138
3/9/78

18. 1898

UCRL-50045-77-2

MASTER

REACTOR CONTAINMENT ANALYSIS FOR BWR SUPPRESSION SYSTEMS (Progress Report for April through October 1977)

L. L. Edwards
Principal Investigator

December 14, 1977

Prepared for U.S. Energy Research & Development
Administration under contract No. W-7405-Eng-48

LAWRENCE LIVERMORE LABORATORY

University of California/Livermore, California/94550

UCRL-50045-77-2

REACTOR CONTAINMENT ANALYSIS FOR BWR SUPPRESSION SYSTEMS (Progress Report for April through October 1977)

L. L. Edwards
Principal Investigator

MS. date: December 14, 1977

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

CONTENTS

Executive Summary	1
Code Status and Auxiliary Studies	1
Computer Simulations	1
Conclusions and Direction of Future Research	1
Analytic Studies of Vent Clearing and Jet-Slug Dynamics	2
Vent-Clearing Phenomenon	2
Equation of Motion	2
Vent-Clearing Time	3
Results	3
Transient-Jet Dynamics	4
Analysis	5
Liquid-Jet Velocity Function	6
Jet-Decay Function	6
Load-History Equation	7
Discussion of Load-History Results	8
Summary	8
Computer Simulations	11
Simulation of Vent Clearing in the UCLA Experiment with a Two-Dimensional, Lagrangian Hydrocode (HEMP)	11
CHAMP Simulations of UCLA and MIT Single-Downcomer Cylindrical-Vessel Pressure-Suppression Experiments	12
References	21

REACTOR CONTAINMENT ANALYSIS FOR BWR SUPPRESSION SYSTEMS (Progress Report for April through October 1977)

EXECUTIVE SUMMARY

This is the third progress report published on work performed for the Nuclear Regulatory Commission (NRC) under contract No. 189 A0166-6. Our goal is to provide the NRC with numerical simulations of air venting into water for three types of pressure-suppression systems and with computational tools to model fluid dynamics involved in venting to a boiling water reactor (BWR) pressure-suppression pool.

Previously, we reported¹ on progress in computer simulations of pressure-suppression-system air-vent clearing with two homogenous, explicit finite-difference codes:

- The CHAMP (Coupled HEMP and Multifluid Eulerian Program) code.
- The Lagrangian HEMP code.

Both are capable of computing the fluid-structure interactions necessary to understand the effects of water on flexible pool walls.

This report updates the air-vent simulation and experimental validation of the computational schemes, as well as summarizing some analytical studies and models.

Code Status and Auxiliary Studies

The CHAMP-IA code has been modified to include the effects of gravity, and logic has been implemented so a temporal pressure variation can be used for boundary conditions. These can be either an Eulerian inflow condition or a Lagrangian pressure condition; the latter simplifies computation of the LLL one-fifth-scale² simulations.

Analytic studies of the vent-clearing process have resulted in two simplified equations whose predictions agree well with both the experiment and code calculations. Studies of time-dependent, jet-slug dynamics have found a single parameter that allows fitting to the experimental and code-computed values of peak pressure on the reactor-vessel floor. Details appear in the Analytic Studies section.

Computer Simulations

The CHAMP-IA³ computer code has simulated UCLA^{4,5} and MIT⁶ experiments. These experiments both consist of a single downcomer pipe in a cylindrical vessel, and both consider the pressure on the vessel bottom a primary parameter. In the simulations, the inflow boundary condition is the measured upstream gas pressure as a function of time. The simulations compute vent clearing and early bubble formation through the peak pressure on the bottom. The computed results agree very well with the experimental.

The HEMP⁷ code was also employed to simulate vent clearing in the UCLA experiment. Computation of the initial bubble growth and peak floor pressure, however, requires rezoning.

As an initial debug run of the multiphase PELE⁸ module of CHAMP-IIA, the single-phase aspects have been employed to compute the UCLA experiment. Vent clearing, initial bubble growth, and floor pressure results are in good agreement with the experiment.

Conclusion and Direction of Future Research

Good agreement was achieved between the CHAMP-IA simulation and the UCLA and MIT experiments by using the vent clearing and peak download phases of the pressure-suppression system.

In later studies we will simulate the LLL one-fifth-scale experiment, as well as continuing the previously computed experiments in real time. In the next period, we will study bubble growth and surface breakthrough. Future plans include studying the effects of structural interaction with flexible containers and further modeling studies, as well as incompressible code simulations.

