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AIR SCALING AND MODELING STUDIES FOR THE 1/5-SCALE MARK I BOILING WATER REACTOR PRESSURE SUPPRESSION EXPERIMENT

W. Lai and E. W. McCauley

January 4, 1978

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AIR SCALING AND MODELING STUDIES FOR THE 1/5-SCALE MARK I BOILING WATER REACTOR PRESSURE SUPPRESSION EXPERIMENT

PREFACE

In this report we attempt to consolidate the work of several researchers whose bench-top experimentation has enriched our knowledge of the dynamic behavior of the boiling water reactor (BWR) pressure suppression system. The behavior of particular interest is the characteristics of the hydrodynamic forces and pool motion of the Mark I pressure suppression system during the air-clearing phase of the postulated loss-of-coolant accident (LOCA). Because of the large size of the actual containment structure, full-scale simulation of a LOCA is impractical. Instead, scale-model tests provide data that support inferences about the behavior of the full-scale system. (In fact, the small size of the apparatus and the indoor environment enable better control of test conditions and quicker, more specialized results than full-size physical testing.) The overall purpose of the main program* is threefold:

- Establishment of scaling laws.

- Design and fabrication of a three-dimensional 1/5-scale test facility.

- Conduct of a comprehensive test program.

This report summarizes table-top investigations that were initiated prior to the 1/5-scale tests. These investigations were designed to provide detailed phenomenological and theoretical understanding of key features of the dynamic behavior of the system. The purpose of this summary is to relate the results predicted by scaling and modeling the Vertical Load Function (VLF) to results from the 1/5-scale torus experiment (whose facility incorporates both a three-dimensional 90° and a 7.5° torus sector).

Substantial portions of the text of this summary are either extracts from or paraphrases of our own earlier reports, as well as those of other investigators. To avoid a surfeit of footnotes and quotation marks, we have exercised the editorial prerogative of presenting a relatively unblemished text with only limited author citation for *specific* contributions. Nevertheless, to

*For details of the 1/5-scale facility, the air test program, and related activities, see Refs. 1-5.

ensure that authors are given appropriate credit for their work, we wish to acknowledge the contributions our colleagues have made to these pages:

In Section 3, we use material from a report co-authored by John Meier (Ref. 17) for results of the cinematographic investigation of rectangular pool dynamics and from a report by John Pitts (Ref. 18) for the discussion of the 1/64-scale torus model.

In Section 4, we rely on the results of air-scaling experiments designed and initiated by Frank Morrison (Ref. 19). The discussions of benchmark experiments, characterization of the VLF, and the effect of downcomer fill level on the response velocity load function (RVLF) are

based on three reports of our own (Refs. 22, 23, and 25).

Readers will find that Section 2 provides a useful perspective on Sections 3 and 4; it presents what we feel are the highlights of the scaling and modeling studies, along with new information and a discussion of how well (or poorly) the results from modeling match the data from the large-scale experiments.

Our debt to our colleagues is evident throughout this report; we trust we have represented their work accurately and must assume responsibility for any errors of interpretation that result from the compression necessary for this compilation.

ABSTRACT

Results of table-top model experiments performed to investigate pool dynamics effects due to a postulated loss-of-coolant accident (LOCA) for the Peach Bottom Mark I boiling water reactor containment system guided subsequent conduct of the 1/5-scale torus experiment and provided new insight into the vertical load function (VLF).

Pool dynamics results were qualitatively correct. Experiments with a 1/64-scale fully modeled drywell and torus showed that a 90° torus sector was adequate to reveal three-dimensional effects; the 1/5-scale torus experiment confirmed this. Table-top scaling-law studies showed (and 1/5-scale torus experiments also confirmed) that the VLF is insensitive to the enthalpy flux parameter. Additionally, table-top experiments produced data suitable for computer code

verification.

Table-top, 1/5-scale torus, and other scaled experiments show an oscillatory VLF; the maximum download is typically double-spiked, whereas the maximum upload is more gradual. The load function contains a high frequency oscillation superimposed on a low frequency one; evidence from measurements and from momentum modeling with a computer indicates that the oscillations have hydrodynamic origins.

The maximum download diminishes with initial downcomer fill level. When the downcomer is initially empty, table-top experiments show that the maximum download degenerates to a sinusoidal shape. This leads to the possibility of decomposing the VLF into a low-frequency-damped sinusoidal load plus a higher frequency (~10 times the low frequency) damped sinusoidal load.

1. INTRODUCTION

The success of the pressure suppression containment system design of a light-water reactor is dependent on the capability of a water heat sink to provide rapid and stable condensation of the released primary high-pressure steam coolant during a hypothetical LOCA. However, during

the initial stage of the LOCA, significant vertical loads due to non-condensable air injection from the drywell are imposed on the toroidal wetwell (see Fig. 1). To gain a better understanding of this aspect of the dynamic behavior of the system, a 1/5-scale three-dimensional pressure

Fig. 1. Cross-section of Peach Bottom BWR Mark I toroidal wetwell.

suppression experimental facility was developed for the Nuclear Regulatory Commission. Extensive testing was performed to quantify the hydrodynamic phenomena and associated forces.

Prior to the 1/5-scale tests, an inexpensive but extensive series of table-top experiments were conducted to investigate the fluid dynamics of the system. These small-scale (1:40) experiments provided detailed phenomenological and theoretical understanding of the key features of the dynamic behavior of the pressure suppression system. The results accurately predicted the transient hydrodynamically induced load function for the large-scale facility that was observed later.

PURPOSE OF THIS REPORT

This report summarizes the table-top investigations initiated prior to the 1/5-scale tests. The objective of this summary, in addition to presenting results of the testing, is to relate the test results to those from the 1/5-scale torus experiment.

ORGANIZATION OF THIS REPORT

Major conclusions from scaling and modeling studies, supported by data published elsewhere and by results from the 1/5-scale experiment are presented in Section 2. In addition, Section 2 contains a more complete discussion of the characteristics of the VLF than has previously been published. It also recapitulates the findings, strengthening some on the basis of new data, and presents a new conclusion regarding the components of the VLF. Sections 3 and 4 summarize the results of the modeling studies; each covers four areas of interest: objective, test apparatus, results and discussion, and conclusions.

Cinematographic investigations are presented in Section 3, which focuses on studies of a rectangular pool, a cylindrical pool, and a 1/64-scale torus model. (The cylindrical pool study has not been reported elsewhere.)

Instrumented experiments are presented in Section 4. Included are results from experiments in four areas: air scaling, generation of benchmark data, characterization of

the response vertical load function* (RVLF), and the effect of downcomer fill level on the RVLF.

Three appendices give details of some of the work reported in Section 4.

2. HIGHLIGHTS AND IMPLICATIONS

The table-top modeling studies provided useful results in the attempt to broaden our understanding of pressure suppression system dynamic behavior. Summarized in this section are the more significant conclusions from studies detailed in Sections 3 and 4. Also presented are further analyses of results. Whenever possible, the presentation is supported by results from larger scale experiments, particularly from the Lawrence Livermore Laboratory (LLL) 1/5-scale experiment.

THREE-DIMENSIONAL EFFECTS

The 1/64-scale torus experimental results (Section 3) indicated that significant three-dimensional (3-D) effects should be expected in the 1/5-scale 90° torus sector. Significantly, the 1/64-scale model showed major bubble action and pool swell in regions of closely spaced downcomers, which implied that pool pressures

should be higher in these regions.

Pressure measurements made in the wetwell of the 1/5-scale experiment confirmed the 1/64-model predictions. Representative of this 3-D effect are the peak pressures measured at the bottom of the wetwell along the axis of the 90° torus (Figs. 2 and 3);⁶⁻⁷

Fig. 2. Spatial variation of the pressure peak along the bottom dead center of the 90° toroidal wetwell [Tests 3.3(a) and 3.3(b)].

*The RVLF is the VLF measured with a load cell.

Fig. 3. Spatial variation of the pressure peak at bottom dead center of the 90° toroidal wetwell (Test 2.8).

note the occurrence of maximum and minimum pressures in the expected regions.

EFFECT OF ENTHALPY FLUX

An important aspect of the air-scaling studies (Section 4) was to evaluate the relevance of the enthalpy flux group $[(RT_o]/[gL]$ or $[h_o \dot{m}]/[\rho_g^{3/2} L^{7/2}]$. The enthalpy flux was varied by a factor of 2 with a vent line orifice. The results show that the maximum download and upload remained essentially unchanged.

The 1/5-scale RVLF results confirmed the behavior of the maximum upload and also showed that the maximum download was insensitive to the enthalpy flux group.⁸⁻⁹ In general, the maximum upload for the hydrodynamic VLF (HVLF) showed a larger variation for the range of parameters studied. Except for a single case, the results for the 90° torus sector showed $\leq 10\%$ change; the results for the 7.5° torus sector showed $\leq 18\%$ change.⁸⁻⁹ The pertinent data are summarized in Tables 1-5.

CHARACTER OF THE VLF

The results of the table-top VLF characterization study (see Section 3) are summarized in Fig. 4. The general distinguishing features of the VLF from table-top experiments are also observed in the RVLF and HVLF from the 1/5-scale experiments (Figs. 5-7). This is not proof, however, that identical mechanisms are operative in all experiments. For instance, the most visible effect at the maximum upload for the 1/5-scale VLF is pool impact of the header; this component obviously does not exist for our bench-top experiments.

The pressure measurements in Ref. 11 exhibit an oscillatory behavior (Fig. 8). The HVLF is obtained by integration of pressure measurements so that it exhibits the same type of

Table 1. Summary of actual test conditions^a for orifice-effect tests.

Test No.	P _{dw} ^o , psia	p, psi/s	Drywell ^b volume, ft ³	Vent line orifice diameter, in.		
				90°		7.5°
				Left vent	Right vent	Vent
1.3	2.946	25.96	348	9.5	9.5	3.63
1.3.1	3.084	27.24	296	9.5	9.5	3.63
2.4	2.994	24.31	296	9.5	9.5	3.63
3.5	3.044	25.63	348	9.5	9.5	3.63
3.1	2.897	28.90	296	10.58	10.58	4.08
3.2	2.9415	25.73	348	None	None	4.08
3.3a	2.984	24.90	348	9.5	0.0	3.63
3.3b	2.975	24.90	348	0.0 ^c	9.5	3.63
3.4a	2.859	25.00	348	None	0.0	None
3.4b	2.953	22.61	348	0.0	None	None

^aDuring all tests, the initial torus water level was 0.2 ft below torus centerline, the downcomer submergence set at 0.8 ft, and drywell overpressure was zero.

^bWater was inadvertently sucked into the drywell during tests 1.3.1, 2.4, 3.1, thereby slightly reducing the drywell volume.

^cThe value 0.0 indicates a blocked vent line.

oscillations (Figs. 9 and 10). The observed frequencies appear to be apparatus-dependent, suggesting, at first, structural vibrations as the cause. However, phase relationships for our flask tests between independent measurements of RVL/F, bottom pressure, and support acceleration substantiate the thesis that these oscillations are excited by hydrodynamic phenomena (see this section and Section 3); it was also shown that the oscillations in the 1/5-

scale pressure and load data originated from hydrodynamic phenomena.²

The double-spiked download peaks are clearly evident in Figs. 4-7. The less abrupt upload is also easily observed. The second download peak, or high frequency pulse (HFP), seems to signal the beginning of the high frequency oscillations. The HFP has also been observed in scale studies from General Electric (GE).¹² The low frequency oscillations are also distinguishable in Figs. 4-7.

Table 2. Effect of $\dot{m}h$ on selected peak parameters.

	Test 2.4	Test 3.1	Test 3.2
Actual initial drywell pressurization rate	167.5 kPa/s (24.3 psi/s)	189.6 kPa/s (27.5 psi/s)	160.0 kPa/s (23.2 psi/s)
Load cell 4 (main outboard):			
Peak download	70.7 kN (15,900 lbf)	71.6 kN (16,100 lbf)	64.5 kN (14,500 lbf)
Peak upload	26.7 kN (6,000 ft-lb)	26.7 kN (6,000 ft-lb)	29.4 kN (6,600 ft-lb)
Load cell 5 (main inboard):			
Peak download	120.3 kN (23,000 ft-lb)	113.4 kN (25,500 ft-lb)	112.5 kN (25,300 ft-lb)
Peak upload	52.0 kN (11,700 ft-lb)	52.0 kN (11,700 ft-lb)	56.9 kN (12,800 ft-lb)
Peak pressure at 180°:			
7.5° Torus	48.3 kPa (7.0 psia)	48.3 kPa (7.0 psia)	47.6 kPa (6.9 psia)
90° Torus, plane 9	46.9 kPa (7.2 psia)	48.3 kPa (7.0 psia)	47.6 kPa (6.9 psia)

Figure 11 shows measurements made with table-top equipment to determine the effects of downcomer fill level on the RVLF (Section 4). Even though the load function changed shape with downcomer fill level, the HFP persists.

