

Analysis of cryogenic propellant behaviour in microgravity and low thrust environments*

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Understanding the behaviour and response of cryogenic propellants during spacecraft flight operations (e.g., engine restart and fluid transfer) is an extremely important aspect of vehicle design. Accurate predictions of fluid motion and slosh amplification are needed to ensure proper settling prior to engine burn and effective vehicle control throughout all phases of the mission. To augment analyses of this type, Marshall Space Flight Center (MSFC) recently acquired FLOW-3D, a CFD package developed by Flow Sciences Inc. This paper describes a recent validation in which FLOW-3D model predictions were compared with MSFC drop tower test data. Although the tests were originally conducted in the 1960s to support design and performance assessments of the Saturn S-IVB stage liquid hydrogen (LH₂) tank, the data have proven useful for verifying the accuracy of the FLOW3D model.

Keywords: space cryogenics; propellants; microgravity

Nomenclature

a Acceleration
Bo Bond number
β Kinematic surface tension

Fr Froude number
σ Surface tension
ρ Density
R Tank dimension (radius)
V Velocity

A fundamental concern in designing spacecraft is the control and positioning of liquid propellants. This issue is especially important for missions involving extended coast periods prior to restart of the main propulsion system. Proper orientation of propellant is necessary for the following reasons:

- 1 It improves performance of the tank vent system (i.e. reduces possibility of liquid expulsion).
- 2 It provides sufficient liquid propellant for engine firing.
- 3 It ensures proper thermal conditions in feedlines prior to ignition (i.e. chilldown).
- 4 It minimizes vehicle disturbances which could impose excessive demands on the attitude control system.

A particularly severe propellant control problem generally exists following main engine cutoff (MECO). Liquid sloshing amplitudes which remain damped during powered flight may attain very large magnitudes following engine shutdown. After MECO propellant potential energy is converted into kinetic energy with removal of imposed constraining accelerations.

Background

This amplification was a critical concern during design and development of the Saturn V/S-IVB stage propellant control system. The Saturn V mission required an extended coast in earth orbit prior to translunar injection. Upon completion of checkout, the engine (J-2) was restarted to place the Apollo CSM/LEM into a translunar trajectory. This required control of propellant in a low gravity environment for up to 4.5 h.

To alleviate these concerns an experimental study was initiated to investigate propellant dynamics of the S-IVB stage. The programme included ground tests using scale models in a drop tower facility (i.e., the source of test data for this paper) and a full-scale flight experiment on board a Saturn launch vehicle.

The ground experiments utilized the 4.3 s drop tower facility at NASA Marshall Space Flight Center. The main goal was to understand the behaviour of a sloshing liquid subjected to a sudden reduction in acceleration. These tests were accomplished primarily with scale models and provided valuable data on fundamental laws and scaling parameters applicable to individual phenomena.

To duplicate adequately all the phenomena present on the Saturn V, a full scale orbital test was planned to confirm the design of the S-IVB propellant control and J-2

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engine thermal conditioning systems. A modified Saturn 1B, designated AS-203, was launched July 5, 1966 into a nominal 100 nautical mile orbit. The mission lasted for four orbits and successfully executed a programmed sequence of events designed to simulate the orbital phase of the Saturn V lunar mission. One orbit however was dedicated solely for obtaining data on cryogenic liquid behaviour. The stage was heavily instrumented and included two TV cameras mounted inside the tank on its upper bulkhead. Although one of the cameras failed prior to liftoff, the other provided an excellent visual record of liquid hydrogen behaviour under a variety of low gravity conditions. This was NASA's first Cryogenic Fluid Management (CFM) flight experiment and remains the only such experiment using a liquid hydrogen test fluid.

Drop tower experiments

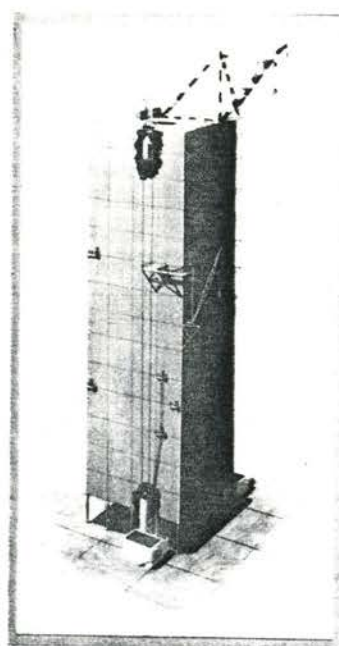
The initial tests utilized a scale model of the Saturn V/S-IVB liquid hydrogen tank. The cylindrical vessel had a 6 in (150 mm) internal diameter and was made of Lucite to enable observation of transient fluid dynamics. Prior to the AS-203 flight, the ground test programme emphasized the study of liquid behaviour with and without the tank's baffle and deflector, and examination of liquid behaviour at orbital insertion. After AS-203, drop tower tests continued with other tank configurations.

MSFC drop tower facility

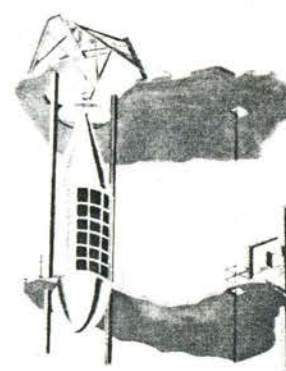
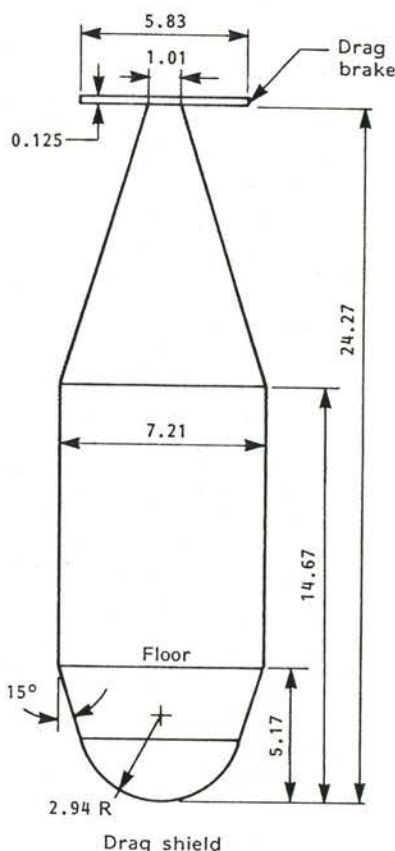
The MSFC drop tower facility is located in the Saturn V Dynamic Test Tower and is still operational. The experiment package was placed inside a protective drag shield and dropped 294 ft (90 m) into a 40 ft tall pneumatic tube which decelerated the drag shield and experimental package. During descent, the experiment package experienced free fall within the drag shield. The drop distance between the bottom of the drag shield (when suspended at the top of the tower) and the top of the pneumatic tube was approximately 294 ft (90 m) and permitted simulated low gravity for periods up to 4.3 s. Because the drop height was so much greater than the distance between the drag shield O.D. and pneumatic tube I.D. (a difference of 3 in (75 mm)) the drag shield was guided by rails during descent (*Figure 1*).