ANALYTIC STUDIES OF VENT CLEARING AND JET-SLUG DYNAMICS (S. W. Kang)

Two separate studies were conducted to investigate the unsteady fluid-dynamic characteristics during vent clearing in the BWR pressure-suppression systems. One dealt with the vent-clearing history, the other with the load history at wet-well bottom.

In the first study, closed-form solutions were obtained under simplified conditions, and the scaling of the vent-clearing time was delineated in terms of the depth that vent tube was submerged and the mean driving pressure. These theoretical results seem to compare favorably with the test data.

For the study of load history, the derived equations are found to be functions of the jet inertia and the jet-decay mode in the liquid pool. Theoretical results obtained from our analysis appear to agree reasonably well with the available data from UCLA and LLL one-fifth-scale experiments.

Vent-Clearing Phenomenon

A BWR is surrounded by a dry well that is connected to a wet well by submerged vents. When a hypothetical loss-of-coolant accident (LOCA) occurs, coolant from the high-pressure BWR enters the lower pressure dry well and flashes to steam. The steam in the dry well forces the air through the vents, clearing them of water. The air enters the pressure-suppression pool of the wet well, forming bubbles in the pool after clearing the vent tube. This can cause condensation or evaporation of the system (including "chugging") and swelling of the liquid pool. Experiments performed under simulated conditions, suggest that one of the critical impacts on the structure takes place during the period surrounding vent-clearing.

The present analysis is concerned with the theoretical treatments of the vent-clearing history and the transient-load characteristics at the pool bottom from immediately after the LOCA to the time the downcomer clears of liquid. These two aspects are discussed separately in detail because knowledge of the vent-clearing phenomena is important to the understanding of the load-history equations.

Equation of Motion

To obtain the equation of motion for liquid in a downcomer driven by pressure from above, we assume:

- An incompressible liquid.

- Negligible frictional effects.
- Negligible surface-tension effects.
- Zero virtual-mass effects.

The control volume (see Fig. 1) consists of the liquid column inside the downcomer between $z = 0$ and $z = L$. The momentum-conservation equation yields

$$\frac{d}{dt} \left[(L - z) \frac{dz}{dt} \right] + \left(\frac{dz}{dt} \right)^2 = \frac{P_1 - P_\infty}{\rho} - gz \quad (1)$$

Introducing dimensionless variables makes this equation more general; it becomes

$$\frac{d^2 \xi}{d\theta^2} = \frac{B(\theta) - \xi}{1 - \xi} \quad (2)$$

where

$$\xi \equiv z/L,$$

$$\theta \equiv t \sqrt{g/L},$$

and

$$B(\theta) \equiv (P_1 - P_\infty)/(\rho g L).$$

Figure 1. Schematic diagram of vent-clearing analysis.

The initial conditions are $t = 0$ and $\xi = 0$. For the cases we are studying (i.e. $P_1 - P_\infty = 10$ kPa, $L = 0.1$ m and $\rho = 10^3$ kg/m³), the magnitude of B is much greater than ξ at all θ except when θ is very close to zero. Thus, we may drop the term ξ (a gravity term from the numerator in Eq. (2)) without much loss in accuracy. In general, B is a function of θ and depends on such mechanisms as the valve openings and the orifice. Once the valve is opened, however, the valve of the driving pressure P_1 and, in turn, the term B should become nearly constant. For this situation and the case where the term B may be held a constant mean value (B_m) and is much greater than ξ , Eq. (2) becomes a nonlinear differential equation of the form

$$\frac{d^2\xi}{d\theta^2} \cong \frac{B_m}{1 - \xi} \quad (3)$$

From Eq. (3) we obtain the velocity (dimensionless) of the vent-clearing liquid column:

$$\frac{d\xi}{d\theta} = \sqrt{2B_m} \sqrt{\xi \frac{1}{1 - \xi}} \quad (4)$$

in which the boundary condition $d\xi/d\tau = 0$ at $\tau = 0$ was used.

An insight into the physical processes may be gained by inspection of Eq. (4), viz, the liquid column starts at a prescribed velocity (zero in our case) and moves slowly, gathering speed down the vent tube. In fact, at the time of vent clearing, the velocity is infinite. This is not surprising because the pressure above is driving less and less mass as the liquid leaves the tube.

