

NASA Technical Memorandum 101440  
AIAA-89-0625

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(NASA-TM-101440) MODELING OF IMPULSIVE  
PROPPELLANT REORIENTATION (NASA) 24 p

CSCI 21H

N89-13495

G3/20 Unclass  
0183404

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Prepared for the  
27th Aerospace Sciences Meeting  
sponsored by the American Institute of Aeronautics and Astronautics  
Reno, Nevada, January 9-12, 1989

**NASA**

## MODELING OF IMPULSIVE PROPELLANT REORIENTATION

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### ABSTRACT

The impulsive propellant reorientation process is modeled using the ECLIPSE Code. A brief description of the process and the computational model is presented. Code validation is documented via comparison to experimentally derived data for small-scale tanks. Predictions of reorientation performance are presented for two tanks designed for use in flight experiments and for a proposed full-scale OTV tank. A new dimensionless parameter is developed to correlate reorientation performance in geometrically similar tanks. Its success is demonstrated.

### INTRODUCTION

The ECLIPSE Code, (Energy Calculations for Liquid Propellants in a Space Environment), is being developed as one component of the reduced gravity fluid management technology program being conducted by the NASA Lewis Research Center (ref. 1). The long range goal of a general tool for computational modeling of liquid propellant behavior in a reduced gravity environment is being pursued by stages with each stage corresponding to a problem of current interest to designers of advanced spacecraft. The ability of ECLIPSE to model jet induced mixing in propellant tanks (refs. 2 and 3) and propellant tank self-pressurization (ref. 4) has been documented. The focus of the work being reported in this paper is the modeling of liquid motion induced by a sudden change in the acceleration environment.

During coast in Low-Earth-Orbit (LEO), liquid propellants can collect in various regions of the propellant tank due to atmospheric drag on the spacecraft. The process of positioning the liquid over the tank outlet by firing auxiliary thrusters is known as impulsive reorientation or settling. Since impulsive reorientation requires the expenditure of propellant, it is important to optimize the process to minimize the associated propellant requirements. If the thrust level is too low, the propellant may not reposition. If it is too high, a large geyser may form and vapor pockets may be trapped in the pool. Proper spacecraft design and operation requires a good understanding of the process and the parameters which control it.

\*Work funded by NASA Grant NAG3-578.

Small-scale experiments have been performed in the NASA Lewis Research Center drop tower and in the Zero-Gravity Facility to examine liquid motion induced by accelerations which model the reorientation process. The experiments were performed in transparent tanks and the fluid motion induced by these accelerations was recorded via high-speed photography. These experiments identified liquid-vapor interface shapes for a zero-g environment (ref. 5) and records of fluid motion induced in partially filled tanks due to an imposed acceleration were produced (ref. 6). Further studies conducted by I. Sumner (ref. 7) examined the energy expended to accomplish reorientation. A performance map for the reorientation process in these small-scale tanks was developed. This reference provides substantial detail for a number of acceleration levels and tank fillings and the results reported in this reference have served as the basis for code validation.

Prediction of reorientation performance has relied on two tools. The simplest is a rigid body dynamics analysis which assumes the propellant pool to behave as a single solid body (ref. 8). Although this analysis is simple to perform, it is such a coarse assumption that large safety factors must be provided when it is used for design purposes. The second tool is described by I. Sumner (ref. 7) and is based on an empirical analysis developed by J. Salzman (ref. 9). The computational procedure is an empirically based approach using a Weber number criteria to preclude geysering and results in calculation of a liquid leading edge velocity. I. Sumner (ref. 7) extended the analysis to include small geysers. Although predictions based on this method correlated well with reported experimental results, it does not start from first principles and its application is limited to similar geometries and conditions.