Experimental package

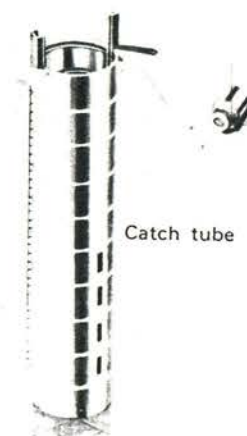
The experimental package consisted of a $3 \times 3 \times 1.5$ ft ($0.9 \times 0.9 \times 0.45$ m) welded angle aluminium frame with a plywood floor on which the necessary test equipment was mounted. The model tank was clamped to the sliding table of a solenoid spring-operated mechanism (*Figure 2*) and enclosed within a light box, which provided illumination of the test specimen for high speed photography. The mechanism was used to establish the initial slosh wave in the liquid. When the solenoid was energized, the spring forced the tank assembly to translate along the



Saturn V dynamic test stand



Drag shield



Catch tube

Facility capabilities	
Payload	— 450 lbs
Low gravity test range	— $10^{-5} g_0$ to $10^{-2} g_0$
Minimum	— $4 \times 10^{-5} g_0$
Maximum	— $10^{-2} g_0$
Drop time	— 4.3 sec.
Total drop weight	— 4000 lbs
Maximum test package	— 3' dia. x 3' high
Deceleration	— less than 25 g's

Figure 1 Marshall Space Flight Center low gravity test facility

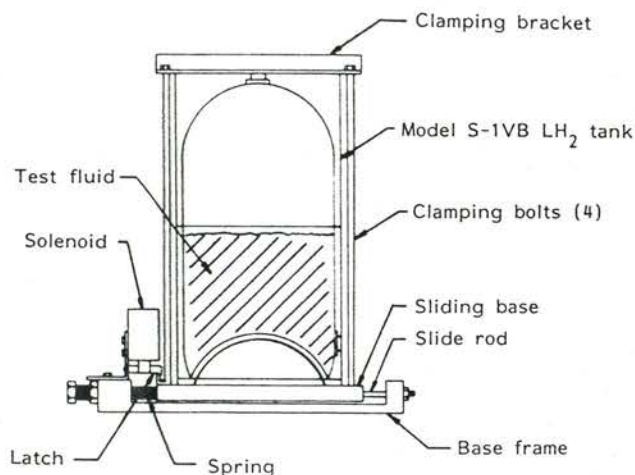


Figure 2 Sketch of impulse mechanism with model tank installed

slide rod and impact against the opposite side of the base frame. The motion and impact of the test container caused formation of a slosh wave within the liquid. The mechanism was designed to permit variation of the initial amplitude by altering either the spring constant, spring tension or travel distance of the sliding table. Unfortunately no record of imparted force measurements have survived. After examining film and analytical data from the original tests, a reasonable approximation for this energy input was used. This will be further discussed in the section outlining the computational analysis.

A nitrogen cold gas thruster pointing downward through the floor's central opening was used to apply a predetermined acceleration to the test fluid during drop. Gas was supplied to the thruster from a 3000 psia (21 MPa) storage bottle mounted on the experiment package. The thruster nozzle was calibrated in the form of plenum pressure *versus* thrust by a precision force-balance technique. By adjusting a pressure regulator on the package, the thruster plenum pressure could be changed to vary the acceleration on the package from one drop to another.

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Experiment procedures

Pretest activities entailed assembling the experiment package, loading the camera with film, centring the thruster nozzle, charging the high pressure nitrogen storage bottle, and placing the mechanism in the drop position. Once assembled, the package was balanced about the vertical axis of the thrust nozzle by adding weight where required. The balancing was performed on a Byrex centre-of-gravity locator (i.e., strain gauge balance table). After balancing, the package was placed in the drag shield, and suspended in its pre-drop position.

The camera, lights, and thruster were actuated 2 s before the drop, to allow stabilization of thruster plenum pressure and to attain full camera speed. A continuously variable 0–10 s timer on the package was preset to actuate the impulse mechanism at the desired time between camera-on and drop. The camera, lights and thruster operation were terminated by onboard circuitry approximately 9 s after initiation. The entire test sequence was executed automatically.

To evaluate the liquid behaviour visually and numerically, films were taken of the test container and liquid at a speed of about 400 frames s^{-1} with a Milliken camera. Numerical data pertinent to the liquid motion were obtained by reading, with a Telerelex machine, the liquid amplitude as a function of time (in a plan perpendicular to the field of view of the camera) from the film. The film exists today on 16 mm and videotape.

Computational analysis

FLOW-3D description

The CFD program used in this analysis, FLOW-3D, calculates fluid free surface shape and motion as a function of imposed acceleration. It is ideally suited for analysis of situations in which environmental acceleration levels are quickly reduced or amplified. This capability along with its accounting of surface tension and easy geometry/obstacle generation make the program ideally suited for analyses of transient propellant fluid dynamics in tanks and feed systems.

FLOW-3D¹ was developed by Flow Sciences Inc. and evolved from the Marker-and-Cell (MAC) program² developed at the Los Alamos Scientific Laboratory. It applies a three-dimensional finite difference solution to the Navier-Stokes equations. The program utilizes the volume of fluid (VOF) algorithm which tracks free surface motion between two fluids and

Table 1 Properties of petroleum ether

Temperature		Density		Temperature		Surface tension		Temperature		Viscosity	
(°C)	(°F)	(g cm ⁻³)	(lbm ft ⁻³)	(°C)	(°F)	(dyn cm ⁻¹)	(lb ft ⁻¹)	(°C)	(°F)	(cSt)	(lbm ft ⁻¹ s ⁻¹)
26.7	80.06	0.6185	38.61	21	69.8	14.9	1.021×10^{-3}	21	69.8	0.39	1.672×10^{-4}
21.0	69.8	0.6382	39.84	10	50.0	16.2	1.11×10^{-3}	10	50.0	0.43	1.86×10^{-4}
15.6	60.08	0.6433	40.16	-4	24.8	17.3	1.185×10^{-3}	-4	24.8	0.47	2.04×10^{-4}

incorporates a fluid surface tension/wall adhesion model. Additional features, such as fluid heat transfer and solid conduction, were not utilized, since bulk fluid motion was the primary concern of this study.

Approach

The only part of FLOW3D that was modified for this analysis was a Fortran subroutine which specifies the external acceleration frame. The routine was altered to duplicate the acceleration levels recorded during the drop tower test.

To model the AS-203 simulator tank, a plane of symmetry was established down the centre line of the tank so that it could be divided in half as shown in Figure 3. This approach was reasonable since the applied disturbance force induced a nearly two-dimensional slosh wave in the fluid medium about this line of symmetry. The modelled half of the tank was represented as a three-dimensional mesh, bounded on all sides by the tank walls (except for the back face which was represented as the plane of symmetry). By utilizing half of the tank, mesh density could be varied easily without increasing the size of the problem domain. Several mesh densities were examined until changes in the fluid free surface and velocity were minimized. This was done to minimize grid density effects. The computer used in this simulation was a VAX 6420.