We now wish to obtain $\xi = f_n(\theta)$. This may be accomplished by once again separating the variables in Eq. (4) and integrating from $\theta = 0$ ($\xi = 0$). Then we have

$$\tau = \text{erf}(\phi) \quad (5)$$

where a new dimensionless time τ is introduced so that

$$\tau \equiv \frac{t}{L} \sqrt{\frac{P_m}{\rho}} \sqrt{\frac{2}{\pi}} = \theta \sqrt{\frac{2B_m}{\pi}} \quad (6)$$

and

$$\phi \equiv \sqrt{-\ln\left(1 - \frac{\tau}{L}\right)} \quad (7)$$

Vent-Clearing Time

An interesting result may be immediately obtained from Eq. (5). As ξ goes to 1 ($z \rightarrow L$) and the vent clears, the term ϕ goes to infinity. Therefore $\text{erf}(\phi)$ goes to 1.0. We then have τ equals 1.0 at vent clearing. Putting the vent-clearing time as $T(s)$, Eq. (6) yields

$$T = L \sqrt{\frac{\rho}{P_m}} \sqrt{\frac{\pi}{2}} \quad (8)$$

Thus we have a physical interpretation that the vent-clearing time is linearly proportional to the original liquid-column submergence (L) and inversely proportional to the square root of the driving pressure from above.

Results

As previously mentioned, Eq. (5) may serve as a universal equation for describing the instantaneous location (as well as the velocity) of the liquid column as a function of both time and other physical parameters (L , P_m , ρ). Thus Eq. (5) is plotted on Fig. 2 in terms of ξ vs τ . It will be of more interest, however, to plot the results of Eq. (5) in physical quantities. We did this for two cases, the UCLA configuration⁹ and the LLL one-fifth-scale configuration.¹⁰ The results, as well as the numerical integration of Eq. (2) under variable driving pressure, are plotted in Figs. 3 and 4, respectively. Both show the experimentally inferred vent-clearing time.

In the UCLA test, the experimentally observed vent-clearing time is about 45 ms after the measured change in the driving pressure from rest. (About 22 ms is reported to have elapsed before any change in the pressure of the air over the liquid column is observed.) A good agreement between the theory and the available test data is observed. Thus the simple, easy-to-apply closed-form solution of Eq. (5) is believed to be a useful equation.

Good agreement is also found with the LLL one-fifth-scale configuration, (Test 1.3.1).

The solution given in Eq. (5) is shown to be a useful result for predicting the dynamic phenomena of the liquid column when subjected to a driving pressure from above during a LOCA.

Figure 2. Vent-clearing dynamics.

Transient-Jet Dynamics

We also investigated the load history at the pool bottom from immediately after the LOCA to the time the vent clears.

A control-volume integral approach is used in our analysis. In related problems, such as steady-flow jets (Refs. 11 and 12) or other fluid-dynamic problems (Refs. 13 to 16), this global-conservation method gives mathematical tractability and delineation of dominant physical parameters with reasonable accuracy.

We derive relevant load-history equations for an incompressible liquid flowing through the control volume using the governing conservation principles. These equations show two physical factors that dominate the jet-slug dynamics: the jet-inertia effect, which enhances the load, and the net radial-momentum efflux effect, which lightens the reaction force—and hence the pressure force—at the bottom of the wet well. (See Fig. 5.)

Figure 3. Vent-clearing history comparison between theory and experiment (UCLA).

Figure 4. Vent-clearing history comparison between theory and experiment (LLL).

Figure 5. Unsteady jet-slug dynamics and radial-momentum efflux effect.

For quantitative calculation, the derived load-history equation requires the vent-clearing characteristic and the mode of jet-decay in the control volume. We investigated the vent-clearing history in the previous section. Now, a model is introduced into the analysis to describe the jet-decay characteristic in the control volume. In particular, the assumed "similarity" function produces a parameter whose magnitude determines the jet-flow behavior.

In what follows, we will describe the steps to this point in mathematical form and then discuss them in greater detail.

Analysis

The control volume selected for investigation of the unsteady jet-slug dynamics is diagrammed in Fig. 5.

In an axisymmetric, cylindrical coordinate system the governing global-conservation equation for axial momentum is:

$$\frac{d}{dt} \left[\int_L^H \int_A \rho u dA dz \right] + \int_S \rho \bar{u} w dS - \int_A \rho V_L^2 dA = (P_L - P_w)A + \int_L^H \rho g A dz \quad (9)$$

The conservation equation for continuity in this same case is:

$$\frac{d}{dt} \left[\int_L^H \int_A \rho dA dz \right] + \int_S \rho w dS - \int_A \rho V_L dA = 0 \quad (10)$$

The symbols denote their usual meaning, and most of these are shown in Fig. 5. (See Ref. 16, Chapters 4 and 6, for basic equation forms.) The term P_L is the static pressure at the end of the vent downcomer pipe at $z = L$, and P_w stands for the wall pressure at the bottom of the wet well. The dA is the incremental cross-sectional area and is equal to $2\pi r dr$, while the dS represents the surface area along z and is equal to $2\pi R dz$.

