COMPARISON OF FLOW-3D CALCULATIONS WITH VERY LARGE AMPLITUDE SLOSH DATA

J. M. Sicilian
Flow Science, Inc.
1325 Trinity Drive
Los Alamos, NM 87544

J. R. Tegart
Martin Marietta Astronautics
P.O. Box 179
Denver, CO 80201

To be presented at the PVP ASME Conference, July 22-27, 1989
Symposium on Computational Experiments

March 1989

INTRODUCTION

Knowledge of the motion of propellants in the tankage of spacecraft is essential to understanding various aspects of their operation and performance. Propellant motion impacts such propulsion functions as expulsion of liquid (including the operation of propellant management systems), venting of gases, and pressurization. For example, in some applications propellant must be settled over the tank outlet before engine start. To design these systems, efficient methods for reorienting the propellants are needed as is knowledge of the time required to settle. In order to vent a tank, it must be known when only gas will be available at the vent inlet. Pressurant usage can be dependent upon the splashing and mixing of the propellant. These are only a few examples of the many possible interactions between the propellant motion and the propulsion system functions.

In some cases the forces produced by the propellant motion must also be known. This is particularly true when the liquid mass is a significant portion of the total spacecraft mass. One example is the orbital maneuvering of a spacecraft. The liquid motion caused by a maneuver can produce forces that in turn alter the spacecraft motion, resulting in interactions between the control system and the propellant. The stability of the control system must be established and, if the forces are too large, a means of damping the liquid motion may be needed.

These issues, regarding propellant motion in maneuvering and restartable spacecraft, illustrate the need for analytical methods of predicting the motion of propellants and the forces produced. One such model, FLOW-3D (a commercial product of Flow Science, Inc., Los Alamos, New Mexico), uses finite-difference methods to solve the Navier-Stokes equations within a three-dimensional mesh. To gain confidence in the ability of FLOW-3D to predict liquid motion and fluid forces, its results were correlated with existing test data. Two test programs, performed in Martin Marietta's Drop Tower Test Facility, were used in the correlation.[1,2] Predictions closely matching the test data were obtained.

EXPERIMENTAL DATA

Under a NASA study[1] an experimental method of producing liquid motion in a subscale tank was developed so that the motion could be observed and the force of the liquid on the tank could be measured. Martin Marietta's Drop Tower Test Facility was used to produce a controlled acceleration environment with axial and lateral components. Clear plastic tank models were installed in a fixture that was suspended by two axial and one lateral load cells, as shown in Fig. 1. The tank could be mounted at various orientations relative to the fixture so as to change the initial liquid position. The fixture and a movie camera were mounted on a slider permitting application of a lateral acceleration component (typically 5 to 20 cm/s^2). The entire drop capsule, carrying the

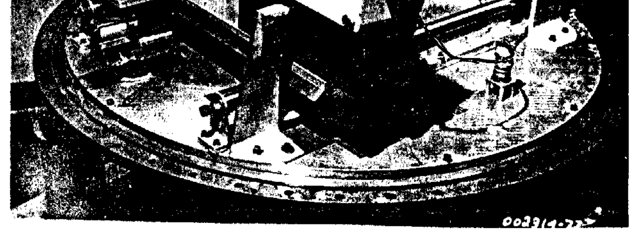


Fig.1. Drop Capsule and Instrumentation

slider and test fixture, accelerated axially (ranging from 39 to 95 cm/s^2) within a drag shield during free fall. The tank size and the accelerations were scaled so that the most significant liquid motion and forces occurred during the two second test period while the drop capsule fell.

The movie camera recorded the liquid motion on 16 mm film at 200 frames per second, and the piezoelectric load cells were capable of measuring the small forces produced by the liquid motion. The force data was processed to yield two force components in the plane of the accelerations and a moment normal to the plane.

This same test apparatus was used to test many different tank configurations. The data from two tank configurations are used here. One is a 12.7 cm diameter cylindrical tank with hemispherical domes (Fig. 2). The tests covered a range of initial positions, fill levels, and accelerations, simulating on-orbit maneuvers.[1]

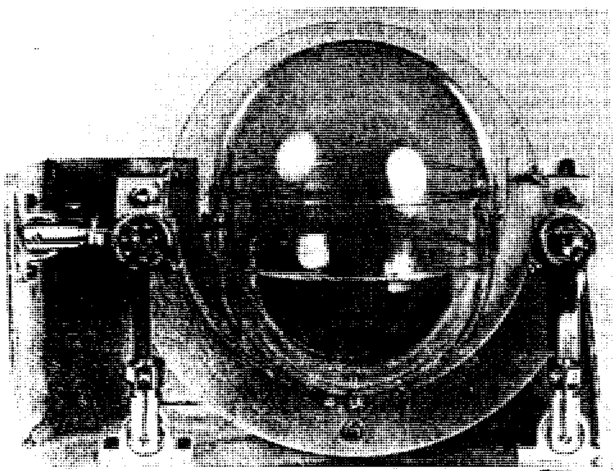


Fig. 2. Cylindrical Tank with Hemispherical Caps

The second data set[2] was based on a one-sixtieth scale model of the oxygen tank of the Space Shuttle external tank (Fig. 3). The forces on the external tank caused by the motion of the residual propellant during separation from the orbiter were simulated. A range of fill levels, initial liquid orientations, and accelerations were again considered.

COMPUTATIONAL METHOD

The FLOW-3D program is a general purpose computer program that uses finite-volume approximations to simulate a wide range of fluid dynamic situations.[3] Although the program includes many physical phenomena, its ability to model transient, incompressible, free-surface flows in complex geometry has led to frequent application to propellant slosh phenomena.[4-8] Critical to the success of these applications is the program's ability to calculate in accelerating reference frames.

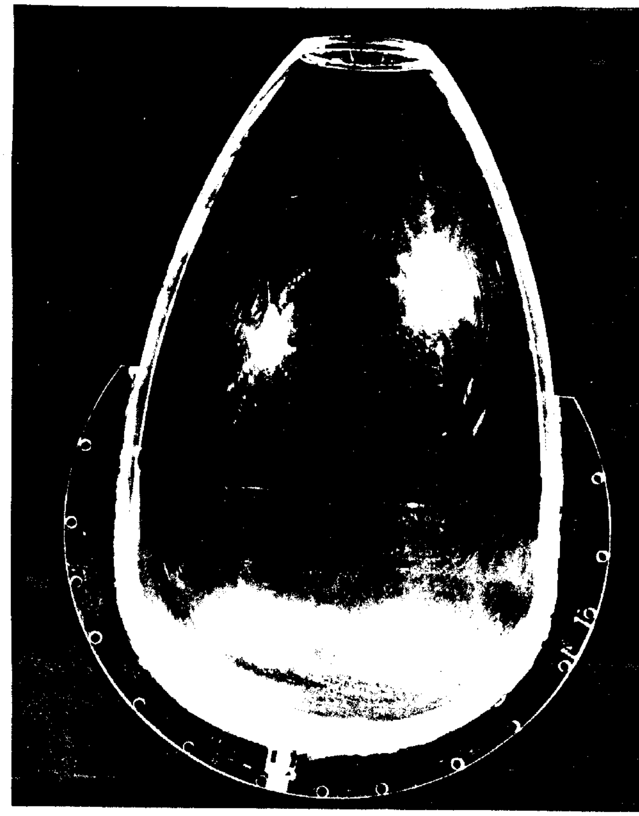


Fig. 3. Shuttle External Tank Model

The basic solution algorithm used by FLOW-3D is the SOLA method developed at the Los Alamos National Laboratory in the early 1970s.[9] Its use of the Volume of Fluid Method (VOF) makes FLOW-3D a three-dimensional extension of the SOLA-VOF program.[10] SOLA solves the transient Navier-Stokes equations by applying forward difference approximations in time with a stabilizing implicit formulation of the pressure gradient terms of the momentum equation coupled to the incompressibility condition.

In FLOW-3D, SOLA has been extended to complex geometries by using the Fractional Area/Volume Obstacle Representation (FAVOR). Based on a three-dimensional rectangular computational mesh, FAVOR utilizes fractional cell volumes and face areas to approximate curved solid boundaries.[11] These area and volume fractions are incorporated into the momentum, continuity, and VOF finite-difference approximations.

To evaluate flows in moving containers, FLOW-3D embeds its computational mesh in a non-inertial reference frame. The non-inertial effects (which may include rotational as well as translational terms) lead to fictitious body forces in the momentum equations. When viewing the computational results, one must recall that all fluid motions are relative to the accelerating tank.

Since the fluid pressure is an integral result of the SOLA method, it is a simple

matter to calculate the force and force moments exerted by the fluid on propellant tanks. (Viscous shear forces are normally small in these applications and are not included in the evaluation of forces.)

The VOF method also leads to simple visualization of the fluid surface, which is again automated within FLOW-3D. These visualizations are simply contour plots of the fluid fraction calculated by the VOF method.

SHUTTLE EXTERNAL TANK CALCULATIONS

Several of the 1/60th scale model tests described in Ref. 2 have been simulated using FLOW-3D. The geometric model used for all simulations was the same. The fluid fill level and applied accelerations were varied to match test conditions. The length of the scale model was about 25 cm.

Since the tank and accelerations for these tests were symmetric about the plane containing the y and z axes, only half of the tank was modeled in our simulations.

Some fluid motion through the symmetry plane was observed in the experiments, most likely a result of slight disturbances from release of the drop capsule. These do not seem to have strongly influenced the observed fluid motion or measured forces and moments. These motions were not included in the simulations.

To simplify specification of the tank geometry, the computational z axis was chosen as the symmetry axis of the tank. Therefore, the FLOW-3D z and y axes coincide with the experimental Z_T and Y_T axes.[2]

The computational grid employed uniform cells in the x and y directions and only slight size variations in the z direction. The total of 2625 cells (in the 3D mesh) seems to adequately resolve the fluid motion except for thin films of fluid adjacent to tank walls.

As described in Ref. 2, the shuttle external tank consists of an ellipsoidal base, a cylindrical section, and a truncated ogival top. All of these sections are included in the FLOW-3D model of the tank.

PHYSICS MODELING

As discussed above, FLOW-3D uses the VOF method to track the motion of free surfaces. Since the Bond number for the simulated tests is about 450, the FLOW-3D surface tension model was not used for these simulations. Similarly, the viscous and wall shear models were not employed as the Reynolds number of 10^5 indicates that viscous effects will be limited to thin boundary layers. Experimental investigation of the influence of surface tension and viscosity confirms the appropriateness of these approximations.[2]

Most of the modeled experiments used constant accelerations (following the release of the capsule), therefore, an equivalent gravitational field was employed instead of the general accelerating reference frame.

EXTERNAL TANK DATA COMPARISON

Four experiments from Ref. 2 were simulated. Tests 21, 5, and 22 all used: the fluorcarbon FC-114B2 as the working fluid, an initial surface inclined 13^o to the tank axis, and accelerations close to 95 cm/s^2 along the z axis. These tests had fill fractions of 5, 10, and 15 percent, respectively. Test 16 employed a varying acceleration history and a 10 percent fill fraction. (Because of the variations in accelerations, the non-inertial reference frame was required for Test 16.)

Qualitatively, the fluid motions observed in the first three experiments were quite similar. The behavior observed in the simulations was also quite similar to the observed experimental motions. Figure 4 compares experimental photographs with computed fluid motions at five times for the 15% case (Test 22). The computed results are near the midplane of the tank. At t=1.2 and 1.6 seconds the simulated flow seems to lead the experimental results by a small amount, although the photographs are somewhat difficult to interpret. Free surface comparisons for Tests 5 and 22 are similar.

Correlation of experimental and computational force components are presented in Figs. 5-10. As described above, three load cell measurements were combined to produce experimental evaluations of the force along and normal to the tank symmetry axis and to evaluate the force moment normal to the plane of symmetry. The reported forces have been shifted to compensate for the mass of the tank and its support structure. The horizontal load cell measurements are less reliable than the vertical because of the lower force magnitudes experience in that direction.

One might suggest shifting the measured forces to agree with the easily predicted force at the initiation of the accelerations. However, these initial forces should be approximately constant while the measured values show strong fluctuations. Therefore, we have adjusted each force component (by an amount constant in time) to yield the best agreement with the simulated results. The initial measured fluctuations are probably due to transient accelerations caused by the release of the capsule, which cannot be simulated since the accelerations are unknown. Thus the comparisons must be thought of as correlation of the variation in force rather than as correlation of the absolute magnitude of force.

We are not presenting correlations of simulated and measured force moments because these moments are particularly sensitive to the less reliable horizontal load cell measurement.

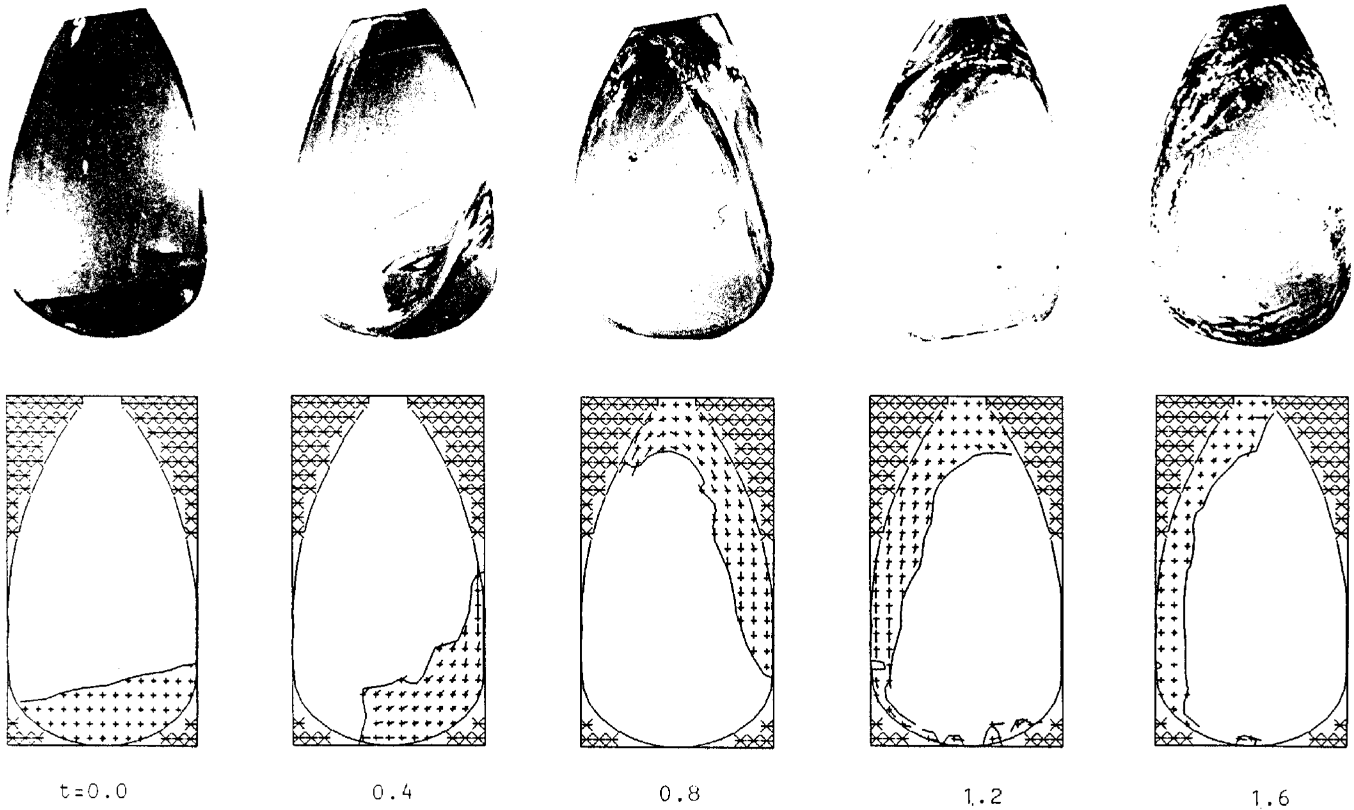


Fig. 4. Observed and Simulated Fluid Motions For Test 22

Test 22

The correlation of measured and simulated forces for the 15% fill case (Test 22) is presented in Figs. 5 and 6. The agreement of the axial force component, Fig. 5, is very good. The peak-to-peak difference in the simulated result is approximately 20% larger than the measured value. The experimental values have been read from rather coarse plots, which leads to errors of the order of 10^4 dynes, which could explain the discrepancy between the data and calculations. The accuracy of the computed result is limited by the mesh resolution and the omission of the release transient from the simulation.

