138
5/23/78

01-91

UCRL-52435

BWR POOL DYNAMICS IN A LOSS OF COOLANT ACCIDENT. CALCULATION OF THE AIR-VENTING PHASE

L. A. Glenn
W. H. McMaster

March 9, 1978

Work performed under the auspices of the U.S. Department of
Energy by the UCLLL under contract number W-7405-ENG-48.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

LAWRENCE LIVERMORE LABORATORY

University of California Livermore, California 94550

UCRL-52435

BWR POOL DYNAMICS IN A LOSS OF COOLANT ACCIDENT. CALCULATION OF THE AIR-VENTING PHASE

**L. A. Glenn
W. H. McMaster**

MS. date: March 9, 1978

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.

BWR POOL DYNAMICS IN A LOSS OF COOLANT ACCIDENT. CALCULATION OF THE AIR-VENTING PHASE

ABSTRACT

We calculated the air-venting phase of a loss of coolant accident (LOCA) in a BWR pool using both compressible and incompressible finite difference schemes, and compared the results with experiments made at the University of California, Los Angeles and the Massachusetts Institute of Technology. The incompressible approach was found to be the most effective, because of the very low flow Mach numbers involved. Theory and experiment were in good agreement.

COMPRESSIBLE APPROACH

Calculation of the air-venting phase of a loss of coolant accident (LOCA) in a BWR pool can theoretically be accomplished with either compressible or incompressible flow models because the attainable maximum fluid velocity is very small in comparison with the speed of sound in water. The compressible flow approach may seem preferable because real water is compressible. One principal disadvantage with this approach is that the computational time step is normally limited by a Courant condition, i.e., by sound-wave propagation across the smallest mesh element. For a typical LOCA, on the order of 100 sound transits occur across the pool prior to vent clearing, which makes this approach very costly.

One method of improving the computational efficiency is to "scale" or reduce the fluid bulk modulus $k = \rho c^2$, where ρ is the density and c the sound speed. This artifact will normally have little or no effect on the solution accuracy as long as the number of pool transits (in the time period of vent clearing) remains large compared with unity. The response time on the tank bottom to impulsive changes at the air-water interface is inversely proportional to the sound speed; thus, too great a reduction of c will produce a load response that is both dispersed and reduced in amplitude. As an example, consider the UCLA experiment.² The distance from the downcomer to the tank bottom is approximately 0.3 m and the true sound speed in water is 1.5 m/ms so that events occurring at the air-water interface are broadcast in 0.2 ms to the pool bottom. Approximate solution for the interface motion

reveals that the time for vent clearing is directly proportional to the downcomer length and inversely proportional to the square root of the overpressure.³ For downcomer length of 0.1 m and overpressure of 20 kPa, this time is approximately 50 ms, allowing 250 sound transits of the pool to occur. If k is reduced by 100 so that c is 0.15 m/ms, we still have 25 transits during vent clearing and the impulse response time on the pool bottom increases from 0.2 to 2 ms. Much further reduction of k will permit the impulse response to assume a significant fraction of the vent clearing time, which will cause unacceptable dispersion of the calculated pressure on the pool bottom. The rise time actually measured was about 8 ms (for example, see the experimental results in Fig. 13).

Another feature of the compressible flow formulation of problems in which the limiting Mach number is very small compared with unity, is aliasing error. This has proven even more troublesome than the problem of excessive computer time. If the computed solution to the venting problem is represented as a Fourier integral, it will consist of the superposed sum of Fourier components, the shortest meaningful wavelength of which is precisely twice the length of the smallest mesh element. Aliasing is associated with the exchange of energy between Fourier components. Normally, the mesh is defined such that the smallest wavelength to be accurately resolved is several mesh element lengths because it is well known that the first few Fourier components tend to be dispersive (hence, the characteristic rounding of steep wave fronts). In