Setting up the problem for computational solution first required establishing initial conditions of the fluid and free surface. In the drop tower experiment this was accomplished by applying a side force to the container, and fluid within the tank.

To set up an accurate simulation it is essential to define the correct amount of kinetic energy to the fluid before the drop. When the slosh wave is at its maximum amplitude, fluid velocities are at a minimum and potential energy is at a maximum. As acceleration acts on the slosh wave, the potential energy is converted to kinetic

energy, resulting in an increase in fluid velocities. In the drop tower tests, the fluid was allowed to slosh back and forth across the test container only one to two times before being dropped, which minimized the energy lost to viscous dissipation. With this in mind, the drop tower test fluid free surface profile before the drop was selected as the starting point in the FLOW-3D simulation. After several test runs it was necessary to modify this profile slightly by increasing its deflection so that the Froude number could be accurately modelled. This modified profile was used as the initial condition in all subsequent FLOW-3D simulations, and is shown in Figure 3.

The next step was to define appropriate fluid motions prior to the drop. This was accomplished by allowing gravity to accelerate the fluid free surface downward and to convert the stored potential energy to kinetic energy. An important derived measurement from the drop tower tests was the Froude number (Fr). This parameter relates fluid surface velocity to the environment acceleration level (i.e., inertial forces/gravitational force):

$$Fr = \frac{V^2}{aR}$$

This number was used to determine how long the selected initial surface profile needed to be acted upon by gravity to produce the required velocity distribution in the fluid before the drop.

Once the initial free surface shape and the time needed to match the Froude number were determined, the issue of drop acceleration profiles could be addressed. The AS-203 test tank was equipped with an accelerometer to monitor the environment of the drop package. These data were taken in the form of strip recordings and to date, none have been found. Due to this limitation the generalized acceleration history described in Reference 3 was utilized and tailored to the drop tower case under consideration. The final gravity level was determined by

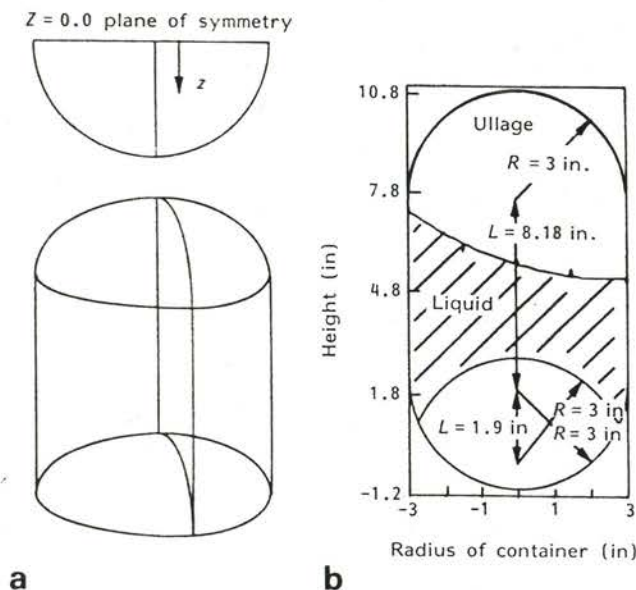


Figure 3 Set-up of computational region: (a) three-dimensional representation; (b) planar representation (cross-section at tank centre). Total mesh cells: 30 x (radial) direction; 40 y (axial) direction; 15 z direction

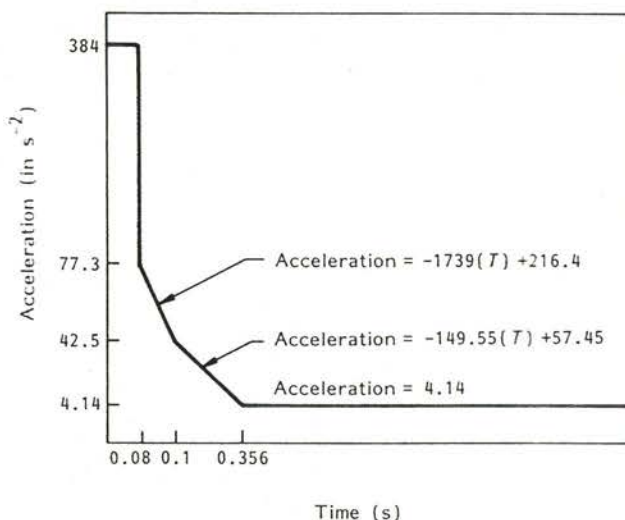


Figure 4 Acceleration history for simulation. Acceleration from time of 0.0 to 0.8 s used to accelerate fluid and provide surface velocities of approximately 13.4 in s^{-1} to match drop Fr number. Drop occurs at 0.08 s. Acceleration tails off after 0.08 s to final steady value of 4.14 in s^{-2}

the test Bond number (Bo) which is the ratio of gravitational forces to capillary forces, that is:

$$Bo = \frac{\rho R^2 a}{\sigma}$$

The acceleration profile used in this computer simulation is shown in *Figure 4* and consists of four linear approximations. The acceleration routine Motion of FLOW-3D was modified to reflect these profiles. The initial period of acceleration is the time required for gravity to convert the fluid potential energy to kinetic energy and match the Fr number before the drop. After the drop, the acceleration level is tailed off in two steps requiring a duration of about 0.2 s. The final level, which is held constant for the remainder of the simulation, is based on the test Bo number.

Results and Discussion

To model the drop tower test, the FLOW-3D computer code required input of the petroleum ether properties listed in *Table 1*. For test number 2F-19, the Froude and Bond numbers were recorded at 14.6 and 24, respectively. For this particular container and test fluid, these values correspond to a fluid velocity of 13.4 m s^{-1} (0.34 m s^{-1}) and an acceleration level of 0.01 a/g .

Computational results are presented in *Figures 5a-f*. Each figure represents a cross-sectional view near the tank's centre and provides a two-dimensional perspective of slosh motions. Experimental results corresponding to the same approximate time are shown alongside to expedite comparisons. The fluid motion, in the computational results, is displayed through the use of velocity vectors located at the cell centres with the magnitude scaled to the largest velocity calculated during that time slice. The computed plots start prior to drop (0.08 s before) and progress in 0.5 s intervals to a maximum time of 3.92 s. It is seen that the slosh wave after drop quickly amplifies by moving to the top of the tank with a small amount of liquid spilling to the opposite side. The wave then retracts with the subsequent slosh front climbing not nearly as high. It is noted that in the later half of the simulation (past 2.5 s) the fluid began to develop voids within its volume not present during this experiment run. During the review of other tests in the same series, however, voids were seen, giving us confidence that even though our test did not have them they were indeed common under similar conditions. This could possibly be due to the method in which the surface tension and free surfaces are calculated within the code. Comparison of the drop tower results with those predicted by FLOW-3D indicates nearly identical free surface shapes and extremely good agreement over the entire test duration.