The correlation of the transverse force components for this test shows greater discrepancy. (The sign of the transverse component is opposite Ref. 2 because of a difference in conventions between the experiment and these simulations.) Although there is less confidence in this force component (since it is closely related to the horizontal load cell measurement), there is less uncertainty associated with reading the data report (about 4×10^3 dynes). The peak-to-peak difference is about 40%. The large discrepancy may be due to numerical force "spikes" that coincide with the physical force minimum and maximum for this calculation. The question is still under investigation.

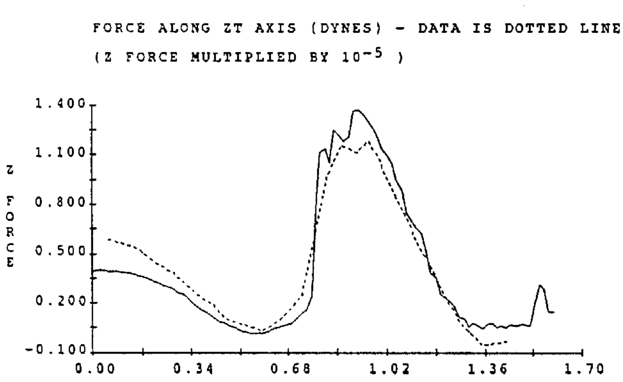


Fig. 5. Axial Force Comparison (Test 22)

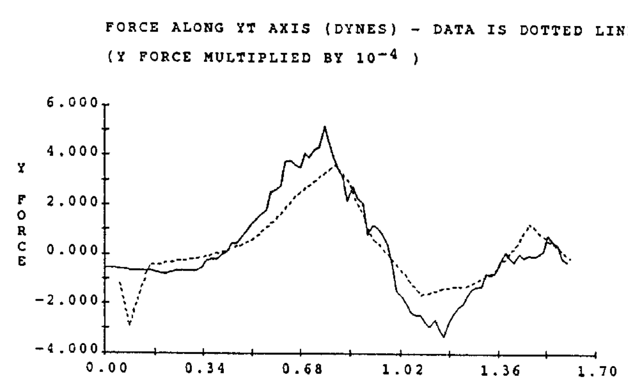


Fig. 6. Transverse Force Comparison (Test 22)

Test 5

Correlations of measured and simulated force components for the 10% fill case (Test 5) are presented in Figs. 7 and 8. While the axial component shows somewhat greater discrepancy, the transverse component agrees well. Again, there seem to be numerical force spikes that contribute to the discrepancy.

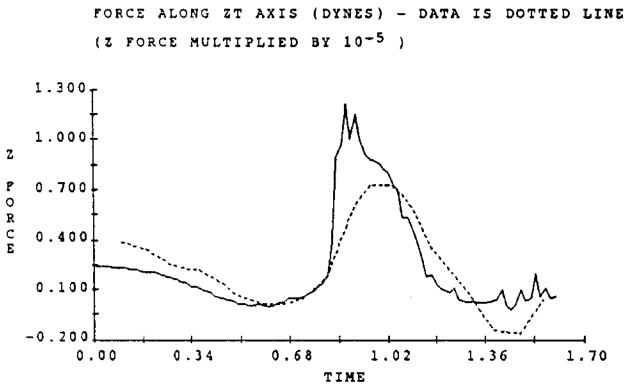


Fig. 7. Axial Force Comparison (Test 5)

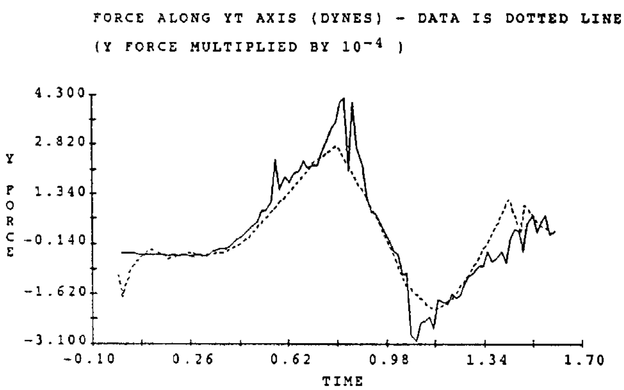


Fig. 8. Transverse Force Comparison (Test 5)

Test 21

Calculations of measured and simulated force components for the 5% fill case (Test 21) are presented in Figs. 9 and 10. As with Test 5, the transverse component agrees well, and there are significant discrepancies with the axial force correlation.

Test 16

We also simulated one test that was performed with a somewhat different acceleration than the others. Test 16 had a fill fraction of 10% (like Test 5), an axial tilt of 13°, and horizontal and vertical accelerations of 52 and 89.3 cm/s^2, respectively. The horizontal component of acceleration was delayed until 0.5 seconds. Therefore, the tests included a situation (from 0 to 0.5 seconds) when the acceleration was directed normal to the free surface. The resulting fluid motion is therefore quite different from that encountered in the other tests. Figure 11 compares the experimental and simulated fluid motions. The details are clearly different as one might expect by observing that this is a physically unstable system during the 0 to 0.5 s time interval. FLOW-3D, however, did predict the breakup of the fluid surface and does predict grossly the fluid motion.

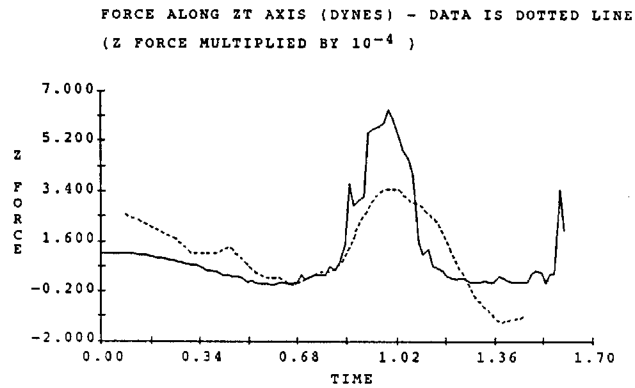


Fig. 9. Axial Force Comparison (Test 21)

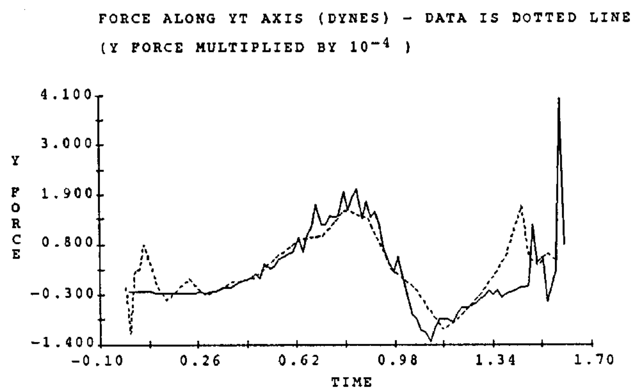
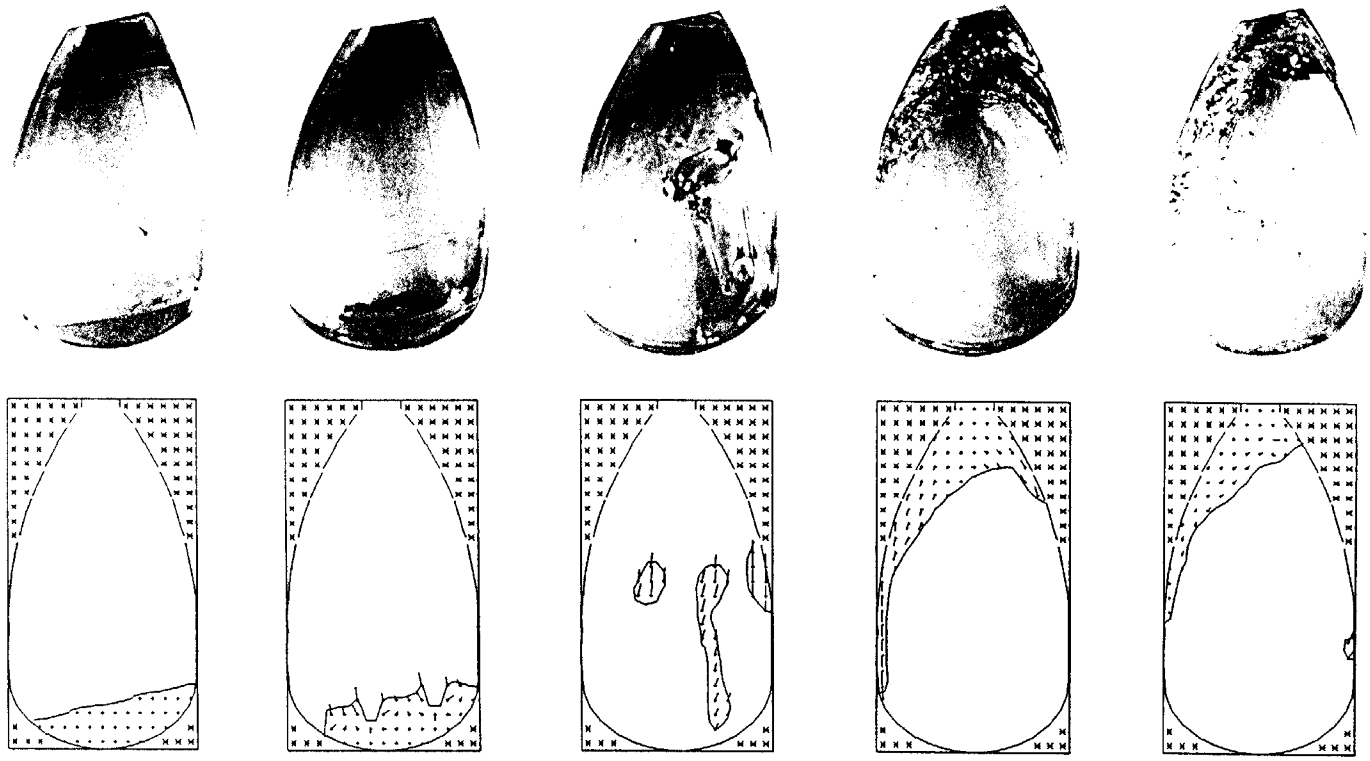


Fig. 10. Transverse Force Comparison (Test 21)

The experiment showed a broad low amplitude peak force in the z direction, while FLOW-3D predicted a sharp force spike near t=1 second. We suspect that the fluid surface broke into small droplets in the experiment resulting in a gentle rain on the tank top. This cannot be predicted by the simulation as the droplet sizes would be much smaller than the computational cells. Surface tension effects may also become very important for this type of flow. Surprisingly, the transverse force component was predicted reasonably well.

Cylindrical Tank Calculations

Three cases were selected for correlation from the Drop Tower Test data.[1] All tests were performed with a tank having a 12.7 cm diameter barrel section, hemispherical domes, and a 16.3 cm overall length.

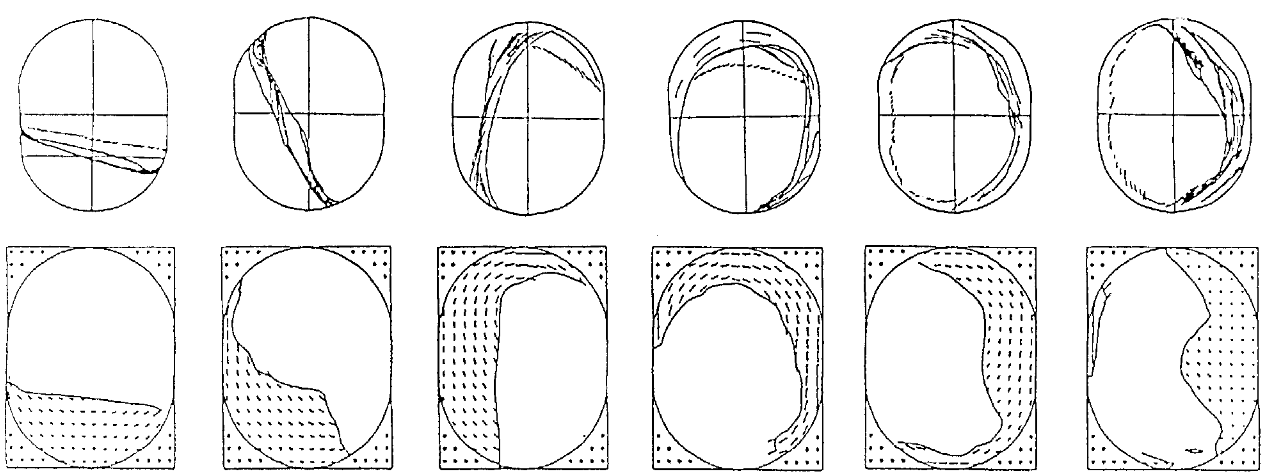


t=0.0 0.4 0.8 1.2 1.6

Fig. 11. Observed and Simulated Fluid Motions for Test 16

Neither viscous nor surface tension forces were considered due to their relative insignificance. The tank was symmetric about the x-z plane and the accelerations lie in this plane, so only half the tank had to be represented with the computational mesh. The tank diameter (x axis) was divided into 16 cells, the tank length (z axis) into 18 cells, and half the tank depth was represented by 8 cells along the y axis, resulting in 2304 mesh cells.

Test 13 had a 25% fill volume with the liquid initially oriented at the tank bottom. Throughout the test an axial acceleration (z) of 87.4 cm/s^2 and a lateral acceleration (x) of 17.5 cm/s^2 were continuously applied, having a net effect of orienting the liquid to the top left of the tank. The calculated liquid motion is compared with sketches prepared from the frames of the motion picture data in Fig. 12. The liquid, reoriented along the left side of the tank, flowed through the



t=0.25 0.55 0.80 1.1 1.4 1.6

Fig. 12. Correlation of Test 13

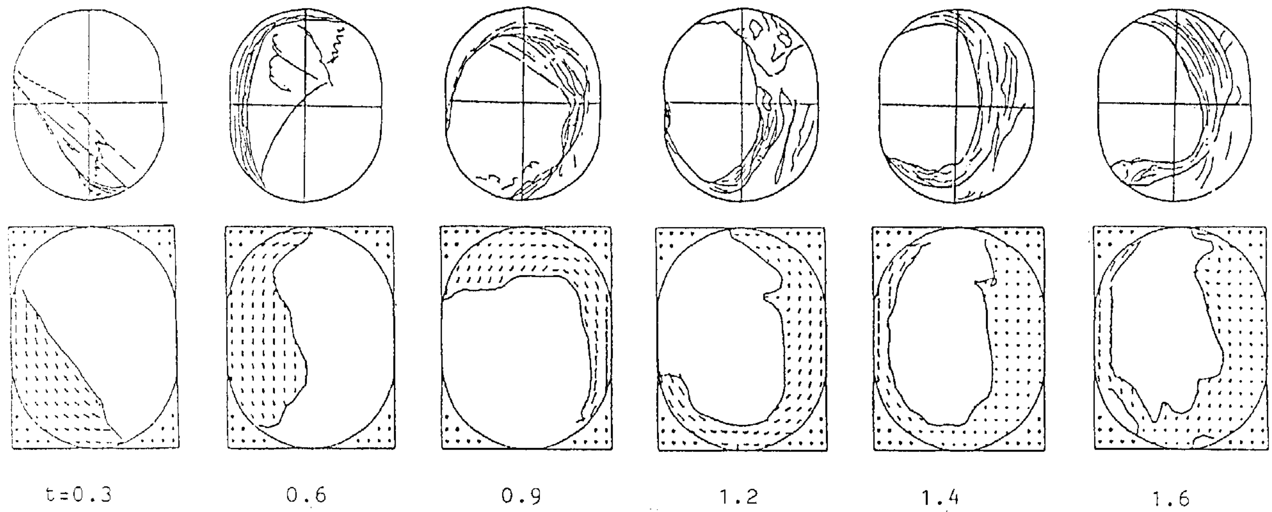


Fig. 13. Correlation of Test 16

upper dome and down the right side. At the end of the test the liquid had come to a stop on the right side of the tank and was reversing to flow back to what would be its final equilibrium position. The sketches represent the view of all the liquid in the tank, while the computed result is a slice through the tank center. The calculated motion matches the experiment very well, lacking only in the minor details of the surface. No correlation with the force measurements were made for these tests.