Physically, the first term on the left-hand side of Eq. (9) corresponds to the axial-inertia forces, whereas the second and the third terms denote the momentum efflux from the control surface along z and the momentum influx from the vent tube, respectively. The two latter terms combined represent the net momentum efflux from the control volume.

We assume incompressibility of the liquid in the control volume. We also assume that the velocity and the pressure distributions are uniform in the radial direction so that $u = u(z,t)$, $P = P(z,t)$, and $V_L = V_L(t)$. By applying these assumptions, combining Eqs. (9) and (10), and substituting $P_L = P_\infty + \rho g L$, we obtain

$$\Omega(t) = \frac{d}{dt} \left(\int_L^H u dz \right) - \frac{1}{2} V_L^2 \quad (11)$$

where

$$\Omega(t) \equiv - [P_w(t) - (P_\infty + \rho g H)]$$

$$\Omega(t) \equiv - [P_w(t) - (P_\infty + \rho g H)]/\rho \quad (12)$$

We see from Eq. (11) that magnitudes of the two competing terms on the right-hand side of the equation depend greatly upon the jet-decay characteristics along z [function $u = u(z,t)$] and the liquid-jet velocity at the end of the vent tube [$V_L = V_L(t)$]. Thus it is imperative that these two functions be determined as accurately as possible.

Liquid-Jet Velocity Function. The function $V_L = V_L(t)$ represents the instantaneous magnitude of the liquid velocity at $z = L$. We observed in the vent-clearing analysis that the closed-form solution obtained by assuming a constant mean driving pressure from above seemed to agree well with the test data. Moreover, the agreement becomes even better if one introduces the equivalent tube-length concept, i.e. $L^* = L + R$, which accounts for the unsteady nature of the flow. This concept has another physically reasonable result; the liquid velocity at the time of vent clearing is no longer infinite. Koch, et. al.¹⁷ also make use of this additional-liquid-slug concept. The results obtained earlier will be used for the velocity history of the liquid column in the vent tube because nothing more accurate has appeared in the literature.

Jet-Decay Function. This function describes the jet-decay characteristics in the control volume and is a rather complicated function even after we simplify it by assuming a uniform-distribution behavior in the radial direction. Numerous studies exist¹⁸⁻²³ on free jets in steady flow. Free jet in this case means that the obstacle (floor) is placed farther from the tube-exit plane than nine pipe-diameter lengths [$(H - L)/D > 9$]. Few papers, however, are available on relatively close distances between the obstacle and the tube exit. One paper on this subject is by Tani and Komatsu.²⁴ These authors experimentally studied the jet-impingement cases in which the ratio $(H - L)/D$ was as small as four under steady-state flow conditions. They obtained the jet-decay behavior along the jet axis (a type of power function for the distance from the nozzle exit). An even smaller H/D case has been studied by Scholtz and Trass,²⁵ in which the magnitude of H/D was as small as $1/4$. The velocity distribution displays a marked decay behavior immediately outside the nozzle exit, a result confirmed both experimentally and theoretically in their analysis.

We have no knowledge of references readily applicable to the analysis of unsteady jet flows to the

present problem. Therefore, we propose the following model. When we assume an incompressible liquid flow, the instantaneous transmission of the signal in the liquid is one of the consequences. It seems reasonable, with this assumption, to use the qualitative results of the steady jet-decay analyses and thus approximate the transient jet-flow characteristic through a "similarity" power-function behavior. In this way, the jet-velocity distribution instantly adjusts to the changing values of the jet velocity at the tube exit (V_L). Thus

$$u(z,t) = V_L(t) \left(\frac{H-z}{H-L} \right)^M. \quad (13)$$

The functional behavior of Eq. (13) is shown in Fig. 6 in terms of a dimensionless jet-axis distance ξ defined to be $\xi = (z-L)/(H-L)$.

It is not clear at this point what is a reasonable value of M for confined unsteady jets. Physically, it seems evident that the parameter M , characterizing the jet-decay behavior along the jet axis, will depend to some extent on the distance between the tube exit and the obstacle (floor). For example, if this distance is infinitely large, the jet flow would stimulate the free-jet phenomena; on the other hand, if this distance is very small (less than one pipe diameter from the exit) the deflection of the flow by the presence of the wall would be noticeable. The distance effect studied in Refs. 24 and 25 for steady jets

Figure 6. Axial jet-decay modes.

will be incorporated qualitatively into the present formulation.