The increased relative magnitude of the HFP when downcomer fill level is reduced to 80% is shown clearly in Fig. 11a. The RVLF for progressively lower initial downcomer fill levels is shown in Fig. 11b; the trace for 80% full is repeated to provide an index for comparison. Note that the time between the first and second

HFP download peaks remain constant at ~ 1.5 ms, even as the HFP becomes dominant (note the trace for 60%). Figure 11c exhibits the same trends at a lower pressure ratio.

The high frequency oscillations in the traces in Fig. 11b seem to be moving left in a path defined by the low frequency envelope. Careful inspection shows that the peak pulse for the initially empty downcomer case is the fourth pulse; the first pulse is just disappearing into the left baseline. The time between pulses has not changed.

Table 3. Variation in the peak hydrodynamic loads due to the vent-line orifice - standard tests.

Test	90° Sector				7.5° Sector			
	L_{dn}^a	$\epsilon\%$	L_{up}	$\epsilon\%$	L_{dn}	$\epsilon\%$	L_{up}	$\epsilon\%$
Group A	39.8	-	17.7	-	3.04	-	1.12	-
3.1	37.4	- 6.0	17.7	0.0	2.74	-9.9	1.08	- 3.6
3.2	35.6	-10.6	22.5	+27.1	2.82	-7.2	1.26	+12.5

^aL in klb.

Table 4. Variation in the peak hydrodynamic loads due to the vent-line orifice - blocked vent line.

Test	90° Sector				7.5° Sector			
	L_{dn}^a	$\epsilon\%$	L_{up}	$\epsilon\%$	L_{dn}	$\epsilon\%$	L_{up}	$\epsilon\%$
Group A	39.8	-	17.7	-	3.04	-	1.12	-
3.3a	18.9	-	7.95	-	2.90	-4.6	0.958	-14.5
3.3b	18.8	-	9.75	-	2.90	-4.6	0.968	-13.6
3.3 sum	37.7	-5.3	17.7	0.0	-	-	-	-
3.4a	20.2	-	9.40	-	2.99	-1.6	1.30	+16.1
3.4b	20.6	-	9.35	-	3.14	+3.3	1.32	+17.9
3.4 sum	40.8	+2.5	18.8	+6.2	-	-	-	-

^aL in klb.

Table 5. Vent-line resistance coefficients for the 1/5-scale torus experiment.¹⁰

Tests	45° Sector		7.5° Sector
	Left	Right	
Nominal	24.1	22.4	21.6
3.1	12.9 ^a	12.9 ^a	12.9 ^a
3.2	5.1	4.7	4.3 ^a

^aCalculated values.

Fig. 4. Origin of VLF characteristics. (a) Hydrodynamic origin: peak downforce results from ejection of water slug into the pool. (b) Hydrodynamic origin: second peak of downforce becomes dominant as downcomer initial fill level is reduced. (c) hydrodynamic origin: maximum upforce given by average, results from combination of pool levitation and compression due to pool swell. (d) Hydrodynamic origin: low frequency carrier wave due to *vertical* oscillations of the expanding air bubble. Frequency *increases* with ullage pressure. Oscillations are in phase with pressure oscillations at bottom of pool. (e) Hydrodynamic origin: high frequency on carrier wave not fully characterized; slight reduction with increase in ullage pressure, oscillations in phase with pressure oscillations at the bottom of the pool.

The characteristic sharp maximum download has changed to a less abrupt sinusoidal download for the initially empty downcomer. Note that the pulse relationship observed in these flask tests

Fig. 5. Typical HVLF for the 7.5° torus sector. (Test 1.3.1)

Fig. 6. Typical RVLF for the 90° torus sector. (Test 1.3.1)

between load peaks and acceleration of the center of the flask support beam is that of the load driving the beam and this is maintained regardless of the downcomer fill level (Figs. 12-14).

Fig. 7. Typical HVLf for the 90° torus sector. (Test 1.3.1)

Fig. 9. Typical pressure trace at the bott of the pool for the 7.5° torus sector. (Test 1.3.1)

Fig. 8. Typical pressure trace at the bottom of the pool for a cylindrical tank (Ref. 11).

Fig. 10. Typical pressure trace at the bottom of the pool for the 90° torus sector. (Test 1.3.1)

i. Downcomer initially full

ii. Downcomer initially 80% full

Fig. 11. Change of the RVLf as a function of initial downcomer fill level (5-litre flask, single downcomer, 2.5 litre water, all vertical scales = 50 lbf/cm).

- a) Nominal pressure ratio 3:1,
timescale = 10 ms/cm.

Figure 11 reveals two additional characteristics. The first is that the download starts earlier as the downcomer fill level decreases. The difference in download starting time for the full downcomer (Fig. 11a) and the empty downcomer (Fig. 11b)

is 40 ms, which is of the order of the clearing time of the full downcomer. The second is that the time duration of the download (measured by extrapolating the initial baseline) remains essentially constant at 38 ms, regardless of the initial downcomer fill level.

The additional data from the downcomer fill level study suggest that the VLF characteristics summarized in Fig. 4 can be decomposed into the two simpler parts illustrated in Fig. 15. This decomposition is consistent with the preliminary indications found by Davy.

EFFECT OF DOWNCOMER FILL LEVEL ON THE VLF

Both maximum download and maximum upload recedes with the initial downcomer fill level (see Section 4). The download results for flask tests conducted with an initial pressure ratio of 15:5 (3:1) (from Fig. 61) are replotted in Fig. 16.

Also shown in Fig. 16 are the MAITAI code calculations for a vertical cylindrical flat-bottomed container with the same geometric ratios as the LLL flask experiments; the initial pressure ratio was 5.8:1.^{15,16} General Electric data derived from 1/12-scale experiments conducted in a short (essentially two-dimensional)

i. Downcomer initially 80% full

ii. Downcomer initially 60% full

iii. Downcomer initially 40% full

iv. Downcomer initially 20% full

v. Downcomer initially empty

b) Nominal pressure ratio 3:1, time scale 0.001 sec/cm

i. Downcomer initially 100% full

ii. Downcomer initially 40% full

c) Nominal pressure ratio 2:1,
timescale = 5 ms/cm.

horizontal cylinder also show the same trend; the initial pressure ratio was 12:1. The curves in Fig. 16 show a common trend toward smaller download with lower initial downcomer fill level.

Fig. 12. Dynamic response of a typical blowdown test conducted with an initially full downcomer (run 1/14-1, 5-litre flask, nominal atmosphere, ullage = 15:5, timescale = 5 ms/cm).

Fig. 13. Dynamic response of a blowdown test conducted with an initially partially (40%) filled downcomer (run 1/21-8, 5-litre flask, nominal atmosphere, ullage = 15:5, nominal pressure ratio 3:1, time-scale = 5 ms/cm).

Fig. 14. Dynamic response of a blowdown test conducted with an initially empty downcomer.

Fig. 15. Suggested composition of the VLF.

Fig. 16. Effect of initial downcomer fill level on the maximum download.

3. CINEMATOGRAPHIC STUDIES

Bubble and pool dynamics resulting from clearing of downcomers in enclosures configured to simulate the Mark I pressure suppression system were studied using high speed motion pictures, primarily. Three container shapes were investigated: rectangular, cylindrical, and 1/64-scale torus.

RECTANGULAR POOL¹⁷

The primary purpose of these tests was to study the effect of downcomer spacing on growth characteristics of bubbles following air injection. The effect of initial downcomer fill level was also investigated.

Test Apparatus

The test apparatus used for these experiments consisted of a pair of partially submerged downcomers located in a rectangular tank of water (see Fig. 17). Most of the important dimensions on the test apparatus were linearly scaled from a BWR Mark I torus in a ratio of 1:38.4. The space between plates A and B (the axial dimension in the torus), was varied to represent the effects of different spacing of downcomer pairs

within the torus on the bubble-formation dynamics.

The air injected into the downcomers was supplied by a shop air supply via 10 ft of 3/8-in.-i.d. plastic tubing. The flow resistance of this tubing was not scaled to the flow resistance between drywell and the torus in a B' plant, nor was an attempt made to scale the air supply and ullage pressures. However, the nature of the bubbles developed in the experiment and the results of

Fig. 17. Geometry of the single downcomer pair experiment.

this experiment provide useful information about the effect of downcomer spacing on bubble growth dynamics. With the pool exposed to atmospheric pressure, inlet pressures were varied in ratios up to $\sim 5:1$. Tests were initiated by a manual, quick-opening valve.

Visualization of the air/water dynamics was provided by two Hycam^{*} cameras that operated at 400 frames per second, viewing simultaneously perpendicular to and parallel to the downcomer pair. Camera focus was centered on the exit of the downcomers. Consequently, initial measurements of the water surface in the figures include approximately 0.2 in. of parallax error.

Results and Discussion

A Vanguard^{*} 16-mm motion analyzer was used to determine the pool and bubble movement as a function of time from the high speed films. The various points considered are indicated in Fig. 18 (which also illustrates a typical bubble-pool swell configuration). The pool-surface rise rate, which is an indicator of impact

Fig. 18. Dimensions selected to represent pool dynamics.

load on the header (Fig. 1), was computed (see Table 6).

Conclusions

Although the apparatus used in these experiments was only partially scaled geometrically, the results indicate the following:

- A close spacing of downcomer pairs is likely to lead to an *increase in the momentum of the water* thrown up by the air bubble.
- An increase in driving pressure will increase the momentum of the water.
- Lowering the initial water level in the downcomer may lead to an increase in the momentum of the water surface.

^{*}Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research & Development Administration to the exclusion of others that may be suitable.

Table 6. Summary of results for pool-dynamics tests conducted in a rectangular pool.

Run No.	Plate spacing ^a -2L, in.	Downcomer level-DFL, in.	Supply pressure, psig	Pool surface rise rate, ft/s
1	9.0	1.25	40	1.49
2	9.0	1.25	60	1.91
3	1.5	1.25	60	2.65
4	1.5	0.47	60	3.22
5	1.5	1.25	40	2.15
6	1.5	0.47	40	2.56
7	3.0	1.25	40	1.54
8	3.0	1.25	60	1.66
9	5.0	1.25	60	1.81
10	5.0	1.25	40	1.74
11	5.0	0.47	40	2.06
12	5.0	0.47	60	2.15

^aScaled Peachbottom downcomer spacings range from 1.406 in. to 4.95 in. The scaled average spacing is 2.28 in.

CYLINDRICAL POOL

The objectives of these tests were threefold:

- To compare the effects of air and N₂ on vent clearing and bubble growth.

- To obtain data for comparison with MAITAI code predictions.^{15,16}

- To compare back- and front-lighting cinematography.

Test Apparatus

Available materials and equipment were adapted to these experiments. As shown in Figs. 19 and 20, the

cylindrical container is a closed-end glass pipe. The downcomer is a piece of acrylic tubing. The geometry was scaled linearly from the MAITAI model (Fig. 21, see Ref. 16), which was scaled approximately linearly from the Peach Bottom Mark I BWR. The MAITAI model dimensions, scaled dimensions, and actual dimensions are listed in Table 7. A standard 1.61-cm-i.d. acrylic tube was used for the downcomer instead of the actual scaled dimension of 1.69 cm i.d. The line resistance and drywell volume were not scaled. Dynamics of the pool resulting from

Fig. 19. Cylindrical pool experiment showing back-lighting arrangement.

downcomer clearing were recorded at 4,000 frames per second with a Bvcam camera. Experiments were conducted with both air and nitrogen as driver gas.

Results and Discussion

Parameters for the six tests are listed in Table 8. The pressure ranges for the tests were selected as a compromise between desired and attainable. The desired pressure was computed from the pressure used

in the MATAI calculations using the accepted scaling law, which states that pressure is proportional to linear scale.* The MATAI input or source pressure is 5.81×10^5 Pa; hence, this series of tests should be conducted at

$$P_o = \frac{15.19}{12.91} \times 5.81 = 6.84 \times 10^5 \text{ Pa} \\ \approx 100.1 \text{ psig}$$

*See Section 4 for a discussion of scaling laws

Fig. 20. Front-lighting arrangement for cylindrical pool tests.