Tests 16 and 17 were similar, having 25% and 50% fill volumes, respectively. For both tests the liquid was initially oriented at a 45 degree angle, and axial and lateral accelerations were again applied throughout the test. Figures 13 and 14 show the comparison between the sketches from the film data and the calculated liquid motion. In both cases the initial motion of the liquid was well represented by the analysis.

At 1.4 sec in Test 16, the liquid leading edge continued around the bottom of the tank in the analysis, while the sketches show it did not. The opposite happened at 1.5 sec in Test 17. The sketches show the leading edge continuing through the tank bottom, while it stopped in the calculation. In exploring this phenomena, it was found that the calculated solution was sensitive to the magnitude of the input acceleration and to the input parameters that influence the accuracy of the computations. For example, with a slightly larger lateral acceleration the leading edge continued through the lower dome in the computed motion for Test 17. The solutions presented here correspond to the best estimates of the accelerations, but the error could be as much as 10%.

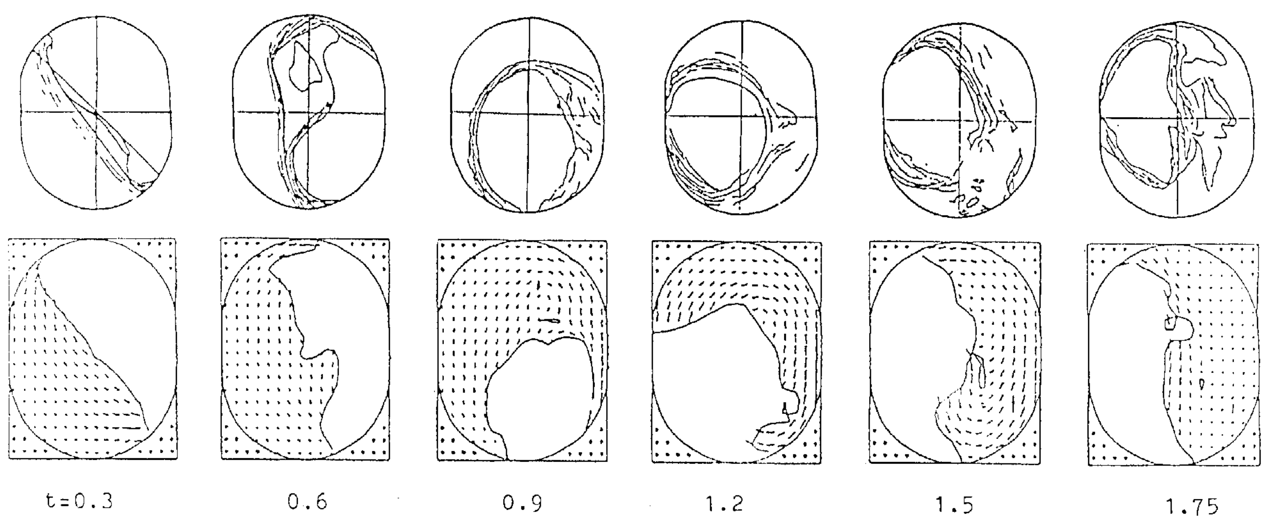


Fig. 14. Correlation of Test 17

In computing the liquid motion, the numerical method causes what appears as energy dissipation. Changes to the behavior of the computed leading edge motion were noted when a finer mesh was used or the maximum compute interval was limited, since these reduce numerical energy dissipation.

Since the behavior of the leading edge at 1.4 to 1.5 sec in Tests 16 and 17 was opposite the data in both cases, it was concluded that specifying the actual acceleration was a more critical factor than the solution accuracy, and further attempts to refine the match with the data were not warranted.

COMPUTER USAGE STATISTICS

The simulations performed as part of this research consumed considerable computational resources. No attempt was made to optimize the calculational cost by selection of input parameters. Only minor sensitivity studies of the results have been performed to date. All calculations were performed on a MicroVAX II computer with 5 megabytes of RAM. (This computer has approximately the same CPU performance as a VAX 11/780.) Table I reports several interesting statistics on the resources used for each calculation.

TABLE I

Computer Usage Statistics for Propellant Slosh Simulations

	Tank Fill Fraction	Average Time-Step Size	Total CPU Time
Shuttle External Tank Model (2625 Cells)			
Test 5	10%	1.5 ms	6.4 hours
Test 16	15%	1.4 ms	6.9 hours
Test 21	5%	1.5 ms	5.8 hours
Test 22	10%	1.2 ms	8.6 hours
Cylinder with Hemispherical Caps (2304 Cells)			
Test 13	25%	1 ms	8.5 hours
Test 16	25%	1 ms	10.1 hours
Test 17	50%	1 ms	13.1 hours

CONCLUSIONS

FLOW-3D simulations of a variety of drop tower experiments show a reliable ability to predict gross fluid motion in conditions of large fluid displacement. Predictions of the force exerted by the fluid on its container are much improved over earlier computations. The predicted forces agree in timing and trend with the measured data. Uncertainty in the magnitude of both force measurements and predictions is sufficient to explain the observed differences between them. Additional experimentation may be required to further refine the current modeling methods.

REFERENCES

1. R.L. Berry and J.R. Tegart, "Experimental Study of Transient Liquid Motion in Orbiting Spacecraft," MCR-76-11, Martin Marietta Corp., Denver, CO, February 1976.

2. R.L. Berry, L.J. Demchak, and J.R. Tegart, "Analysis and Test for Space Shuttle Propellant Dynamics," NASA CR 3683, Martin Marietta Corp., Denver, CO, June 1983.

3. J.M. Sicilian, C.W. Hirt, and R.P. Harper, "FLOW-3D: Computational Modeling Power for Scientists and Engineers," Flow Science, Inc. report (FSI-87-00-1), 1987.

4. T.W. Eastes, Y.M. Chang, C.W. Hirt, and J.M. Sicilian, "Zero-Gravity Slosh Analysis," ASME Winter Annual Meeting, Miami, FL, November 1985.

5. R.E. Martin, "Effects of Transient Propellant Dynamics on Deployment of Large Liquid Stages in Zero-Gravity with Application to Shuttle/Centaur," 37th Annual Astronautical Congress, Innsbruck, Austria, Oct. 3-10, 1986 (IAF-86-119), Acta Astronautica, Vol. 15, No. 6/7, pp. 331-340, 1987.

6. J. Navickas, C.R. Cross, and D.D. Van Winkle, "Propellant Tank Forces Resulting from Fluid Motion in a Low-Gravity Field," ASME Symposium in Microgravity Fluid Mechanics, Winter Annual Meeting, Anaheim, CA, December 7-12, 1986.

7. J.J. Der and C.L. Stevens, "Liquid Propellant Tank Ullage Bubble Deformation and Breakup in Low Gravity Reorientation," AIAA/SAE/ASME/ASEE 23rd Joint Propulsion Conference, San Diego, CA, June 1987 (AAIA-87-2021).

8. C.W. Hirt and R.P. Harper, "Fluid Slosh in a Spinning and Oscillating Dish," Flow Science, Inc. Technical Note #9 (FSI-88-TN9), March 1988.

9. C.W. Hirt, B.D. Nichols, and N.C. Romero, "SOLA-A Numerical Solution Algorithm for Transient Fluid Flows," LASL report, LA-5852, April 1975.

10. C.W. Hirt and B.D. Nichols, "Volume of Fluid (VOF) Method for the Dynamics of Free Boundaries," J. Comp. Physics, 39, 201, January 1981.

11. C.W. Hirt and J.M. Sicilian, "A Porosity Technique for the Definition of Obstacles in Rectangular Cell Meshes," Fourth International Conference on Ship Hydrodynamics, Washington, DC, September 1985.

Smolinski office
412-624-9784

The American Society of Mechanical Engineers

212-705-7722
TWX 710-581-5267

345 East 47th Street
New York, NY 10017

OFFER OF A TECHNICAL PAPER

IMPORTANT: Papers will not be published unless this Form is signed and returned.

PROPOSED TITLE OF PAPER Comparison of FLOW-3D Calculations with Very Large Amplitude Slosh Data

AUTHOR(s) J. M. Sicilian and J. R. Tegart

ABSTRACT (attach, in duplicate, so that the scope and character of the paper may be known)

APPROXIMATE DATE MANUSCRIPT WILL BE AVAILABLE March 15, 1989

PAPER OFFERED FOR PRESENTATION AT THE (conference and session) PVP ASME Conference July 22-27, 1989 Symposium on Computational Experiments

☐ *As part of the Society's continuing effort to encourage greater interaction between the technical and the regional/sectional activities, check this box if you or another author are willing to re-present this paper, and indicate any travel or other limitations.*

In accordance with ASME policy, outlined on the reverse side of this sheet, I certify that to the best of my knowledge this paper will represent:

☒ The first publication of original material or ☐ An original compilation of information from a number of sources as specifically noted by footnotes and/or bibliography

In submitting a finished manuscript for publication, I attest that the sole author(s) will be the individual(s) whose name(s) will appear on the title page, with the possible exception of editorial or research assistance, and agree to pay any mandatory excess page charges (see over).

I am offering this paper to The American Society of Mechanical Engineers in accordance with the statements set forth on both sides of this form. This form, signed by all the authors, must be received at ASME Headquarters before the manuscript can be accepted for publication. Verbatim reproduction of this paper by anyone will be permitted by ASME provided appropriate credit is given to the author(s) and ASME.

☒ I also grant and assign exclusively to The American Society of Mechanical Engineers for its use any and all rights of whatsoever kind or nature now or hereafter protected by the Copyright Laws (common or statutory) of the United States and all foreign countries in all languages in and to the above named article, including all subsidiary rights.

☐ This paper was produced in the course of my employment by the U.S. Government and hence is in the public domain.

AUTHORS (Lead Authors and Co-Authors):

Name J. M. Sicilian Signature James Sicilian Date 3-13-89
Address Flow Science, Inc., 1325 Trinity Drive, Los Alamos, NM 87544
Telephone 505-662-2637

Name J. R. Tegart Signature Date 3-15-89
Address Martin Marietta Astronautics, P.O. Box 179, Denver, CO 80201
Telephone 303-977-3758

Name Signature Date
Address
Telephone

Mr. Tegart will send a copy with his signature.

Name Signature Date
Address
Telephone

Reprinted From
PVP — Vol. 176, Computational Experiments
Editors: W. K. Liu, P. Smolinski, R. Ohayon,
J. Navickas, and J. Gvildys
Book No. H00491 — 1989

The American Society of Mechanical Engineers

COMPARISON OF FLOW-3D CALCULATIONS WITH VERY LARGE AMPLITUDE SLOSH DATA

J. M. Sicilian, Senior Scientist
Flow Science, Inc.
Los Alamos, New Mexico

J. R. Tegart, Senior Staff Engineer
Martin Marietta Astronautics
Denver, Colorado

INTRODUCTION

Knowledge of the motion of propellants in the tankage of spacecraft is essential to understanding various aspects of their operation and performance. Propellant motion impacts such propulsion functions as expulsion of liquid (including the operation of propellant management systems), venting of gases, and pressurization. For example, in some applications propellant must be settled over the tank outlet before engine start. To design these systems, efficient methods for reorienting the propellants are needed as is knowledge of the time required to settle. In order to vent a tank, it must be known when only gas will be available at the vent inlet. Pressurant usage can be dependent upon the splashing and mixing of the propellant. These are only a few examples of the many possible interactions between the propellant motion and the propulsion system functions.

In some cases the forces produced by the propellant motion must also be known. This is particularly true when the liquid mass is a significant portion of the total spacecraft mass. One example is the orbital maneuvering of a spacecraft. The liquid motion caused by a maneuver can produce forces that in turn alter the spacecraft motion, resulting in interactions between the control system and the propellant. The stability of the control system must be established and, if the forces are too large, a means of damping the liquid motion may be needed.

These issues, regarding propellant motion in maneuvering and restartable spacecraft, illustrate the need for analytical methods of predicting the motion of propellants and the forces produced. One such model, FLOW-3D (a commercial product of Flow Science, Inc., Los Alamos, New Mexico), uses finite-difference methods to solve the Navier-Stokes equations within a three-dimensional mesh. To gain confidence in the ability of FLOW-3D to predict liquid motion and fluid forces, its results were correlated with existing test data. Two test programs, performed in Martin Marietta's Drop Tower Test Facility, were used in the correlation.[1,2] Predictions closely matching the test data were obtained.

EXPERIMENTAL DATA

Under a NASA study[1] an experimental method of producing liquid motion in a subscale tank was developed so that the motion could be observed and the force of the liquid on the tank could be measured. Martin Marietta's Drop Tower Test Facility was used to produce a controlled acceleration environment with axial and lateral components. Clear plastic tank models were installed in a fixture that was suspended by two axial and one lateral load cells, as shown in Fig. 1. The tank could be mounted at various orientations relative to the fixture so as to change the initial liquid position. The fixture and a movie camera were mounted on a slider permitting application of a lateral acceleration component (typically 5 to 20 cm/s^2). The entire drop capsule, carrying the

Fig.1. Drop Capsule and Instrumentation

slider and test fixture, accelerated axially (ranging from 39 to 95 cm/s^2) within a drag shield during free fall. The tank size and the accelerations were scaled so that the most significant liquid motion and forces occurred during the two second test period while the drop capsule fell.

The movie camera recorded the liquid motion on 16 mm film at 200 frames per second, and the piezoelectric load cells were capable of measuring the small forces produced by the liquid motion. The force data was processed to yield two force components in the plane of the accelerations and a moment normal to the plane.