Plots of fluid kinetic energy, x-coordinate centre of gravity (c.g.) and y-coordinate c.g. *versus* time are shown in *Figures 6, 7 and 8*, respectively. These plots illustrate how quickly energy in the system is damped. They also indicate the type of forces which would be present on a vehicle experiencing sloshing of this nature.

Figure 6 shows that the kinetic energy of the system is at a maximum at the time of drop. This is expected

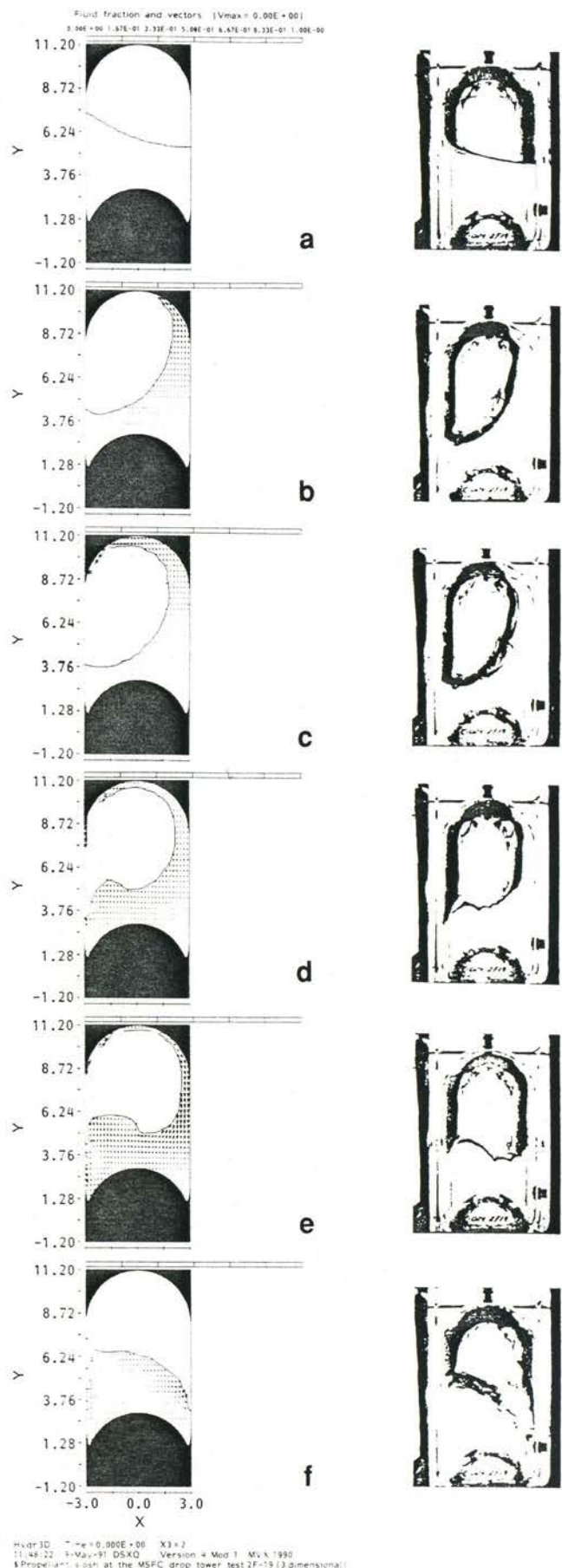


Figure 5 FLOW-3D and drop tower result at time: (a) -0.10 s (directly before drop); (b) 0.5 s; (c) 1.0 s; (d) 2.0 s; (e) 2.5 s; (f) 4.0 s

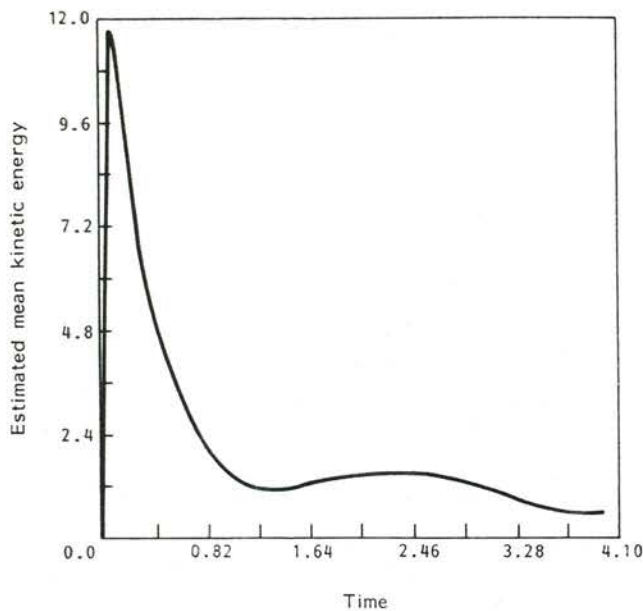


Figure 6 Estimated mean kinetic energy

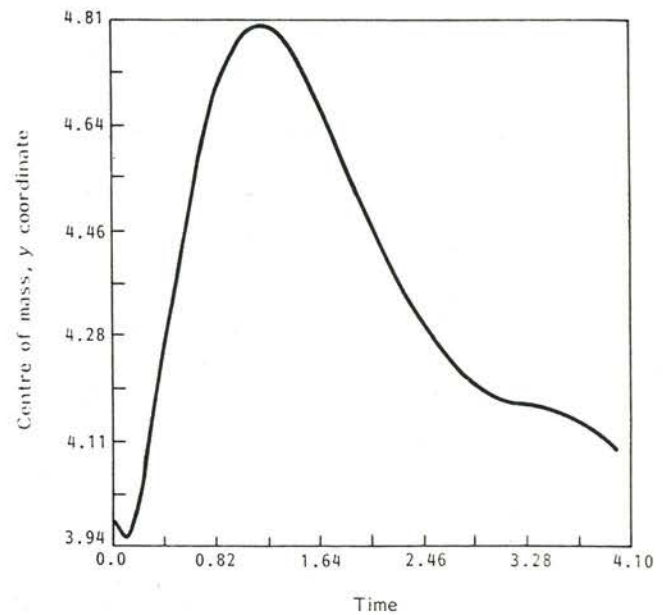


Figure 8 Centre of mass, y location

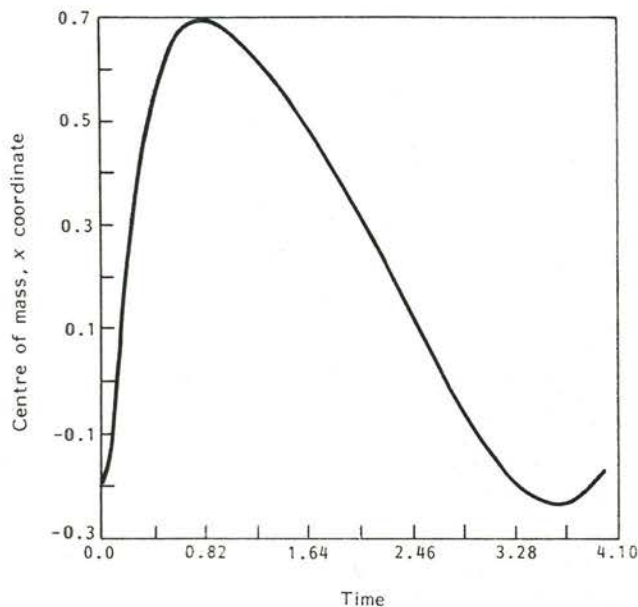


Figure 7 Centre of mass, x location

since at that moment, the Froude number is matched. Kinetic energy then decays rapidly as the fluid oscillates in the surface tension dominated low gravity environment.