A maximum of 90 psig was used to limit the effect of pool splash (pool splash caused the vented foam plastic plug to be ejected from the container when the source pressure was greater than 90 psig). The high speed films provided the data comparison for the MAITAI calculations.

The downcomer clearing times determined from the high speed films were 0.0043 s for Test MC3 and 0.0047 s for MC4. As shown in Table 8, these two tests differed only in

the driving gas. These clearing times may be considered identical within the attainable accuracy of measurements. Figures 22 and 23 are frames from the high speed films of tests MC3 and MC4. Note the approximately 1:1 correspondence in bubble growth and pool shape. It is evident from Figs. 22 and 23 that, within the limitations of observation, air and N_2 sources produce essentially the same initial bubble growth.

Fig. 21. Single downcomer geometry, on-axis.

Table 7. Dimensions of cylindrical pool test apparatus.

Dimensions, cm	MAITAI	Scaled	Actual
1d	1.44	1.69	1.61
i.d.	12.96	15.19	15.19
H	19.08	22.36	22.36
d	9	10.55	10.55
h	2.88	3.38	3.38
l	12.96	15.19	15.19

According to the scaling laws (discussed in Section 4), time is proportional to the square root of a linear dimension. The times for the MAITAI-computed events (Fig. 24) scaled to the size of cylindrical pool experiments are summarized in

Table 9. Comparing Fig. 24 with Figs. 22 or 23 shows that actual bubble growth and pool surface breakthrough is slower than MAITAI predictions. Figures 22 and 23 also show that the actual shape of the bubble assumes the arrow-head-like

Table 8. Parameters for test conducted in cylindrical pool.

Test No.	P_{O_2} , psia	Plage, atm	Gas
MC1	50	1	air
MC1	50	1	air
MC1	90	1	air
MC4	90	1	N ₂
MC5	50	1	air
MC6	90	1	air

Fig. 22. Selected frames from high speed motion pictures of Test MC3 (air source).

cross-section predicted by the computer code for time ≥ 7 ms. Although MAITAI code predictions are tailored more for the pressure and time range of a safety relief valve discharge than for a postulated LOCA, it is evident that they are qualitatively correct.

Both back-lighting and front-lighting provided sufficient illumination for cinematography at $\sim 4,000$ frames per second: the bubble is dark with back-lighting and bubble surface phenomena are accentuated. For this reason, fluid velocities on the surface of back-lighted bubbles are easier to measure than those from front-lighted bubbles.

Conclusions

The results of these experiments indicate the following:

- Within the limitations of observation, air and N_2 sources produce identical vent clearing and bubble growth.
- Although event times and magnitudes are not predicted accurately, pool dynamics behavior computed with the MAITAI code agrees qualitatively with observed behavior.
- For the test configuration, both front- and back-lighting produce satisfactory movies at $\sim 4,000$ frames per second.

1/64-SCALE TORUS MODEL STUDY¹⁸

The primary purpose of this study was to determine the adequacy of modeling the wetwell with a 90° torus sector.

Test Apparatus

Figure 25 is a photograph of the 1/64-scale model. The transparent acrylic construction provides total viewing. The model was fabricated to permit selective positioning of vertical barriers in the wetwell and to block off selected vent lines. Selective insertion of barriers permitted evaluation of the effect of several sizes of torus segments and of blocked vent lines.

The pressure history in the drywell and wetwell was recorded with oscilloscopes; Table 10 lists the location of measurements and type of transducers. Typical transducer data sheets are found in Appendix A.

To prepare for a test, the drywell dome was sealed with a burst disk. The apparatus was evacuated to the desired pressure and the burst disk was ruptured. Rupture of the disk triggered the oscilloscope to record the pressure history.

The pressures used were not scaled, due to the limits imposed by the water and the model. The minimum pressure

Fig. 23. Selected frames from high speed motion pictures of Test MC4 (N_2 source).

Fig. 24. Sequential bubble growth (density dot plot), single downcomer, on-axis, from MATIAT calculations.

Fig. 25. Photograph of the 1/64-scale torus model.

was determined by the boiling point of the water. The maximum pressure was determined by the burst pressure of the model. A Hycam camera provided cinematography at 400 frames per second.

Results and Discussion

Three series totaling 100 tests were conducted. The first series was conducted with the torus consisting only of the bottom half. The second and third series were conducted with

Table 9. Scaled times of MAITAI-computed events.

MAITAI predicted times, ms	Cylindrical pool experimental times, ms
1	1.08
2	2.17
3.5	3.79

the complete torus; the initial pressures in the drywell and wetwell were subatmospheric. All series tested the effects of barriers and blocked vent lines.

The toroidal wetwell was designed with $22\text{-}1/2^\circ$ between planes of symmetry. There are eight evenly spaced vent lines connecting the drywell to the wetwell in the complete torus. Tests were conducted with barriers placed at the planes of symmetry. Evaluation of asymmetric flow due to blockage requires a minimum of two vent lines, i.e., a 90° torus sector.

Critical examination of the high speed films showed that bubble dynamics and pool surface motion were independent of the torus segments size; the minimum size tested was

Table 10. Transducer characteristics for the 1/64th-scale model tests.^a

Location	Transducer	Manufacturer's stated accuracy
Top of drywell test series #2	Kulite, Model HKMS-375-50A (0-50 psia)	± 1.50 psia
Test series #3	Bell & Howell, Model 4-312 (0-5 psid)	± 0.05 psid
Top of toroidal wetwell test series #2	Kulite, Model HKMS-375-25A (0-25 psia)	± 0.75 psia
Test series #3	Bell & Howell, Model 4-312 (0-5 psid)	± 0.05 psid
Bottom of toroidal wetwell test series #2	No transducer	---
Test series #3	Kulite, Model HKMS-375-25A (0-25 psia)	± 0.75 psia

^aIn test series, #1 only photographic records were obtained.

22-1/2° (Fig. 26). The films also showed most vigorous bubble action in regions of closely spaced downcomers; pool swell was also more prominent in these regions. The pressure traces show the delay in pressurization of the drywell and the wetwell (Figs. 27 and 28).

Pool dynamics action was not affected when one vent line was blocked. However, changes were noticeable as successively more vent lines were blocked. These results suggest that the minimum, two-vent-line 90° sector was necessary for the 1/5-scale torus.

Conclusions

- Comparisons of pressure-time traces and high speed motion pictures of the 1/64-scale apparatus reveal no difference between results with a full 360° sector of the toroidal wetwell and those with a 90° sector.

- Comparison of pressure-time traces and high speed motion pictures of the 1/64-scale apparatus reveal no difference between results with a full 360° and with a 90° sector of the toroidal wetwell.

- Tests on the 1/64-scale apparatus show no difference in the phenomena between tests with a 360°, 45°, or 22-1/2° sector of the toroidal wetwell. However, a 90° sector is required as a minimum for tests associated with vent-line asymmetry for the 1/5-scale apparatus.

- Three-dimensional effects were observed on tests with the 1/64-scale apparatus. Bubble action and pool swell were largest in regions where the downcomers were closely spaced. Little bubble action or pool swell were observed where the vent lines attach to the ringheader.

- The major hydrodynamic phenomena that exist in the pressure suppression system following a LOCA were observed in tests of the 1/64-scale apparatus.

- Results when one of eight vent lines was blocked indicated no difference from tests when all eight vent lines were open. However, if more than one vent line was blocked, decreases did occur in both the pool swell and in the magnitude of the structure of the pressure-time traces in the toroidal wetwell.

(a)

(b)

Fig. 26. Comparison of photographic results: (a) 360° and (b) 90° torus sector.

Fig. 27. Comparison of pressure traces for the top of the drywell (initial pressure = 8.6×10^4 Pa.) (a) 360° sector, (b) 90° sector.

Fig. 23. Comparison of pressure traces for the top of the toroidal wetwell (initial pressure = 8.6×10^4 Pa.).

4. INSTRUMENTED STUDIES

Scaling laws, developed to predict plant loads from loads measured with scaled models, were studied with instrumented table-top experiments. Fully instrumented benchmark experiments were conducted to establish a set of reference data suitable for computer code verification. Tests were also conducted to characterize the VLF and to investigate the effect of downcomer fill level on the VLF.

SCALING LAW EXPERIMENTS¹⁹

This limited study was conducted to experimentally establish the pool-dynamics modeling or scaling law to ensure that the 1/5-scale results could be applied to actual plants. Earlier, Moody²⁰ derived a law that is generally accepted in industry for predicting plant loads from measurements made with geometrically reduced models. In terms of dimensionless groups, the scaling law may be expressed* as

$$\frac{F}{\rho_g g L^3} = \phi \left(\frac{P_i}{\rho_g g L}, \frac{P_o}{\rho_g g L}, \frac{RT_o}{g L}, f, \gamma, \frac{t_g^2}{L} \right) \quad (1)$$

(Eq. (1) is hereafter designated Model A.) The factor (RT_o/gL) was shown to be equivalent to the enthalpy

flux parameter of Moody when γ is constant^{13,19,20}:

$$\frac{h_o \dot{m}}{\rho_g g^{3/2} L^{7/2}} \times \frac{\gamma RT_o}{g L (\gamma - 1)^{3/2}} \quad (2)$$

Method and Test Apparatus

Modeling laws apply to physical phenomena and are not restricted to specific hardware. To test the validity of scaling pool dynamics phenomena, it is sufficient to focus on pool-dynamics phenomena generated in geometrically scaled apparatus; the apparatus need not be faithful reproductions of the full-sized plant nor of plant operating parameters. The resulting measurements (e.g., peak forces) will not be applicable to the full-sized plant; to be applicable, data must be generated with models configured and parameters sized after the full-sized plant. The observed phenomena are, however, those representative of the large-scale or prototype systems.

Tests were conducted with two sizes of boiling flasks and downcomers (Fig. 29). In this manner, the scaling of the measured forces resulting from pool dynamics may be compared for similar systems. Figure 30 shows the basic equipment. (The Hycam camera for cinematographic

*The Glossary of Terms identifies the variables.

Fig. 29. Basic experimental flask configuration.

coverage at ~900 frames per second is in the foreground.) Figure 31 is a schematic of the experimental apparatus. Figure 32 is a block diagram showing the instrumentation and controls (see Appendix A for typical transducer data sheets). Tests with other sizes of flasks and with other fluids than water were planned. Time and funding constraints, however, permitted only a portion of the planned experiments to be conducted.

The camera is started prior to the test. When the framing rate becomes constant, a zero-crossing switch is closed and the valve opens a few ms later to initiate flow. An amplified signal from the pressure transducer

near the valve triggers a stroboscope and fires a flashbulb. The stroboscope pulse duration is so short — only about one μ s — that it may be missed on the film; the stroboscope pulse was, however, observed on film in approximately 40% of the experiments. The flashbulb (AG1B) light lasts several ms but peaks about 2 ms after initiation, due to thermal inertia.

The signal from the pressure transducer also triggers the oscilloscope. The voltage output of the load cell is recorded for about 45 ms using a single sweep on the oscilloscope display. This period is sufficient to obtain the response through the time of interest. Since the start of

Fig. 30. Test apparatus.

the oscilloscope trace is practically simultaneous with the stroboscopic light signal recorded on film, the oscilloscope recorded load cell trace and the high speed movie has a common fiducial.

Four safe, transparent liquids of widely different densities and proportional scaling pressures were used in these experiments to allow perfect scaling (according to any of the four scaling models considered by us) at room temperature.

Experiments were conducted with variations in length scale, liquid density, driving pressure (P_0), and initial pressure (P_1). Additionally, deliberate exploration of distortions by varying temperatures was also planned; however, the time available was too short to accomplish this.

Results and Discussion

Figure 33 shows a typical RVLF for these tests. The existence of low and higher frequency oscillations is

Fig. 31. Schematic of load-cell support system.

Fig. 32. Block diagram of scaling test equipment.

evident. The shorter duration of the maximum download spike compared with the upload is prominently displayed. The upload is significant, even though the test geometry does not have a header. The labels in Fig. 33 define the quantities used in this section.

The restricted range of variables studied, coupled with the limited

number of tests, prohibited application of customary dimensionless group correlation procedures. Instead, more fundamental approaches were used that involved testing the effect of parameters as dictated by the scaling law and testing simplified scaling laws derived by neglecting parameters of minor significance.

Fig. 33. Typical oscilloscope load trace.