This same test apparatus was used to test many different tank configurations. The data from two tank configurations are used here. One is a 12.7 cm diameter cylindrical tank with hemispherical domes (Fig. 2). The tests covered a range of initial positions, fill levels, and accelerations, simulating on-orbit maneuvers.[1]

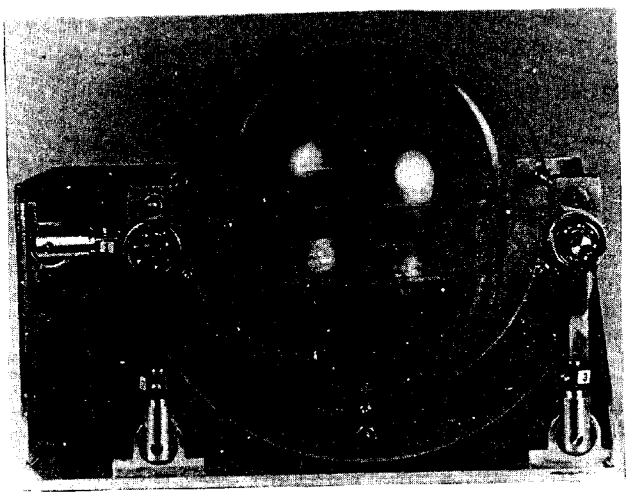


Fig. 2. Cylindrical Tank with Hemispherical Caps

The second data set[2] was based on a one-sixtieth scale model of the oxygen tank of the Space Shuttle external tank (Fig. 3). The forces on the external tank caused by the motion of the residual propellant during separation from the orbiter were simulated. A range of fill levels, initial liquid orientations, and accelerations were again considered.

COMPUTATIONAL METHOD

The FLOW-3D program is a general purpose computer program that uses finite-volume approximations to simulate a wide range of fluid dynamic situations.[3] Although the program includes many physical phenomena, its ability to model transient, incompressible, free-surface flows in complex geometry has led to frequent application to propellant slosh phenomena.[4-8] Critical to the success of these applications is the program's ability to calculate in accelerating reference frames.

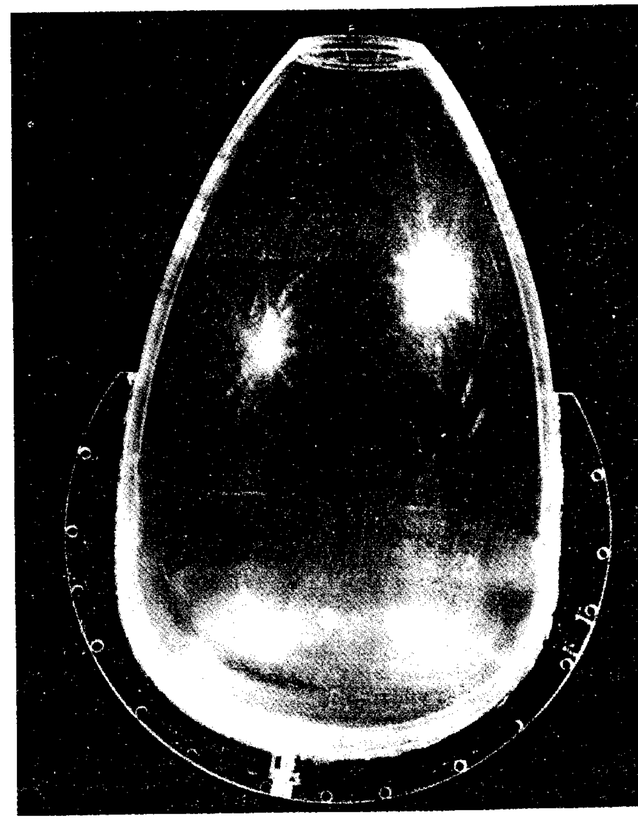


Fig. 3. Shuttle External Tank Model

The basic solution algorithm used by FLOW-3D is the SOLA method developed at the Los Alamos National Laboratory in the early 1970s.[9] Its use of the Volume of Fluid Method (VOF) makes FLOW-3D a three-dimensional extension of the SOLA-VOF program.[10] SOLA solves the transient Navier-Stokes equations by applying forward difference approximations in time with a stabilizing implicit formulation of the pressure gradient terms of the momentum equation coupled to the incompressibility condition.

In FLOW-3D, SOLA has been extended to complex geometries by using the Fractional Area/Volume Obstacle Representation (FAVOR). Based on a three-dimensional rectangular computational mesh, FAVOR utilizes fractional cell volumes and face areas to approximate curved solid boundaries.[11] These area and volume fractions are incorporated into the momentum, continuity, and VOF finite-difference approximations.

To evaluate flows in moving containers, FLOW-3D embeds its computational mesh in a non-inertial reference frame. The non-inertial effects (which may include rotational as well as translational terms) lead to fictitious body forces in the momentum equations. When viewing the computational results, one must recall that all fluid motions are relative to the accelerating tank.

Since the fluid pressure is an integral result of the SOLA method, it is a simple

matter to calculate the force and force moments exerted by the fluid on propellant tanks. (Viscous shear forces are normally small in these applications and are not included in the evaluation of forces.)

The VOF method also leads to simple visualization of the fluid surface, which is again automated within FLOW-3D. These visualizations are simply contour plots of the fluid fraction calculated by the VOF method.

SHUTTLE EXTERNAL TANK CALCULATIONS

Several of the 1/60th scale model tests described in Ref. 2 have been simulated using FLOW-3D. The geometric model used for all simulations was the same. The fluid fill level and applied accelerations were varied to match test conditions. The length of the scale model was about 25 cm.

Since the tank and accelerations for these tests were symmetric about the plane containing the y and z axes, only half of the tank was modeled in our simulations.

Some fluid motion through the symmetry plane was observed in the experiments, most likely a result of slight disturbances from release of the drop capsule. These do not seem to have strongly influenced the observed fluid motion or measured forces and moments. These motions were not included in the simulations.

To simplify specification of the tank geometry, the computational z axis was chosen as the symmetry axis of the tank. Therefore, the FLOW-3D z and y axes coincide with the experimental Z_T and Y_T axes.[2]

The computational grid employed uniform cells in the x and y directions and only slight size variations in the z direction. The total of 2625 cells (in the 3D mesh) seems to adequately resolve the fluid motion except for thin films of fluid adjacent to tank walls.

As described in Ref. 2, the shuttle external tank consists of an ellipsoidal base, a cylindrical section, and a truncated ogival top. All of these sections are included in the FLOW-3D model of the tank.

PHYSICS MODELING

As discussed above, FLOW-3D uses the VOF method to track the motion of free surfaces. Since the Bond number for the simulated tests is about 450, the FLOW-3D surface tension model was not used for these simulations. Similarly, the viscous and wall shear models were not employed as the Reynolds number of 10^5 indicates that viscous effects will be limited to thin boundary layers. Experimental investigation of the influence of surface tension and viscosity confirms the appropriateness of these approximations.[2]

Most of the modeled experiments used constant accelerations (following the release of the capsule), therefore, an equivalent gravitational field was employed instead of the general accelerating reference frame.

EXTERNAL TANK DATA COMPARISON

Four experiments from Ref. 2 were simulated. Tests 21, 5, and 22 all used: the fluorcarbon FC-114B2 as the working fluid, an initial surface inclined 13^o to the tank axis,[2] and accelerations close to 95 cm/s^2 along the z axis. These tests had fill fractions of 5, 10, and 15 percent, respectively. Test 16 employed a varying acceleration history and a 10 percent fill fraction. (Because of the variations in accelerations, the non-inertial reference frame was required for Test 16.)

Qualitatively, the fluid motions observed in the first three experiments were quite similar. The behavior observed in the simulations was also quite similar to the observed experimental motions. Figure 4 compares experimental photographs with computed fluid motions at five times for the 15% case (Test 22). The computed results are near the midplane of the tank. At t=1.2 and 1.6 seconds the simulated flow seems to lead the experimental results by a small amount, although the photographs are somewhat difficult to interpret. Free surface comparisons for Tests 5 and 22 are similar.

Correlation of experimental and computational force components are presented in Figs. 5-10. As described above, three load cell measurements were combined to produce experimental evaluations of the force along and normal to the tank symmetry axis and to evaluate the force moment normal to the plane of symmetry. The reported forces have been shifted to compensate for the mass of the tank and its support structure. The horizontal load cell measurements are less reliable than the vertical because of the lower force magnitudes experience in that direction.

One might suggest shifting the measured forces to agree with the easily predicted force at the initiation of the accelerations. However, these initial forces should be approximately constant while the measured values show strong fluctuations. Therefore, we have adjusted each force component (by an amount constant in time) to yield the best agreement with the simulated results. The initial measured fluctuations are probably due to transient accelerations caused by the release of the capsule, which cannot be simulated since the accelerations are unknown. Thus the comparisons must be thought of as correlation of the variation in force rather than as correlation of the absolute magnitude of force.

We are not presenting correlations of simulated and measured force moments because these moments are particularly sensitive to the less reliable horizontal load cell measurement.

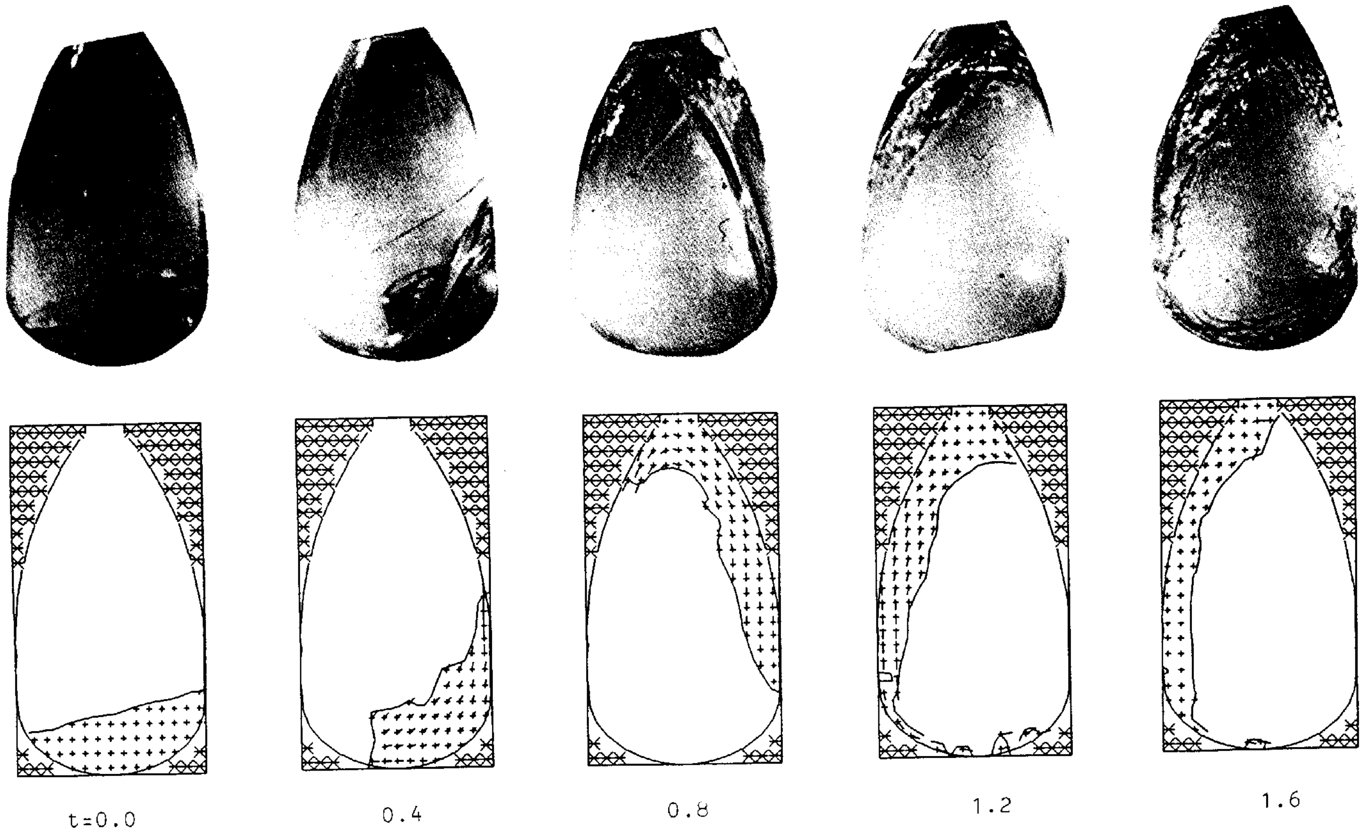


Fig. 4. Observed and Simulated Fluid Motions For Test 22

Test 22

The correlation of measured and simulated forces for the 15% fill case (Test 22) is presented in Figs. 5 and 6. The agreement of the axial force component, Fig. 5, is very good. The peak-to-peak difference in the simulated result is approximately 20% larger than the measured value. The experimental values have been read from rather coarse plots, which leads to errors of the order of 10^4 dynes, which could explain the discrepancy between the data and calculations. The accuracy of the computed result is limited by the mesh resolution and the omission of the release transient from the simulation.

The correlation of the transverse force components for this test shows greater discrepancy. (The sign of the transverse component is opposite Ref. 2 because of a difference in conventions between the experiment and these simulations.) Although there is less confidence in this force component (since it is closely related to the horizontal load cell measurement), there is less uncertainty associated with reading the data report (about 4×10^3 dynes). The peak-to-peak difference is about 40%. The large discrepancy may be due to numerical force "spikes" that coincide with the physical force minimum and maximum for this calculation. The question is still under investigation.

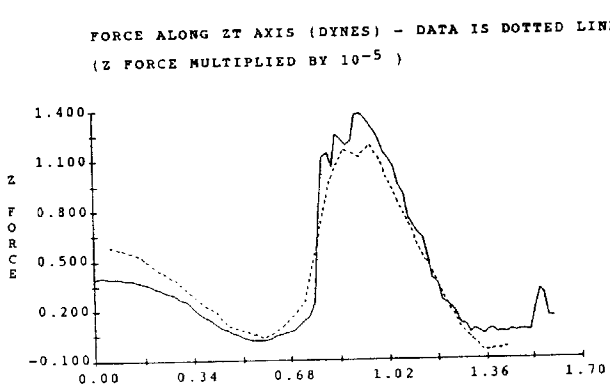


Fig. 5. Axial Force Comparison (Test 22)

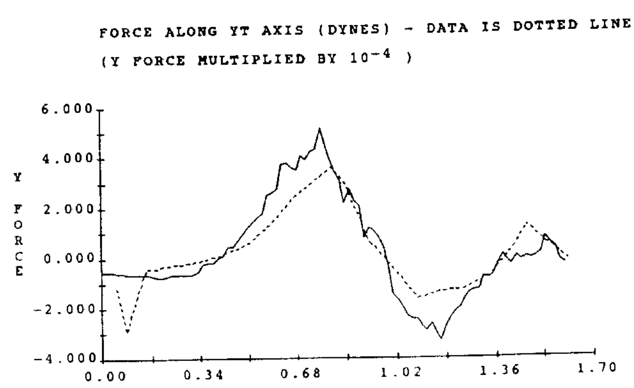


Fig. 6. Transverse Force Comparison (Test 22)

Test 5

Correlations of measured and simulated force components for the 10% fill case (Test 5) are presented in Figs. 7 and 8. While the axial component shows somewhat greater discrepancy, the transverse component agrees well. Again, there seem to be numerical force spikes that contribute to the discrepancy.

