies, no downcomers being located in the regions where the vent pipes attach to the ringheader.

During a hypothetical LOCA, a steam or recirculation line is assumed to break, and steam or water or both are discharged into the drywell. This results in air, followed by steam, being injected through the downcomers and into the toroidal wetwell. The steam condenses as it mixes with the water in the wetwell. Pressure inside both drywell and toroidal wetwell is kept below safe, containable limits.

Fluid dynamics phenomena associated with the initial air-injection process result in a downward, followed by an upward, load on the toroidal wetwell. The peak of the downward load occurs at the time when the pressure below the water surface reaches its first peak. This corresponds to about the time that air starts to emerge from the downcomers. The peak upward occurs just before air bubbles break through the water surface, in the lower portion of the toroidal wetwell, and communicate with the air space above. Because the bubbles are over-expanded at the time of bubble breakthrough, air rushes into the region of the bubbles. This causes an inflection in the air pressure-time history taken above the water surface.

Note that for the Peach Bottom downcomer geometry, the dynamic air-water interface during clearing action is a complex surface, having a general slope such that air first exits from the downcomers at a position farthest from the vertical centerline of the toroidal wetwell. In addition, the interface has an undulating characteristic, suggesting that some type of instability (e.g., Taylor instability) is present. In no case is the dynamic air-water interface a plane boundary during the clearing action.

The hydrodynamically generated loads that are produced in the injection process induce stresses in the structural components of the pressure-suppression system. Although the structural components are conservatively designed, large-scale experiments to verify

predicted loads are desirable to assure that adequate safety margins exist. Of particular interest are the vertical loads that are produced in and on the supports of the toroidal wetwell.

The peak vertical loads occur during the period when air is being purged from the drywell and before steam reaches the toroidal wetwell. From an experimental standpoint, results that are obtained prior to steam reaching the toroidal wetwell are independent of the gas used to pressurize the drywell. In the first phase of our experimental program, we pressurized the drywell with nitrogen. A second phase is planned where the drywell will be pressurized with steam, so we can examine the late-time, oscillatory, steam condensation phenomena.

2. Experimental facility

Primary components of the experimental facility include a bank of six nitrogen-storage vessels, a drywell, and 90° and 7.5° segments of the toroidal wetwell. The nitrogen-storage vessels are connected to and pressurize the drywell at the desired rate for a particular test. This drywell pressurization rate may be varied by changing the volume and initial pressure of the nitrogen-storage vessels. The volume of the drywell is scaled to properly supply both the 90° and 7.5° segments of the toroidal wetwell.

The 90° and 7.5° segments of the toroidal wetwell, including ringheaders and downcomers, are 1/5-scale geometrical models of the Peach Bottom Nuclear Power Plant. A wall thickness of 19 mm ensures that the 1/5-scale toroidal wetwell is an essentially rigid structure. Figure 2 shows the 1/5-scale toroidal wetwell in both plan view and cross section. The 90° segment is supported externally with two trunnions at the transverse center and one auxiliary support at the bottom of one end. Each support contains a load cell. A three-point support system eliminates redundancy that could over-range the load cells as forces resulting from long-term thermal transients (e.g., diurnal temperature changes) develop.

Inside the 90° sector, the ringheader is connected to the toroidal wetwell by four vertical struts in the same general fashion as the full-scale plant. Each of these four internal supports also contains a load cell. Redundancy in the ringheader-support system is eliminated by the inclusion of a flexible joint at the midplane of the ringheader. The 7.5° segment was included so that two-dimensional and three-dimensional effects could be compared during each test.

The test pad upon which the toroidal wetwell sectors are mounted is a reinforced-concrete subgrade pit. The steel-reinforced-concrete pad is 0.3-m thick. Beneath this, an integral reinforced-concrete beam 0.9 by 0.9 m, is placed in line with the main 90°-sector trunnion supports. The foundation deflections were conservatively calculated by applying simultaneously about twice the sum of all expected peak loads. All computed deflections were equal to or less than 0.2 mm. This small deflection assures that the test pad offers a rigid base for the toroidal-wetwell sectors.

Additional details of the test facility and some of the results from the experiments are included in Refs. 2 and 3.