The experiments can be grouped into four series based on the values of the dimensionless groups. The parameters of these series, based on water, are shown in Table 11. The length L is arbitrarily chosen to be the downcomer submergence. Series I and II were conducted with a 5-litre flask and four fluids (Table 12). Series III and IV used a 0.5-litre flask. All four liquids were used in Series III, but only water was used in Series IV. (Series III and IV are identical except for the flow restriction in Series IV tests.)

In all series, water was the basis fluid. For Series I, the basis source pressure p_0 was set at 15 psia and the initial drywell and ullage pressure p_i at 5 psia. The corresponding pressure sets for the other working fluids were calculated from the dimensionless group $p/\rho_0 gL$. The pressure sets for test Series II, III, and IV were computed from the Series I pressures using the geometric scale factor $\sqrt[3]{10}$. Test Series II, conducted with the 5-litre flask, used the same pressures as the Series III (0.5-liter flask) to explore the

Table 11. Summary of dimensionless groups (Series I-IV).

Quantity	5-litre flask		0.5-litre flask	
	Series I	Series II	Series III	Series IV
$p_o/\rho_L gL$	332	154	332	332
$p_i/\rho_L gL$	110	51	110	110
RT_o/gL	2.7×10^5	2.7×10^5	5.8×10^5	5.8×10^5
K	89.6	89.6	91.5	193.9
γ	1.4	1.4	1.4	1.4
p_o/p_i	3	3	3	3

implications of the Model C scaling law discussed below.

Effect of Pool Fluid Density

The maximum downward force, the maximum upward force, and the time elapsed between the force maxima were selected for comparison. According to Model A, tests employing different liquids with different densities will scale together, provided the pressures

are varied in proportion, other variables remaining constant. Thus, $p_i/\rho_L gL$ and $p_o/\rho_L gL$ are each fixed. Then, as in Eq. (1), the resultant hydrodynamic forces will scale in proportion to the density. That is,

- $F/\rho_L gL^3$ should have the same value in each test within a series.

- The timescale should be unaffected by the density and pressure changes.

- Corresponding values of $F/\rho_L gL^3$ should be observed at corresponding values of $t^2 g/L$.

Table 12. Working fluids used in scaling experiments.

Fluid	Specific gravity, gm/cm^3
Dow Corning 200	0.761
Water	1.000
1,1,1-trichloroethane	1.325
1,1,2-trichloroethane	1.4432

Results of exploring the validity of the first two statements above are shown in Figs. 34-38. Figure 34 demonstrates that maximum downward force scales as predicted. Figures 35-37 verify that the scaling also describes the upward force. In each figure showing force versus density, the resultant force is proportional

Fig. 35. Variation of maximum upforce with specific gravity of pool fluid (Series I tests).

Fig. 36. Variation of maximum upforce with specific gravity of pool fluid (Series II tests).

Fig. 34. Variation of maximum downforce with specific gravity of pool fluids: (a) Series I tests, (b) Series II tests, and (c) Series III and IV tests.

Fig. 37. Variation of maximum upforce with specific gravity of pool fluid (Series III and IV tests).

Fig. 38. Effect of specific gravity of pool fluid on time interval between maximum forces.

to density. Figure 38 shows that the timescale is independent of density, as predicted. The data scale within acceptable errors, according to Model A.

Testing Significance of Groups

The number of groups in Eq. (1) may be reduced if nearly constant parameters are dropped. If the temperature dependence is assumed to be small (as though the flow were essentially barotropic), the temperature and gas constant can be removed from the parameter set. This leaves nine variables, three dimensions and, consequently, six groups, thus reducing Model A to Model B:

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

If thermal effects are significant and we ignore gravitational effects,

we have ten variables, four dimensions, and, again, six groups. Under these conditions, Model A reduces to Model C:

$$\frac{F}{P_1 L^2} = \phi \left(\frac{P_1}{P_0}, \frac{P_1}{\rho_l R T_0}, f, \gamma, \frac{t_g^2 P_1}{\rho_l L^2} \right) \quad (3)$$

If we assume that the temperature group $R T_0 / g L$ can be compensated for by changing (increasing) the flow resistance ($K = f L / D$) of the model over that of the reference system, then Model A may be written as Model D:

$$\frac{F}{\rho_l g L^3} = \phi \left(\frac{P_1}{\rho_l g L}, \frac{P_0}{\rho_l g L}, K, \gamma, \frac{t_g^2}{L} \right). \quad (4)$$

$K = f \frac{L}{D}$ is defined by

$$\left(f \frac{L}{D} \right)_m = \frac{L r}{L_m} \left[1 + \left(f \frac{L}{D} \right)_r \right] - 1. \quad (5)$$

The modification is developed in terms of enthalpy flux by Moody.^{20a}

The predictive capability of each model can be tested by comparing experimental results among the test series. The mean values of these comparisons for all fluids tested are shown in Tables 13-16. Examination of the tabulated data permits evaluation of the scaling models.

Table 13. Maximum downforce comparison.

Model	Function	Reference	Series	Model	Series	Difference between means, %	Is difference significant at 0.05 confidence level?
B	$F/\rho_{\ell}gL^3$	1563 ± 22	I	1467 ± 84	III	-6	No
C	F/p_1L^2	16.72 ± 0.79	II	13.25 ± 0.76	III	-21	Yes
D	$F/\rho_{\ell}gL^3$	1563 ± 22	I	1283 ± 68	IV	-18	Yes

Table 14. Maximum upforce comparison.

Model	Function	Reference	Series	Model	Series	Difference between means, %	Is difference significant at 0.05 confidence level?
B	$F/\rho_{\ell}gL^3$	855 ± 24	I	846 ± 46	III	-1	No
C	F/p_1L^2	9.03 ± 0.39	II	7.64 ± 0.41	III	-15	Yes
D	$F/\rho_{\ell}gL^3$	855 ± 24	I	856 ± 21	IV	+0.1	No

Table 15. Comparison of times to maximum downforce.

Model	Function	Reference	Series	Model	Series	Difference between means, %	Is difference significant at 0.05 confidence level?
B	$t \sqrt{g/L}$	0.2400 ± 0.0038	I	0.1787 ± 0.0055	III	-25	Yes
C	$t \sqrt{p_i/\rho_k L^2}$	2.098 ± 0.054	II	1.880 ± 0.058	III	-10	Yes
D	$t \sqrt{g/L}$	0.2400 ± 0.0038	I	0.1720 ± 0.0084	IV	-29	Yes

Table 16. Comparison of time intervals between load maxima.

Model	Function	Reference	Series	Model	Series	Difference between means, %	Is difference significant at 0.05 confidence level?
B	$t \sqrt{g/L}$	0.1407 ± 0.0042	I	0.225 ± 0.011	III	+64	Yes
C	$t \sqrt{\frac{p_i}{\rho_k L^2}}$	1.841 ± 0.086	II	2.369 ± 0.113	III	+29	Yes
D	$t \sqrt{g/L}$	0.1407 ± 0.0042	I	0.2168 ± 0.0111	IV	+57	Yes

In each comparison, we make the *null* hypothesis that the means* are equal. We use the Student's *t* test to establish whether the differences in these means are significant. Rejection of the *null* hypothesis is, consequently, a reasonable position to take when rejection is indicated. If rejection is not indicated, we reserve judgment, but any differences between means may well be solely due to chance.

As shown in Table 13, the maximum downward force is predicted most closely by Model B (i.e., when the model flow resistance is the same as that of the reference system). Model C, the gravity-free model, and Model D, the modified flow-resistance model, both underestimate this force by a considerably larger margin. As Table 14 demonstrates, the maximum upward force is closely predicted by both Model B and Model D, independently of the model flow resistance. Again, Model C underestimates the forces. Because the maximum downward force nearly coincides with downcomer clearing, it appears that the additional flow restriction introduced in Model D to simulate the post-peak-download bubble formation reduces the early forces below the scaled values without significantly

affecting the peak upload. The agreement for the maximum upward forces most likely results from the fact that the flow at this later stage is largely governed by the postinjection liquid response. This relative independence of maximum upload from maximum download has been observed in the loss of fluid test (LOFT) experiments.²¹

Models B and D fail to predict the observed times; time does not scale as predicted by these models (see Tables 15 and 16). Time is more closely scaled by Model C, although significant differences remain between computation and observation. Since gravity must certainly have little effect on the gas motion prior to significant liquid motion in the downcomer, it seems entirely reasonable that Model C should better scale the time to maximum download. (See *Benchmark Experiments*, below, for additional discussion of the scaling of time.)

Conclusions

The results of the air-scaling tests conducted suggest the following conclusions:

- The predictability of peak download in the reference system is best obtained from the model whose flow resistance *K* is the same as that of the reference system.

*The 90% confidence level was selected.

- The predictability of peak down-load in the reference system is impaired by introduction in the model of the increased flow resistance of Model D or the gravity-free modeling of Model C.

- The reference-system peak upload is equally well predicted by models having either a flow resistance equal to that of the reference system (Model B) or a flow resistance increased as indicated by Eq. (7) (Model D).

- Failure to scale the temperature group of Model A does not significantly distort the peak load scaling.

- Time or time intervals are not well scaled by the models.

BENCHMARK EXPERIMENTS²²

The primary purpose of this experiment was to produce quantitative data to validate various air-water dynamic computations; the experiments were performed because relevant benchmark data were not available from outside sources. The secondary purposes of this study was to provide *a test bed for instrumentation and postexperiment data processing techniques* to be used in the 1/5-scale pressure suppression experiment to provide additional measurements for the air-water scaling study.

Test Apparatus

Tests were performed with the same basic apparatus used in the air-water scaling studies¹⁹ (Figs. 30 and 31). The experiment was designed to correlate the load on the flask due to vent-clearing-induced pool dynamics with the transient gas velocity and gas pressure in the downcomer. The gas temperature, the strain on the flask, and the pressure at the bottom of the flask were also determined for collaborative data. To make the required measurements, four modifications were made to the basic apparatus:

- An orifice was inserted immediately upstream of the downcomer to measure the mass flow rate. (The gas velocity was calculated from the mass flow rate.)

- The bottom of the flask was modified to accept a pressure transducer.

- A thermocouple was installed in the downcomer to measure the temperature of the entering air.

- Strain gages were located on the flask exterior to determine wall response (Fig. 39).

Measurements

All measurements were recorded simultaneously. The instrumentation and their locations are summarized in

Fig. 39. Block diagram of benchmark test instrumentation.

Table 17 and Fig. 40. (See Appendix A for typical transducer data sheets.) Tests were performed in a 5-litre flask half-filled with water and with two sets of initial pressure (SET X: driving pressure $P_0 = 1$ atm, pressure above the pool $P_1 = 1/3$ atm; and Set Y: $P_0 = 2$ atm, $P_1 = 1$ atm). The first set is a repeat of one condition used in the scaling studies; in this way, the scaling studies also were further quantified. ~

The measurements were recorded on an analog tape recorder, Ampex Model CP-100, digitized at a sampling rate of 53,580 points per second, and

computer-reproduced in analog form. The vertical force history was also recorded with a Tektronics Model 564 oscilloscope on Polaroid film for immediate examination. In addition, a film record of the pool dynamics for selected runs was made with a Hycam camera at a rate of ~900 frames per second. Individual fiducials were provided in the taped record and the high speed film with an electrical signal and a flashbulb, respectively. Later study showed that thermal delay of the flash bulb caused the movie fiducial to lag that on the tape by 2 ms.

Table 17. Summary of benchmark experiment instrument characteristics.

Transducer	Excitation voltage	Sensitivity	Remarks
Rig			
P-3	6.45	0.155 MV/V/PSIA	Kulite, S/N 2778-1-57
P-2	6.10	0.164 MV/V/PSIA	Kulite, S/N 2778-1-59
P-4	6.13	0.0816 MV/V/PSIA	Kulite, S/N 2596-7-9-B1-83
L-1	--	250 lb/volt	Kistler load cell.
			Range Switch = 500 Black
T-1	--	--	Ch/Const. 0.001 dia. wire
			0°C Ref. Temp. BLH
S-1	6.667	120 ^a	Factor 96.4% - 116 µε/volt
S-2	6.667	120 ^a	Factor 95.8% - 115 µε/volt
S-3	6.667	120 ^a	Factor 94.3% - 113 µε/volt
S-4	6.667	120 ^a	Factor 95.8% - 115 µε/volt
S-5	6.667	120 ^a	Factor 96.9% - 116 µε/volt
S-6	6.667	120 ^a	Factor 96.2% - 115 µε/volt

^aAssumed gage factor of 120. Reduce by factor in remarks column.