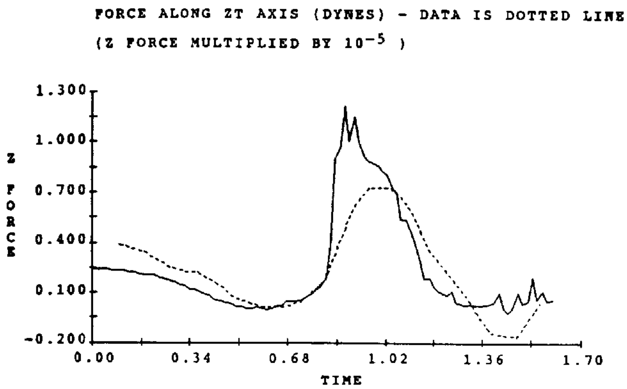


Fig. 7. Axial Force Comparison (Test 5)

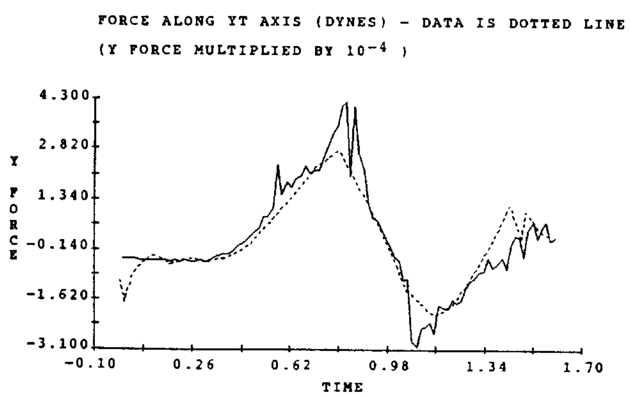


Fig. 8. Transverse Force Comparison (Test 5)

Test 21

Calculations of measured and simulated force components for the 5% fill case (Test 21) are presented in Figs. 9 and 10. As with Test 5, the transverse component agrees well, and there are significant discrepancies with the axial force correlation.

Test 16

We also simulated one test that was performed with a somewhat different acceleration than the others. Test 16 had a fill fraction of 10% (like Test 5), an axial tilt of 13°, and horizontal and vertical accelerations of 52 and 89.3 cm/s^2, respectively. The horizontal component of acceleration was delayed until 0.5 seconds. Therefore, the tests included a situation (from 0 to 0.5 seconds) when the acceleration was directed normal to the free surface. The resulting fluid motion is therefore quite different from that encountered in the other tests. Figure 11 compares the experimental and simulated fluid motions. The details are clearly different as one might expect by observing that this is a physically unstable system during the 0 to 0.5 s time interval. FLOW-3D, however, did predict the breakup of the fluid surface and does predict grossly the fluid motion.

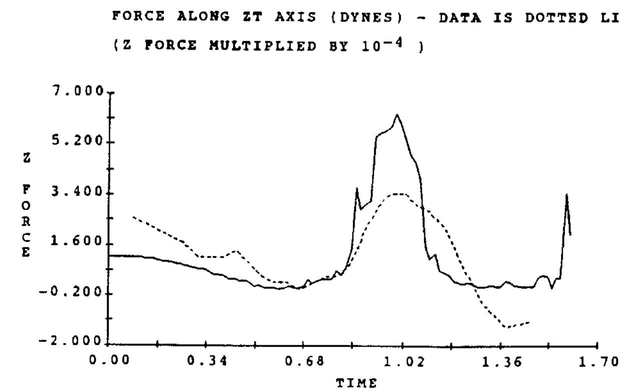


Fig. 9. Axial Force Comparison (Test 21)

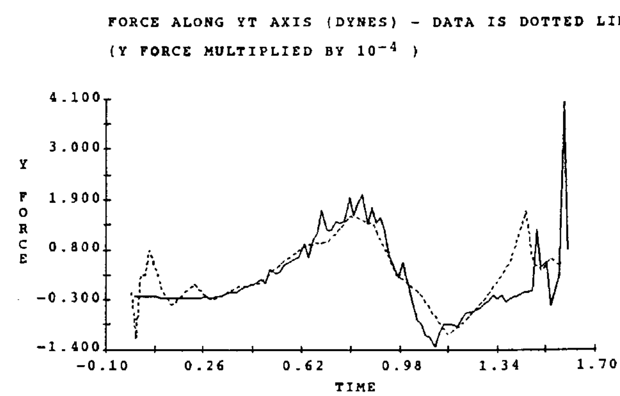


Fig. 10. Transverse Force Comparison (Test 21)

The experiment showed a broad low amplitude peak force in the z direction, while FLOW-3D predicted a sharp force spike near t=1 second. We suspect that the fluid surface broke into small droplets in the experiment resulting in a gentle rain on the tank top. This cannot be predicted by the simulation as the droplet sizes would be much smaller than the computational cells. Surface tension effects may also become very important for this type of flow. Surprisingly, the transverse force component was predicted reasonably well.

Cylindrical Tank Calculations

Three cases were selected for correlation from the Drop Tower Test data.[1] All tests were performed with a tank having a 12.7 cm diameter barrel section, hemispherical domes, and a 16.3 cm overall length.

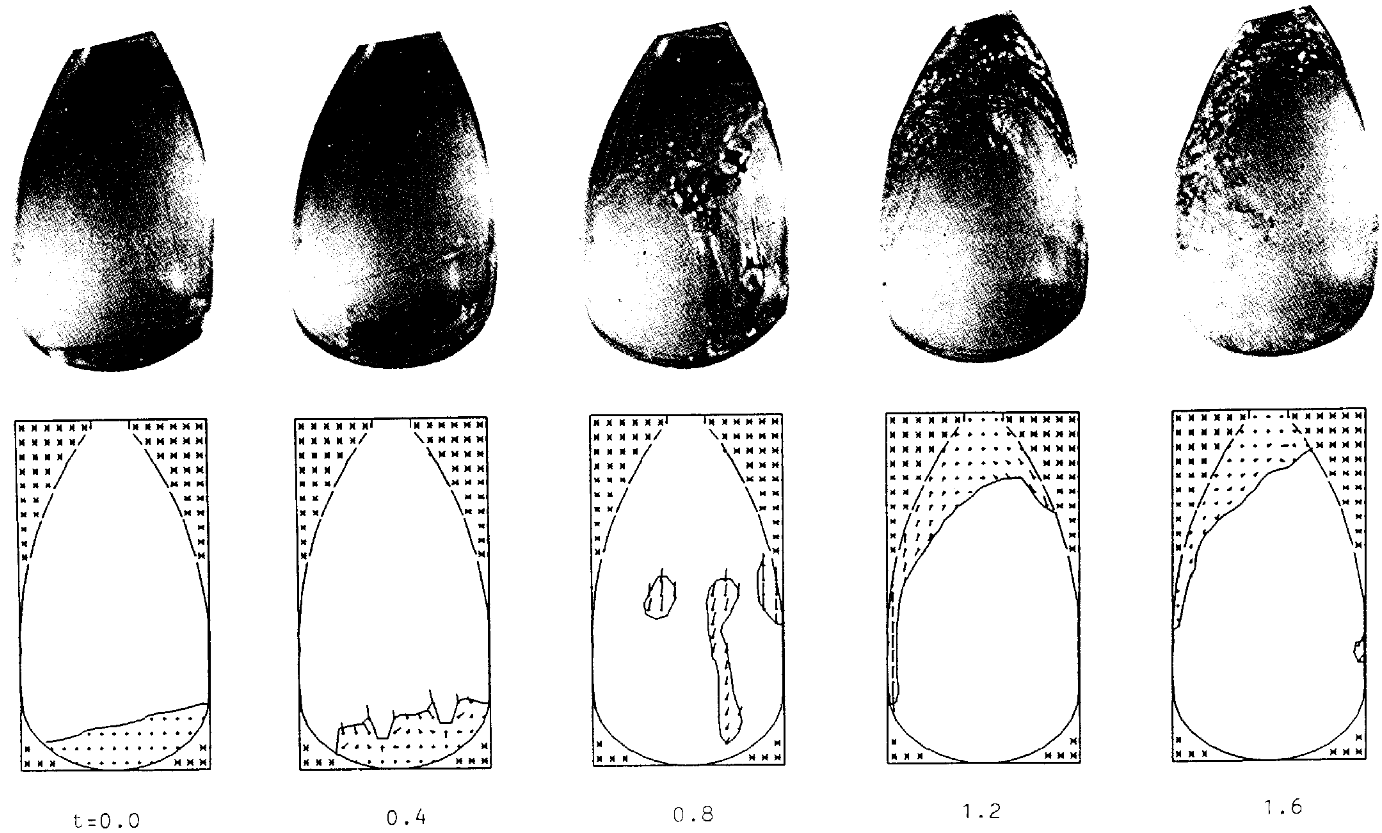


Fig. 11. Observed and Simulated Fluid Motions for Test 16

Neither viscous nor surface tension forces were considered due to their relative insignificance. The tank was symmetric about the x-z plane and the accelerations lie in this plane, so only half the tank had to be represented with the computational mesh. The tank diameter (x axis) was divided into 16 cells, the tank length (z axis) into 18 cells, and half the tank depth was represented by 8 cells along the y axis, resulting in 2304 mesh cells.

Test 13 had a 25% fill volume with the liquid initially oriented at the tank bottom. Throughout the test an axial acceleration (z) of 87.4 cm/s^2 and a lateral acceleration (x) of 17.5 cm/s^2 were continuously applied, having a net effect of orienting the liquid to the top left of the tank. The calculated liquid motion is compared with sketches prepared from the frames of the motion picture data in Fig. 12. The liquid, reoriented along the left side of the tank, flowed through the

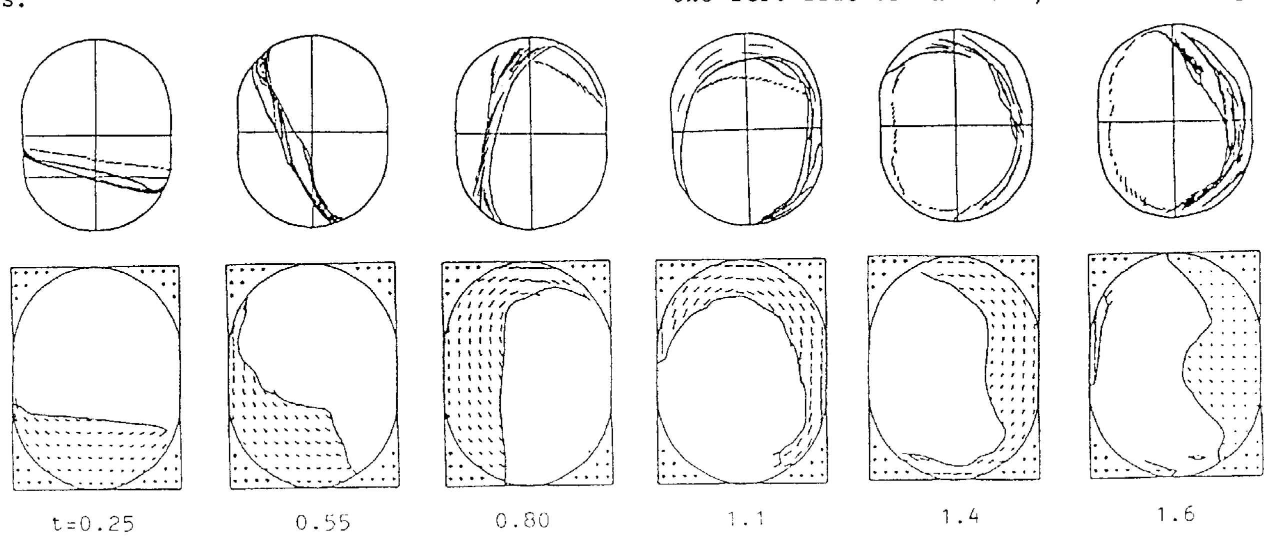
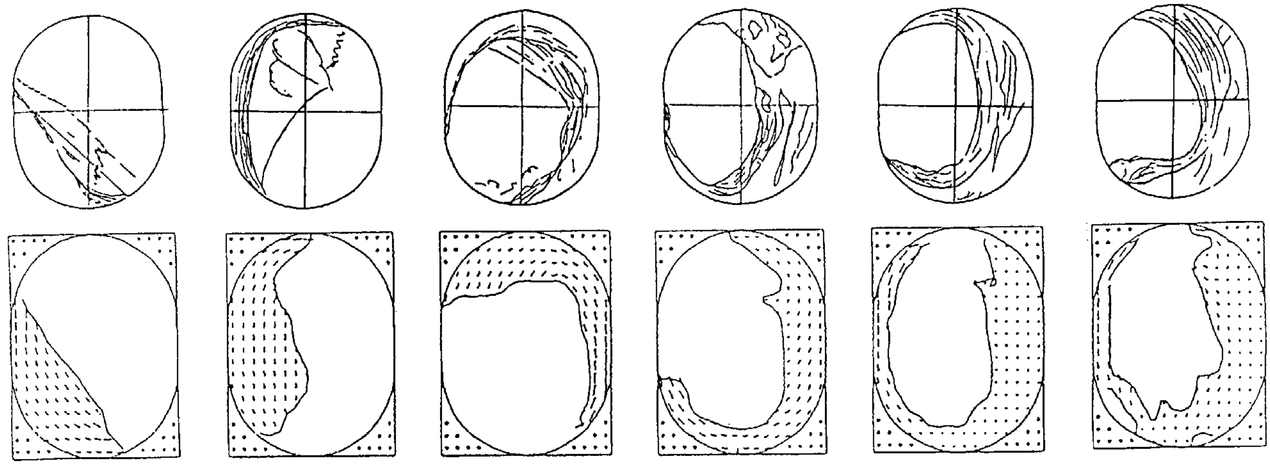


Fig. 12. Correlation of Test 13



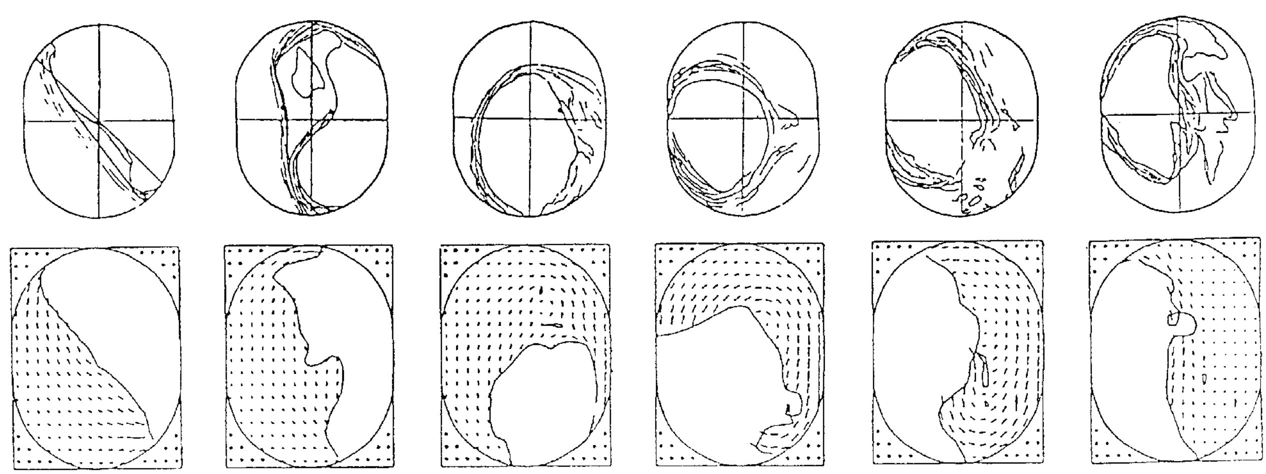
t=0.3 0.6 0.9 1.2 1.4 1.6

Fig. 13. Correlation of Test 16

upper dome and down the right side. At the end of the test the liquid had come to a stop on the right side of the tank and was reversing to flow back to what would be its final equilibrium position. The sketches represent the view of all the liquid in the tank, while the computed result is a slice through the tank center. The calculated motion matches the experiment very well, lacking only in the minor details of the surface. No correlation with the force measurements were made for these tests.

Tests 16 and 17 were similar, having 25% and 50% fill volumes, respectively. For both tests the liquid was initially oriented at a 45 degree angle, and axial and lateral accelerations were again applied throughout the test. Figures 13 and 14 show the comparison between the sketches from the film data and the calculated liquid motion. In both cases the initial motion of the liquid was well represented by the analysis.