flows with very low limiting Mach number, it has also been shown that the components interact in such a way that energy cascades down from the long wavelengths to the short;⁴ if appropriate dissipative mechanisms are not present, the amplitude of the short wavelengths can grow without bound. A physical analogy is the energy of turbulence that generally moves from large to small eddies, beyond which it is eventually dissipated or degraded into internal energy by friction. Unfortunately, the dissipative mechanisms normally available in typical compressible codes such as HEMP do not sufficiently discriminate over wavelength to allow selective damping of one- or two-zone waves. Thus, in the air-venting problem, increasing the magnitude of the artificial viscosity had limited success because the fluid exiting the bottom of the downcomer was subjected to large shearing strains that were greatly inhibited by the increased viscosity. Damping the short wavelength components could not be accomplished without also damping the long wavelengths, thereby introducing unsatisfactory solution error.

The aliasing problem is exemplified by the simulation of the UCLA experiment.² Figure 1 shows the interface displacement as a function of time. Good agreement between the experimental result, one-dimensional incompressible, inviscid venting theory, and the HEMP calculation is evidenced. Figure 2 shows the (HEMP) Lagrangian mesh displacement through vent clearing at $t = 50$ ms; Fig. 3 shows the bubble formation 10 ms thereafter. Although no excessive mesh distortion is noted, the vertical displacement along the axis of symmetry does exhibit a spatial wiggle, especially obvious near the tank bottom and at $t = 60$ ms. This wiggle is easily explained when one views the pressure history along the axis. Figure 4 depicts the pressure in the zone immediately below the air-liquid interface; the experimentally derived pressure applied to this interface varied linearly from 0 initially to 20 kPa at 50 ms, after which it sharply decreased again to 0 at 63 ms. This linear behavior is apparent in the first zone below only until about 13 ms, after which severe oscillations appear. The

Fig. 1. Interface displacement as a function of time for the UCLA experiment, $P^* = 20$ kPa, $t^* = 50$ ms, $L = 0.1$ m.

Fig. 2. HEMP simulation of UCLA experiment through vent clearing.

Fig. 3. HEMP simulation of UCLA experiment 10 ms after vent clearing.

period of these oscillations is very regular and corresponds to the transit time of an acoustic wave back and forth across two zones. The amplitude peak is more than 8X the maximum applied pressure at 50 ms. Nevertheless, integration of the Fig. 4 result through $t = 40$ ms yielded an oscillation-free parabolic force-time function well within 1% of the applied force at the interface. This suggested that the unwanted pressure oscillations might be removed with a simple low-pass filter. The

real part of the discrete Fourier transform of the Fig. 4 pressure signal is illustrated in Fig. 5. The representation is symmetric about the center of the abscissa, the point of highest frequency. The minimum computational time step was approximately $5 \mu\text{s}$ at $t = 60$ ms and the maximum was about $30 \mu\text{s}$ when the mesh was everywhere rectilinear, near $t = 0$. Because the Fourier analysis requires a uniform sampling interval, pressure was interpolated with a mean sampling interval of $T = 60$

Fig. 4. Pressure history in zone immediately below air-liquid interface in downcomer.

ms/3250 samples = 18.46 μ s. The maximum frequency is then $1/2T = 27$ kHz. The sharp, high amplitude spike in Fig. 5 corresponds to a period of $T_1 \approx 318$ μ s, approximately the acoustic transit time back and forth across two zones in the downcomer. For our purposes, the useful signal is contained between this spike and the vertical axis. The digital filter, through which this transform was passed, had unit amplitude on the vertical axis, with rapid rolloff to zero at a frequency corresponding to ap-

proximately $1/4T_1$, as depicted in Fig. 6, in which the horizontal scale coincides with that in Fig. 5. After filtering, the inverse transform is traced by the solid line in Fig. 7; the dashed line on this figure is the actual pressure applied to the air-liquid interface, one zone above. The solid line tracks the dashed line until $t = 43$ ms, at which time there is a sharp decrease followed by a similar increase at 50 ms; thereafter, both signals fall off together. This behavior is consistent with the physical model in

Fig. 5. Real part of discrete Fourier transform of Fig. 4 pressure signal. N is total number of samples and T is the sampling interval.

