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Lawrence Livermore Laboratory

PRELIMINARY CHARACTERIZATION OF THE PRESSURE SUPPRESSION EXPERIMENT
LOAD RESPONSE AND SOURCE ANALYSIS - AIR TEST SERIES

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August 8, 1977

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NOMENCLATURE

A_c = Area Cross Section

A_o = Acceleration Amplitude

B = Body Force Per Unit Mass

cs = Control Surface

cv = Control Volume

dA = Differential Area

F_s = Surface Forces Acting on the Control Volume Surface

h = Height of Water Column

v = Volume

V = Velocity

ρ = Mass Density

ω = Circular Frequency

τ = Time

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CHARACTERIZATION OF THE PRESSURE SUPPRESSION EXPERIMENT
LOAD RESPONSE AND SOURCE ANALYSIS*

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1.0 ABSTRACT

Data from air tests conducted on the 1/5-Scale Model Mark I Pressure Suppression Facility at Lawrence Livermore Laboratory were analyzed for the purpose of determining the various sources of load signature characteristics. It was determined that hydrodynamic vertical loading function embodies effects from:

- a) Momentum flux associated with flow from the downcomers,
- b) Momentum rate associated with bulk pool motion,
- c) Unbalanced internal pressure forces related to phenomena associated with vent clearing.

The integral form of the linear momentum equation is used to derive qualitative and quantitative insight into the mechanics of the hydrodynamic loading function. Amplitude spectra derived from Fourier transformations show that the 25 Hz (approximate) structural mode is the only frequency which appears consistently in all wave forms which were spectrum analyzed. The load signature is characterized by a double peak download persisting about 75 msec, followed by a less severe multi-peaked upload of approximately 100 msec duration. Analytical evidence as well as empirical correlations are given to support the conclusion that the double peak download has a hydrodynamic source. Evidence is presented to show that some structural character is superimposed on the hydrodynamic loading but not to a degree sufficient to appreciably affect the magnitude of peak loading.

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¹ Mechanical Engineering Department Summer Faculty Assigned to Thermo Fluid Mechanics Group of Nuclear Test Engineering Division.

2.0 INTRODUCTION

The purpose of this report is to provide some understanding of the general character of load cell signature and the sources which induced the load signature characteristics. The reader is especially directed to UCID-17446-1 (the first quick-look report) for description of the experimental facility design, scaling and purpose.

The 1/5-scale Mark I model Pressure Suppression Experimental Facility was built for the purpose of simulating a loss-of-coolant accident (LOCA)*. Of particular interest was the determination of vertical loads which would be induced on the torus wetwell, should such a failure occur. Preliminary results are contained in a series of quick-look reports.¹ The purpose of quick-look reports was to provide a summary of experimental results from a series of 27 tests.

The 1/5-scale BWR Mark I Test Facility is shown in figure 1. A cross-section of the toroidal wetwell is shown in figure 2. A loss-of-coolant accident is simulated when a diaphragm is ruptured in the high pressure supply line allowing nitrogen to flow into the drywell at a controlled pressurization rate. As the drywell pressurizes, nitrogen forces water out of the downcomers and eventually vents to the wetwell. "Initial vent clearing" is defined as the time at which air initially crossed the plane of the downcomer opening into the wetwell. Until initial vent clearing occurs, the flow and resulting forces are similar to the classical problem of flow in a pipe with a 180° bend. This problem is analytically treated in several fluid dynamics books.²

The integral form of the linear momentum equation as it applies to a control volume (equation 1) can be used effectively to provide insight into the nature of the hydrodynamic loading.

*The configuration of the 1/5 scale facility is that of the Peach Bottom Plant.

Figure 1* 1/5-Scale BWR Mark I Test Facility
(photographed during construction).

*From UCID-17446-1

Figure 2* Scaled Test Configuration of BWR Mark I Pressure Suppression System (elevation view - looking South).

*From UCID-17446-1

$$F_s + \iiint_{cv} B \rho dv = \iint_{cs} V(\rho V dA) + \frac{\partial}{\partial \tau} \iiint_{cv} V(\rho dv) \quad (1)$$

This report deals primarily with qualitative aspects of the above equation by examining the equation term-by-term for hydrodynamic loading characteristics.

3.0 QUALITATIVE CHARACTERISTICS OF HYDRODYNAMIC PHENOMENON

3.1 INTRODUCTION

The qualitative character of the hydrodynamic phenomena is defined by the sequence of flow regimes observed to occur within a given 1/5-scale air test; pre-vent clearing, vent clearing, pool swell/bubble growth, bubble rupture, and finally oscillating flow in and out of the downcomers. Major changes in flow occur after initial vent clearing and when the bubble(s) surface in the ullage. The final flow regime develops when the pressure difference between downcomers and ullage has diminished to the point of favoring an oscillating flow in and out of downcomers. Similar flow regimes were identified in bench model tests.^{3,4}

A scenario for these regimes is constructed from the available evidence; where evidence is lacking, heuristic judgment based on fundamental fluid dynamics concepts will be used.

3.2 PRE-VENT CLEARING

Until initial vent clearing, the accelerating flow is relatively well behaved. The down forces are predictable from momentum flux calculations. Water from the downcomers flows as a jet into the wetwell; thus the pressure in the exit plane of the downcomers is equal to the ullage pressure plus the hydrostatic head due to downcomer submergence. The primary resistance to the accelerating flow into the torus is due almost totally to the inertia of the water slug in the downcomers. Pressure losses from orifice plate as well as major and minor loss factors have negligible effect on the velocity of flow during the pre-vent clearing period. They consequently have little influence on the character of the vertical loading.

3.3 VENT CLEARING

Vent clearing is not a one-dimensional event. Figure 3 shows a series of three frames, viewing a downcomer from port 1-95 for NRC Test 1.3. Venting is consistently characterized by first clearing of the outside wall of the downcomer (relative to the ringheader). The series of frames shown in figure 4^a illustrate the relatively long period of time required for complete vent clearing. One can see in the series of slides the effect of a slug of water penetrating the bubble and piercing the liquid region below the bubble. Frame number 2835, figure 4, occurs 40 msec after initial vent clearing.