At 1.4 sec in Test 16, the liquid leading edge continued around the bottom of the tank in the analysis, while the sketches show it did not. The opposite happened at 1.5 sec in Test 17. The sketches show the leading edge continuing through the tank bottom, while it stopped in the calculation. In exploring this phenomena, it was found that the calculated solution was sensitive to the magnitude of the input acceleration and to the input parameters that influence the accuracy of the computations. For example, with a slightly larger lateral acceleration the leading edge continued through the lower dome in the computed motion for Test 17. The solutions presented here correspond to the best estimates of the accelerations, but the error could be as much as 10%.



t=0.3 0.6 0.9 1.2 1.5 1.75

Fig. 14. Correlation of Test 17

In computing the liquid motion, the numerical method causes what appears as energy dissipation. Changes to the behavior of the computed leading edge motion were noted when a finer mesh was used or the maximum compute interval was limited, since these reduce numerical energy dissipation.

Since the behavior of the leading edge at 1.4 to 1.5 sec in Tests 16 and 17 was opposite the data in both cases, it was concluded that specifying the actual acceleration was a more critical factor than the solution accuracy, and further attempts to refine the match with the data were not warranted.

COMPUTER USAGE STATISTICS

The simulations performed as part of this research consumed considerable computational resources. No attempt was made to optimize the calculational cost by selection of input parameters. Only minor sensitivity studies of the results have been performed to date. All calculations were performed on a MicroVAX II computer with 5 megabytes of RAM. (This computer has approximately the same CPU performance as a VAX 11/780.) Table I reports several interesting statistics on the resources used for each calculation.

TABLE I

Computer Usage Statistics for Propellant Slosh Simulations

	Tank Fill Fraction	Average Time-Step Size	Total CPU Time
Shuttle External Tank Model (2625 Cells)			
Test 5	10%	1.5 ms	6.4 hours
Test 16	15%	1.4 ms	6.9 hours
Test 21	5%	1.5 ms	5.8 hours
Test 22	10%	1.2 ms	8.6 hours
Cylinder with Hemispherical Caps (2304 Cells)			
Test 13	25%	1 ms	8.5 hours
Test 16	25%	1 ms	10.1 hours
Test 17	50%	1 ms	13.1 hours

CONCLUSIONS

FLOW-3D simulations of a variety of drop tower experiments show a reliable ability to predict gross fluid motion in conditions of large fluid displacement. Predictions of the force exerted by the fluid on its container are much improved over earlier computations. The predicted forces agree in timing and trend with the measured data. Uncertainty in the magnitude of both force measurements and predictions is sufficient to explain the observed differences between them. Additional experimentation may be required to further refine the current modeling methods.

REFERENCES

1. R.L. Berry and J.R. Tegart, "Experimental Study of Transient Liquid Motion in Orbiting Spacecraft," MCR-76-11, Martin Marietta Corp., Denver, CO, February 1976.

2. R.L. Berry, L.J. Demchak, and J.R. Tegart, "Analysis and Test for Space Shuttle Propellant Dynamics," NASA CR 3683, Martin Marietta Corp., Denver, CO, June 1983.

3. J.M. Sicilian, C.W. Hirt, and R.P. Harper, "FLOW-3D: Computational Modeling Power for Scientists and Engineers," Flow Science, Inc. report (FSI-87-00-1), 1987.

4. T.W. Eastes, Y.M. Chang, C.W. Hirt, and J.M. Sicilian, "Zero-Gravity Slosh Analysis," ASME Winter Annual Meeting, Miami, FL, November 1985.

5. R.E. Martin, "Effects of Transient Propellant Dynamics on Deployment of Large Liquid Stages in Zero-Gravity with Application to Shuttle/Centaur," 37th Annual Astronautical Congress, Innsbruck, Austria, Oct. 3-10, 1986 (IAF-86-119), Acta Astronautica, Vol. 15, No. 6/7, pp. 331-340, 1987.

6. J. Navickas, C.R. Cross, and D.D. Van Winkle, "Propellant Tank Forces Resulting from Fluid Motion in a Low-Gravity Field," ASME Symposium in Microgravity Fluid Mechanics, Winter Annual Meeting, Anaheim, CA, December 7-12, 1986.

7. J.J. Der and C.L. Stevens, "Liquid Propellant Tank Ullage Bubble Deformation and Breakup in Low Gravity Reorientation," AIAA/SAE/ASME/ASEE 23rd Joint Propulsion Conference, San Diego, CA, June 1987 (AAIA-87-2021).

8. C.W. Hirt and R.P. Harper, "Fluid Slosh in a Spinning and Oscillating Dish," Flow Science, Inc. Technical Note #9 (FSI-88-TN9), March 1988.

9. C.W. Hirt, B.D. Nichols, and N.C. Romero, "SOLA-A Numerical Solution Algorithm for Transient Fluid Flows," LASL report, LA-5852, April 1975.

10. C.W. Hirt and B.D. Nichols, "Volume of Fluid (VOF) Method for the Dynamics of Free Boundaries," J. Comp. Physics, 39, 201, January 1981.

11. C.W. Hirt and J.M. Sicilian, "A Porosity Technique for the Definition of Obstacles in Rectangular Cell Meshes," Fourth International Conference on Ship Hydrodynamics, Washington, DC, September 1985.

Reprinted From
PVP — Vol. 176, Computational Experiments
Editors: W. K. Liu, P. Smolinski, R. Ohayon,
J. Navickas, and J. Gvildys
Book No. H00491 — 1989

The American Society of
Mechanical Engineers

COMPARISON OF FLOW-3D CALCULATIONS WITH VERY LARGE AMPLITUDE SLOSH DATA

J. M. Sicilian, Senior Scientist
Flow Science, Inc.
Los Alamos, New Mexico

J. R. Tegart, Senior Staff Engineer
Martin Marietta Astronautics
Denver, Colorado

INTRODUCTION

Knowledge of the motion of propellants in the tankage of spacecraft is essential to understanding various aspects of their operation and performance. Propellant motion impacts such propulsion functions as expulsion of liquid (including the operation of propellant management systems), venting of gases, and pressurization. For example, in some applications propellant must be settled over the tank outlet before engine start. To design these systems, efficient methods for reorienting the propellants are needed as is knowledge of the time required to settle. In order to vent a tank, it must be known when only gas will be available at the vent inlet. Pressurant usage can be dependent upon the splashing and mixing of the propellant. These are only a few examples of the many possible interactions between the propellant motion and the propulsion system functions.

In some cases the forces produced by the propellant motion must also be known. This is particularly true when the liquid mass is a significant portion of the total spacecraft mass. One example is the orbital maneuvering of a spacecraft. The liquid motion caused by a maneuver can produce forces that in turn alter the spacecraft motion, resulting in interactions between the control system and the propellant. The stability of the control system must be established and, if the forces are too large, a means of damping the liquid motion may be needed.

These issues, regarding propellant motion in maneuvering and restartable spacecraft, illustrate the need for analytical methods of predicting the motion of propellants and the forces produced. One such model, FLOW-3D (a commercial product of Flow Science, Inc., Los Alamos, New Mexico), uses finite-difference methods to solve the Navier-Stokes equations within a three-dimensional mesh. To gain confidence in the ability of FLOW-3D to predict liquid motion and fluid forces, its results were correlated with existing test data. Two test programs, performed in Martin Marietta's Drop Tower Test Facility, were used in the correlation.[1,2] Predictions closely matching the test data were obtained.

EXPERIMENTAL DATA

Under a NASA study[1] an experimental method of producing liquid motion in a subscale tank was developed so that the motion could be observed and the force of the liquid on the tank could be measured. Martin Marietta's Drop Tower Test Facility was used to produce a controlled acceleration environment with axial and lateral components. Clear plastic tank models were installed in a fixture that was suspended by two axial and one lateral load cells, as shown in Fig. 1. The tank could be mounted at various orientations relative to the fixture so as to change the initial liquid position. The fixture and a movie camera were mounted on a slider permitting application of a lateral acceleration component (typically 5 to 20 cm/s^2). The entire drop capsule, carrying the

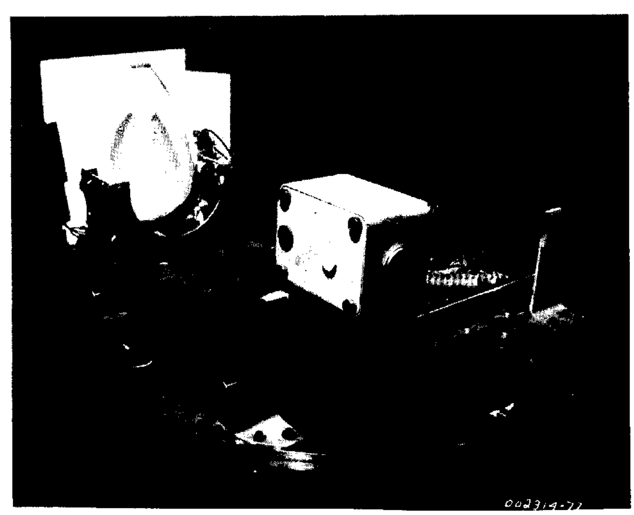


Fig.1. Drop Capsule and Instrumentation

slider and test fixture, accelerated axially (ranging from 39 to 95 cm/s^2) within a drag shield during free fall. The tank size and the accelerations were scaled so that the most significant liquid motion and forces occurred during the two second test period while the drop capsule fell.

The movie camera recorded the liquid motion on 16 mm film at 200 frames per second, and the piezoelectric load cells were capable of measuring the small forces produced by the liquid motion. The force data was processed to yield two force components in the plane of the accelerations and a moment normal to the plane.

This same test apparatus was used to test many different tank configurations. The data from two tank configurations are used here. One is a 12.7 cm diameter cylindrical tank with hemispherical domes (Fig. 2). The tests covered a range of initial positions, fill levels, and accelerations, simulating on-orbit maneuvers.[1]

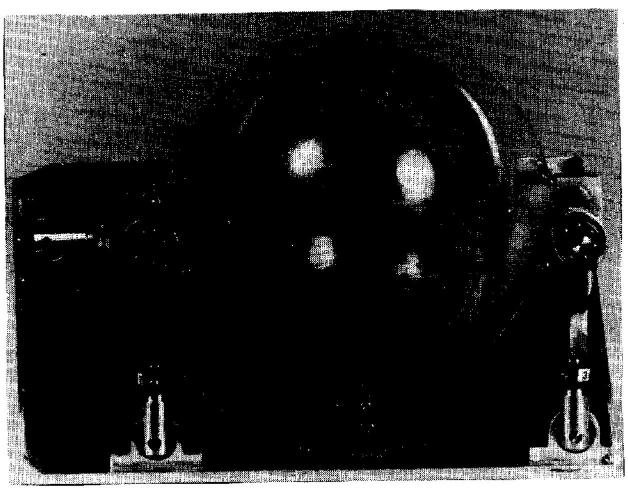


Fig. 2. Cylindrical Tank with Hemispherical Caps

The second data set[2] was based on a one-sixtieth scale model of the oxygen tank of the Space Shuttle external tank (Fig. 3). The forces on the external tank caused by the motion of the residual propellant during separation from the orbiter were simulated. A range of fill levels, initial liquid orientations, and accelerations were again considered.

COMPUTATIONAL METHOD

The FLOW-3D program is a general purpose computer program that uses finite-volume approximations to simulate a wide range of fluid dynamic situations.[3] Although the program includes many physical phenomena, its ability to model transient, incompressible, free-surface flows in complex geometry has led to frequent application to propellant slosh phenomena.[4-8] Critical to the success of these applications is the program's ability to calculate in accelerating reference frames.

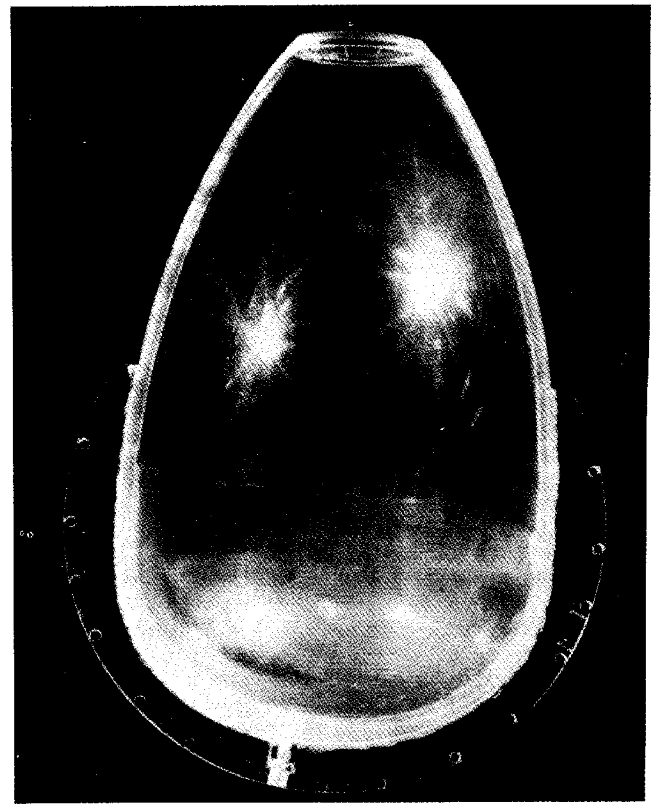


Fig. 3. Shuttle External Tank Model

The basic solution algorithm used by FLOW-3D is the SOLA method developed at the Los Alamos National Laboratory in the early 1970s.[9] Its use of the Volume of Fluid Method (VOF) makes FLOW-3D a three-dimensional extension of the SOLA-VOF program.[10] SOLA solves the transient Navier-Stokes equations by applying forward difference approximations in time with a stabilizing implicit formulation of the pressure gradient terms of the momentum equation coupled to the incompressibility condition.

In FLOW-3D, SOLA has been extended to complex geometries by using the Fractional Area/Volume Obstacle Representation (FAVOR). Based on a three-dimensional rectangular computational mesh, FAVOR utilizes fractional cell volumes and face areas to approximate curved solid boundaries.[11] These area and volume fractions are incorporated into the momentum, continuity, and VOF finite-difference approximations.

To evaluate flows in moving containers, FLOW-3D embeds its computational mesh in a non-inertial reference frame. The non-inertial effects (which may include rotational as well as translational terms) lead to fictitious body forces in the momentum equations. When viewing the computational results, one must recall that all fluid motions are relative to the accelerating tank.

Since the fluid pressure is an integral result of the SOLA method, it is a simple

matter to calculate the force and force moments exerted by the fluid on propellant tanks. (Viscous shear forces are normally small in these applications and are not included in the evaluation of forces.)

The VOF method also leads to simple visualization of the fluid surface, which is again automated within FLOW-3D. These visualizations are simply contour plots of the fluid fraction calculated by the VOF method.

SHUTTLE EXTERNAL TANK CALCULATIONS

Several of the 1/60th scale model tests described in Ref. 2 have been simulated using FLOW-3D. The geometric model used for all simulations was the same. The fluid fill level and applied accelerations were varied to match test conditions. The length of the scale model was about 25 cm.

Since the tank and accelerations for these tests were symmetric about the plane containing the y and z axes, only half of the tank was modeled in our simulations.

Some fluid motion through the symmetry plane was observed in the experiments, most likely a result of slight disturbances from release of the drop capsule. These do not seem to have strongly influenced the observed fluid motion or measured forces and moments. These motions were not included in the simulations.