Test Procedure

The test apparatus was prepared for a selected test condition by setting the initial pressures. When the instrumentation, conditioning equipment, and recording equipment were ready, a master switch was activated to start the camera. When the camera reached the selected steady-framing rate, the following events were initiated: tape recorder started, ballast tank solenoid valve opened to initiate air flow through the downcomer, mag tape and film were indexed with a fiducial mark, and

oscilloscope triggered. The air flowed continuously for more than 50 ms; the precursor scaling experiments had shown that 50 ms was sufficient to contain the period of primary interest. During this flow time, the supply air pressure maintained a constant value.

Results and Discussion

A total of nine tests were conducted. Table 18 presents the test conditions and selected results. The results were the first from experiments performed with the modified

Fig. 40. Location of transducers for the benchmark experiment.

Table 18. Selected results from benchmark experiments.

Test	Initial press ratio, P _i /P _o	Maximum loads				Press flask bottom		Average strain at max. download		
		Taped data		Oscilloscope data		At max download, psig	At max upload, psig	Temp., °F	Long. (even # gages), µin./in.	Trans. (odd # gages), µin./in.
		Down #f	Up #f	Down #f	Up #f					
X1	1/3	124	40	105	40	3.4	+0.5	78.8	6	1
X2	1/3	116	42	100	40	0.4	0.5	82.4	7	0
X3	1/3	112	34	100	40	2.8	-1.5	81.9	8	2
X4	1/3	120	45	--	--	0.5	-0.5	83.3	8	1
Y1	1/2	155	47	--	--	6.5	-0.5	79.2	8	0
Y2	1/2	153	43	140	40	4.0	-0.8	80.1	10	0
Y3	1/2	160	43	145	40	4.7	-0.1	79.7	11	1
Y4	1/2	150	44	140	40	6.0	-0.5	78.8	10	1
Y5	1/2	160	48	--	--	4.6	0.9	83.8	10	1

flask apparatus and with the measurements tape recorded. Under normal circumstances, the data would have been replaced by new data after improvements were made on the instrumentation. However, due to circumstances beyond our control, suggested improvements could only be recorded for posterity.

Notwithstanding the shortcomings, this initial set of data contained new information that helped to explain the forces arising from pool dynamics. Each measurement was examined critically to provide significant physical insights.

The load or force experienced by the load cell has a shape reminiscent of a damped vibration curve (Figs. 41-43). Figure 43b is included to

show repeatability. The short duration of the initial download peak, compared with that of the subsequent gross load durations, indicates different causative phenomenon. The high speed film shows that the initial downforce occurs near the moment of downcomer clearing (Fig. 44). Essentially simultaneously, a pressure spike of the same duration as the initial downward force appears at the bottom of the flask (Fig. 45). In other words, vent clearing and arrival of the pressure pulse at the bottom of the flask occur nearly simultaneously.

If we postulate that the pressure pulse results from a pressure disturbance initiated by vent clearing that travels downward at sound speed,

Fig. 41. Typical RVLf for benchmark tests (Test Y4).

Fig. 42. Typical oscilloscope trace of RVLf for benchmark tests (Test Y4).

the travel time or delay time will be $\sim 60 \mu s$. This short a time is not distinguishable with current instrumentation. Hence, the nearly simultaneous occurrence of events is reasonable.

(a)

(b)

Fig. 43. Oscilloscope traces for benchmark Test No. X3(a) and air scaling Test No. 3(b) under identical conditions.

The initial downforce imparts a downward acceleration to the flask. Since the water is neither rigid nor integral with the flask, but can move independently, the downward acceleration imparted to the flask leaves the water momentarily suspended. Thus, the bottom transducer will experience a momentary reduction of pressure

Fig. 44. Pool configuration at maximum download.

(Fig. 45). In effect, the flask experiences a net increase in pressure resulting in an upward force (Fig. 41). Once initiated by the first downforce, the flask support system, water, and

Fig. 45. Pressure variation at the bottom of the flask (Tests Y4, P4).

air system seems to oscillate as a damped-spring mass unit. For Test Y4, the damped-spring mass system oscillated at ~80 Hz. This means that after the initial downforce, application of the remaining load curve to predict time of events in similar systems requires inclusion of vibration characteristics. (Appendix B is a reanalysis of scaling results for the time lapse between maximum download and maximum upload. The reanalysis shows that a substantial reduction of percent difference from the mean value is achieved by inclusion of mass and spring constant, the two parameters that characterize undamped vibrating spring-mass systems. The minor movement of the flask during acceleration should have negligible

effect on the magnitude of the first download.)

Further confirmation of the spring-mass behavior is exhibited by pressures observed at P3 and P4 (Figs. 45 and 46). The observed pressures are in phase with the force trace. In addition, P3 should lead P4 by $\sim 60 \mu s$, a time that is not distinguishable. We note that P3 tracks the pressure as the air clears the downcomer. Therefore, P3 should (and does) show maxima at downloads followed by minima in pressure as the air in the bubble adjusts to the external environment. Correspondingly, P4 measures the pressure at the bottom of the flask and shows maxima and minima corresponding to downloads and uploads respectively.

The high speed films show the bubble touching the bottom of the

Fig. 46. Pressure variation downstream from the orifice (Tests Y4, P3).

flask at approximately the time of the maximum upload (at ~ 24 ms in Fig. 41). The bubble remains near the bottom of the flask and continues to grow in size to the end of the force trace at ~ 50 ms. No visual evidence appears to indicate the higher frequency oscillations superimposed on the primary load trace originate from visible macroscopic behavior of the bubble, but may be derived from other coupling mechanisms; other possibilities include high frequency oscillations of the bubble, transverse or longitudinal vibration of the frame securing the flask to the load cell, and transverse vibration of the flask and water.*

Gas Velocity

The gas velocity in the downcomer was calculated from the volume flow rate. The volume flow rate was determined from the measured differential pressure across a statically calibrated orifice. The static calibration of the orifice is given in Fig. 47. The average velocity and flow rate in the downcomer for test Y4 are plotted in Figs. 48 and 49.

*In the characterization of the VLF below, the low frequency oscillations are traced to vertical oscillations of the bubble. Also, the high frequency oscillations seem to be initiated by the second pulse of the double-peak download.

Fig. 47. Static calibration of orifice.

Because of the noise level exhibited by the ΔP data (Fig. 50), the reduction of ΔP to volume flow rate and velocity are based on average values. Zero time for these curves was determined by the intersection of the time axis with the extrapolation of ΔP to zero pressure; $\Delta P = 0$ corresponds to no flow.

The positions of the down and up loads (transferred from Fig. 41) are indicated in Figs. 48 and 49. A qualitative chronology of events may be constructed for the essentially four-step injection process of compression, downcomer clearing,

Fig. 48. Average air velocity in downcomer for Test Y4.

Fig. 49. Average air volume flow rate in downcomer for Test Y4.

Fig. 50. Pressure differential across the orifice (Test Y4).

bubble growth, and pool swell (Table 19).

Gas Temperature

Although the gas should remain close to room temperature during the test, the gas temperature actually increased during injection, probably because of heating by the flood lights.

Flask Rigidity

The flask rigidity was checked by measuring the strain on the external surface both transverse and parallel to the downcomer. The measurements show negligible surface strain, indicating that the flask behaved essentially in a rigid manner. The even-numbered gages, oriented parallel to the downcomer, show the expected maximum strain coinciding approximately

with the time of the initial maximum download (Table 18).

Conclusions

The following may be concluded:

- The maximum download results from a pressure pulse generated when the downcomer clears.
- The maximum upload and subsequent low frequency load fluctuations seem to result from oscillation of a damped spring-mass system.
- Scaling the time for the load curve to similar flask systems requires inclusion of vibration characteristics of the air-water flask or container system.
- The air injection velocity history in the downcomer may be separated into four phases that are controlled by the dynamics of the system:

Table 19. Qualitative chronology of events during air injection for Test Y4.

Approximate time, ms	Step	Event
0-~4	1	Compression of air space in downcomer above the water level
~4-9.5 9.5	2	Clearing of water in downcomer, maximum download
9.5-~16	3	Essentially unimpeded growth of bubble, possibly over expansion of bubble, pool is levitated
>~16	4	Interaction of compressibility of gases internal and external to bubble

Step (1): The air space in the downcomer is compressed.

Step (2): The water is driven from the downcomer into the pool.

The downcomer is cleared. The velocities are relatively low. Maximum download occurs during this step.

The sharpness of the average envelope is a function of fill level in the downcomer. Step (3): The bubble forms. The air velocity in the downcomer is higher than in Step (2). The maximum upload occur during this step. Levitation of the pool and compression of the ullage occur.

Step (4): The gases internal and external to the bubble interact to cause an unsteady velocity and subsequent pressure and load oscillations.

- The flask may be considered rigid for these experiments.

CHARACTERIZATION OF THE VERTICAL LOAD FUNCTION²³

This study was conducted to define the mechanisms that give rise to the observed loads and oscillations in the VLF following the maximum download. To assure adequate experimental control, vibration characteristics of the experimental systems and support structure were investigated systematically (see Appendix C).

Test Apparatus

The experiment was performed with the same basic apparatus used in the

air-water scaling study¹⁹ (Figs. 31 and 32). Measurements were made with an accelerometer, a load cell, and a pressure transducer along the axis of the downcomer (transducer data sheets are presented in Appendix A).

Results and Discussion

Several blowdown tests were conducted with the 5-litre flask supported in the original high-inertia support system* to provide a basic set of data to judge improvements (Table 20). Figure 51 shows a typical load trace transduced by the 50-kHz piezoelectric load cell used in all scaling and model studies. Four features are of particular interest in the VLF:

- The maximum download.
- The maximum upload.
- The damped sinusoid carrier wave following the peak upload (f_1).
- The damped high frequency sinusoid superimposed on the carrier wave (f_2).

*Details of the different support systems are found in Appendix C. In essence, 250 lb of lead bricks were strapped firmly to the support beam. This is called the *high inertia* support system. The support beam for the *soft* support system was a 24-by-2-by-3/4-in. steel bar. A 4-in. I-beam was firmly strapped to the support beam to form the *stiff* support system.

Table 20. Maximum dynamic loads and average oscillations due to blowdown — high inertia support system.^a

Run	Nominal pressure ratio, atm/ullage	Force, lb		Frequency, Hz	
		Down	Up	Low-f1	High-f2
1	15/5	110.0	42.5	50	471
2	15/5	98.0	43.0	50	444
	Mean	104.0	42.8	50	457.5
3	15/7.5	95.5	42.0	62	465
4	15/7.5	95.5	42.0	59	455
	Mean	95.5	42.0	60.5	460

^aConfiguration: 5-litre flask, 2.5 litre water, downcomer i.d. = 1.6 cm, downcomer submergence = 3.2 cm.

Figure 52 shows typical load traces (three separate tests) when the flask is supported in the *soft* support system. These VLF's are obviously distorted; the download and upload maxima are essentially equal and the data are unusable. The responses for two of the three tests were identical and are superimposed in Fig. 52.

Listed in Table 21 are the data from tests with the 5-litre flask supported in the wholly *stiff* support system. The peak up- and downloads in Tables 20 and 21 are in good agreement; the largest discrepancy is ~20% between the averages for the download, for a nominal pressure ratio ($P_o:P_i$) of 15:7.5.* For most of the tests listed in Table 21, the cross-beam acceleration at midspan, the

dynamic load, and the pressure at the bottom of the flask were simultaneously recorded. All transducers were coaxial with the downcomer. Figure 53 is a set of typical traces of the dynamic event; the reduced amplitude of high frequency oscillations in the VLF is obvious when compared with Fig. 51. The effect is evident of the *stiff* system in clarifying the second download peak, which occurs ~1.5 ms after the maximum spike (Fig. 51). This second peak is discussed in the section on damped high frequency oscillations.

*The variation exhibited by the data in Tables 20 and 21 are attributable to inaccuracies in setting the initial conditions.