At the moment initial vent clearing develops, flow velocity is relatively small (≈ 30 fps). Thus, the pressure in the downcomer exit plane suddenly becomes that of the drywell because vent line pressure losses are negligible. This becomes a major source of the peak download. The water above the downcomer exit plane serves as a temporary inertial barrier which preserves the pressure difference between the exit plane and the ullage. The consequence is a substantial pressure force download which persists for approximately 50 msec. That particular force is contained in the first term of equation 1.

3.4 POOL SWELL

The bubble grows spherically quite rapidly following vent clearing to a diameter of approximately 1.5 ft in 35 msec. Because of the 24 downcomers in the 90° torus sector, the rapid bubble growth produces a rapid growth of pool swell. Films show the pool swell to be relatively well behaved until it reaches the ringheader (approximately 100 msec following initial vent clearing).

^aNote that the view of figure 4 is rotated 90° from that of figure 3.

FIGURE 3. FRAME SERIES (2-msec interval) FROM NRC TEST 1.3 SHOWING ASYMETRIC VENT CLEARING

FIGURE 4. FRAME SERIES SHOWING BUBBLE GROWTH AND LATE VENT CLEARING. (Frame #2835 is 40 msec after initial vent clearing)

The time of pool swell wash over the ringheader corresponds to measured peak uploads and slightly precedes the bubble breakthrough. When breakthrough occurs, air flow velocity through the downcomers peaks quickly because inertial resistance of the water has dissipated, allowing downcomers to vent directly into the ullage through the cavity formed by the rising bubble. The static pressure in the exit plane of the downcomers at breakthrough is slightly lower than the static pressure in the ullage. This is due primarily to the dynamic pressure associated with high flow velocity exiting the downcomers. A net pressure upload results from this temporary condition.

Breakthrough is followed by a collapse of the bubble cavity. The collapsing cavity produces a net momentum rate of change resulting in a further peak downward load on the torus that reaches a maximum at about 700 msec after initial vent clearing.

3.5 LATE TIME OSCILLATIONS

Momentum rate changes of the pool mass which result from bulk pool motion following initial collapse of the cavity produces a series of low frequency (approximately 1 Hz) late time oscillations (see figure 6) which become prominent approximately 2 to 3 seconds after initial vent clearing. The oscillations can be related (from films) to water flow in and out of downcomers. One can observe water flowing in and out of the downcomer (Port 1-95, NRC Air Test 1.3) at approximately the same frequency measured by the load cells. Conditions favorable to oscillating flow in the downcomers will occur at such time that the difference in the downcomer pressure and ullage pressure is equal to the hydrostatic head produced by the 0.8 ft of downcomer submergence. Unfortunately, some of the pressure transducers saturated too early to allow confirmation of the exact time of the favorable pressure difference. It

apparently occurs in NRC Air Test 1.3 about 2.25 seconds after initial vent clearing.

Oscillating flow leads to cyclic vent clearing because the drywell behaves as an air spring persisting in positive pressurization. All of the hydrodynamic forces expressed in equation 1 become cyclicly reimpresed on the torus at similarly reduced levels.

3.6 THE EQUATION OF MOTION

The equation of motion (the linear momentum equation for the vertical cartesian axis) is shown in equation 1a in integral form.²

$$(F_s)_y + \iiint_{cv} B_y \rho dv = \iint_{cs} v_y (\rho V \cdot dA) + \frac{\partial}{\partial \tau} \left(\iiint_{cv} v_y \rho dv \right) \quad (1a)$$

The equation is applicable to transient flow for a control volume fixed in inertial space. (Consider the control volume defined in figure 5.) The equation expresses the following equality: The sum of the force distributions on the control volume is balanced by the sum of the rate of efflux of momentum across the control surface plus the rate of change of momentum inside the control volume.

The first term on the left of equation 1a incorporates surface forces on the control surface. Surface forces include the vertical transient pressure forces plus the transient reaction on the control surface which results from force contribution of all of the terms in the equation.

The second term incorporates the body forces which act throughout control volume. They include gravitational forces and buoyant forces. The body forces have no impact on the load signature prior to vent

FIGURE 5. REFERENCE CONTROL VOLUME FOR EQUATION-1

clearing because the weight the system does not change and the bouyant forces will not impact until after vent clearing.

The first term on the right side of equation-1a expresses the momentum flux crossing the control surface boundary. The vertical loading during the pre-vent clearing period is dominated by this term because the water from the downcomer jet into the wetwell at a velocity up to 32 fps (≈ 44000 GPM). The result is intensive momentum flux absorption by the pool mass. The vent clearing process, however, results in this term experiencing a sharp magnitude reduction. Herein lies the primary contributor to the double peak observed on the load response.

The second term on the right expresses the time rate of change of momentum of the fluid elements within the control volume. It produces negligible contribution to the hydrodynamic forces during pre-vent clearing. This term becomes important with the advent of bubble growth and ensuing mass pool motion.

Preliminary results from computer modeling of Equation 1a indicates the pressure forces, represented in the first term on the left hand side, have the greatest impact on the character and magnitude of early-time vertical loading. Preliminary results further indicate the next most important impact is derived from momentum flux, followed by the time rate of change of control volume momentum, and finally by the buoyant forces.

4.0 THE GENERAL CHARACTER OF THE VERTICAL LOAD SIGNATURE

4.1 INTRODUCTION

The response vertical load signature (loadsum) is defined as the signal pattern produced from the sum of the external torus load cells (L-4A, L-5A, L-1). The load cell signature is characterized by a double-peak download followed by multi-peak upload. The magnitude of the transient download is greater than the upload by a factor of approximately 2X. Figures 6 and 7 show the loadsum for NRC Air Test 1.3; these plots have not been corrected for the effect of ullage pressure rise. Figure 7 is a time-expanded window in the 0.5 second time interval of maximum interest. This particular time frame captures the period during which the download and upload are maximum.