To simplify specification of the tank geometry, the computational z axis was chosen as the symmetry axis of the tank. Therefore, the FLOW-3D z and y axes coincide with the experimental Z_T and Y_T axes.[2]

The computational grid employed uniform cells in the x and y directions and only slight size variations in the z direction. The total of 2625 cells (in the 3D mesh) seems to adequately resolve the fluid motion except for thin films of fluid adjacent to tank walls.

As described in Ref. 2, the shuttle external tank consists of an ellipsoidal base, a cylindrical section, and a truncated ogival top. All of these sections are included in the FLOW-3D model of the tank.

PHYSICS MODELING

As discussed above, FLOW-3D uses the VOF method to track the motion of free surfaces. Since the Bond number for the simulated tests is about 450, the FLOW-3D surface tension model was not used for these simulations. Similarly, the viscous and wall shear models were not employed as the Reynolds number of 10^5 indicates that viscous effects will be limited to thin boundary layers. Experimental investigation of the influence of surface tension and viscosity confirms the appropriateness of these approximations.[2]

Most of the modeled experiments used constant accelerations (following the release of the capsule), therefore, an equivalent gravitational field was employed instead of the general accelerating reference frame.

EXTERNAL TANK DATA COMPARISON

Four experiments from Ref. 2 were simulated. Tests 21, 5, and 22 all used: the fluorcarbon FC-114B2 as the working fluid, an initial surface inclined 13^o to the tank axis, and accelerations close to 95 cm/s^2 along the z axis. These tests had fill fractions of 5, 10, and 15 percent, respectively. Test 16 employed a varying acceleration history and a 10 percent fill fraction. (Because of the variations in accelerations, the non-inertial reference frame was required for Test 16.)

Qualitatively, the fluid motions observed in the first three experiments were quite similar. The behavior observed in the simulations was also quite similar to the observed experimental motions. Figure 4 compares experimental photographs with computed fluid motions at five times for the 15% case (Test 22). The computed results are near the midplane of the tank. At t=1.2 and 1.6 seconds the simulated flow seems to lead the experimental results by a small amount, although the photographs are somewhat difficult to interpret. Free surface comparisons for Tests 5 and 22 are similar.

Correlation of experimental and computational force components are presented in Figs. 5-10. As described above, three load cell measurements were combined to produce experimental evaluations of the force along and normal to the tank symmetry axis and to evaluate the force moment normal to the plane of symmetry. The reported forces have been shifted to compensate for the mass of the tank and its support structure. The horizontal load cell measurements are less reliable than the vertical because of the lower force magnitudes experience in that direction.

One might suggest shifting the measured forces to agree with the easily predicted force at the initiation of the accelerations. However, these initial forces should be approximately constant while the measured values show strong fluctuations. Therefore, we have adjusted each force component (by an amount constant in time) to yield the best agreement with the simulated results. The initial measured fluctuations are probably due to transient accelerations caused by the release of the capsule, which cannot be simulated since the accelerations are unknown. Thus the comparisons must be thought of as correlation of the variation in force rather than as correlation of the absolute magnitude of force.

We are not presenting correlations of simulated and measured force moments because these moments are particularly sensitive to the less reliable horizontal load cell measurement.

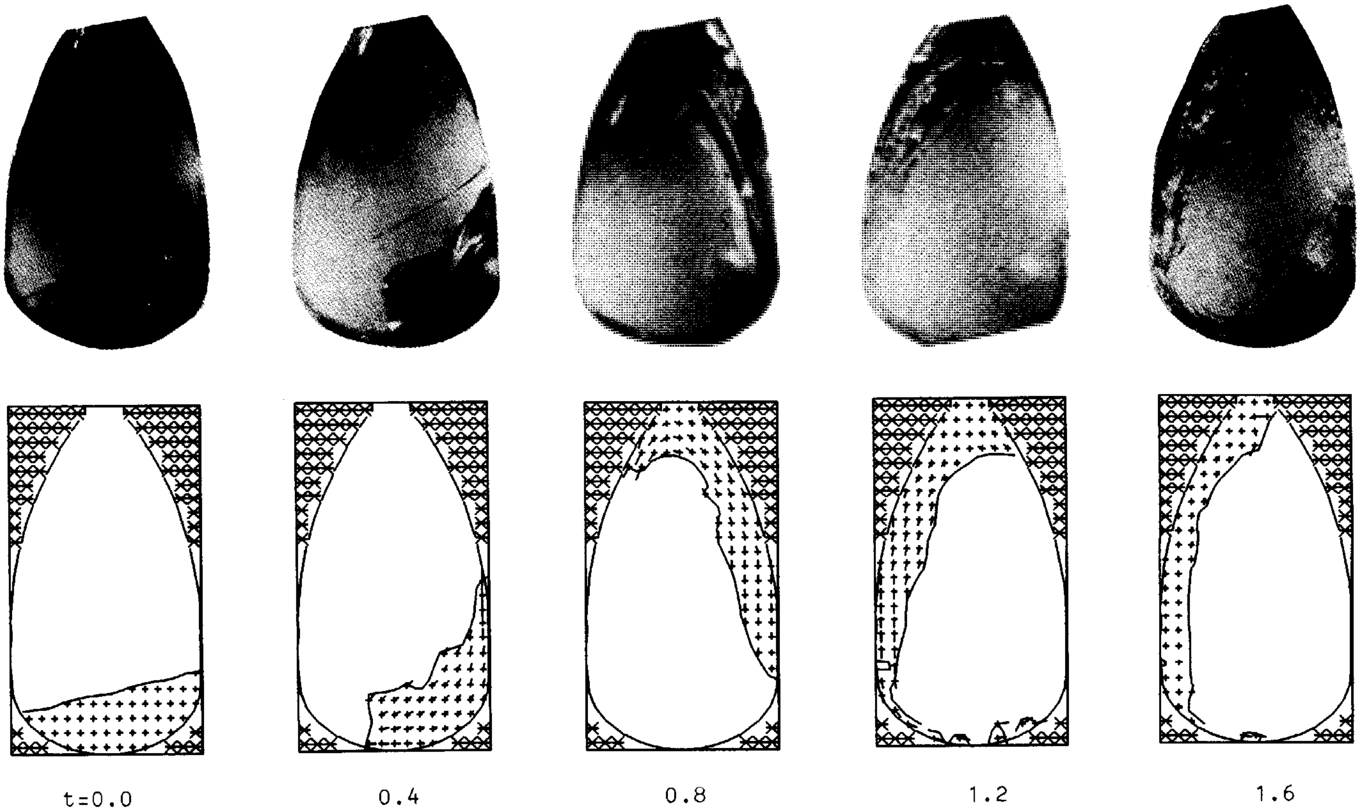


Fig. 4. Observed and Simulated Fluid Motions For Test 22

Test 22

The correlation of measured and simulated forces for the 15% fill case (Test 22) is presented in Figs. 5 and 6. The agreement of the axial force component, Fig. 5, is very good. The peak-to-peak difference in the simulated result is approximately 20% larger than the measured value. The experimental values have been read from rather coarse plots, which leads to errors of the order of 10^4 dynes, which could explain the discrepancy between the data and calculations. The accuracy of the computed result is limited by the mesh resolution and the omission of the release transient from the simulation.

The correlation of the transverse force components for this test shows greater discrepancy. (The sign of the transverse component is opposite Ref. 2 because of a difference in conventions between the experiment and these simulations.) Although there is less confidence in this force component (since it is closely related to the horizontal load cell measurement), there is less uncertainty associated with reading the data report (about 4×10^3 dynes). The peak-to-peak difference is about 40%. The large discrepancy may be due to numerical force "spikes" that coincide with the physical forc minimum and maximum for this calculation. Th question is still under investigation.

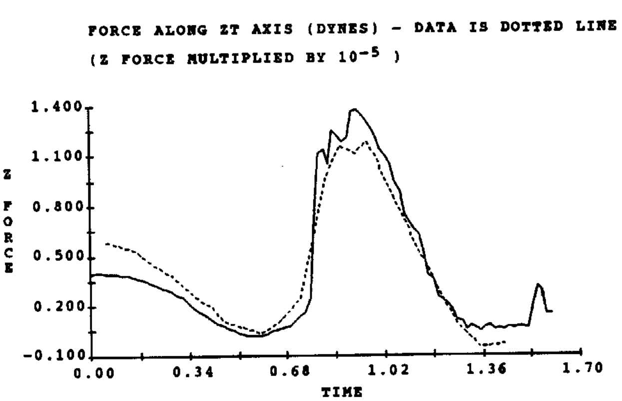


Fig. 5. Axial Force Comparison (Test 22)

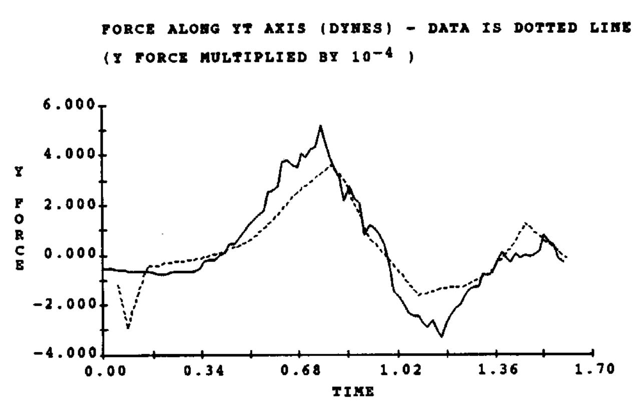


Fig. 6. Transverse Force Comparison (Test 22

Test 5

Correlations of measured and simulated force components for the 10% fill case (Test 5) are presented in Figs. 7 and 8. While the axial component shows somewhat greater discrepancy, the transverse component agrees well. Again, there seem to be numerical force spikes that contribute to the discrepancy.

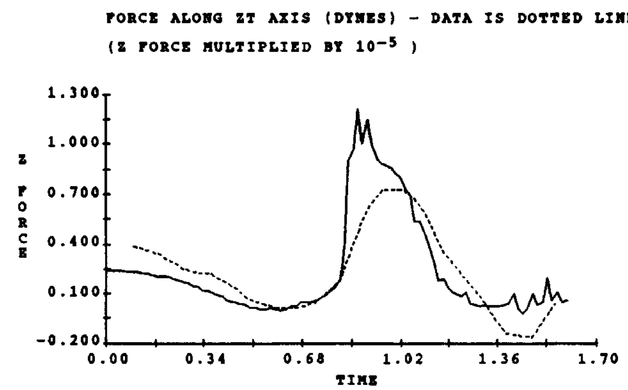


Fig. 7. Axial Force Comparison (Test 5)

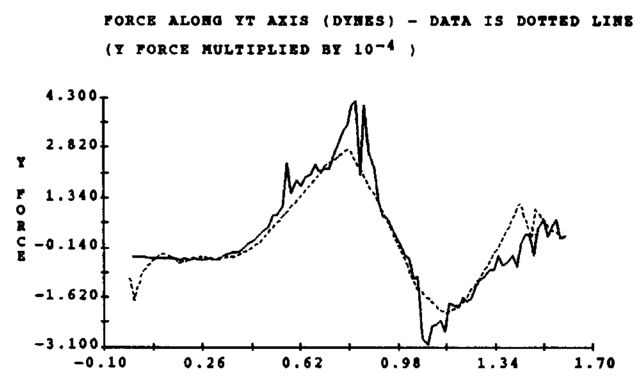


Fig. 8. Transverse Force Comparison (Test 5)

Test 21

Calculations of measured and simulated force components for the 5% fill case (Test 21) are presented in Figs. 9 and 10. As with Test 5, the transverse component agrees well, and there are significant discrepancies with the axial force correlation.

Test 16

We also simulated one test that was performed with a somewhat different acceleration than the others. Test 16 had a fill fraction of 10% (like Test 5), an axial tilt of 13°, and horizontal and vertical accelerations of 52 and 89.3 cm/s², respectively. The horizontal component of acceleration was delayed until 0.5 seconds. Therefore, the tests included a situation (from 0 to 0.5 seconds) when the acceleration was directed normal to the free surface. The resulting fluid motion is therefore quite different from that encountered in the other tests. Figure 11 compares the experimental and simulated fluid motions. The details are clearly different as one might expect by observing that this is a physically unstable system during the 0 to 0.5 s time interval. FLOW-3D, however, did predict the breakup of the fluid surface and does predict grossly the fluid motion.

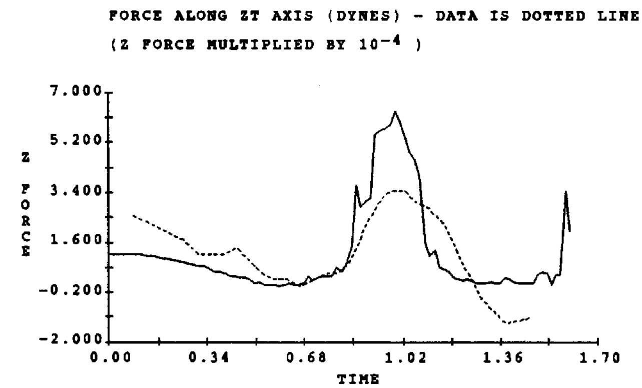


Fig. 9. Axial Force Comparison (Test 21)

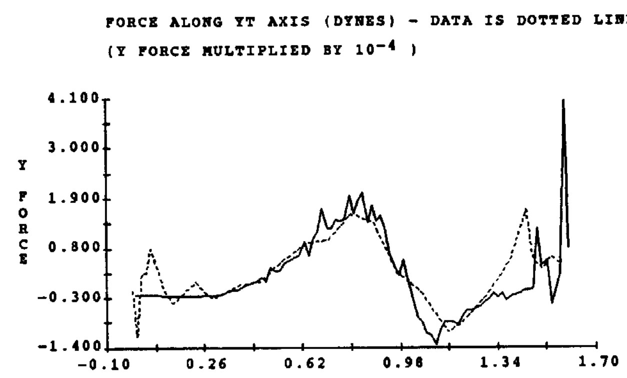


Fig. 10. Transverse Force Comparison (Test 21)

The experiment showed a broad low amplitude peak force in the z direction, while FLOW-3D predicted a sharp force spike near t=1 second. We suspect that the fluid surface broke into small droplets in the experiment resulting in a gentle rain on the tank top. This cannot be predicted by the simulation as the droplet sizes would be much smaller than the computational cells. Surface tension effects may also become very important for this type of flow. Surprisingly, the transverse force component was predicted reasonably well.

Cylindrical Tank Calculations

Three cases were selected for correlation from the Drop Tower Test data.[1] All tests were performed with a tank having a 12.7 cm diameter barrel section, hemispherical domes, and a 16.3 cm overall length.