Table 21. Maximum dynamic response and average oscillations due to blowdown - stiff support system.^a

Run	Nominal press. ratio, atm/ullage	Force, lb		Pressure, psig		Accel, g		Freq, Hz	
		Down	Up	+	-	Down	Up	Low	High
V41-2	15/5	99.0	50.0	- ^b	- ^b	1.30	0.85	49	700
V43-4	15/5	89.5	42.5	-	-	1.18	0.81	50	710
V45-6	15/5	96.5	45.0	-	-	1.18	0.84	52	700
V53-4	15/5	90.5	40.0	-	-	0.92	0.67	49	767
1/14-1	15/5	102.5	47.0	2.94	0.47	1.45	0.62	50	679
1/14-2	15/5	92.5	43.5	2.49	0.43	1.35	0.62	53	800
1/14-3	15/5	94.0	42.5	2.71	0.29	1.35	0.62	53	800
1/21-1	15/5	110.0	45.0	3.12	0.37	- ^b	- ^b	51	750
1/21-2	15/5	87.5	50.0	2.39	0.37	-	-	51	769
1/21-3	15/5	97.5	44.0	2.61	0.43	-	-	56	- ^c
1/21-4	15/5	112.5	52.5	3.30	0.48	1.54	0.87	53	708
1/24-1	15/5	89.5	44.0	2.46	0.36	1.25	0.62	54	700
	Mean	96.8	45.5	2.75	0.40	1.28	0.72	51.8	734.8
V47-8	15/7.5	79.0	40.0	- ^b	- ^b	1.09	0.92	59	-
V49-50	15/7.5	81.0	42.0	-	-	1.11	0.84	59	710
V51-52	15/7.5	79.0	43.0	-	-	1.21	0.73	57	700
V55-56	15/7.5	79.0	41.0	-	-	1.17	0.73	61	741
1/14-4	15/7.5	87.5	42.5	2.33	0.43	1.14	0.80	62	-
1/14-5	15/7.5	80.0	45.0	2.51	0.53	1.20	0.75	59	714
1/21-11	15/7.5	72.5	40.0	2.08	0.37	1.06	0.91	62	750
	Mean	79.7	41.9	2.31	0.44	1.14	0.81	60	723.0
1/14-6	15/10	55.0	22.5	1.65	0.31	0.76	0.85	69	700
1/14-7	15/10	58.5	25.0	1.65	0.25	0.75	0.83	67	-
	Mean	56.8	22.8	1.65	0.28	0.76	0.84	68	700

^a Configuration: 5-litre flask, 2.5 litre water, downcomer i.d. = 1.6 cm, downcomer submergence = 3.2 cm.

^b Data missing because transducers not available.

^c The scales selected for the oscilloscope was such that high frequency oscillations became indistinct.

Fig. 51. Origin of VLF characteristics. (a) Hydrodynamic origin: peak downforce results from ejection of water slug into the pool. (b) Hydrodynamic origin: second peak of downforce becomes dominant as downcomer initial fill level is reduced. (c) Hydrodynamic origin: maximum upforce given by average, results from combination of pool levitation and compression due to pool swell. (d) Hydrodynamic origin: low frequency carrier wave due to *vertical* oscillations of the expanding air bubble. Frequency *increases* with ullage pressure. Oscillations are in phase with pressure oscillations at bottom of pool. (e) Hydrodynamic origin: high frequency on carrier wave not fully characterized; slight reduction with increase in ullage pressure, oscillations in phase with pressure oscillations at the bottom of the pool.

The data listed in Tables 20 and 21 were obtained from Polaroid photographs of oscilloscope traces. Average deflections were used to calculate the force, pressure, and acceleration. Where sizable oscillations exist, such as during the upload of a VLF for the *high inertia* system (Fig. 51), the

maximum deflection is taken as that of the average curve through the high frequency oscillations. Additionally, the high and low frequencies were determined by favoring the earlier part of the VLF.

The Maximum Upload

The maximum upload is attributed to the combined effects of pool levitation and ullage compression due to pool rise. The force due to pool levitation may be estimated (Fig. 54a); the pressure is assumed to vary linearly to 85% of the maximum at the pool surface, as suggested by the G.E. 1/12-scale tests. The force due to ullage compression may also be estimated by calculating the isothermal pressure rise in the hemispherical volume of gas as the volume decreases (Fig. 54b).

Fig. 52. Typical RVLF for blowdown in a soft support system.

All time scales 5 ms/cm

Fig. 53. Dynamic response of a typical blowdown test conducted with an initially full downcomer (run 1/14-1, 5-litre flask, nominal atmosphere, ullage = 15:5, time-scale = 5 ms/cm).

Fig. 54. Estimated forces due to (a) levitation of the pool and (b) compression of the ullage.

Careful analysis of high speed movies show that the average pool rise at maximum upload is between 0.2 and 0.3 in. Figure 54 shows that this pool rise will cause an upload of ~ 27 lb. Table 21 shows that the pressure at the bottom of the flask at maximum upload varies between -0.29 and -0.53 psig. A change of -0.4 psig will result in an upforce of 21 lb. The sum of these loads is 48 lb, which is the same magnitude as that measured for the 15:5 tests. These calculations show that the

maximum upload does result from a combination of pool levitation and ullage compression.

Damped Carrier Wave

Examination of the average carrier (or low) frequencies listed in Tables 20 and 21 shows the following:

- The frequencies increase with ullage pressure.
- The frequencies are essentially the same for the VLF's measured either with the high inertia or the stiff systems.

Compressing the timescale on the oscilloscope shows that these low frequency oscillations damp out rapidly (Fig. 55); except for the timescale, the test conditions for Figs. 53 and 55 are the same. These observed effects are consistent with air-water interactions (they were suggested at a Review Group Meeting²⁴).

Note in Fig. 55 that the accelerometer trace shows the beam still vibrating after the pressure and VLF have essentially damped out. The vibration of the beam after the pressure and VLF signals have damped out shows that structural interaction for the stiff support has no effect on the oscillating behavior of the pressure and VLF traces. Instead, Fig. 55 shows that the crossbeam is reacting sympathetically to the dynamic loads.

Fig. 55. Typical dynamic response traces showing the rapid damping of the pool disturbances (run 1/14-2, 5-litre flask, nominal atmosphere, ullage = 15:5, time-scale = 10 ms/cm).

Disruptions of the pool begin ~20 ms after the maximum download.

The distortions in the pressure trace from a smooth sinusoid, especially in the tail portion, are attributed to pool splash. In addition to the pressure fluctuations, the pressure in the flask rises steadily due to continuous flow of gas into the flask. This effect is exhibited in the pressure trace by the gradual positive shift in the base pressure line with time.

The magnitude of the low frequency oscillations resulting from the dynamic events suggest that the causative disturbances should be observable. With this in mind, the high speed films (~900 frames per second) of air-water scaling tests were examined. The results confirmed that the oscillating carrier wave results from air-water interactions arising from *vertical* oscillations of the bubble. During expansion, the bubble dynamically adjusts to the pool confinement and continuing air injection by oscillating vertically, much as a piston. Plotting the motion-picture frame numbers (equivalent to time) corresponding to the high and low positions of the bubble onto the VLF shows a 1:1 correlation between bubble position and load (Fig. 56); the slight mismatch results primarily from the discrete frames available (900 frames per second).

Fig. 56. Correspondence between bubble position and carrier oscillations: (a) Frame 11, downcomer cleared (indexed arbitrarily to maximum download). (b) Frame 21, bubble at high position. (c) Frame 31, bubble at low position. (d) Frame 39, bubble at high position. (e) Frame 47, bubble at low position. (All frames are relative to frame 11.)

Vertical oscillations of the bubble have also been observed for a lower test pressure ratio. The results tabulated in Table 21 and plotted in Fig. 57, shows that the carrier wave frequency increases with ullage pressure. This is the expected trend for air-water interaction.

Damped High Frequency Oscillations

It is evident that the amplitude of the high frequency oscillations in the VLF for the stiffer flask strut support system was diminished by a factor of at least 3 from that for

Fig. 57. Effect of ullage pressure on oscillation frequencies.

the high inertia system (compare Figs. 51 and 53). Nevertheless, the persistence of these oscillations suggests further investigation.

Especially interesting is the ever-present second download peak, which seems to signal the beginning of the high frequency oscillations; the pressure trace suggests a second impact at the bottom of the flask. This high frequency peak (HFP) arrives ~ 1.5 ms after the maximum download for the high inertia system and has been observed in G.E. scaling studies (both 1/12- and 1/4-scale), but on a different timescale. Also, as noted in Section 2, this first HFP becomes dominant as the downcomer fill level decreases (Figs. 58 and 59).

Downcomer initially full

Downcomer initially 80% full

Fig. 58. Change of the VLF as a function of downcomer fill level (5-litre flask, single downcomer, 2.5 litre water, vertical scales = 50 ft/lb/cm, nominal pressure ratio 3:1, timescale = 5 ms/cm).

In addition to the decreased magnitude, the stiffer flask strut support system has increased the high frequency oscillations from 460 Hz to ~ 700 Hz (Tables 20 and 21). Also, Table 20 (high inertia system) shows the average high frequencies are approximately independent of ullage pressure; however, Table 21 (stiff

Fig. 59. Dynamic response of a blow-down test conducted with an initially partially (40%) filled downcomer (run 1/21-8, 5-litre flask, nominal atmosphere, ullage = 15:5, nominal pressure ratio 3:1, timescale = 5 ms/cm).

support) shows the average high frequencies tend to reduce with ullage pressure (plotted in Fig. 57).

Careful examination of the three dynamic response traces (such as Fig. 53) shows nearly perfect correspondence among high frequency oscillations. The events are also phased properly, i.e., a download gives rise to a down acceleration and an increase in pressure. Unfortunately, acceleration trace after the second peak contains high-amplitude kHz-level oscillations that hide the lower frequency component of interest.

Although attributing high frequency oscillations to structural support interaction is tempting, it is difficult to conceive of an interaction that would result in synergistic, in-phase response between load and pressure at the bottom of the flask. Identification of the mechanisms responsible for the high frequency oscillations will require further investigation.

Conclusions

The results of this study show that pool dynamics phenomena account for oscillations observed in the typical VLF for LLL bench-top tests. Specifically,

- The average loads are not affected by the high frequency oscillation; i.e., identical loads are

obtained with the average trace from the high inertia support system and from the stiff support system.

- The maximum upload is caused by the coupled phenomena of pool levitation and pool swell from the bubble growth.

- The low frequency damped carrier wave oscillations following the maximum upload result from vertical oscillations of the bubble as it adjusts to its surroundings.

- The maximum download originates from hydrodynamics and is double-peaked.

EFFECT OF DOWNCOMER FILL LEVEL ON THE VLF²⁵

This is an experimental study of the effect of downcomer fill level (DFL) on the VLF.

Test Apparatus

This study was conducted with the stiffened support system used in the experiments to characterize the VLF. The dynamic load and the pressure at the bottom of the flask were simultaneously recorded; the load cell and pressure transducer were coaxial with the downcomer. The acceleration at the middle of the support beam was also recorded; these data are presented in Section 2. The transducer data sheets are presented in Appendix A.

Results and Discussion

Shown in Fig. 60 are typical VLF and pressure traces for the full downcomer. The maximum down and uploads, and the corresponding positive and negative pressures at the bottom of the flask are tabulated in Table 22. The data in Table 22 are plotted in Fig. 61 and 62.

(a)

(b)

Fig. 60. Typical VLF (a) and pressure (b) at the bottom of the flask (5-litre flask) single downcomer, 2.5 l water; nominal pressure ratio 15:5, timescale = 10 ms/cm.

Table 22. Variation of maximum dynamic response to blowdown with downcomer fill level.^a

Run	Nominal press. ratio atm/ullage	Force, lb		Pressure, psig		Fill level, %
		Down	Up	+	-	
1/21-2	15/5	95.0	45.0	2.39	0.37	100
1/21-3	15/5	97.5	44.0	2.61	0.43	100
1/21-5	15/5	81.0	41.5	2.25	0.33	80
1/21-6	15/5	76.5	39.0	2.27	0.31	80
1/21-7	15/5	60.0	35.0	1.69	0.22	60
1/21-8	15/5	54.5	33.0	1.34	0.23	40
1/21-9	15/5	40.0	29.0	1.08	0.18	20
1/21-10	15/5	27.5	22.5	0.92	0.10	0
1/21-11	15/7.5	72.5	40.0	2.08	0.37	100
1/21-12	15/7.5	47.5	30.0	1.19	0.29	40
1/21-13	15/7.5	45	30.0	1.40	0.26	40

^aConfiguration: 5-litre flask, 2.5 litre water, downcomer i.d. = 1.6 cm, downcomer submergence = 3.2 cm.

Figure 60 shows that after ~20 ms, the traces are gradually distorted from a smooth sinusoid by pool surface breakup followed by pool splash. The positive drift of the base line for the pressure trace (Fig. 60) is the result of rise in ullage pressure due to the continued gas flow into the flask. The negative pressures associated with the peak upload that are listed in Table 22 were not corrected for the baseline change; the baseline change is a function of the gas flow rate, which is very nonlinear with

time. Critical analysis indicates that the amplitude and not the direction of change of the pressure at the bottom of the flask is affected by the continuing rise in base pressure.