For the purpose of comparing load cell signatures, figures 8, 9, and 10 are time-expanded windows from NRC Air Test 2.5, 2.6, and 1.6, respectively; these plots have not been corrected for the ullage pressure rise. Nominal downcomer submergence was 9.6 inches for Tests 1.3 and 1.6. NRC Air Test 2.5 had a greater than nominal downcomer submergence (13.4 inches) while NRC Air Test 2.6 had a less than nominal downcomer submergence (5.8 inches). Pressurization rate of the drywell was approximately the same for NRC Air Tests 1.3, 2.5, and 2.6 (~ 27 psi/sec). The pressurization rate for NRC Air Test 1.6 was 32.8 psi/sec. Diagrams showing the location of transducers for the four tests are shown in figures 11a and 11b.

4.2 RELATIONSHIP OF FLOW REGIMES TO THE LOAD CELL SIGNATURE

Following diaphragm rupture, drywell pressurization initiates flow through the vent pipes. The largest initial resistance to flow is the inertia of the slug of water in the downcomer. Films show that a nominal pressurization rate of 27 psi/sec will produce velocities near 32 fps just prior to vent clearing for nominal downcomer submergence.

REPLOT RUN R 08/07/77 16:44:24

A

LOADSUM NRC TEST1.3

FIGURE 6. LOADSUM FOR NRC TEST 1.3

REPLOT RUN R 08/07/77 16:49:19

A
LOADSUM NRC TEST 1.3

FIGURE 7. LOADSUM (0.5 SECOND WINDOW) OF NRC TEST 1.3

REPLOT RUN R 08/07/77 18:36:23

A

LOADSUM NRC TEST2.5

FIGURE 8. LOADSUM FOR NRC TEST 2.5

REPLOT RUN R 08/07/77 19:00:58

A

LOADSUM NRC TEST2.6

FIGURE 9. LOADSUM FOR NRC TEST 2.6

REPLOT RUN R 08/07/77 18:09:10

A

LOADSUM NRC TEST1.6

FIGURE 10. LOADSUM FOR NRC TEST 1.6

NRC-1

INSTRUMENTATION LOCATIONS FOR TORUS

LOCATION	TYPE OF XDCR	TRANSDUCER NO.																			
		SECTION																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
12°	P				15		29			42		7				56				57	
14°	T	1									20										
18°	PS					1	3				5										
37°	PS					2	4				6										
45°	P	1	110		16		30			43		45									
73°	T		110																		
78°	P																				
128°	P				17		31			44		8									
135°	T	2			5		8			11							13			14	
140°	P				18		32														
155°	P	2			19		33			46		47									
160°	P				20		34														
165°	P	3			21		35			48		9									
175°	T	3		111	6		9					12									
180°	P	4		111	22	13	36	14		49		10									
195°	P	5			23		37			50		11									
200°	P				24		38														
205°	P	6			25		39			52		51									
220°	P				26		40														
235°	P				27		41			54		53									
270°	P																				
315°	P				28					55		12									
323°	PS										7										
342°	PS										8										

P = Pressure
T = Thermocouple, Fluid
PS = Pool Swell

Figure 11a . Instrumentation Locations for Torus.

NRC-1

INSTRUMENTATION LOCATIONS FOR TORUS LOADS, RINGHEADER LOADS, AND ACCELERATION

LOCATION	TYPE OF XDCR	TRANSDUCER NO.						
		SECTION						
		1	2	3	4	5	6	7
0°	A	1			3			7
	L							
90°	A				4			
	L				4a,b			
180°	A	2			5			8
	L	1	2	3		6	7	8
270°	A				6			
	L				5a,b			

A = Accelerometer

L = Load Cell

SECTIONS

Figure 11b Instrumentation Locations for Torus Loads, Ringheader Loads, and Acceleration.

Flow through the downcomers may be treated one-dimensionally. For the one-dimensional case the first term on the right of equation 1a reduces to the simple algebraic expression shown in equation 2.

$$\iint_{cs} \bar{v}_y (\rho V \cdot dA) \equiv \dot{m} (\bar{v}_{1y} - \bar{v}_{2y}) \quad (2)$$

where $\dot{m}$ is the mass flow rate exiting the downcomers, $\bar{v}_{1y}$ is the velocity of flow exiting the downcomers and $\bar{v}_{2y}$ is the pool swell velocity in the plane of the downcomers. Equation 2 predicts the download due to momentum flux transfer to be approximately 5500 lbf.^a This occurs near the time of initial vent clearing. Through analysis of films of the event one can determine, within the accuracy of the timing marks on the film,^b the exact time of initial vent clearing. Within the accuracy limitations just described, one can determine that the measured load is essentially identical to that predicted by equation 2. This suggests the download prior to vent clearing is due almost entirely to momentum flux transfer to the wetwell.

The second term on the right of equation 1a is the time rate of change of momentum of the control volume elements. Until vent clearing begins, the fluid in the torus pool is homogeneous. The mass flow rate downward from downcomers is equal to the mass flow rate of pool swell upward in the plane of the downcomers. Hence, one would expect this term to be negligible under the conditions that exist just prior to vent clearing.

^a $\dot{m} \Delta \bar{V} \approx 4.4 \times 10^4 \text{ gpm} \times 7.5 \text{ lb/gal} \times 1 \text{ min}/60 \text{ sec} = 5500 \text{ lbf.}$

^b The nominal frame rate of the cameras is 1000 frames per second. However, the timing marks on the film indicate the cameras varied as much as 2% from the nominal rate. Therefore, extreme care must be taken in relating time of visually observed events to measured responses.

4.3 THE DOUBLE-PEAK DOWNLOAD

The first downpeak occurs approximately 10 msec after initial vent clearing. The second downpeak follows the first by about 40 msec. The second downpeak is followed by an upload which peaks just prior to bubble breakthrough.

The hydrodynamic double-peak download may be understood by considering the following superimposed combination of forces which are expressed in equation 1a:

1. Following initial vent clearing a transient downward vertical pressure force is impressed on the torus because drywell pressure is exposed directly to the exit plane of the downcomers.
2. A rapid decrease in momentum flux transfer is experienced immediately following vent clearing because of the large density change of the fluid influx.
3. The second downpeak is derived primarily from a persistence of the pressure force and an increase in momentum efflux from pool swell.