Load-History Equation. Combining Eqs. (4), (11), and (13), and using dimensionless variables for greater applicability, we obtain the load-history equation

$$\phi(r) \sim \frac{\left(\frac{H}{L} - 1 \right)}{(M+1) \left(1 + \frac{R}{L} \right)} \left[\frac{B(r) - \psi}{1 - \psi} \right] - B_m \ln \left(\frac{1}{1 - \psi} \right), \quad (14)$$

where

$$\phi \equiv \frac{\Omega}{gL^*} = \frac{P_w - (P_\infty + \rho gH)}{\rho gL^*},$$

$$B \equiv \frac{P_1 - P_\infty}{\rho gL^*},$$

$$B_m \equiv \frac{P_m}{\rho gL^*},$$

$$\psi \equiv \frac{z}{L^*},$$

$$\tau \equiv \frac{t}{L^*} \sqrt{\frac{P_m}{\rho}} \sqrt{\frac{2}{\pi}}.$$

The approximate sign is used instead of the equality symbol because the velocity term V_L is based on the approximate closed-form results of the vent-clearing analysis. We believe this procedure is reasonable with some assumptions.

Moreover, Eq. (14) is entirely tractable when combined with the vent-clearing result for ψ , i.e.

$$\tau = \text{erf}(\mu), \quad (15)$$

where

$$\mu \equiv (-\ln(1 - \psi))^{1/2} \text{ and}$$

τ is already defined in Eq. (14).

Recapitulating, we have derived an expression for the load history that depends on two competing physical phenomena, the inertia effect, which enhances the load response, and the net momentum-efflux term, which relieves the load response at the wet-well bottom.

Discussion of Load-History Results

Inspection of these two effects in Eq. (14) provides the general observation that inertia term depends on H/L , R/L , ψ , and especially M for a given configuration. No definitive value for M can be applied to the present analysis from separate investigation. Because of this and the rather encompassing nature of the parameter M , we propose to determine its value from comparing the UCLA experiment with the present approximate theory. This value would apply only to the load-history study. If the range of M values is physically reasonable, the theory should apply to other similar tests (such as the LLL one-fifth-scale tests) with the same M -value range and should yield reasonable comparisons. With this in mind, comparison was made between the UCLA test results⁹ and the present theory. The pressure history obtained by UCLA is shown in Fig. 7. We wish to predict satisfactorily the load history $P_w(t)$ with the known $P(t)$. The vent-clearing theory predicts a somewhat speedier liquid-column motion, by about 5 ms, but, considering the accuracy resolution involved, this amount of discrepancy is permissible. By adjusting the vent-clearing time by 5 ms, the present load-history theory was applied to the conditions of the UCLA test for $M = 3$ and $M = 4$. This is shown in Fig. 8. Based on comparison of the test result for P_w in Fig. 7 and the theory for P_w in Fig. 8, the most appropriate range for the parameter M seems to be between 3 and 4. Physically, this would signify a rather precipitous reduction in the axial velocity as the jet slug approaches stagnation condition at the wet-well bottom wall. (The axial velocity is assumed to be radially uniform.) This results in an increased efflux of the mass through the side surface, i.e., an enhanced jet deflection. The range seems plausible when the relatively small distance between the jet exit and the obstacle and the assumption of incompressibility are considered.

If the value of M is reasonable, the theory should predict with acceptable accuracy the load-history

Conditions

$$L = 0.1 \text{ m}$$

$$\psi = 0.047 \text{ m}$$

$$H = 0.367 \text{ m}$$

$$P_0 = 122 \text{ kPa}$$

$$P_m = 9 \text{ kPa}$$

$$P_\infty = 101 \text{ kPa}$$

Figure 7. Pressure-history curves for $M = 4$ and $M = 5$ in the UCLA experiment.

under other conditions. For this purpose, the test data taken at LLL¹⁰ were chosen. In particular, the Test 1.3.1 results and theory were compared. (See Fig. 9.) Figures 10 and 11 give histories of the driving air pressure in the ringheader and at the bottom of the torus, respectively. (It is noted that Fig. 11 is redrawn from the data of Fig. 2-11 in Ref. 10, showing only the region of present interest.)

Although the physical configurations for the test apparatus and the theory are not strictly the same, sufficient similarity was believed to exist to warrant comparisons between theory and experiment. The theoretical results based on $M = 3$ and $M = 4$ are shown in Fig. 12, where the time scale was adjusted by 5 ms to match the vent-clearing history.