#### NOMENCLATURE

a	acceleration
Bo	Bond number
F	volume-of-fluid function
Fr	Froude number
g	body force per unit mass, typically gravitational
h	length dimension, typically tank length
h*	nondimensionalized length
p	pressure
R	tank radius
Re	Reynolds number
Se	settling number
t, T	time

$u, v$      $x$  and  $y$  velocity components respectively  
 $v_f$     velocity of liquid leading edge  
 $x, y$     spatial coordinates, cartesian or axisymmetric ( $x$  in radial direction)  
 $\theta$     fractional cell volume open to flow  
 $\mu$     dynamic viscosity  
 $\nu$     kinematic viscosity  
 $\xi$     switching integer  
 $\rho$     density  
 $\sigma$     surface tension

#### ECLIPSE CODE

The ECLIPSE Code is a descendant of the family of SOLA Codes written at the Los Alamos National Laboratory. In particular, the NASA-VOF2D Code (ref. 10) was used as the foundation upon which ECLIPSE is being built. The base-line code solves the laminar hydrodynamic problem using the Volume-Of-Fluid, (VOF), algorithm to determine the location of the free surface. The computational model uses a VOF function,  $F$ , to track the free surface, and a cell blockage function,  $\theta$ , to model partial cell blockage. Equations expressing conservation of mass, the force-momentum balance, and the  $F$ -transport equation can be written:

$$\frac{1}{x\xi} \frac{\partial(x\xi\theta u)}{\partial x} + \frac{\partial(\theta v)}{\partial y} = 0 \quad (1)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = g_x - \frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left[ \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \xi \left( \frac{1}{x} \frac{\partial u}{\partial x} - \frac{u}{x^2} \right) \right] \quad (2)$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = g_y - \frac{1}{\rho} \frac{\partial p}{\partial y} + \nu \left[ \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \xi \left( \frac{1}{x} \frac{\partial v}{\partial x} \right) \right] \quad (3)$$

$$\frac{\partial F}{\partial t} + u \frac{\partial F}{\partial x} + v \frac{\partial F}{\partial y} = 0 \quad (4)$$

The equations are discretized using finite-difference procedures applied to a staggered grid with velocities defined at the cell faces and pressure at the cell center. The SOLA algorithm is used to march the solution through time. The VOF algorithm is used to determine both the location and the local radius of curvature of the free surface. The curvature is then used to compute an appropriate surface tension force which is imposed on the field as an equivalent pressure. The solution marches through time and an automatic step-size adjustment limited by stability criteria is provided (details of the stability criteria used in ECLIPSE can be found in ref. 11).

Although many features such as heat transfer and thermodynamic models have been added during the development of ECLIPSE, only minor modifications to the baseline code were required to study impulsive reorientation. The routine which provides an initial low-g fluid configuration has been modified so that the liquid can be positioned at either end of the tank. A set of variables have been incorporated to impose a time dependent acceleration environment on the fluid in the tank. The ability to terminate execution based on a criteria for completion of reorientation has been incorporated into the code. Finally, additional output options have been added to enhance the tracking of variables of specific interest to the study of the reorientation process.

## CODE VALIDATION

Six cases were selected from I. Sumner (ref. 7) to serve as verification that ECLIPSE accurately models the impulsive reorientation process. A summary of the test conditions is presented in table I. The fineness ratio, FR, is the ratio of tank axial length to tank radius. The percentage of the tank occupied by liquid is recorded in the column labeled FL. TCTFE is trichlorotrifluoroethane, R is the tank radius, and the balance of the variables are self explanatory. These cases were selected to provide a range of geyser formation from large to nonobservable.

A typical computational mesh used to model these cases is presented in figure 1. The liquid is shown at the top of the tank in a zero-g configuration. The mesh has been refined near the maximum tank radius (i.e., tank wall) in order to assure a smooth transition of the flow from the barrel section into the head. Although all figures presented in this report show a full cross-section through the tank, the code solves the problem in cylindrical coordinates the settling acceleration and resulting flow is axisymmetric. Therefore, only half the number of cells depicted are required to perform the computations.

A sequence of flow fields computed for the conditions specified for Test 5 is displayed in figure 2. A comparison between computational prediction and experimental observation of geyser tip location as a function of time is presented in figure 3. ECLIPSE predicts formation of a geyser with a maximum height of 3.2 cm whereas I. Sumner (ref. 7) reports a maximum geyser height of 3.3 cm. ECLIPSE predicts dissipation of the geyser into the rising free surface at approximately 1.05 sec whereas I. Sumner (ref. 7) reports this event at approximately 1.10 sec. A comparison between computational prediction and experimental observation of geyser tip location as a function of time for Test 1 is shown in figure 4. A. Patag (ref. 12) in his thesis on the work presented herein, presents comparisons between the data from the experiment listed in table I and the computational predictions. In general, reasonable agreement was obtained with a single exception. The parameters specified for Test 8 combine to induce large leading edge velocities as the liquid moves along the tank walls. At geyser inception at the bottom of the tank, the free surface model in ECLIPSE fails to track correctly the formation of a pool and the initial growth of the geyser. Computed flow fields for Test 8 are shown in figure 5. It should be noted that the kinetic energy imparted to the liquid is high. As such, it is highly inefficient and would require an excessive expenditure of propellant to produce these conditions in a real spacecraft. Since the current study is focused on optimization of the reorientation process, the