Pressure forces producing the flow are initially almost entirely spent in overcoming the inertial resistance of the water slug in the downcomers. A very small fraction of the potential driving energy is spent on major and minor losses. As soon as vent clearing is initiated, however, the exit plane of the downcomers becomes exposed directly to the pressure in the drywell. The water mass above the exit plane of the downcomers tends to provide an isolation barrier for the pressures which build at the exit plane of the downcomers during and immediately following the vent clearing. The resulting sudden release of air into the pool combined with the relatively constant pressure in the ullage produces a substantial downforce which persists until

pressure in the ullage and the exit plane of the downcomers approximately equalize. Because peak downloads occur while flow velocity is relatively low, orifice plates have little effect on peak downloads.

The momentum flux term in equation 1a and equation 2 is the product of the mass flow rate and the velocity vector. When the vents clear, the mass flow rate into the control volume decreases greatly because of the difference in density of water and air. If vent clearing were ideally one-dimensional, then the mass flow rate entering the control volume would suddenly change by a factor of $\sim 800\times$. At the instant vent clearing occurred, the momentum flux transfer rate would suddenly diminish because of the advent of air flow in place of water flow into the wetwell.

Films show that the vent clearing process requires 40 to 60 msec. A jet of water can be observed piercing the water below the bubble formation 40 msec after vent clearing is initiated (ref. figure 4). Hence, because vent clearing does require a substantial amount of time to complete, and is obviously not one-dimensional, one should expect the sharpness of the load decrease to be diminished relative to the ideal one-dimensional case.

The magnitudes of the double peak downloads are also influenced by the time rate of change of control volume momentum and, to a lesser degree, by the buoyant lift of the air bubbles. As the bubbles develop substantially and start moving toward the ullage, the time rate of change of momentum of the control volume becomes appreciable because of a growing mass of air replacing liquid water moving in the vertical direction.

It should be pointed out that the double down peak observed in all 90° torus load tests is also produced in most 7.5° torus data from $\iint PdA$. The significance of the occurrence of the double-peak in the simulated load from the 7.5° section comes out of consideration of the fact that section is

essentially totally rigid. This further supports the thesis that the double-peak has a hydrodynamic source.

REMARKS ABOUT $\iint PdA$

The $\iint PdA$ from experimental data files by Altenbach and McCauley⁷ should almost perfectly represent the hydrodynamic loading input. The pressure transducers should simply reproduce the time history force pattern imposed on them from all sources (momentum flux time rate of change of the control volume, transient vertical pressure forces, and structural interaction). The numerical integration of the pressure data records should produce a very accurate description of forces imposed on the torus. The limitation to its being the "perfect" input representative is in the lack of a larger number of pressure transducers positioned around the circumference of the torus and the distortion which structural interaction will produce. Since only one structural mode is substantially excited, one would not expect structural interaction to cause a great deal of distortion (see section 5.3 for analysis of vibration induced pressures). In any case, the $\iint PdA$ represents accurately the hydrodynamic force input especially during the download period which includes the double-peak.

The upload is multi-peaked probably because of structural excitation combined with pool swell wash of the ringheader. Peak upload occurs just prior to bubble breakthrough.

4.4 SUMMARY OF LOAD RESPONSE SIGNATURE

The frequencies contained in the double-peak load are closely tuned to structural mode predicted by Arthur's analysis⁵ and verified by Posehn's⁶ experimental procedure (this will be discussed in greater detail in section 5). Posehn describes this mode as "vertical bending" (mode #5). While the 25 Hz rings distinctly in the load cells, its effect on peak loading appears to be

negligible. One will observe that the depth of the trough of the double-peak is not as pronounced in plots of the $\iint p dA^a$ (see quick-look report #7)¹ as it is in the load cell response. This result is not surprising when one considers that the upward movement of the torus (from its elastically charged down position) will tend to overshoot (because of inertia) even in the face of a restoring hydrodynamic force trying to push it back toward the second maxima of the double-peak.

One can more clearly understand the impact of the vertical pressure force induced during the vent clearing process by considering figure 12. Figure 12 is a superposition plot of two pressure transducers from NRC Air Test 1.3. The pressure transducer, P67, is in a downcomer at the mid-section of the torus. The pressure transducer, P7, is in the ullage region of the wetwell approximately at the midsection of the torus. Prior to vent clearing, the pressure in the downcomer is isolated from the plane of the downcomer exit by the inertia of the water slug. Upon initiation of vent clearing, the static pressure in the downcomer is exposed directly to the exit plane of the downcomers in the wetwell. The maximum pressure difference scaled from the plot is approximately 3.0 psi. That pressure difference is enough to produce a vertical download of ~30,000 lbf.

4.4.1 THE EFFECT OF DOWNCOMER SUBMERGENCE

Peak loading increases with increased depth of submergence of downcomers in the wetwell. The reason for this occurrence is understood by considering the time required for clearing the water slug from the downcomers. As mentioned earlier, the primary resistance to flow prior to vent clearing is the inertia of the water in the downcomers. A greater submergence of the

^aHydrodynamic vertical load function

REPLOTT RUN R 08/07/77 16:59:22

A B
P67(NRC1.3) P7(NRC1.3)

FIGURE 12. OVERLAY OF DOWNCOMER PRESSURE AND ULLAGE PRESSURE

downcomers produces a larger mass to be ejected from the downcomers, resulting in a greater time interval between drywell pressurization start and initial vent clearing. The greater time interval allows two terms in equation 1 to reach larger magnitudes at vent clearing time; they are the vertical pressure forces and the momentum flux.