Reasonable agreement is believed to exist between the experimental load history of LLL Test 1.3.1. (Fig. 11) and the theoretical prediction (Fig. 12).

Summary

Any quantitative result reflects both the qualitative assumptions made (i.e., physical models) and the qualitative approximations. The major simplifications introduced into the present study are the

Figure 8. Theoretical pressure history for the UCLA configuration.

Figure 9. Pressure-history curves for $M = 4$ and $M = 5$ in the LLL Test 1.3.1.

Figure 10. Experimental ringheader-pressure history (P-87) for the LLL Test 1.3.1, 7.5 deg sector.

Figure 11. Experimental wall-pressure history during vent clearing for the LLL Test 1.3.1.

incompressibility of the liquid, the use of the closed-form results for the vent-clearing analysis, and the choice of the parameter M to describe the unsteady jet-decay behavior. A more accurate vent-clearing history would be desirable to improve quantitative

comparison with experiments. A separate, unsteady jet study in confined configurations, practically nonexistent in the literature to our knowledge, would enhance the possibility of determining the value of M more accurately. Theoretical or experimental investigation of the unsteady jet-flow phenomena would be a worthwhile future project.

In summary, an approximate preliminary theory for the load history up to vent clearing was developed based on a conceptual model of two competing physical parameters: inertia and net momentum-efflux. A dominant parameter M , describing the jet-decay behavior, was delineated from the theory. For values of M near $M = 4$, the theoretical predictions appear to agree reasonably well with the experimental data of both UCLA and LLL, in terms of the load history at the bottom of the wet well under a LOCA.

Quantitative refinements to the present, "zeroth-order" theory can be made, either by removing some of the assumptions made or introducing more elaborate models into the present analysis.

Figure 12. Theoretical pressure history for the LLL Test 1.3.1.

COMPUTER SIMULATIONS

Simulation of Vent Clearing in the UCLA Experiment with a Two-Dimensional Lagrangian Hydrocode (HEMP)

(L. A. Glenn)

• The HEMP code has been used to simulate the UCLA vent-clearing process. Computed results give excellent agreement with both one-dimensional theory and experiment.

Kang (see the section on Analytic Studies) has shown that the time for vent clearing in the downcomer of a reactor pressure-suppression system is inversely proportional to the square root of the driving pressure and directly proportional to the original liquid-column length. These results are

strictly valid only for one-dimensional, incompressible flow, assuming constant driving-pressure difference. Where the driving-pressure difference is roughly linear over time, as in the UCLA experiment,^{3,4} numerical integration of the equation of motion confirms that approximate scaling still holds. Figure 13 shows the interface displacement z as a function of time. When scaled, no significant difference in results was noted. The value of 0.02 MPa is precisely the maximum driving pressure measured at $t_* = 50$ ms (corresponding to $\tau = 1.26$) in the UCLA experiment. Thus, agreement with experiment is excellent.

The extent to which a HEMP calculation matches the predicted interface displacement is a good test of

Figure 13. Computed and theoretical vent clearing.

the simulation capability of the two-dimensional Lagrangian (axisymmetric) code. A Lagrangian calculation of the vent-clearing phenomenon is non-trivial because the fluid exiting the bottom of the downcomer is subjected to large shearing strains that grossly distort the mesh. Figure 14 shows this mesh distortion at three times. The air zones above the liquid interface have been omitted for the sake of clarity (with the exception of the first layer, as indicated in the figure). At $\tau = 0.5$ (27 ms) the interface has displaced slightly more than 10%, so that one of the 10 original liquid two-zone layers within the downcomer has completely cleared the exit. At $\tau = 1.0$ (43 ms), interface displacement is more than half the original 10 cm, and six layers have cleared. Finally, at $\tau = 1.26$ (49 ms) all 10 layers originally within the downcomer have cleared. We observe that the aspect ratio of some of these zones has increased from the original values slightly over unity to more than 10 at vent-clearing. Nevertheless, the calculated interface displacement seen in Fig. 13 is in very good agreement with both the one-dimensional theory and the experiment. It should be possible to continue the simulation beyond vent clearing by appropriately rezoning the mesh. This calculation and the resultant pressure distribution on the wet-well bottom surface will be described in the next progress report.

CHAMP Simulations of UCLA and MIT Single-Downcomer Cylindrical-Vessel Pressure-Suppression Experiments

(L. L. Edwards)

- The CHAMP-IA computer code has simulated the vent clearing, initial bubble growth, and peak floor pressures in both the UCLA and MIT experiments. Agreement between computed results and experimental measurements is good.