The c.g. motion in Figures 7 and 8 indicates that the fluid centre of mass travelled approximately 9% of the axial tank length (or a normalized distance of $\Delta y/R = 0.29$) from its rest position. The slosh wave likewise causes the mass centre to travel approximately 13% of the tank width (diameter) in the radial direction (or a normalized distance of $\Delta x/R = 0.266$ from its rest position).

Variation in the z -direction was found to be negligible, as expected, and is ignored in this discussion. The fluid wave period is another parameter that was considered. Examination of the x -direction c.g. plot shows that the low gravity slosh wave has a period of approximately

4 s. This value, as well as those predicted for the centre of gravity movement, compare extremely well with the discussion in Reference 3, which addresses wave properties for low gravity slosh.

Conclusions

This analysis confirms the FLOW-3D code's suitability for predicting low-g fluid slosh behaviour. The predicted fluid motion could result in significant forces exerted on a space vehicle with large propellant tankage. A similar analysis could analyse the effect of incorporating baffles and screens to impede the initiation of any unwanted side loads due to slosh.

The acceleration transition profile between 1-g and the steady-state low gravity level was determined to be significant in simulating the drop tower liquid-vapour interface shape for each time increment. However, the overall general behaviour was not significantly affected by the transition profile. Therefore in actual vehicle applications, the engine thrust tailoff profile should be included in computer simulations if the precise interface *versus* time definition is needed.

Acknowledgements

The authors would like to thank Mr Leon Hastings for his assistance in providing the test data used in this paper. His technical guidance is also greatly appreciated.

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ABSTRACT

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NOMENCLATURE

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BACKGROUND

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To model the AS-203 simulator tank, a plane of symmetry was established down the center line of the tank so that it could be divided in half as shown in Fig. 3. This approach was reasonable since the applied disturbance force induced a nearly two dimensional slosh wave in the fluid media about this line of symmetry. The modeled half of the tank was represented as a three dimensional mesh, bounded on all sides by the tank walls (except for the back face which

was represented as the plane of symmetry). By utilizing half of the tank, mesh density could be varied easily without increasing the size of the problem domain. Several mesh densities were examined until changes in the fluid free surface and velocity were minimized. This was done to minimize grid density effects. The computer used in this simulation was a VAX 6420.

Setting up the problem for computational solution first required establishing initial conditions of the fluid and free surface. In the drop tower experiment this was accomplished by applying a side force to the container, and fluid within the tank.

To set up an accurate simulation it is essential to define the correct amount of kinetic energy to the fluid before the drop. When the slosh wave is at its maximum amplitude, fluid velocities are at a minimum and potential energy is at a maximum. As acceleration acts on the slosh wave, the potential energy is converted to kinetic energy resulting in an increase in fluid velocities. In the drop tower tests, the fluid was allowed to slosh back and forth across the test container only one to two times before being dropped, which minimized the energy lost to viscous dissipation. With this in mind, the drop tower test fluid free surface profile before the drop was selected as the starting point in the FLOW-3D simulation. After several test runs it was necessary to modify this profile slightly by increasing its deflection so that the Froude Number could be accurately modeled. This modified profile was used as the initial condition in all subsequent FLOW-3D simulations, and is shown in Figure 3.

The next step was to define appropriate fluid motions prior to the drop. This was accomplished by allowing gravity to accelerate the fluid free surface downward and to convert the stored potential energy to kinetic energy. An important derived measurement from the drop tower tests was the Froude

number (Fr). This parameter relates fluid surface velocity to the environment acceleration level (i.e., inertial forces/gravitational force):

$$Fr = \frac{V^2}{aR}$$

This number was used to determine how long the selected initial surface profile needed to be acted upon by gravity to produce the required velocity distribution in the fluid before the drop.

Once the initial free surface shape and the time needed to match Froude number was determined, the issue of drop acceleration profiles could be addressed. The AS-203 test tank was equipped with an accelerometer to monitor the environment of the drop package. This data was taken in the form of strip recordings and to date, none have been found. Due to this limitation the generalized acceleration history described in Reference [3] was utilized and tailored to the drop tower case under consideration. The final gravity level was determined by the test Bond Number (Bo) which is the ratio of gravitational forces to capillary forces, that is:

$$Bo = \frac{\rho R^2 a}{\sigma}$$

The acceleration profile used in this computer simulation is shown in Figure 4 and consists of four linear approximations. The acceleration routine Motion of FLOW-3D was modified to reflect these profiles. The initial period of acceleration is the time required for gravity to convert the fluid potential energy to kinetic energy and match the Fr number before the drop. After the drop, the acceleration level is tailed off in two steps requiring a duration of about two tenths of a second. The final level which is held constant for the remainder of the simulation is based on the test Bo number.

RESULTS AND DISCUSSION

To model the drop tower test, the FLOW-3D computer code required input of the petroleum ether properties listed in Table 1. For test number 2F-19, the Froude and Bond numbers were recorded at 14.6 and 24, respectively. For this particular container and test fluid, these values correspond to a fluid velocity of 13.4 inches/second and an acceleration level of 0.01 a/g .

Computational results are presented in Figs. 5a-5f. Each figure represents a cross sectional view near the tank's center and provides a two dimensional perspective of slosh motions. Experimental results corresponding to the same approximate time are shown along side to expedite comparisons. The fluid motion, in the computational results, is displayed through the use of velocity vectors located at the cell centers with the magnitude scaled to the largest velocity calculated during that time slice. The computed plots start prior to drop (0.08 seconds before) and progress in 0.5 second intervals to a maximum time of 3.92 seconds. It is seen that the slosh wave after drop quickly amplifies by moving to the top of the tank with a small amount of liquid spilling to the opposite side. The wave then retracts with the subsequent slosh front climbing not nearly as high. It is noted that in the later half of the simulation (past 2.5 seconds) the fluid began to develop voids within its volume not present during this experiment run. During the review of other tests in the same series, however, voids were seen giving us confidence that even though our test did not have them they were indeed common under similar conditions. This could possibly be due to the method in which the surface tension and free surfaces are calculated within the code. Comparison of the drop tower results with those predicted by FLOW-3D indicate nearly identical free surface shapes and extremely good agreement over the entire test duration.

Plots of fluid kinetic energy, x-coordinate center of gravity (c.g.) and y-coordinate c.g. versus time are shown in Figs. 6, 7, and 8, respectively. These plots illustrate how quickly energy in the system is damped. They also indicate the type of forces which would be present on a vehicle experiencing sloshing of this nature.