4.4.2 THE EFFECT OF PRESSURIZATION RATE OF THE DRYWELL

An increase in the drywell pressurization rate results in increased vertical loading on the torus. One may again understand the effect of pressurization rate by considering equation 1. An increased pressurization rate will cause the surface forces on the exit plane of downcomers to be greater immediately following vent clearing. The inertia of the slugs of water in the downcomers again dominate the time required for vent clearing to begin. A greater pressurization rate will result in a larger pressure differential between the downcomer exit plane and the ullage at the time of initial vent clearing. Consequently a larger vertical download is produced. In addition, the higher pressurization rate will obviously cause a higher velocity at the time of vent clearing, which results in increased momentum flux transfer to the pool.

4.4.3 SENSITIVITY OF PEAK LOADING TO DOWNCOMER WATER MASS

The table below shows how the submergence and the pressurization rate differed in three tests and also shows the peak upload and peak download (from load cells) for each test. From the table, one can determine that a 22% increase in pressurization rate resulted in a 22% increase in peak download. One can also determine that a 39.6% increase in downcomer submergence resulted in a net 39.4% increase in peak download. (The effect of the slightly above nominal pressurization rate on the measured download for Test 2.5 was removed by the linear interpolation so that the net effect

of submergence could be determined^a.) This suggests that downcomer submergence is at least as important a parameter in terms of loading effect as the pressurization rate.

NRC AIR TEST	PRESSURIZATION RATE	DOWNCOMER SUBMERGENCE	PEAK ^b DOWNLOAD	PEAK ^b UPLOAD
NRC TEST 1.3	26.8	9.6"	4.1×10^4	1.8×10^4
NRC TEST 1.6	32.8	9.6"	5.0×10^4	2.25×10^4
NRC TEST 2.5	28.6	13.4"	6.1×10^4	2.25×10^4

a

By linear interpolation of peak download data in NRC Test 1.3 and 1.6, the effect of the slightly above nominal pressurization rate in Test 2.5 can be removed from the measured download. Thus, the increased load due to only the increased submergence can be determined. The process used is illustrated as follows:

$$DL(SUB) \left[1 + \frac{28.6 - 26.8}{26.8} \right] = 6.1 \times 10^4 \text{ lbf}$$

$$\therefore DL(SUB) = 5.72 \times 10^4 \text{ lbf}$$

$$\Delta - DL(SUB) = \frac{5.72 \times 10^4 - 4.1 \times 10^4}{4.1 \times 10^4} \times 100\%$$

$$= \underline{\underline{39.4\%}}$$

$$\Delta - SUB = \frac{13.5 - 9.6}{9.6} \times 100\%$$

$$= \underline{\underline{39.6\%}}$$

where

$DL(SUB)$ = Extracted download with nominal pressurization rate and with 13.5" submergence

$\Delta - DL(SUB)$ = Percent load change from nominal due to increased submergence.

$\Delta - SUB$ = Percent increase in submergence from nominal.

^b uncorrected for ullage pressure rise.

4.4.4 BUBBLE OSCILLATION

The possibility that bubble oscillations might be responsible for the 25 Hz frequency in the load cell response was investigated. Some analytical detail is presented in Appendix-A for reference. In light of analysis and observations presented in section 3. and 4. of this report, bubble oscillations appear to make no significant contribution to the load signature. It is possible for a 6" diameter bubble to oscillate naturally at 25 Hz but the bubbles grow to a much larger diameter too quickly to generate a 25 Hz ring.

5.0 FREQUENCY ANALYSIS

5.1 INTRODUCTION

Calculations from a dynamic response analytical model developed by Arthur⁵ and the experimental analysis from impulse inputs by Posehn⁶ revealed several possible structural modal frequencies. Posehn's experimental analysis was derived from the use of a calibrated impact hammer on the existing experimental facility. Analytical modal calculations by Arthur, based on "as constructed" conditions predicted the lowest natural frequency of the 90° torus to be about 25 Hz. Arthur's model also predicts several frequencies beyond the range of interest (0-75 Hz). Posehn's experimental analysis revealed a possible seven modes of structural vibrations below 75 Hz. One should not expect all of these possible modes to be present in the NRC air test data^a because the hydrodynamic loading function is far from being a delta-function.

^aNote that frequencies up to 174 Hz if existent, can be extracted from the raw data of the Air test series.

The approximate 25 Hz mode, which is defined by Posehn as "vertical bending" (mode-5), is the only structural frequency that consistently shows up in all the data. Other frequencies show up in some of the data but never of the characteristic magnitude of the 25 Hz. Hence, the 25 Hz structural frequency is the only one of primary importance in the 1/5 scale model experiments as far as can be determined within the frequency resolution of the 2.8635 msec sample interval.

5.2 FOURIER ANALYSIS

One may qualitatively measure frequency content by simply examining a time-domain event and "picking out" dominant frequencies that appear to repeat. However, an amplitude response derived from a Fourier transform will provide more absolute insight into relative amplitude magnitudes of dominant frequencies and it will further reveal the more obscure frequency content not perceivable from studying the time-domain function alone. Any real, bounded event whose transient response is known may be Fourier transformed.

An (FFT) Fast Fourier Transform code developed by Weaver⁸ (code name: FOURIER) was used for frequency analysis. A simple data manipulation code (code name: MIXFO) was developed for the purpose of converting PSE data files into a format (time, real value, imaginary value) required by the Fourier code. (Code description and its use procedure are presented in Appendix B.)

5.2.1 PSE DATA FILES PROCESSED:

The plots of the transient response and frequency amplitude response of selected load cells, 180⁰ pressure transducers, and accelerometers from Test 1.3, Test 1.6, Test 2.4, Test 2.5 are presented in Appendix C. For the purpose of providing a quick reference to physical location of the transducers, the reader is referred to figures 11a and 11b.

Particular attention is given to the 25 Hz ring noted in all torus load cells during peak load times. Conclusions relative to its specific source are presented after

- comparison of vertical motion of the torus (via accelerometers) with load cell and pressure response.
- elementary force/pressure modeling induced by torus accelerations.
- Fourier analysis of 24 pertinent data records.