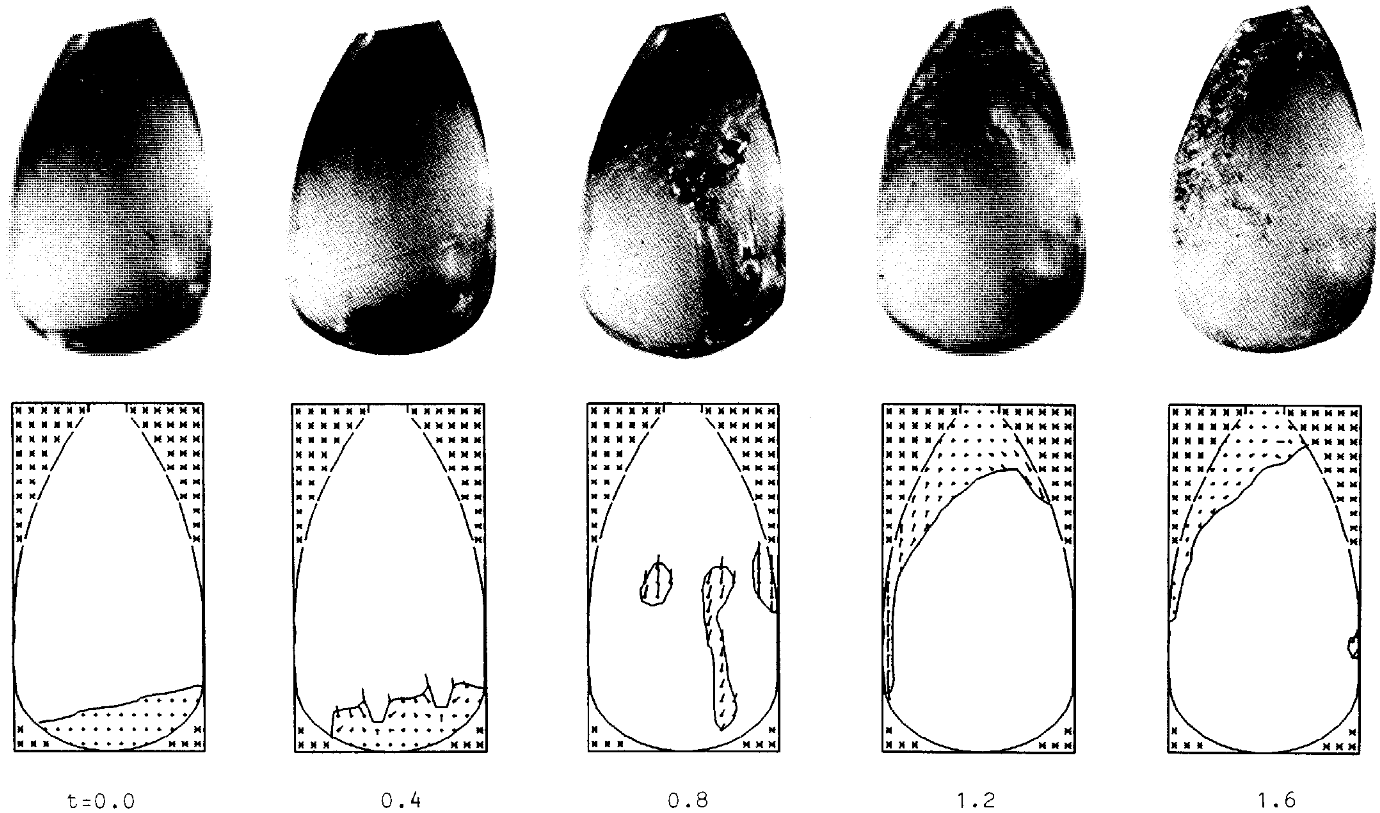


Fig. 11. Observed and Simulated Fluid Motions for Test 16

Neither viscous nor surface tension forces were considered due to their relative insignificance. The tank was symmetric about the x-z plane and the accelerations lie in this plane, so only half the tank had to be represented with the computational mesh. The tank diameter (x axis) was divided into 16 cells, the tank length (z axis) into 18 cells, and half the tank depth was represented by 8 cells along the y axis, resulting in 2304 mesh cells.

Test 13 had a 25% fill volume with the liquid initially oriented at the tank bottom. Throughout the test an axial acceleration (z) of 87.4 cm/s^2 and a lateral acceleration (x) of 17.5 cm/s^2 were continuously applied, having a net effect of orienting the liquid to the top left of the tank. The calculated liquid motion is compared with sketches prepared from the frames of the motion picture data in Fig. 12. The liquid, reoriented along the left side of the tank, flowed through the

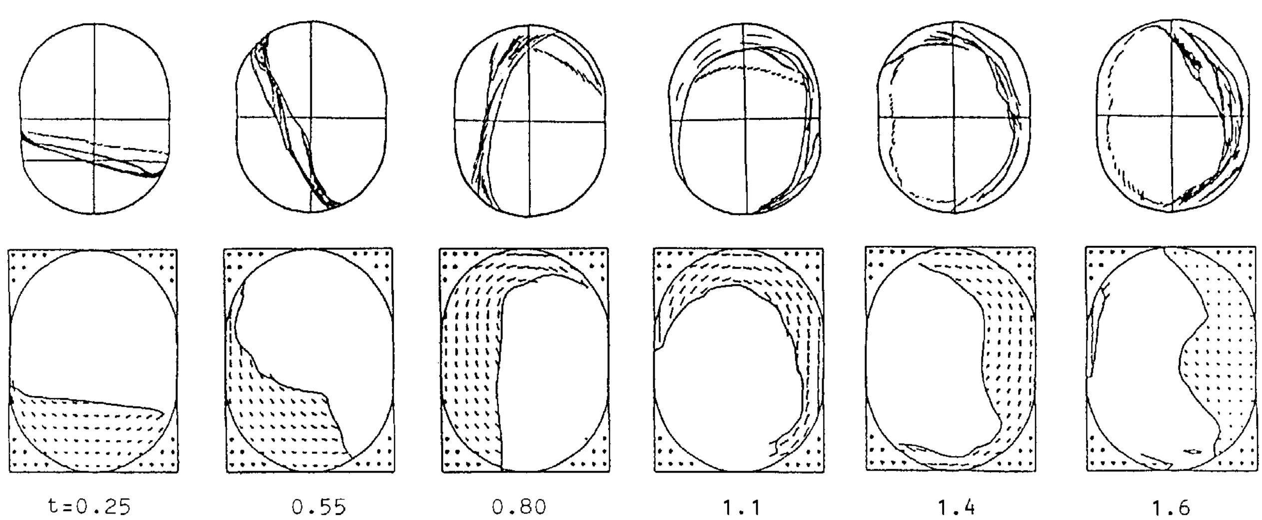


Fig. 12. Correlation of Test 13

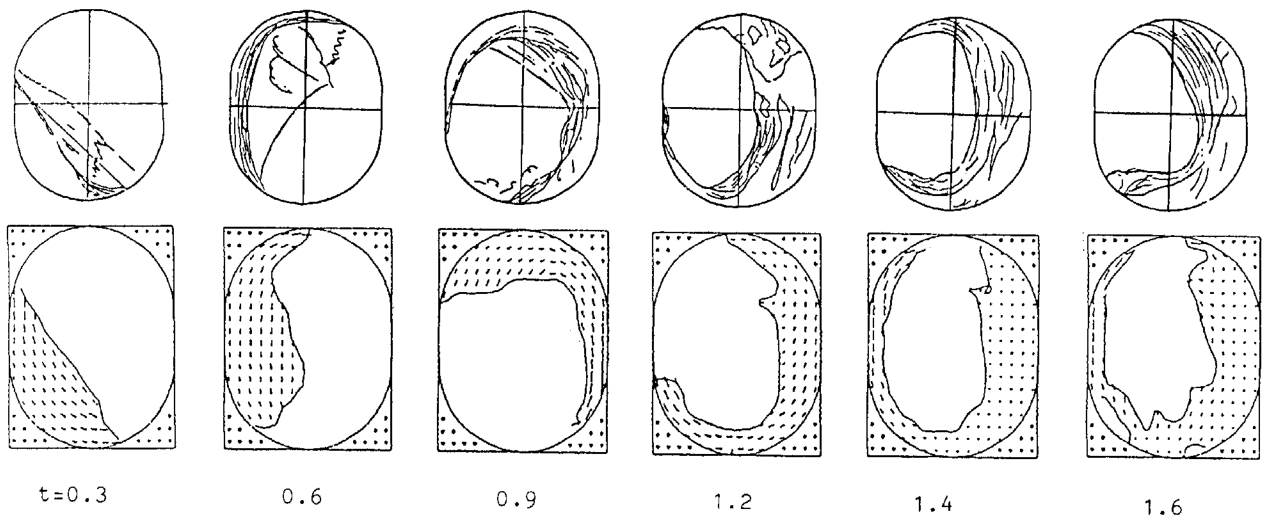


Fig. 13. Correlation of Test 16

upper dome and down the right side. At the end of the test the liquid had come to a stop on the right side of the tank and was reversing to flow back to what would be its final equilibrium position. The sketches represent the view of all the liquid in the tank, while the computed result is a slice through the tank center. The calculated motion matches the experiment very well, lacking only in the minor details of the surface. No correlation with the force measurements were made for these tests.

Tests 16 and 17 were similar, having 25% and 50% fill volumes, respectively. For both tests the liquid was initially oriented at a 45 degree angle, and axial and lateral accelerations were again applied throughout the test. Figures 13 and 14 show the comparison between the sketches from the film data and the calculated liquid motion. In both cases the initial motion of the liquid was well represented by the analysis.

At 1.4 sec in Test 16, the liquid leading edge continued around the bottom of the tank in the analysis, while the sketches show it did not. The opposite happened at 1.5 sec in Test 17. The sketches show the leading edge continuing through the tank bottom, while it stopped in the calculation. In exploring this phenomena, it was found that the calculated solution was sensitive to the magnitude of the input acceleration and to the input parameters that influence the accuracy of the computations. For example, with a slightly larger lateral acceleration the leading edge continued through the lower dome in the computed motion for Test 17. The solutions presented here correspond to the best estimates of the accelerations, but the error could be as much as 10%.

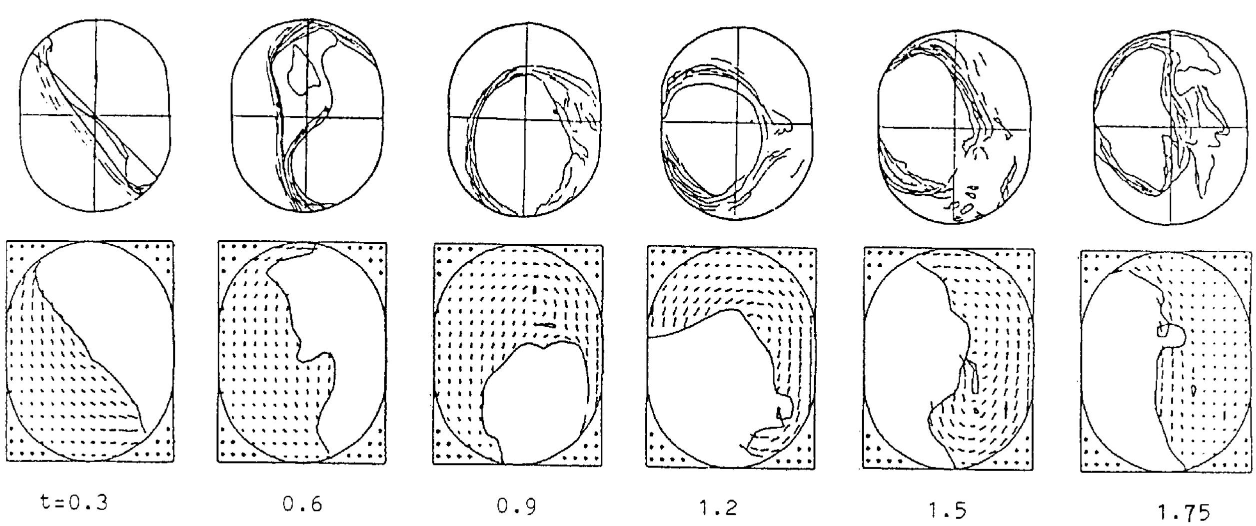


Fig. 14. Correlation of Test 17

In computing the liquid motion, the numerical method causes what appears as energy dissipation. Changes to the behavior of the computed leading edge motion were noted when a finer mesh was used or the maximum compute interval was limited, since these reduce numerical energy dissipation.

Since the behavior of the leading edge at 1.4 to 1.5 sec in Tests 16 and 17 was opposite the data in both cases, it was concluded that specifying the actual acceleration was a more critical factor than the solution accuracy, and further attempts to refine the match with the data were not warranted.

COMPUTER USAGE STATISTICS

The simulations performed as part of this research consumed considerable computational resources. No attempt was made to optimize the calculational cost by selection of input parameters. Only minor sensitivity studies of the results have been performed to date. All calculations were performed on a MicroVAX II computer with 5 megabytes of RAM. (This computer has approximately the same CPU performance as a VAX 11/780.) Table I reports several interesting statistics on the resources used for each calculation.

TABLE I

Computer Usage Statistics for Propellant Slosh Simulations

	Tank Fill Fraction	Average Time-Step Size	Total CPU Time
Shuttle External Tank Model (2625 Cells)			
Test 5	10%	1.5 ms	6.4 hours
Test 16	15%	1.4 ms	6.9 hours
Test 21	5%	1.5 ms	5.8 hours
Test 22	10%	1.2 ms	8.6 hours
Cylinder with Hemispherical Caps (2304 Cells)			
Test 13	25%	1 ms	8.5 hours
Test 16	25%	1 ms	10.1 hours
Test 17	50%	1 ms	13.1 hours

CONCLUSIONS

FLOW-3D simulations of a variety of drop tower experiments show a reliable ability to predict gross fluid motion in conditions of large fluid displacement. Predictions of the force exerted by the fluid on its container are much improved over earlier computations. The predicted forces agree in timing and trend with the measured data. Uncertainty in the magnitude of both force measurements and predictions is sufficient to explain the observed differences between them. Additional experimentation may be required to further refine the current modeling methods.

REFERENCES

1. R.L. Berry and J.R. Tegart, "Experimental Study of Transient Liquid Motion in Orbiting Spacecraft," MCR-76-11, Martin Marietta Corp., Denver, CO, February 1976.

2. R.L. Berry, L.J. Demchak, and J.R. Tegart, "Analysis and Test for Space Shuttle Propellant Dynamics," NASA CR 3683, Martin Marietta Corp., Denver, CO, June 1983.

3. J.M. Sicilian, C.W. Hirt, and R.P. Harper, "FLOW-3D: Computational Modeling Power for Scientists and Engineers," Flow Science, Inc. report (FSI-87-00-1), 1987.

4. T.W. Eastes, Y.M. Chang, C.W. Hirt, and J.M. Sicilian, "Zero-Gravity Slosh Analysis," ASME Winter Annual Meeting, Miami, FL, November 1985.

5. R.E. Martin, "Effects of Transient Propellant Dynamics on Deployment of Large Liquid Stages in Zero-Gravity with Application to Shuttle/Centaur," 37th Annual Astronautical Congress, Innsbruck, Austria, Oct. 3-10, 1986 (IAF-86-119), Acta Astronautica, Vol. 15, No. 6/7, pp. 331-340, 1987.

6. J. Navickas, C.R. Cross, and D.D. Van Winkle, "Propellant Tank Forces Resulting from Fluid Motion in a Low-Gravity Field," ASME Symposium in Microgravity Fluid Mechanics, Winter Annual Meeting, Anaheim, CA, December 7-12, 1986.

7. J.J. Der and C.L. Stevens, "Liquid Propellant Tank Ullage Bubble Deformation and Breakup in Low Gravity Reorientation," AIAA/SAE/ASME/ASEE 23rd Joint Propulsion Conference, San Diego, CA, June 1987 (AAIA-87-2021).

8. C.W. Hirt and R.P. Harper, "Fluid Slosh in a Spinning and Oscillating Dish," Flow Science, Inc. Technical Note #9 (FSI-88-TN9), March 1988.

9. C.W. Hirt, B.D. Nichols, and N.C. Romero, "SOLA-A Numerical Solution Algorithm for Transient Fluid Flows," LASL report, LA-5852, April 1975.

10. C.W. Hirt and B.D. Nichols, "Volume of Fluid (VOF) Method for the Dynamics of Free Boundaries," J. Comp. Physics, 39, 201, January 1981.

11. C.W. Hirt and J.M. Sicilian, "A Porosity Technique for the Definition of Obstacles in Rectangular Cell Meshes," Fourth International Conference on Ship Hydrodynamics, Washington, DC, September 1985.