Figure 6 shows that the kinetic energy of the system is maximum at the time of drop. This is expected since at that moment, the Froude number is matched. Kinetic energy then decays rapidly as the fluid oscillates in the surface tension dominated low gravity environment.

The c.g. motion in Figs. 7 and 8 indicates that the fluid center of mass traveled approximately 9% of the axial tank length (or a normalized distance of $\Delta y/R=0.29$) from its rest position. The slosh wave likewise causes the mass center to travel approximately 13% of the tank width (diameter) in the radial direction (or a normalized distance of $\Delta x/R=.266$ from its rest position).

Variation in the z-direction was found to be negligible, as expected, and is ignored in this discussion. The fluid wave period is another parameter that was considered. Examination of the x-direction c.g. plot shows that the low gravity slosh wave has a period of approximately 4 seconds. This value, as well as those predicted for the center of gravity movement, compare extremely well with the discussion in Reference [3] which addresses wave properties for low gravity slosh.

CONCLUSIONS

This analysis confirms the FLOW-3D code's suitability for predicting low-g fluid slosh behavior. The predicted fluid motion could result in significant forces exerted on a space vehicle with large propellant tankage. A similar analysis could analyze the effect of incorporating baffles and screens to impede the

initiation of any unwanted side loads due to slosh.

The acceleration transition profile between 1-g and the steady-state low gravity level was determined to be significant in simulating the drop tower liquid-vapor interface shape for each time increment. However, the overall general behavior was not significantly affected by the transition profile. Therefore in actual vehicle applications, the engine thrust tailoff profile should be included in computer simulations if the precise interface versus time definition is needed.

ACKNOWLEDGEMENTS

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- 2) J.E. Welch, F.H. Harlow, J.P. Shannon, and B.J. Daly, "The MAC Method: A Computing Technique for Solving Viscous, Incompressible, Transient Fluid-Flow Problem Involving Free Surfaces," Los Alamos Scientific Laboratory report LA-3425, 1975.
- 3) Toole, L.E.; and Hastings, L.J.: An Experimental Study of the Behavior of a Sloshing Liquid Subjected to a Sudden Reduction in Acceleration, NASA TMX-53755, August 6, 1968.