5.2.2 VERTICAL ACCELERATION OF TORUS

Consider the three 180° accelerometers (A2, A5, A8) for Air Test 1.3. Figures 14, 16 and 18 show their transient response. Peak download is followed by a relatively singular ≈ 25 Hz oscillation. The up-peaks and down-peaks for all three transducers are closely in phase. Thus, the midsection of 90° torus is moving vertically in phase with the extreme ends at ≈ 25 Hz in accordance with mode #5 defined by Posehn⁶. The in-phase vertical acceleration oscillations of the 90° torus can produce prominent pressure oscillations of the same frequency, as will be shown in section 5.3.

5.2.3 AMPLITUDE SPECTRA

The waveform from accelerometer A-2 (located at south end of the torus), shown in figure 14, is clearly dominated by a 25Hz (approx.) frequency. Other frequencies are present, however, that are revealed through Fourier transformation. The Fourier transform of the wave pattern produces the amplitude spectrum shown in figure 15. As expected, the amplitude spectrum peaks at 25Hz. Even though the 25Hz frequency dominates the waveform, other significant frequencies (11Hz, 34 Hz, 52 Hz, 62 Hz) also are present.

The waveform from accelerometer A-5, located at the bottom of the torus at section 11 (mid-section), is shown in figure 16. Since this accelerometer is at the mid-section of the torus it is in a more favorable position to couple other structural dynamic interaction than A-2 which was located in the end of the torus. For that reason, one sees less of a single frequency dominance as shown in the amplitude spectrum in figure 17. Still however, the 25Hz dominates this waveform. The amplitude spectrum shows that three other frequencies of substantial amplitude are contained in the waveform; they are at 11Hz, 38 Hz, and 58Hz. Similar comparisons may be made by examining figures 18 and 19 which are, respectively, the time response waveform and the amplitude spectrum from accelerometer A-8, located on the torus end opposite A-2.

All of the pressure transducers in the wet region of the torus show essentially the same frequency content. They are dominated by the low frequency (less than 10 Hz) hydrodynamic input. However, the 25 Hz frequency shows up consistently in all pressure waveforms. Similarly,

5.2.3 AMPLITUDE SPECTRA (cont'd)

the load response is consistently dominated by the same low frequency hydrodynamic input but the approximate 25 Hz is present in all load cell waveforms. Selected transient waveforms and corresponding amplitude spectra from Tests 1.3, 1.6, 2.5, and 2.6 are in Appendix-C.

5.3 VIBRATION INDUCED PRESSURE RESPONSE

The purpose of the following analysis is to illustrate quantitatively how torus vibration can induce pressure oscillations in the "wet region" of the torus. The frequency content of the waveforms are compared and a simple vibration induced pressure response model is developed which shows that the amplitude of the 25Hz pressure response corresponds very closely to that transduced in the wet region of the torus.

Figure 13 illustrates a beaker of water on a shaker plate being driven with an acceleration of $A_0 \sin(\omega\tau)$. The dynamic force imposed on the bottom of the water column will be directly proportional to the product of acceleration of the plate and mass of the water column. Assumptions implied are rigid column walls, negligible effects from compressibility of the water and an acceleration amplitude less than local gravity. Equation-3 expresses the force introduced to the bottom of the water column.

$$F(\tau) = \rho h A_c A_0 \sin(\omega\tau) \quad (3)$$

where

ρ = mass density of the water

h = column height

A_c = cross sectional area of the water column

FIGURE 13. VIBRATION-INDUCED PRESSURE RESPONSE
MODEL

5.3 VIBRATION INDUCED PRESSURE RESPONSE (cont'd)

The resulting dynamic pressure that a transducer located at the bottom of the water column should measure is given by the following relation

$$P(\tau) = \rho h A_0 \sin(\omega \tau) \quad (4)$$

The pressure amplitude is seen to vary in direct proportion to the product of water column height and the acceleration amplitude.

The nominal water column height above the torus bottom is 3 feet. The torus acceleration amplitude is of the order of 0.5 g's. From equation 4 one can determine the pressure amplitude in response to a 0.5 g acceleration amplitude should be 0.65 psi. Examination of pressure waveforms in Appendix C (e.g., Figures 21 and 22) corresponding to transducers located at 180° (the bottom of the torus) show superimposed pressure amplitudes at 25 Hz which correspond quite closely to that calculated above.

5.3.1 Phase Correlation

There is a danger in drawing conclusions based on "phase" observations between two waveforms produced by two different types of transducers. The peaks on a transient response will shift in time when the other function is added to it. For example, when a ramp function is added to the sine wave the time of the peaks will shift to the right if the ramp has a positive slope and to the left if it has a negative slope.

One may safely compare the phase of two functions if they have the same input source. However, the accelerometer has a single source (torus motion) but the pressure and/or load cell responses have additive sources. Since the accelerometers respond solely to the motion of the torus, and the pressure transducers respond to vibration induced loading as well as hydrodynamically induced loading the peak of the resulting pressure response will not match the time of acceleration peaks unless one of the

5.3.1 PHASE CORRELATION (cont'd)

pressure input is constant. Because of the above expressed reasons it is probably impossible to draw reliable conclusions about phase relationships between pressure, acceleration, and load cell waveforms.

6.0 SUMMARY OF CONCLUSIONS

Conclusions are presented at various points within the discussion of the preceding sections. Presented below is a summary of the more important conclusions resulting from this study.

- 1) The 25 Hz frequency structural mode is the only one of significant importance of 1/5 scale test. It is the only frequency which consistently appears in all of the data which were analyzed.
- 2) While structural dynamic effects are perceivable in the measured load response, they do not have an appreciable effect on the peak loading of the torus.
- 3) The " $\iint P da$ " is an excellent representation of hydrodynamic input force. One should however, expect it to be slightly tainted with the 25 Hz frequency resulting from excitation of the vertical bending mode⁶.
- 4) The peak vertical loading is quite sensitive to both the mass quantity of water in the downcomers and to the drywell pressurization rate. An increase in either the pressurization rate or the downcomer submergence results in increased loading.
- 5) The hydrodynamic loading has three principal components, all of which are identified in equation-1a. They are the vertical pressure forces, the momentum flux, and the time rate of change of momentum of the control volume.