3. Analysis3.1 Scaling relationships

Scaling relationships are needed so that data obtained may be applied to a full-scale plant. A number of investigators have used dimensional analysis on Mark I pressure-suppression systems to develop relationships that are valid until the bubbles break the water surface in the toroidal wetwell. Morrison [4,5] applied the Buckingham Pi theorem to obtain

$$\frac{F}{\rho g L^3} = \phi \left(\frac{P_1}{\rho g L}, \frac{P_0}{\rho g L}, \frac{RT}{g L}, f, \gamma, \frac{t^2 g}{L} \right), \quad (1)$$

where F is force, ρ is liquid density, g is the gravitational constant, L is length, P_1 and P_0 are the initial and applied pressures, respectively, R is the gas constant, T is absolute temperature, f is the frictional coefficient, γ is the ratio of gas specific heats, and t is time.

If each grouping above is held constant for both the model and the full-scale plant, then exact scaling is achieved. From a practical standpoint, all groupings except RT/gL can be held constant. The full-scale characteristic temperature is around 300K. Therefore, if the same gas is utilized, a temperature around 60K would be required in a 1/5-scale model. Although R can be lowered by changing gases between model and full-scale system, with normal gases, it can only be lowered by a factor of two below that for air. Imperfect scaling still results.

Experimental work was conducted at the Lawrence Livermore Laboratory in which air was discharged through a partially submerged vent system into 5-l and 0.5-l spherical flasks [5]. Results from these experiments suggest that peak downloads and peak uploads in the toroidal wetwell are scaled equally well by maintaining all groupings constant except for RT/gL . In hypotheses used by others [6], f is also varied. The scaling relationships of all investigators are consistent in that, between model and full-scale plant,

$$F \propto L^3, P \propto L, \text{ and } t \propto \sqrt{L}. \quad (2)$$

For this reason, air tests on the 1/5-scale facility were conducted with initial and applied pressures that were 1/5 of those in a full-scale plant. Forces would be 1/125 of those in a full-scale plant and would occur in $1/\sqrt{5}$ the time.

3.2 Structural Response

Structural analyses [7,8] were performed to ensure that the fluid-structure interaction in the toroidal wetwell did not adversely affect measurements of vertical load and other parameters. The analyses were performed in two parts. First, closed-form solutions were obtained, using simplified models of the toroidal wetwell components, to predict the natural frequencies and static deflections under maximum expected loads. Table 1 summarizes the final results. In actuality, the results of the calculations influenced the preliminary design of the components; those components which exhibited too low a natural frequency or too high a static deflection were redesigned. In the final design, the maximum expected stress for all components was below allowable limits. External components were carefully designed to conform to the Unfired Pressure Vessel Code [9] of the American Society of Mechanical Engineers.

Second, a finite element analysis of the toroidal wetwell on flexible supports was made, using the SAP4 computer code [10]. The toroidal wetwell was modeled with seven nodes. Curvature of the toroidal wetwell in plan view was included when the positions of the nodes were established. The weight of the 7.6-cm-thick end closures was concentrated at the appropriate nodes on each end of the toroidal wetwell; and the remaining weight, including water, was distributed uniformly among all nodes.

The toroidal wetwell analyses included both torsion and transverse shear effects. The vertical stiffness of each of the three external supports was calculated by combining the effects of the support structure itself with the manufacturer's specified stiffness of the load cells. The test pad was considered to be rigid.

The input for the hydrodynamic-loading function was applied vertically and was distributed over the length of the toroidal wetwell. The magnitude of the loading function was established from upper-limit estimates of the vertical-loading function of the full-scale plant and was scaled for a 1/5-scale experiment by use of eq. (2). The input loading function and calculated sum of the response of the three load cells are indicated in Fig. 3. As shown, the calculated response adequately represents the input for the vertical loading function. This result shows that, for the rigidly designed toroidal wetwell, the sum of the measured external loads in the 1/5-scale experiment would be close to the actual hydrodynamic loading function.