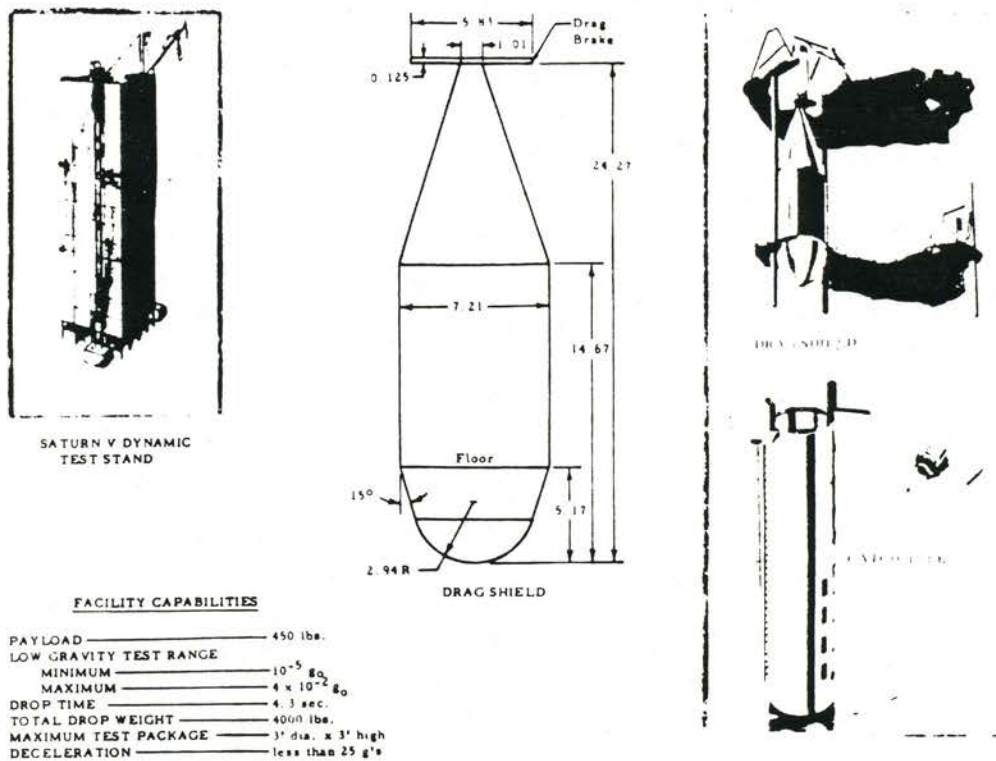


FIGURE 1 Marshall Space Flight Center Low Gravity Test Facility

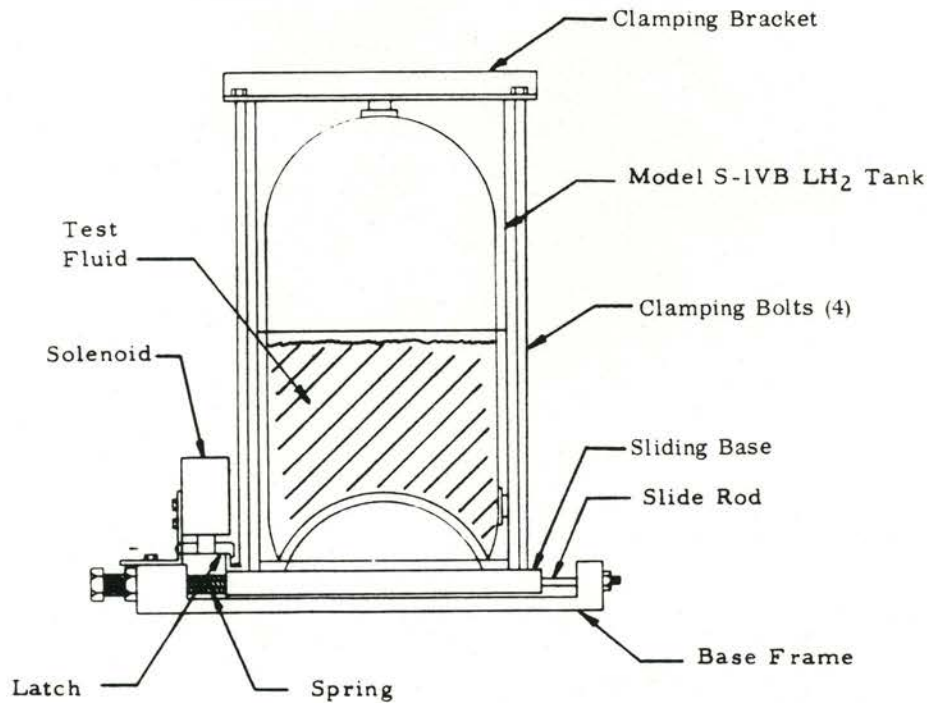


FIGURE 2 Sketch of Impulse Mechanism with Model Tank Installed

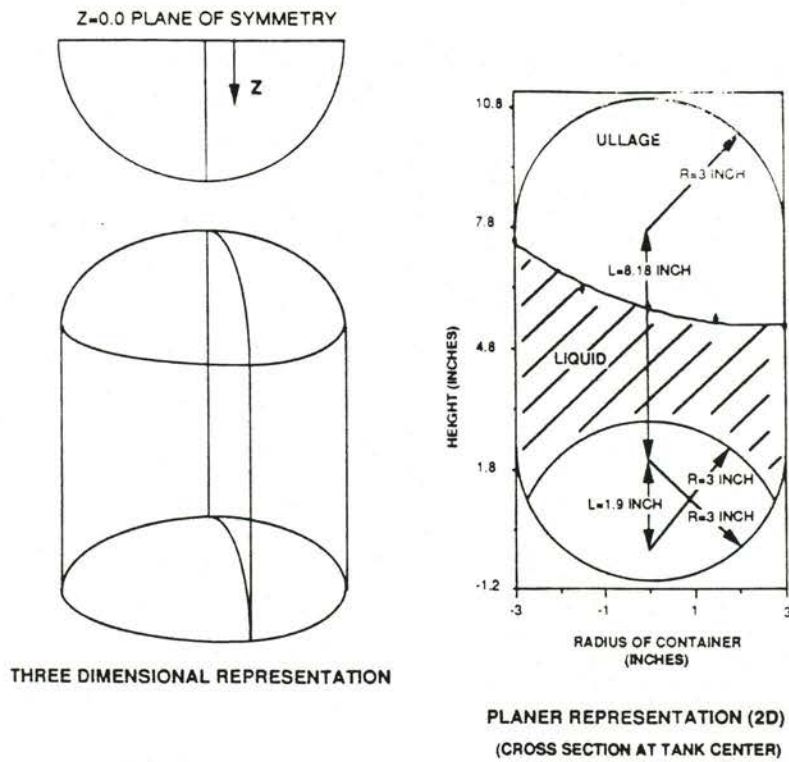


FIGURE 3 SET UP OF COMPUTATIONAL REGION

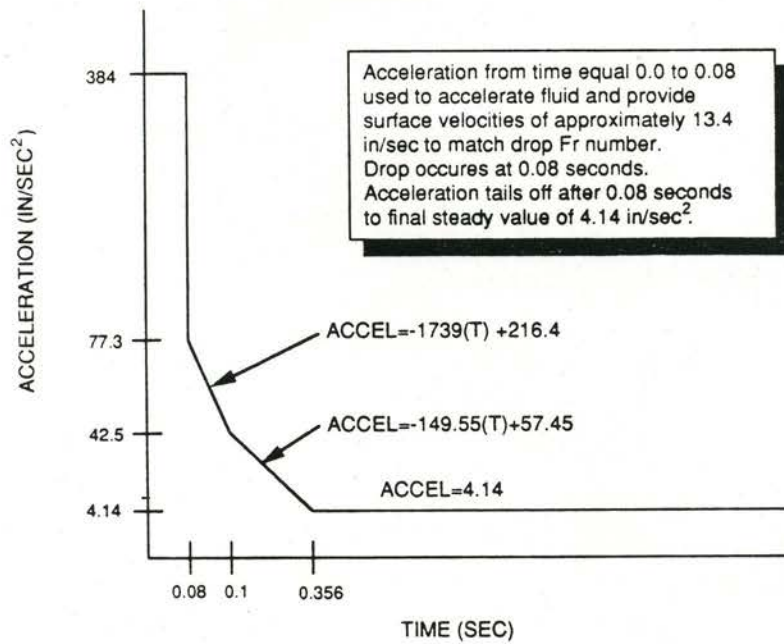
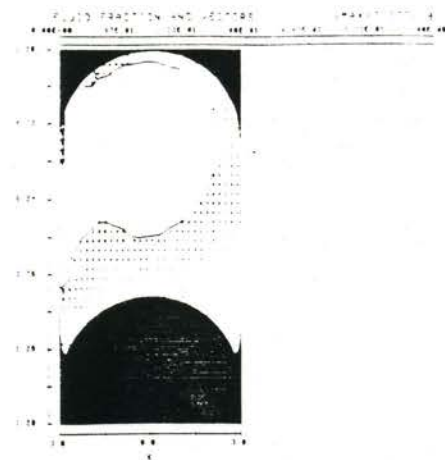


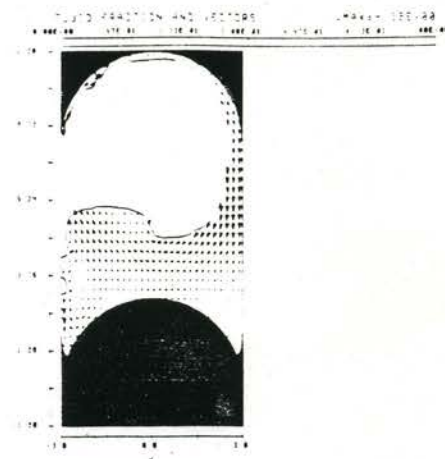
FIGURE 4 ACCELERATION HISTORY FOR SIMULATION



HYDRO TIME=2.00E+00 (s) 2
 18.02 5-MAY-91 09:00 VERSION=400.1.000 1990
 PROPELLANT SLUSH AT THE HYDRO DROP TOWER TEST 2P-1913 3-DIMENSIONAL



Figure 5c. Flow 3D and Drop Tower result at time = 2.0 sec



HYDRO TIME=2.50E+00 (s) 2
 18.02 5-MAY-91 09:00 VERSION=400.1.000 1990
 PROPELLANT SLUSH AT THE HYDRO DROP TOWER TEST 2P-1913 3-DIMENSIONAL

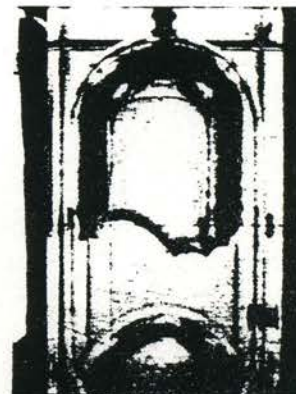
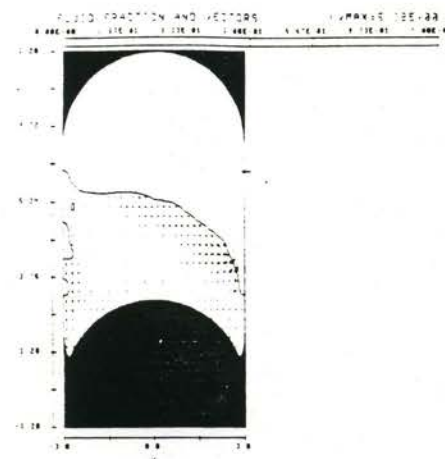