6.0 SUMMARY OF CONCLUSIONS (cont'd)

- 6) The double peak download is caused by hydrodynamically-coupled phenomena.
- 7) Late time oscillations in the load cell response are related to cyclic secondary vent clearing. The cyclic vent clearing occurs when the pressure difference between the downcomers and the ullage diminish to a value approaching the hydrostatic head of the downcomer submergence. One should expect the frequency of late time oscillations to be sensitive to both pool volume and torus geometry.
- 8) Bubble oscillation following vent clearing is unlikely to have any appreciable effect on the load cell response.

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APPENDIX-A

Bubble Oscillation:

The 25 Hz "early time" ring could possibly result from early bubble formation. A spherical air bubble oscillating in an infinite liquid medium has a fundamental frequency, f_o , defined by --

$$f_o = \frac{1}{2\pi r_o} \left(\frac{3p_o g_c}{\rho} \right)^{1/2} \quad (2)$$

where

r_o = nominal bubble radius

ρ = mass density of liquid

p_o = nominal bubble pressure

A spherical bubble of nominal 6" diameter and nominal pressure of 7 psia would oscillate at 25 Hz. The frequency would be expected to slightly decrease as the bubble ascended because of lower hydrostatic pressure. The cycle period does increase (according to tabular output) by 6 ms from beginning of oscillation until early time bulk fluid effects destroy the singularity of its character. This fact reinforces confidence in the concept of an early time bubble oscillation. However, a true resultant pressure forcing function should also display a clean 25 Hz harmonic; clearly, the approximate pressure function defined above does not, even though its peaks and troughs are coincident with a 25 hz function.

APPENDIX B - MIXFO-1

A simple data manipulation code was developed for the purpose of converting PSE data files into a format acceptable to Joe Weaver's Fourier Code. The Fourier Code produces an amplitude spectrum from the data file. The code requires an input of real and imaginary components of the data along with the time corresponding to those values. One must read in the time values T1 and T2 which bracket the event to be transformed. For example if you read in the time values of 2.2, 3.2 the code will select data from the input file for one-second time interval between 2.2 and 3.2 seconds and that will be the data transformed. Care must be taken to insure that the values of T1 and T2 are selected so that fewer than 2000 data points are bracketed.

A listing of the source file is shown on page the following page. It is set up to allow one to five data files to be read and converted at one time. The output files DATAF010 through DATAF050 are in the appropriate (1X, 6E12.4) format compatible with the FOURIER transform code. The code MIXFO-1 is stored on tape GL622. An example illustrating the use of FOURIER and MIXFO-1 is shown on the following page.

MIXFO-1

7/15/77

```

2 C
3 C   THIS CODE READS ANY 3492-POINT PSE DATA FILE AND SELECTS EVERY
4 C   POINT BRACKETED BY TFIRST (T1) AND TLAST (T2). YOU MUST SELECT
5 C   T1 AND T2 SO THAT THERE ARE FEWER THAN 2000 DATA POINTS. THE
6 C   DATA ARE THEN MIXED WITH 0-IMAGINARY VALUES AND TIME-VALUES
7 C   IN A FORMAT SUITABLE FOR JOE WEAVER'S FOURIER CODE.
8 C
9 C
10  PROGRAM MIX1(INPUT1,TAPE1=INPUT1,INPUT2,TAPE2=INPUT2,
11 1 INPUT3,TAPE3=INPUT3,INPUT4,TAPE4=INPUT4,INPUT5,TAPE5=INPUT5,
12 1 DATAFD10,TAPE10=DATAFD10,DATAFD20,TAPE20=DATAFD20,
13 1 DATAFD30,TAPE30=DATAFD30,DATAFD40,TAPE40=DATAFD40,
14 1 DATAFD50,TAPE50=DATAFD50)
15 C
16 C
17     DIMENSION T(4000),VR(4000),VI(4000)
18     CALL DEVICE(6HCREATE,6HDATAFD,50000)
19     WRITE(59,10)
20 10  FORMAT(24HINPUT TFIRST,TLAST-2F5.2)
21     READ(59,15) T1,T2
22 15  FORMAT(2F5.2)
23     M1=(T1/2.8635E-03)/6.
24     N1=M1*6 + 1
25     M2=(T2/2.8635E-03)/6.
26     N2=M2*6
27     NF=(M2-M1)*6
28     WRITE(10,150) NF
29     WRITE(20,150) NF
30     WRITE(30,150) NF
31     WRITE(40,150) NF
32     WRITE(50,150) NF
33 150 FORMAT(I4)
34     T(1)=0.
35     VI(1)=0.
36     DO 20 I=2,3492
37     T(I)=T(I-1) + 2.8635E-03
38     VI(I)=0.0000E+00
39 20  CONTINUE
40     READ(1,100) (VR(I),I=1,3492)
41     WRITE(10,100) (T(I),VR(I),VI(I),T(I+1),VR(I+1),VI(I+1),I=N1,N2,2)
42     READ(2,100) (VR(I),I=1,3492)
43     WRITE(20,100) (T(I),VR(I),VI(I),T(I+1),VR(I+1),VI(I+1),I=N1,N2,2)
44     READ(3,100) (VR(I),I=1,3492)
45     WRITE(30,100) (T(I),VR(I),VI(I),T(I+1),VR(I+1),VI(I+1),I=N1,N2,2)
46     READ(4,100) (VR(I),I=1,3492)
47     WRITE(40,100) (T(I),VR(I),VI(I),T(I+1),VR(I+1),VI(I+1),I=N1,N2,2)
48     READ(5,100) (VR(I),I=1,3492)
49     WRITE(50,100) (T(I),VR(I),VI(I),T(I+1),VR(I+1),VI(I+1),I=N1,N2,2)
50 100 FORMAT(1X,6E12.4)
51     CALL EXIT
52     END

```


APPENDIX-C

AMPLITUDE SPECTRA

REALIST 1000 1000 1000 1000 1000 1000 1000 1000 1000 1000
A.
DL1341067 R-2

FIGURE 14. TORUS ACCELERATION (A-2, NRC Test 1.3)