Because the calculated load-cell response agrees well with the input for the vertical loading function, the external support system was considered adequate. Note that the individual traces of the three load cells differ in magnitude and shape. The main trunnion support closest to the drywell has the largest magnitude, because the toroidal wetwell curves inward around the drywell. From the viewpoint of effect-moment arms, a uniform static load placed along the axis of the 90°-sector of a toroidal wetwell would give a larger reaction load on the main trunnion support closest to the drywell than on the one farthest from the drywell. The auxiliary support at the end of the toroidal wetwell has the smallest magnitude and oscillates around a mean value of zero.

4. Comparison of experimental results

In air tests performed with the 1/5-scale experimental facility, several parameters were varied, including initial drywell-pressurization rate, downcomer submergence and length, vent-line flow resistance, and asymmetry effects. Test results for a nominal case are shown in Fig. 4 where both the hydrodynamic and response vertical-load functions are plotted with time. The dashed curve (Fig. 4) represents the sum of the three external load cells (response) and can be compared to the analogous calculated trace (dashed curve) in Fig. 3. Note that the general characteristics of these two curves are similar, but the magnitude of the curve in Fig. 4 is less. This difference in magnitude should be expected, in part, because the predicted results were based on an estimated, upper-limit, vertical-loading function.

The solid line of Fig. 4 shows the actual, hydrodynamic vertical-loading function as determined by spatial integration of pressure measurements on the boundaries of the toroidal wetwell. The actual hydrodynamic loading function corresponds to the estimated input for the vertical-loading function (see solid line, Fig. 3). The curve for the actual hydrodynamic loading function exhibits a more complicated shape, as would be expected, than the estimated input for the vertical-loading function shown on Fig. 3. Note that the curves of

Fig. 4 closely agree with each other indicating that, because of the rigid torus design, the sum of the external load cell measurements is a good representation of the hydrodynamic loading function. This confirms the adequacy of the toroidal wetwell support structure and the accuracy of the calculated response of the support system.

5. Conclusions

Dimensional analysis is used to show that $F \propto L^3$, $P \propto L$, and $t \propto \sqrt{L}$. Imperfect modeling is necessary, because, between a model and a full-scale plant, it is not practical to hold the grouping RT/gL constant. Both bench-top and 1/5-scale experiments show that modeling is insensitive to the friction factor, f . The friction factor is proportional to the vent-line loss coefficient.

Components of the 1/5-scale toroidal-wetwell sectors have high natural frequencies and small deflections under maximum anticipated loads. The analyses, performed prior to obtaining experimental data, showed that the design of the 1/5-scale facility would be adequate and that accurate data would be obtained.

A structural analysis, using a finite-element computer code, showed that structural response of the toroidal wetwell would not interfere with measurements of the vertical load. Experimental results confirmed that the analysis was accurate and that the load response, measured externally by the three main load cells, was very close to the actual hydrodynamic vertical-loading function.

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TABLE I. Summary of closed-form dynamic analyses of the components of the 1/5-scale toroidal wetwell.

Item	Mode shape:		Natural frequency (Hz)	Maximum anticipated load	Maximum anticipated deflection (mm)
	—	- - -			
One-half of the ringheader in bending			220	6800 N/m	0.036
One-half of the ringheader on flexible supports			330	6800 N/m	0.015
Ringheader ovalization			210	6800 N/m	0.38
Downcomer			530	500 N	0.051
Toroidal wetwell on three rigid supports			48	--	--

Figure Captions

Fig. 1. Cross section of a full-scale pressure-suppression system of a Mark I-BWR power plant.

Fig. 2. Schematics of toroidal wetwell sectors and the drywell: (a) Plan view of 90° and $1/2^\circ$ sectors, and (b) cross section of 90° sector.

Fig. 3. Comparison of the estimated input for vertical loading function and the predicted response for the 90° sector of the 1/5-scale toroidal wetwell. Zero time on Fig. 3 corresponds to 3s on Fig. 4.

Fig. 4. Experimental data from test of a nominal case, showing the actual, hydrodynamic vertical-loading function and the response of the 90° sector of the toroidal wetwell (Test 1.3.1). Zero time on Fig. 3 corresponds to 3s on Fig. 4.

Pitts - Fig. 1

Picts - Fig. 2

Pitts - Fig. 3

Pitts - Fig. 4

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