Figure 5d. Flow 3D and Drop Tower result at time = 2.5 sec



HYDRO TIME=4.00E+00 (s) 2
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 PROPELLANT SLUSH AT THE HYDRO DROP TOWER TEST 2P-1913 3-DIMENSIONAL

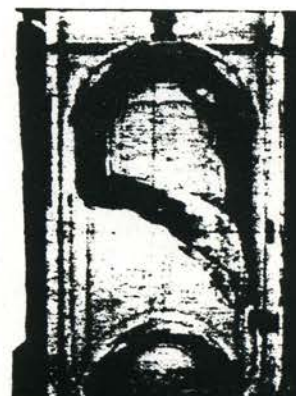


Figure 5e. Flow 3D and Drop Tower result at time = 4.0 sec

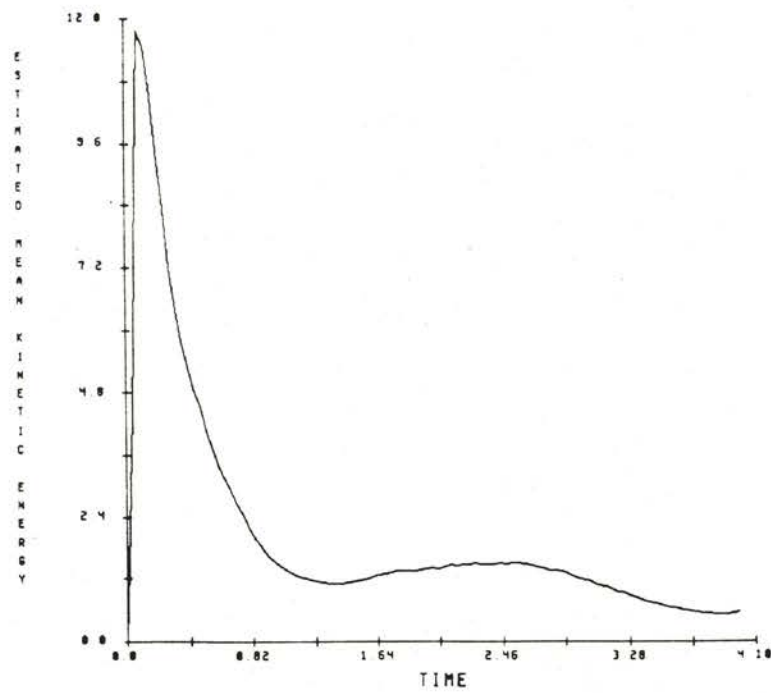


FIGURE 6 Estimated Mean Kinetic Energy

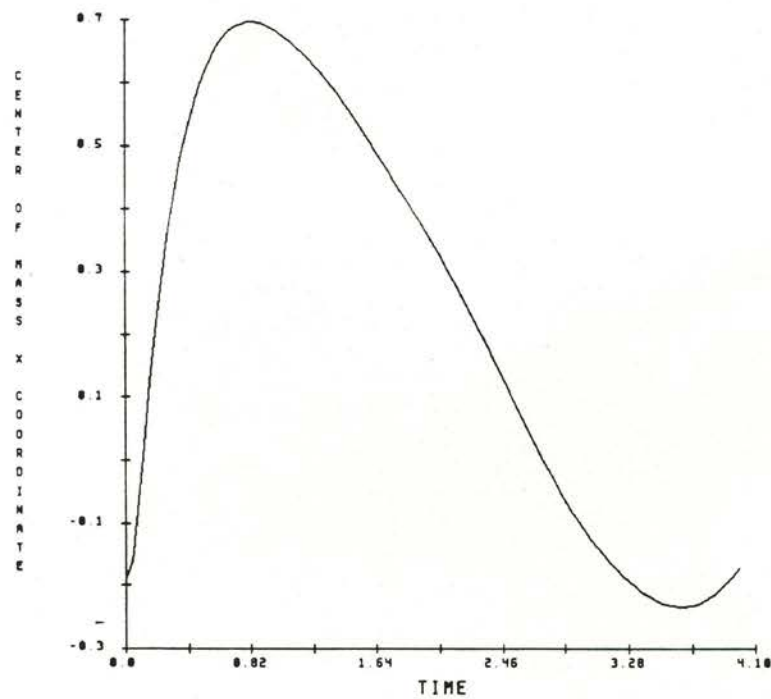


FIGURE 7 Center of Mass, x Location

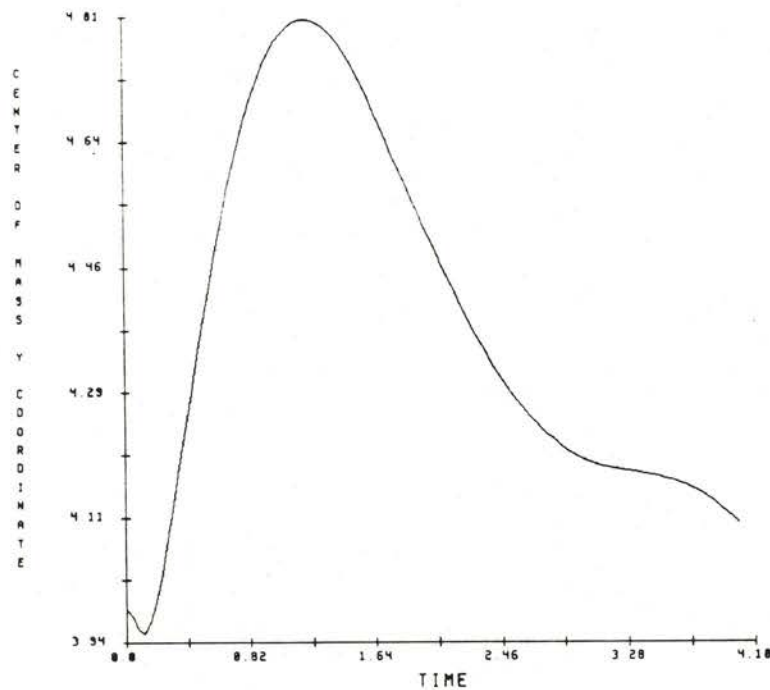


FIGURE 8 Center of Mass, y Location

Temperature		Density		Temperature		Surface Tension		Temperature		Viscosity	
$^{\circ}\text{C}$	$^{\circ}\text{F}$	gm/cm^3	lb_m/ft^3	$^{\circ}\text{C}$	$^{\circ}\text{F}$	dyne/cm	lb_f/ft	$^{\circ}\text{C}$	$^{\circ}\text{F}$	centistokes	$\text{lb}_m/\text{ft sec}$
26.7	80.06	0.6185	38.61	21	69.8	14.9	1.021×10^{-3}	21	69.8	0.39	1.672×10^{-4}
21.0	69.8	0.6382	39.84	10	50.0	16.2	1.11×10^{-3}	10	50.0	0.43	1.86×10^{-4}
15.6	60.08	0.6433	40.16	-4	24.8	17.3	1.185×10^{-3}	-4	24.8	0.47	2.04×10^{-4}

Table 1. Properties of Petroleum Ether