Straight lines have been drawn through the data plotted in Figs. 61 and 62 to indicate the trends. Additional tests are required to establish error bounds for the data; the indicated trends, however, should be correct. The peak pressure at the pool bottom (corresponding to the peak upload) increases with DFL, and

Fig. 61. Effect of downcomer fill level on the maximum download and pressure at the bottom of the flask (5-litre flask, single downcomer, 2.5 litre water).

the pressure at the bottom of the pool at maximum upload shows the same trend (Fig. 62), but in a negative direction.

Figures 61 and 62 show that both maximum download and maximum upload reduce with downcomer fill level. The peak pressure at the bottom of the pool also decreases with downcomer fill level. The same trends are observed for both pressure ratios;

Fig. 62. Effect of downcomer fill level on the maximum upload and pressure at the bottom of the flask (5-litre flask, single downcomer, 2.5 litre water).

the loads are lower at a lower pressure ratio (15:7.5) is water is initially in the downcomer (DFL > 0). Although measurements at zero fill level are made only for 15:5, the loads appear independent of initial pressure ratio for an initially empty downcomer (DFL=0).

The maximum upload results from both levitation of the pool caused by the download and vertical oscillations of the bubble. As the download decreases with reduced DFL, the download is reduced and the maximum upload decreases. Since the reduction in pressure at the bottom of the flask results from levitation, the pressure reduction will be less when

levitation decreases; this is the trend exhibited in Fig. 62.

The pressure data in Fig. 62 are indistinguishable for the two pressure ratios studied (compare ϕ and Δ). Further experiments are required for confirmation.

Conclusions

The results of experiments with the LLL 5-litre test apparatus show the following effects of downcomer fill level on the maximum loads of the VLF:

- The maximum download and maximum upload reduce with initial level of fluid in the downcomer. The maximum download experiences the higher reduction; for an initially empty downcomer, the maximum download is 30% of that for an initially full downcomer. The corresponding value for the maximum upload is 49%.

- The amount of reduction in vertical load with initial fluid level in the downcomer decreases with the ratio between external and ullage pressures.

5. OVERALL CONCLUSIONS

The conclusions for each study have been presented in the separate sections. Presented in this section are the primary conclusions; most are based on comparison of table-top results with other results, especially those from the 1/5-scale torus experiment.

The primary conclusions are as follows:

- Pool dynamics in the pressure suppression pool resulting from postulated LOCA exhibit significant three-dimensional effects. This was observed in the 1/64-scale torus tests and confirmed by the 1/5-scale torus experimental results.

- The 1/5-scale torus experiment confirms table-top results, which indicated that the VLF is insensitive to the enthalpy flux parameter.

- The character of the VLF is best summarized in Fig. 4 (repeated for convenience as Figs. 51 and C.1).

- The VLF may be decomposed into two damped sinusoidal components, a low frequency component and a high frequency component.

- The VLF reduces with initial downcomer fill level. When the downcomer is initially empty, the VLF is a smooth sinusoid.

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GLOSSARY OF TERMS

<u>Variable</u>	<u>Description</u>	<u>t</u>	Time
c	Specific heat	U	Flow speed
D	Diameter	γ	Ratio of specific heats
F	Force	ρ	Density.
f	Friction factor	<u>Subscript</u>	<u>Description</u>
g	Gravitational constant	d	Down
h_o	Stagnation enthalpy	g	Gas
k	Spring constant	i	Initial ullage condition
K	Flow resistance $f \frac{L}{D}$	ℓ	Liquid
L	Length	m	Model system
$\dot{m}$	Mass flow rate	ma	Actual model
M	Mass	o	Drywell condition
P	Pressure, absolute	p	Constant pressure
R	Gas constant	r	Reference system
S	Characteristic dimension	u	Up
T	Temperature		

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APPENDIX A
TYPICAL TRANSDUCER DATA SHEETS

Products, Inc.

TEST REPORT

☒ Pressure Transducer ☐ _____ Customer P.O. # 7601145
 MODEL NO. XTMS-1-190-100A SERIAL NO. 2596-7-9-B1-83
 Tested to: ☒ Kulite Specifications ☐ Customer Specs. _____

LEAD CONNECTIONS

*INPUT

- ☒ Red (+)
☒ Black (-)

OUTPUT

- ☒ Green (+)
☒ White (-)

*Before connecting, adjust supply voltage not to exceed maximum voltage.

Rated Pressure 100 psia ☐ Gage ☐ Sealed
 Maximum Pressure 200 psia ☒ Absolute ☐ Differential
 Maximum Pressure Reference Side ☐ 30 psi ☐ _____

CAUTION: Do not press on the pressure sensitive area with a sharp object.

Tested at ☐ 5 VDC ☒ 10 VDC ☐ _____
 Maximum Input Voltage ☐ 5 VDC ☒ 10 VDC ☐ _____
 Sensitivity 0.0816 mv/v/psi (☐ Nominal)
 Zero Pressure Output ☒ Less than $\pm 3\%$ F.S. ☐ _____
 Input Impedance 1137 Ohms Output Impedance 250 Ohms

TEMPERATURE COMPENSATION MODULE

- ☐ None Supplied ☐ Near End of Leads
☒ Inside the Transducer ☐ _____ from Housing
☐ Other _____

TEMPERATURE COMPENSATION MODULE INCLUDES

- ☒ Thermal effect on zero 1
☐ Thermal effect on sensitivity (see Note A)
☒ Thermal effect on zero ☒ less than 12 % F.S./100°F ☐ _____
☐ Thermal effect on sensitivity ☐ less than _____ % F.S./100°F ☐ _____
 For compensated range ☒ 80°F to 180°F ☐ _____

Note A: When compensation of thermal effect on sensitivity is not included in the module, please consult the appropriate product bulletin for the recommended method of excitation.

REMARKS O-RING SUPPLIED MAXIMUM TORQUE 1.5 IN. LBS

Tested by K.C. Inspected by [Signature] Date 4/11/75

Fig. A1. Typical transducer data sheet: test report.

Load cell

To: Tom Schaffer, Calibration of Kistler Mod 932 Force Link, SN 39039,
Range 0-250 lbs, Chg amp SN 322, JK, on 8/18/76, Sens 8.25, Range 200, Tension

Input	Output	
Force	(Volts)	(Volts)
lbs	Incr	Decr
0.0	0.002	0.002
20.000	-0.199	-0.199
40.000	-0.400	-0.400
60.000	-0.602	-0.602
80.000	-0.803	-0.803
100.000	-1.006	-1.006
120.000	-1.208	-1.208
140.000	-1.411	-1.411
160.000	-1.613	-1.613
180.000	-1.815	-1.815
200.000	-2.017	-2.017
250.000	-2.522	

Terminal point values		
Theoretical	Deviation (volts)	
(Volts)	Incr	Decr
0.002	0.000	0.000
-0.200	0.001	0.001
-0.402	0.002	0.002
-0.604	0.002	0.002
-0.806	0.003	0.003
-1.008	0.002	0.002
-1.210	0.002	0.002
-1.412	0.001	0.001
-1.614	0.001	0.001
-1.816	0.001	0.001
-2.018	0.001	0.001
-2.522	0.0	0.0

Excitation = 0.0 volts

Sensitivity = -1.00960E-02 volts/lbs

Span = -2.5240 volts

Zero offset = 0.0016 volts

Error band = -0.12% to +0.0% of FSO

Input resistance = N/A Ohms: Output resistance = N/A ohms

Shunt calib = N/A

LLL force and pressure
calibration facility
bldg 231, rm 1662
ext 8609

Fig. A2. Transducer data sheet: typical load cell calibration.

Fig. A3. Transducer data sheet: accelerometer calibration.

APPENDIX B

REANALYSIS OF AIR-WATER POOL DYNAMICS SCALING

The original analysis, summarized in Section 4, may be found in Ref. 19. The reanalysis presented here emphasizes the improvement and omits the detailed mathematical development. If we assume negligible damping, the basic parameters characterizing a vibrating spring-mass system are spring constant k and mass M of the system. Inclusion of the parameters gives

$$F = \phi(L, \rho_g, g, P_1, P_0, t, M, k, f, \gamma).$$

No new dimensions were introduced, so that the number of dimensionless groups increased from six to eight. By judicious combination of independent groups, we obtain for Model B*

$$\frac{F}{L^3 \rho_g g} = \psi \left(\frac{P_1}{L \rho_g g}, \frac{P_0}{L \rho_g g}, \frac{t^2 k}{M}, \frac{M}{L^3 \rho_g}, \frac{k}{L P_1}, f, \gamma \right) \quad (1)$$

When compared with the results in Eq. (1) (Section 4), shows that the characteristic time group has been modified from $t^2 g/L$ to $t^2 k/M$; the latter group is recognized as similar to that of the period of an undamped oscillator. In addition, two new

groups have appeared. A ratio of the masses

$$\frac{M}{\rho_g L^3}$$

The mass M and spring constant k are ill-defined since the vibrating system has not been identified. However, the period of vibration of a spring-mass system is proportional to $\sqrt{M/k}$ and may be extracted from measurements. Neglecting damping, the results show that the model and reference period ratio is

$$\frac{T_{ma}}{T_p} = \sqrt{\frac{M_{ma}}{K_{ma}} \frac{k_r}{M_r}} = \frac{7}{20}, \quad (B1)$$

where ma designates the actual model and r designates the reference. This ratio can be applied to correct the lapse time between maximum download and maximum upload presented in Table 16. For Model B and D

$$t_m = \sqrt{\frac{L_m}{L_r}} t_r, \quad (B2)$$

where subscript m designates the model. From this analysis

$$t_r = t_{ma} \sqrt{\frac{M_r}{k_r} \frac{k_{ma}}{M_{ma}}}. \quad (B3)$$

*Please refer to Section 4.

After combining Eqs. (B2) and (B3), the corrected time is

$$t_{ma} = \sqrt{\frac{L_r}{L_m}} \sqrt{\frac{k_r}{M_r} \frac{M_{ma}}{k_{ma}}} t_m$$

or

$$t_{ma} \sqrt{\frac{g}{L}} = \sqrt{\frac{L_r}{L_m}} \sqrt{\frac{k_r}{M_r} \frac{M_{ma}}{k_{ma}}} t_m \frac{g}{L} \quad (B4)$$

Equation (B4) shows that the time group for the model must be corrected by the square roots of the length ratios and period ratios. By a similar analysis, the corrected time group for Model C is

$$T_{ma} \sqrt{\frac{P_i}{\rho_e L^2}} = \sqrt{\frac{k_r}{M_r} \frac{M_{ma}}{k_{ma}}} \left(\frac{L_r}{L_m} \right) t_m \sqrt{\frac{P_i}{\rho_e L^2}} \quad (B5)$$

Applying Eqs. (B4) and (B5) to the results in Table 16, we obtain the results in Table B1.

Now, the differences are consistently low, and the improvement is obvious. Recall that two additional groups have been introduced. The new groups contain the unknown mass and spring constant of the system. It is likely that one or both of these groups changes between the prototype and model. Hence, either or both of the new dimensionless groups may account for the remaining discrepancy.

Table B1. Reanalyzed results for the time interval between maximum download and maximum upload.

Model	$\left(t \sqrt{\frac{g}{L}} \right)_{ref.}$	$t_{ma} \sqrt{\frac{g}{L}}$	Difference between means, %	
			New	Old
B	0.1407	0.1156	-17.8	+64
C	3.15	3.08	- 2.0	+33
D	0.1407	0.111	-20.8	+57

APPENDIX C

VIBRATION STUDY OF THE FLASK SUPPORT SYSTEM

INTRODUCTION

The oscillatory nature of the RVLF (Fig. C1) prompts suspicion that the the oscillations are structurally induced. This study was conducted to

Fig. C1. Origin of VLF characteristics. (a) Hydrodynamic origin: peak downforce results from ejection of water slug into the pool. (b) Hydrodynamic origin: second peak of downforce becomes dominant as downcomer initial fill level is reduced. (c) Hydrodynamic origin: maximum upforce given by average, results from combination of pool levitation and compression due to pool swell. (d) Hydrodynamic origin: low frequency carrier wave due to *vertical* oscillations of the expanding air bubble. Frequency *increases* with ullage pressure. Oscillations are in phase with pressure oscillations at bottom of pool. (e) Hydrodynamic origin: high frequency on carrier wave not fully characterized; slight reduction with increase in ullage pressure, oscillations in phase with pressure oscillations at the bottom of the pool.

insure that vibration of the experimental apparatus (Figs. 31 and 32) did not affect the RVLF or other measurements.