FIGURE 15. AMPLITUDE SPECTRUM OF WAVEFORM FROM ACCELEROMETER A-2 FOR TEST 1.3

REFLECTOR 1 114-77 15 OF 29

41134109: A-5

FIGURE 16. TORUS ACCELERATION (A-5, NRC TEST 1.3)

FIGURE 17. AMPLITUDE SPECTRUM OF WAVEFORM FROM ACCELEROMETER A-5 FOR TEST 1.3

REFLIT RUN 1 07/14/77 13:06:57
A
WL134306: P-8

FIGURE 18. TORUS ACCELERATION (A-8, NRC TEST 1.3)

FIGURE 19. AMPLITUDE SPECTRUM OF WAVEFORM FROM A-8 FOR NRC TEST 1.3

REPLLOT RUN: 6 07 14 77 12:19 13
P
WL131111: P-4

FIGURE 20. PRESSURE RESPONSE FROM P-4 FOR NRC TEST 1.3

FIGURE 21. AMPLITUDE SPECTRUM OF WAVEFORM FROM P-4, TEST 1.3

FIGURE 22. AMPLITUDE SPECTRUM OF PRESSURE TRANSDUCER P-4 WITH FREQUENCY 0-5HZ FILTERED

REPLLOT FROM 0 07-14-77 11:53-18
A
WL131106. P-10

FIGURE 23. PRESSURE RESPONSE FROM P-10, NRC TEST 1.3

FIGURE 24. AMPLITUDE SPECTRUM OF WAVEFORM FROM PRESSURE TRANSDUCER P-4, TEST 1.3

FIGURE 25. AMPLITUDE SPECTRUM OF PRESSURE TRANSDUCER P-10 WITH FREQUENCY 0-5HZ FILTERED

REPLLOT RUN 2 07 13-77 17 15 47
P
WL134112 L-4A

FIGURE 26. LOAD CELL RESPONSE (L-4A) FOR NRC TEST 1.3

FIGURE 27. AMPLITUDE SPECTRUM OF WAVEFORM FROM LOAD CELL L-4A, TEST 1.3

REFLOT BOX 3.87 13477 17 19.22
R
NL134114:L-5A

FIGURE 28. LOAD CELL RESPONSE (L-5A) FOR NRC TEST 1.3

FIGURE 29. AMPLITUDE SPECTRUM OF WAVEFORM FOR LOAD CELL L-4A, TEST 1.3

FIGURE 31. AMPLITUDE SPECTRUM OF WAVEFORM FROM L-1, NRC TEST 1.3

REFLECT A/N 0 00 13:07 17 09:27
A
WL134103:L-2

FIGURE 32. RINGHEADER LOAD CELL RESPONSE (L-2) FOR NRC TEST 1.3

FIGURE 33. AMPLITUDE SPECTRUM OF LEAD CELL L-2, TEST 1.3

REPLIT RUN U 07-16-77 15:36:59

A

HL164106: A-2

FIGURE 34. TORUS ACCELERATION (A-2) FOR NRC TEST 1.6

FIGURE 35. AMPLITUDE SPECTRUM OF WAVEFORM FROM A-2 FOR TEST 1.6

REFLIT RUN 1 07 16 77 16 40 10

AL161196 P-10

FIGURE 36. PRESSURE RESPONSE FROM :-10 FOR NRC TEST 1.6

FIGURE 37. AMPLITUDE SPECTRUM OF WAVEFORM FROM PRESSURE TRANSDUCER P-10 FOR TEST 1.6

REPLIT RUN 1 07 15:07 15:38:36

DL154112: L-4A

FIGURE 38. LOAD CELL RESPONSE (L-4A) FOR NRC TEST 1.6

FIGURE 39. AMPLITUDE SPECTRUM OF WAVEFORM FROM LOAD CELL L-4A for NRC TEST 1.6

REPLLOT RUN 0 07/16/77 15:42:08

WL254106: A-2

FIGURE 40. TORUS ACCELERATION (A-2) FOR NRC TEST 2.5

FIGURE 41. AMPLITUDE SPECTRUM OF WAVEFORM FROM ACCELEROMETER A-2 FOR NRC TEST 2.5

RELOT RUN 07/16/77 15:45:13

WL251106: P-10

FIGURE 42. PRESSURE RESPONSE FROM P-10 FOR NRC TEST 2.5

FIGURE 43. AMPLITUDE SPECTRUM OF WAVEFORM FROM PRESSURE TRANSDUCER P-10 FOR NRC TEST 2.5

REPLOT RUN U 07/15/77 15:43:21

R

WL254112: L-4A

FIGURE 44. LOAD CELL RESPONSE (L-4A) FOR NRC TEST 2.5

FIGURE 45. AMPLITUDE SPECTRUM OF WAVEFORM FROM LOAD CELL L-4A FOR NRC TEST 2.5

REFLOT RUN 0 27/15.77 15:46:40
P
ML264109: A-2

FIGURE 46. TORUS ACCELERATION (A-2) FOR NRC TEST 2.6

FIGURE 47. AMPLITUDE SPECTRUM OF WAVEFORM FROM ACCELEROMETER A-2 FOR TEST 2.6

REPLOTT RUN U 07-16/77 15:49:58
5
WL261106: P-10

FIGURE 48. PRESSURE RESPONSE FROM TRANSDUCER P-10 FOR NRC TEST 2.6

FIGURE 49. AMPLITUDE SPECTRUM OF THE WAVEFORM FROM PRESSURE TRANSDUCER P-10 FOR NRC TEST 2.6

FIGURE 50. AMPLITUDE SPECTRUM OF PRESSURE TRANSDUCER P-10 WITH FREQUENCIES 0.5HZ FILTERED

REPLOTTED RUN U 07/16/77 15:48:11

R

ML264115: L-4A

FIGURE 51. LOAD CELL RESPONSE (L-4A) FOR NRC TEST 2.6

FIGURE 52. AMPLITUDE SPECTRUM OF WAVEFORM FROM L-4A
FOR NRC TEST 2.6

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