Fig. 6. Low-pass filter.

which rapid acceleration of the liquid at the bottom of the downcomer, just prior to vent clearing at 50 ms, would be expected to bring pressure relief to the fluid above.

Figure 8 shows the temporal variation of pressure of the fluid zone initially at the bottom of the downcomer and Fig. 9 shows the zone at the tank bottom (pressures in both figures are on the symmetry axis of the tank). The oscillations appear first on the tank bottom where the fluid motion is least. Also, the clipped pressure signal at $P = -100$ kPa in Fig. 9 results from the dynamic tensile strength assigned (somewhat arbitrarily) to the water. The low-pass filter of Fig. 6 was also applied to these pressure traces, with the results shown in Figs. 10 and 11. Again, the signal-to-noise ratio is surprisingly high. At the tank bottom, the pressure remains below 10% of the applied interface value until just prior to vent clearing, when a rapid surge occurs. The peak pressure at the bottom exceeds the peak interface value by about 7% and occurs about 2 ms later, just the transit time for an acoustic signal originating at the interface (in our artificial water with sound speed reduced tenfold). The axial pressure history may be considered a measure of the rate at which momentum crosses the downcomer exit, so that this rapid pressure surge (and its timing) is consistent with the physical model. It is also consistent with the results obtained for the MIT⁵ and LLL⁶ LOCA experiments. The UCLA experimental data, for a nominal overpressure of 20

Fig. 7. Inverse transform (solid line) obtained after passing the Fourier transform (real part shown in Fig. 5) of the pressure trace of Fig. 4 through the low-pass filter of Fig. 6. Dashed line is pressure applied to air-liquid interface, one zone above.

kPa, are shown in Figs. 12 and 13. The peak tank bottom pressure (with static head of 3.3 kPa included) is only 60% of the peak pressure recorded in the upstream air space. A possible explanation for the discrepancy may lie in the rise time of the Statham transducer, reported to be 8 ms in the experiment.⁷ In Fig. 13, we show that this is also approximately the rise time recorded for the two tests. However, the computed rise time in Fig. 11 is only half this value (about 4 ms) so that the measurement system would presumably be unable to match the calculated response. Moreover, the Fig. 6 filter had rolloff to zero at 780 Hz, corresponding to a period of about 1.3 ms. When a test filter with a pass cutoff of 390 Hz was tried, the period increased to 2.6 ms, the peak pressure dropped 35% from the 22 kPa evidenced in Fig. 11, and the rise time increased from 4 to 8 ms, in agreement with the experimental result. Yet a third result, intermediate between the HEMP estimate and the experiment, has been obtained in preliminary calculations with an incompressible (Eulerian) solution algorithm, described below; thus, we are not yet certain that the filtered HEMP results are accurate.

It is also possible to eliminate the computational instability by spatial, rather than temporal, filtering. In integrating the barotropic vorticity equation, Phillips⁸ periodically discarded all wavelength components smaller than 4 mesh elements by performing a Fourier analysis on the grid point data every N^{th} time step and reconstituting the smoothed field

Fig. 8. Pressure history in zone initially at bottom of downcomer. Note that Fig. 4 is axis of symmetry

as a new initial value problem. Another possible solution is the use of an active smoothing operator built into the finite-difference algorithm¹⁰ rather than filtering *a posteriori*. Several of these were tried in conjunction with the HIMP code, but without success.