PROCEDURE

Figures C2 and C3 show that the downcomer/flask system is supported by a strut assembly (three-legged) from a load cell secured to a horizontal crossbeam. The beam ends are firmly fastened to vertical rods attached to a metal table. Vibration characteristics of the support system were investigated systematically to insure absence of support structure resonances in the VLF frequencies of interest. Oscillations were excited by a hammer blow. Those frame components found to exhibit excitable frequencies near observed oscillations in typical VLF's were selectively stiffened to permit separation of effects.

RESULTS AND DISCUSSION

Initially, the excited frequencies were deduced from the integrated load cell response; additional measurements were made with an accelerometer during the later course of experimentation. The high frequency content of the

Fig. C2. Test apparatus.

response depended on the strength of the hammer blow. Stiffness was judged by the lowest frequency oscillation which often contained harmonics. In spite of these difficulties, the results will show that the method used is adequate.

High Inertia Support System

Figure C2 shows the original support system which has high inertia by virtue of the 250 lb of lead bricks strapped firmly to the crossbar. Attachment of the mass in this

way increased the resonance frequency of the support. Table C1 lists the lowest excited frequencies sensed by the load cell when a hammer blow was applied to the positions H1-H5 as indicated in the footnote; refer to Fig. C2 to correlate these positions with the system. The flask, fluid, and downcomer are attached during these tests. The data show a slight increase in frequency when other than the crossbar or flask support is struck; this suggests that a different mode of vibration was excited.

Fig. C3. Block diagram of scaling test equipment.

Table C1. Vibration frequencies of original experimental apparatus. High-inertia support system (250 lb lead bricks strapped firmly to crossbar) with flask, fluid, downcomer in place.

Run	Lowest freq., ^a Hz	H1 ^b	H2	H3	H4	H5
5	400	X				
6	417		X			
7	455			X		
8	500					X
9	588				X	

^aMeasured with load cell.

^bThe support system vibrations were excited with a hammer blow. H1 = center of crossbar; H2 = flask support; H3 = back edge of table; H4 = front edge of table; H5 = crossbar over end support.

Soft System

To insure that system frequency was attributable to the added mass, the lead bricks were removed. The flask, fluid, and downcomer were supported by the cross beam through the load cell during

these tests. The results of striking the system at the various points H1, H2, and H5, are listed in Table C2. This soft system was shown to have unacceptable vibration characteristics in Section 4.

Table C2. Vibration frequencies of soft support system (lead bricks removed from crossbar) with flask, fluid, downcomer in place.

Run	Lowest freq., ^a Hz	H1 ^b	H2	H3	H4	H5
10	100	X				
11	100		X			
12	100					X
13	95	X				
14	95	X				

^aMeasured with load cell.

^bThe support system vibrations were excited with a hammer blow. H1 = center of crossbar; H2 = flask support; H3 = back edge of table; H4 = front edge of table; H5 = crossbar over end support.

Stiff Support System

A steel I-beam ($\nabla 16$ lb), with cross-section shown in Fig. C4, was rigidly clamped to the crossbar in place of the lead bricks. The vibration characteristics of the new system were then systematically studied. The results are tabulated in Table C3.

With the flask, fluid, and downcomer in place, a hammer blow at midspan of the crossbeam excited low frequency oscillations slightly less than 500 Hz measured by the load cell (Runs 18, 19, 20). These frequencies were $\nabla 100$ Hz higher than the comparable test for the high inertia system

(Run 5, Table C1). This is attributed to the stiffer system afforded by the I-beam. For these runs, ullage pressure was varied from 1 atm to a 20-in. vacuum. These oscillations seem to be independent of ullage pressure, and that suggests independence from air-water interaction.

The flask, fluid, downcomer, and flask support were then removed and an equivalent mass of lead (9 lb) was fastened directly to the load cell (Runs V1, V2, V4). The lowest frequency of oscillation observed was 1667 Hz (Table C3). The test was repeated after moving the dead weight to the end of a $3/8$ -by- $12-3/4$ -in. rod that was attached to the load cell; the lead mass was thus positioned at approximately the center of mass of the liquid in the flask. The lowest frequency was then 405 Hz (Run V5). Reattaching the flask, fluid, downcomer, and flask support after removing the lead mass and rod confirmed the previous results (compare Runs V6, V7 with 18, 19, 20). The flask was then emptied to determine the effect of the fluid. With the same excitation hammer blow at midspan, the lowest frequency was $\nabla 900$ Hz (Runs V8, V9). The influence of the fluid mass is evident.

Fig. C4. Cross-section of I-beam used to rigidize crossbar of support system.

To further isolate the vibrating source responding to the fluid mass, the flask, fluid, and downcomer were

Table C3. Vibration frequencies of the rigid support system - original flask holder.^a

Run	Lowest freq., ^b Hz	Test Conditions
18	483	20-in. vac. in ullage } flask, fluid, downcomer attached to load cell. Average of these frequencies in Table 4.
19	476	
20	492	
V1	1667	Lead weight ^c close coupled to load cell.
V2	1667	
V4	1667	
V5	405	Lead weight ^c at end of 3/8-in.-by-12-3/4-in. rod attached to load cell; dead weight at center of mass of fluid. This frequency in Table 4.
V6	471	Flask, fluid, downcomer attached to load cell, 1 atm in ullage. Average in with Runs 18, 19, 20.
V7	462	
V8	857	Empty flask, downcomer attached to load cell. Average of these frequencies in Table 4.
V9	952	
V10	439	Lead weight ^c at end of 3/8-in.-by-6-1/8-in. rod attached to flask holder; lead weight at center of mass of fluid.
V11	438	
V12	500	Lead weight ^c close coupled to flask holder. This frequency in Table 4.
V16	500	Empty flask, downcomer attached to load cell; lead weight equivalent to fluid ^d attached to flask holder.

^aThe original flask support was assembled with 3-1/4-in.-diameter-by-6-3/8-in.-long tie rods. Excitation by applying hammer blow to midspan of cross-beam.

^bMeasured with load cell.

^c9 lbs lead weight equivalent of flask, fluid, downcomer, and flask holder. The flask holder weighs 1.2 lb.

^d2.5 l H₂O.

replaced with an approximately equivalent lead weight. This equivalent weight (9 lb) was first suspended at the end of a 6-1/8-in. rod that, in turn, was attached to the bottom of the flask holder. This placed the weight at the center of the mass of the fluid. The response of the system was ~ 440 Hz (Runs V10, V11) or essentially the same as the response when the flask, fluid, and downcomer were attached to the system (compare with Runs V6, V7). When the equivalent mass was attached directly to the bottom of the flask holder, the vibration frequency increased to 500 Hz (Table C3, Run V12); this increase is insignificant in comparison with the change from an average of 477 Hz to 1667 Hz after replacing the flask, fluid, downcomer, and flask holder with an equivalent lead weight (9 lb) attached directly to the load cell (compare Runs 18, 19, 20 with V1, V2, V4). The responding source is evidently in the flask holder.*

As a further check, an empty flask and downcomer were attached to the

flask holder; the fluid was replaced with an equivalent mass of lead (5.5 lb) that was attached to the bottom of the flask holder in the region of the neck of the flask. The system again responded at 500 Hz (Table C3, Run V16); evidently, the empty flask and downcomer had minimal effect.

The results of a systematic calculation of the resonance frequencies of the components that make up the flask support are shown in Table C4. From this, it was determined that the longitudinal or axial resonance of the tie rods that hold the assembly together was close to measured values. For example, for the flask support assembly with 3-1/4-in. diameter tie rods and with flask, fluid, and downcomer attached the calculated resonance was 403 Hz, while the measured frequency was 477 Hz (see also configurations 1 and 2 of Table C4 for other results). These tie rods were then replaced by 3-3/4-in. diameter stainless steel bar stock that increased the calculated resonant frequency of the flask support to 1650 Hz and 2283 Hz with and without fluid in the flask, respectively (Table C4, configuration 3). However, the load cell measurements indicated an unexpectedly low average oscillating frequency of 606 Hz (average of Runs V22 to V26, Table C5). Test description: and results with the rigid support system and

*The flask holder may have a low resonance frequency, as is suggested in Section 4. Note also that the calculated resonance of the hex support legs (Fig. C2) is ~ 330 Hz with the high inertia system and ~ 1030 Hz with the stiff support system; these calculations assume that the weight of the crossbeam is an integral part of the hex support leg.

Table C4. Calculated axial resonance of flask support rods^a compared with measured frequencies.

Configuration	Calculated resonance frequency, Hz	Ave. measured frequency ^c , Hz	
		Load cell	Accel.
(1) Flask support assembled with 3-1/4-in. diam by 6-3/8-in. tie rods			
- with flask, fluid, downcomer	403	477	--- ^d
- with empty flask, downcomer	646	904	---
- 9-lb weight close coupled	379 ^b	500	---
(2) 9-lb weight at end of 3/8-in.-by- 12-3/4-in. rod - direct attachment to load cell			
	445	405	---
(3) Flask support assembled with 3-3/4-in.- by-5.3-in. round bar stock			
- with flask, fluid, downcomer	1650	606	1500
- with empty flask, downcomer	2283	1161	---

$$^a f = 3.13 \sqrt{\frac{K}{W}} = 3.13 \sqrt{\frac{EA}{LW}}, \text{ units are Hz, \#, in.}$$

E = modulus of elasticity

A = cross section area

L = length

W = load supported by rod.

^bThe 9-lb weight includes the weight of the flask support but was used for convenience. The excess weight decreases the calculated resonance frequency from 403 Hz to 379 Hz.

^cAverage values calculated from data noted in Tables C3 and C5.

^dThe accelerometer was not available at the time these tests were performed.

rigid flask holder are given in Table C5.

An accelerometer with a magnetic base became available and this permitted selective determination of component frequencies. When positioned at the attachment point between flask holder and load cell, the

accelerometer showed an average frequency of 1500 Hz (Table C4 or Table C.5, Run V33). With the accelerometer still positioned at the attachment point between the flask holder and load cell, simultaneous measurements were made with the load cell. The results confirmed the

Table C5. Vibration frequencies of rigid support system — new rigid flask holder.^a

Run	Lowest freq., ^b Hz	Test conditions
V20	1212	Empty flask, downcomer attached to load cell. Average of these frequencies in Table C4.
V21	1111	
V22	628	Flask, fluid, downcomer attached to load cell. Average of these frequencies in Table C4.
V23	600	
V24	600	
V25	600	
V26	600	
V28	1500	Vertical excitation of crossbeam at midspan; flask, fluid, downcomer attached to load cell. Accelerometer reading.
V30	1500	Lateral excitation of crossbeam at midspan; flask, fluid, downcomer attached to load cell. Accelerometer reading.
V31	1400	Vertical excitation of table top center (H3, Fig. 2) flask, fluid downcomer attached to load cell. Accelerometer reading.
V33	1500	Vertical excitation of flask holder; flask, fluid, downcomer attached to load cell. This frequency in Table C4. Accelerometer. ^c
V34	605	Load cell } Flask, fluid, downcomer attached Accelerometer ^c } to load cell; 20-in. vac. in ullage.
V35	2000	
V36	625	Load cell } Flask, fluid, downcomer attached Accelerometer ^c } to load cell; ullage exposed to atm.
V37	1667	

^aThe new flask holder was assembled with 3-3/4-in.-diam-by-5.3-in.-long stainless steel bar stock. Excitation by applying hammer blow to midspan of crossbeam except as noted. Ullage at atm except as noted.

^bExcept as noted, frequencies were determined from load cell response.

^cAccelerometer located at attachment point between load cell and flask holder.

separate measurements (Table C5, Runs V34, V35, V36, V37 and Fig. C4), i.e., the load cell showed oscillations of 600 Hz, whereas the accelerometer showed oscillations in

the kHz range. Since the load cell was functioning properly, the measurements suggested that fluid motion resonance could be the source; the water-air system could oscillate as

(a)

(b)

Fig. 65. Load-cell (a) and accelerometer (b) response to hammer blow at midspan.

a spring. This type of pool action was suggested earlier (see Ref. 24). At this point, the vibration study was suspended in favor of blowdown

tests to provide evidence suitable to test the water-air spring hypothesis. The remainder of the data in Table C5 are self-explanatory.