Inability of ECLIPSE to successfully model Test 8 is not viewed as a significant handicap.

Based on the evidence presented in the preceding paragraphs, it was concluded that ECLIPSE is a suitable tool for modeling pulsed settling.

#### SCALE MODEL OTV TANKS

One component of the NASA Lewis reduced gravity fluid management technology program is development of a flight experiment to examine a variety of fluid management issues. When the computational modeling effort was initiated, this experiment was known as the Cryogenic Fluid Management Facility (ref. 1), (CFMF), but has since been renamed the Cryogenic On-Orbit Liquid Depot, Storage, Acquisition and Transfer Satellite (ref. 13), (COLD-SAT). The original design used a 0.25-scale model of a propellant tank proposed by Boeing for a space based Orbit Transfer Vehicle, (OTV). This tank was selected as a prototype for studying the effect of acceleration level on reorientation performance. The design of the experiment relied on two Shuttle Reaction Control System (RCS) thrusters to provide an acceleration environment of  $7.85 \text{ cm/s}^2$ , ( $8 \times 10^{-3}g$ ).

For the code validation phase, the investigator reviewed graphical displays of the flow field evolution and judged settling to be achieved when a sufficient quantity of liquid had collected into a pool at the "bottom" of the tank. To eliminate the subjective nature of this evaluation, a measurable parameter was defined. Since the depth of the pool at the tank centerline can be tracked as the flow field evolves, the liquid is considered settled when this depth exceeds 20 percent of the total tank length. The settling time is defined as the elapsed time between initiation of thrust and satisfaction of this criterion. Although a few apparently anomalous settling times were predicted at the lower thrust levels, the settling criterion worked well for the majority of cases.

Figure 6 shows the shape and dimensions of the 0.25 tank as well as the computational mesh used to analyze the propellant motion within it. The analyses were performed for a tank 50 percent full of liquid hydrogen with all of the propellant initially collected at the top of the tank. Figure 6 shows the corresponding shape of the initial free surface. Figure 7 displays a sequence of flow fields which occur during the reorientation process with a  $8 \times 10^{-3}g$  settling force. The liquid leading edge moves rapidly towards the bottom of the tank. A large geyser forms within 8 sec of thrust initiation. The geyser is so severe that the liquid rebounds from the top of the tank before collecting into a pool after approximately 16 sec has elapsed. The liquid motion has been so violent significant vapor pockets have been encapsulated in the pool.

If this process occurred in a real propulsion application, it might be necessary to extend the thruster firing period to insure that the vapor pockets are expelled from the pool before the main rocket is started.

I. Sumner's report indicates that optimal reorientation for the 0.25 tank should occur for an acceleration level of approximately  $3.6 \times 10^{-3} \text{ cm/s}^2$ , ( $3.7 \times 10^{-5}g$ ). This level is predicted to be optimal in the sense that it minimizes expenditure of propellant. Figure 8 presents a sequence of flow fields

corresponding to this acceleration level. The liquid moves smoothly toward the bottom of the tank collecting into a sizeable pool within 1.5 min. A moderate geyser was formed but fewer vapor pockets were trapped within the pool. After approximately 3 min, almost all of the liquid has collected in the bottom of the tank. I. Sumner (ref. 7) proposed that the reorientation process be judged complete when either the geyser settles back into the pool or the liquid film has cleared the tank wall. The propellant expenditure to accomplish reorientation is roughly proportional to the vehicle delta-v incurred during reorientation. The value to delta-v is easily computed by multiplying the specified acceleration by the elapsed time required to accomplish reorientation. Using the RCS thrusters results in a vehicle delta-v of 125 cm/s whereas the optimal acceleration level corresponds to a delta-v of 6.5 cm/s, a fuel savings factor of almost 20:1.