A considerable effort has also been made to formulate a compressible algorithm in an Eulerian frame, with the air-water interface being variously defined with imbedded, moving, polygonal bound-

aries (CHAMP),¹¹ or directly on (PFF). The advection terms inherent in these methods provide an additional mechanism for dissipation so that the aliasing error problem was less severe and the oscillations less regular than with HIMP. However, it was not possible to entirely eliminate unwanted oscillations, and the solutions obtained were considerably more dispersive, even with higher mesh density, which caused an increase in the already excessive computer cost.

Fig. 9—Pressure history in zone at tank bottom on axis of symmetry

INCOMPRESSIBLE FORMULATION

An incompressible formulation of the vent clearing problem effectively eliminates the unwanted sound waves by introducing an elliptic behavior into the equations; all regions of the flow field are then in instantaneous communication. A very fast code was developed for this application by the EASI group,¹⁴ based on a simplified marker-and-cell method called SOLA.¹⁵ In this algorithm, a dif-

ference analog of the two Navier-Stokes equations is first solved for the velocities at time $t + \Delta t$ from the right-hand side of the equations evaluated at t . The velocities so obtained do not necessarily satisfy the continuity equation.

$$\nabla \cdot \mathbf{u} = 0$$

Fig. 10. Inverse transform obtained after passing the pressure trace of Fig. 8 (initially at bottom of downcomer) through the Fig. 6 filter.

Fig. 11. Inverse transform obtained after passing the pressure trace of Fig. 9 (at tank bottom on axis of symmetry) through the Fig. 6 filter.

Fig. 12. Upstream pressure, P_1 , for 20 kPa UCLA experiments.

Fig. 13. Tank bottom (center) pressure, P_2 , for 20 kPa UCLA experiments.

In iterative fashion, the divergence in each cell is then driven to zero by adjusting the pressure with only the Lagrangian form:

$$U^{(k)} = U^{(k-1)} + (\Delta t / \Delta X) \Delta^{(k-1/2)} P,$$

where the superscripts indicate iteration-to-iteration values. The new cell pressure is

$$P^{n+1} = P^n + \Delta^{(final)} P$$

The ΔP 's are found by substituting the $U^{(k)}$'s into the difference analog of the divergence condition and solving what then amounts to a trivial linear equation.

With the SOLA method, only limited treatment of moving interfaces is specified. An experimental version, SOLA VOF, was apparently used for the vent-clearing study, but details of this code have not been published. In our adaptation, PELEIC, the air-liquid interface and the subsequent bubble growth and surface interaction are accounted for

with a void-fraction algorithm¹² similar to that previously developed for the compressible code PELE. Another innovation is that the code can account for a flexible pool bottom, the motion of which is directly coupled to the fluid dynamics within.

Preliminary results obtained with PELEIC, simulating the UCLA and MIT experiments, have been encouraging. Figure 14 shows the calculated

pressure on the tank bottom for a UCLA test, with the overpressure, indicated by the dashed curve, applied to the air-water interface. The time for vent clearing is in good correspondence with the Fig. 1 result; the peak pressure in Fig. 14 is obtained several milliseconds thereafter, as expected. The amplitude of the peak is intermediate between that predicted with HEMP and the experimental result. The sensitivity of this result to such parameters as

Fig. 14. Calculation of the UCLA experiment with PELEIC.

the iterative convergence criterion, transport differencing, mesh size, and time step has not been determined so that the computational accuracy cannot yet be assured.

Simulation of the MIT experiment with PELEIC resulted in a predicted pressure at the pool bottom some 25% below the measured value, as seen in Fig. 15. In part, this may be a result of vibrations set

Fig. 15. Calculation of the MIT experiment with FELEIC.

Fig. 16. Bubble growth in the calculation of the UCLA experiment with PELEIC.

30 ms

34 ms

Fig. 17. Bubble growth in the calculation of the MIT experiment with PELEIC.

up in the wetwell structure in response to the suddenly applied load.⁵ In any case, P_2 appears to equal or exceed P_1 at vent clearing, or slightly thereafter, so that the peak pressure may be influenced somewhat by the experimental geometry, specifically the downcomer-to-pool diameter ratio. For the MIT setup, this ratio was 0.18; for UCLA, it was 0.10. The larger relative pool size in the UCLA experiment could act to disperse the bottom load.