Using information from the UCLA and MIT experiments, we have validated the CHAMP-IA vent-clearing simulation and examined the initial bubble

growth through peak down loads in the BWR pressure-suppression system.

The UCLA experiment, when set up for the CHAMP calculation (Fig. 15), used air and water initially at 101.3 kPa (1 atmosphere) with the driving over-pressure from above P_0 at 21.7 kPa (3 psi). The experimentally measured upstream air pressure P_1 is applied at the Eulerian mesh boundary about 130 cm above the water surface. No other parameters in the computation are determined from the experiment. The bulk modulus of water, however, is scaled down¹ by two orders of magnitude to circumvent the Courant time-step condition.

Figure 16 depicts the computational mesh used for the simulation and Figs. 17 through 19 show the interface positions at vent clearing and early bubble growth. Water-velocity vectors at every other mesh cell show the flow field.

Comparison between theory, experiment, and computation are shown in Figs. 20 and 21. Some delay in reaching peak flow pressure is observed and appears to be a result of our scaling the speed of sound in water down by a factor of 10.

The MIT experiment uses helium and water and is depicted schematically in Fig. 22 (taken from Ref. 5). We use a vessel diameter of $D = 28$ cm and had an initial wet-well pressure of $P_1 = 113.3$ kPa (85 torr). The driving pressure P_0 was 339.9 kPa (255 torr) for the experiment. This simulation was zoned and computed much the same as the UCLA experiment. The computed vent clearing occurred at 31.9 ms. The computed results were added to Fig. 23 (taken from Ref. 5).

The peak floor pressure calculated was 39.43 kPa (296 torr) at 37.2 ms, whereas experimentally about 42 kPa (315 torr) was observed at a slightly earlier time. The MIT report indicated the peak-pressure measurements were affected somewhat by elastic oscillation set up by the wet-well floor response. This computation was done with an absolutely rigid floor. Future simulations that include floor response will help understand the magnitude of the effects.

Figure 14. HEMP simulation for the UCLA experiment.

UCLA

CHAMP

Figure 15. Schematic of UCLA experiment and CHAMP simulation.

Figure 16. Portion of CHAMP computational mesh. Only the right half is computed in an axisymmetric mode. Dowacomer air covers approximately 50 zones, ullage air, approximately 306 zones, and water, approximately 1430 zones.

CHPCODHYHY K50PHHC3

TIME 7.179E+04

CYCLE 2127

Figure 17. CHAMP interfaces and velocity vectors at 71.79 ms.

CHPCODHYHY K50PHHC3

TIME 7.725E+04

CYCLE 2494

Figure 18. CHAMP interfaces and velocity vectors at 77.25 ms.

CHPCODHYHY K50PHHC3

TIME 8.186E+04

CYCLE 2795

Figure 19. CHAMP interfaces and velocity vectors at 81.86 ms.

Figure 20. Two-dimensional vent clearing for the UCLA simulation. The solid line represents the one-dimensional theory with vent clearing at 69.4 ms. The broken line represents the two-dimensional CHAMP, with vent clearing at 71.8 ms.

Figure 21. A comparison of pressure vs time for the UCLA and CHAMP results.

Figure 22. A sketch of the MIT test facility showing wet-well geometry and the locations of pressure transducers $P_1(t)$ to $P_4(t)$.

Figure 23. Pressure histories measured in a medium-sized system of helium and water; $P_1 = 85$ torr; $P_0 = 255$ torr; $d_1/d = 0.470$.

REFERENCES

1. B. R. Bowman and L. L. Edwards, *Reactor Containment Analysis for BWR Pressure Suppression Systems (Progress Report for January through for BWR Pressure Suppression Systems (Progress Report for January through March 1977)*, Lawrence Livermore Laboratory, Rept. UCRL-50045-77-1 (Jun. 1, 1977).
2. J. H. Pitts and E. W. McCauley, "A 1/5-Scale Experiment of a Mark I Boiling Water Reactor Pressure Suppression System under Hypothetical LOCA Conditions," in Proc. of the American Nuclear Society Topical Meeting on Thermal Reactor Safety (Sun Valley, Idaho, Jul. 31-Aug. 4, 1977), also Lawrence Livermore Laboratory, Rept. UCRL-79143 (Jul. 1977).
3. L. L. Edwards, R. B. Hickman, J. K. Hobson and T. C. Michels, *CHAMP: A Coupled HEMP And Multifluid Eulerian Program for Fluid Flow Simulations*, Lawrence Livermore Laboratory Rept. (in preparation).
4. C. K. Chan, private communication (Aug. 26, 1977).
5. B. R. Bowman, Summary of Trip to UCLA, Lawrence Livermore Laboratory H Division Technical Memorandum (Apr. 12, 1977). Readers outside the laboratory who desire further information on LLL internal documents should address their inquiries to the Technical Information Department, Lawrence Livermore Laboratory, Livermore, California 94550.
6. W. G. Anderson, P. W. Huls and A. A. Sonin, *Modeling of Pool Swell Dynamics, Progress Report*, NUREG-0288, NRC-4 (Mar. 1977).
7. M. L. Wilkins, Calculation of Elastic Plastic Flow, Lawrence Livermore Laboratory, Rept. UCRL-7322, Rev. 1 (1969).
8. W. H. McMaster, "Development of the Multiphase Code PELE," in Lawrence Livermore Laboratory Progress, Rept. UCRL-50045-76-4 (Mar. 1977).
9. I. C. Catton, C. K. Chan, V. K. Dhir, and C. Y. Liu, *Suppression Pool Dynamics, Quarterly Progress Report, July 1, 1976-September 30, 1976*, NUREG-0264-1; also, C. K. Chan (private communication).
10. E. W. McCauley and J. H. Pitts, *Mark I 1/5-Scale Boiling Water Reactor Pressure Suppression Experiment—Quick-look Report*, Lawrence Livermore Laboratory, Rept. UCID-17446-4 (Jun. 3, 1977).
11. G. N. Abramovich, *The Theory of Turbulent Jets* (MIT Press, 1963).
12. N. Rajaratnam, *Turbulent Jets* (Elsevier, Amsterdam-New York, 1976).
13. F. Kreith, *Principles of Heat Transfer*, 2nd ed. (International Textbook Co., 1965), pp.297-305.
14. S. W. Kang, "Nonequilibrium, Ionized, Hypersonic Flow over a Blunt Body at Low Reynolds Number," *AIAA Journal* 8 (7) (Jul. 1970), pp. 1263-1270.
15. H. Schlichting, *Boundary Layer Theory* (Pergamon Press, 1955), pp. 206-214.
16. A. G. Hansen, *Fluid Mechanics* (J. Wiley and Sons, 1964), Chapters 4-6.
17. E. H. Koch, E. Frenkel, L. Slegers and H. A. Weissaupt, "Dynamic Loads on Pressure Suppression Containments," *Proc. Second Int. Conf. on Structural Mechanics in Reactor Technology* (Berlin, Sep., 1973), Vol. VI-Part B Supplement, J 1/5, pp. 1-14.
18. F. O. Witzke, *A Study of Impinging, Axisymmetric Turbulent Flows: The Wall Jet, the Radial Jet, and Opposing Free Jets*, Sandia Report (Livermore) SAND 74-8257 (Jan. 1975).
19. S. K. Ohja and S. Gollakota, "Jet Impingement on a Curved Surface," *AIAA Journal* 15 (4), (Apr. 1977), pp. 453-454.
20. M. Poreh and J. E. Cermak, "Flow Characteristics of a Circular Submerged Jet Impinging Normally on a Smooth Boundary," *Proc. Sixth Midwestern Conference on Fluid Mechanics* (1959), pp. 198-212.
21. M. Wolfshtein, "Some Solutions of the Turbulent Impinging Jet," *Journal of Basic Engineering (ASME)*, (Dec. 1970), pp. 915-922.
22. S. Yamaguchi and T. Maki, "Jet Flames Stabilized by a Counter Air Stream," *Bull. Japan Soc. Mech. Engrs.* 14, (73), (1971), pp. 683-693.
23. R. Matsumoto and K. Kimoto, "A Study of Opposing Jets in Air Stream and their Flame—1st Report, A Structure of Two Dimensional Opposing Jets in the State without Flames," *Bull. Japan Soc. Mech. Engrs.* 16 (95) (May 1973), pp. 838-850.
24. I. Tani and Y. Komatsu, "Impingement of a Round Jet on a Flat Surface," *Proc. Eleventh Int. Congress of Applied Mechanics* (Munich, 1964), H. Goertler, ed., pp. 672-676.
25. M. Scholtz and O. Trass, "Mass Transfer in a Nonuniform Impinging Jet—Part I. Stagnation Flow-Velocity and Pressure Distribution," *AIChE Journal* 16 (1) (Jan. 1970), pp. 82-90.