Bubble growth in these two experimental simulations was similar, as seen in Figs. 16 and 17. In the UCLA simulation, breakthrough of the pool surface did not occur until well after peak down and upload, in qualitative agreement with experiment. In the MIT simulation, however, the radial bubble growth was arrested by the pool diameter and pool surface breakthrough occurred earlier. The void fraction algorithm does not yet correctly treat this interaction, so the results obtained beyond this point are incorrect and are therefore not shown in Figs. 15 and 17.

Some preliminary calculations were also made with PELEIC to demonstrate the effect on the pool

bottom pressure, in the UCLA experiments, of changes in the flexural rigidity of the bottom end plate. The structural response was calculated assuming that the plate inertia could be neglected, so that the solution (for arbitrary spatial pressure distribution) could be built up at each time from quasistatic theory by the method of superposition.¹³ Even for steel plates as thin as 1 mm, with corresponding maximum deflection of about 20 mm (roughly 4% of the plate diameter), the peak pool bottom pressure differed by only about 1% from the rigid-wall result. We tentatively conclude that, if coupling of the structural response to the fluid mechanics is important, resonance phenomena cannot be ignored and the inertia of the structure must be considered.

Finally, even with structural interaction, PELEIC is a very efficient code. Each of the solutions described above took less than a minute to run on our CDC 7600 computer system. This is an improvement of at least two orders of magnitude compared with the compressible codes previously used.

REFERENCES

1. B. R. Bowman and L. L. Edwards, *Reactor Containment Analysis for BWR Suppression Systems*, Progress Report for January through March 1977, Lawrence Livermore Laboratory, Rept. UCRL-50045-77-1 (1977).
2. B. Bowman, Lawrence Livermore Laboratory, personal communication (1977).
3. S. W. Kang, Lawrence Livermore Laboratory, personal communication (1977).
4. J. G. Charney, R. Fjortoft, and J. von Neumann, "Numerical Integration of the Barotropic Vorticity Equation," *Tellus* 2, no. 4, (1950).
5. W. G. Anderson, P. W. Huber, and A. A. Sonin, *Modeling of Pool Swell Dynamics*, Rept. NUREG-0288 March 1977.
6. J. H. Pitts and E. W. McCauley, *Vertical Forces Induced in a 1/5 Scale Mark I BWR Toroidal Wetwell*, Lawrence Livermore Laboratory, Rept. UCRL-79825, (1977).
7. I. Catton, "Suppression Pool Dynamics," *Quarterly Progress Report, October 1-December 31, 1976*, NUREG-0264-2, May 1977.
8. N. A. Phillips, "An Example of Non-linear Computational Instability," in *Atmosphere and Sea in Motion*, Rossby Memorial Volume (Rockefeller Inst. Press, NY, 1959).
9. A. Grammelvedt, "A Survey of Finite-Difference Scheme, for the Primitive Equations for a Barotropic Fluid," *Monthly Weather Review*, 97 (1969).
10. C. W. Hirt and B. D. Nichols, "Vent Clearing Hydrodynamics," presented at Fifth Water Reactor Safety Research Information Meeting (National Bureau of Standards, Gaithersburg, Md., 1977).
11. C. W. Hirt, B. D. Nichols, and N. C. Romero, *SOLA — A Numerical Algorithm for Transient Fluid Flows*, Los Alamos Scientific Laboratory Rept. LA-5852, (1975).
12. W. McMaster, Lawrence Livermore Laboratory, "PELEIC," in publication.
13. Algorithm derived by G. L. Goudreau from S. Timoshenko in *Theory of Plates and Shells* (McGraw-Hill, N.Y., 1959), p.67.