As the design of COLD-SAT evolved, the tank scale and shape were changed to more accurately emulate current OTV design concepts and to minimize tank thermal mass. The resulting tank geometry is presented in figure 9. This is a 0.215-scale model of a tank known as the Boeing Short SB OTV. Analyses therefore shifted to this new tank using the computational mesh shown in figure 9. Acceleration environments between  $2 \times 10^{-5}$  and  $1 \text{ cm/s}^2$  were studied for a tank 50 percent full of liquid hydrogen. Figure 10 presents a sequence of flow field depicting the reorientation process for an imposed acceleration of  $3.92 \times 10^{-2} \text{ cm/s}^2$  ( $4.00 \times 10^5 \text{ g}$ ). Settling time and vehicle delta-v were focused upon as the key parameters representing settling performance.

Settling time is of obvious interest for the scheduling of orbital maneuvers. Vehicle delta-v is used as measure of efficiency since it is directly correlated to the propellant expenditure. Figure 11 displays the relationship predicted between settling time and acceleration level. The anomalous settling times encountered at some of the lower accelerations have not yet been fully investigated, but are believed to be a resonance between the acceleration level and the geyser rise velocity. A somewhat arbitrary settling criteria was used in this study and may also contribute to anomalous settling times. Figure 12 displays the relationship between vehicle delta-v and acceleration level.

#### FULL-SCALE OTV TANK

Upon completion of the small-scale tank analyses, attention was focused on a full-scale Boeing Short SB OTV. Modeling of the reorientation processes in this tank covered a range of acceleration environments from  $1.57 \times 10^{-4} \text{ cm/s}^2$  ( $1.60 \times 10^{-7} \text{ g}$ ) to  $7.85 \times 10^{-1} \text{ cm/s}^2$  ( $8.00 \times 10^{-4} \text{ g}$ ) and included tanks 25, 50, and 75 percent filled with liquid hydrogen. The same mesh was used for these analyses as was used for the scale model of the same shape. Figure 13 shows a sequence of velocity fields predicted for a 75 percent full tank subject to an imposed acceleration environment of  $1.96 \times 10^{-2} \text{ cm/s}^2$  ( $2.00 \times 10^{-5} \text{ g}$ ). Figures 14 to 16 display the relationship between settling time and acceleration level for the three fill levels. Again, anomalies are encountered at the lower accelerations. Figures 17 to 19 display the relationship between vehicle delta-v and acceleration level. The trends are not surprising, but ECLIPSE now provides a far more accurate tool for trading settling time versus propellant expenditure than was previously available.

## DIMENSIONLESS SCALING OF REORIENTATION

Since ECLIPSE provides a tool capable of modeling the reorientation process in both scale model tanks and full-scale tanks, it became possible to search for a dimensionless parameter capable of scaling experimental results from small-scale tanks to full-scale spacecraft tanks. In particular, the results for the scale model Boeing SB OTV tank and for the full-scale tank were used as the basis for this investigation. Following the investigators, the first attempt at correlation used the Bond number based on tank diameter as the scaling parameter. The data did not collapse using this scaling parameter.

Various combinations of what were thought to be the relevant dimensionless variables (Bo, We, Fr, Re) were tried. The most successful attempt at correlating delta-V was a nondimensional grouping this paper defines as settling number.

$$Se = \frac{\mu(Ra)^{1/2}}{\sigma} = \text{Settling Number} \quad (5)$$

The Settling Number can be written as a function of more recognized dimensionless parameters:

$$Se = \frac{(BoWe)^{1/2}}{Re} \quad (6)$$

When viewed in this light, it is seen as representing the ratio of viscous and gravitational forces to surface tension forces.

The proof of a proposed correlating parameter is in the viewing the results. Figure 20 shows the relationship between vehicle delta-v and Se for the Boeing Short SB OTV with a tank filling of 50 percent. A single straight line passes through all 24 data points. Unfortunately, the analyses performed for the scale model tank included only a few cases with 25 and 75 percent fillings. Although these analyses also correlate into a straight line, they are too few to claim as support for the correlating parameter. They are however distinctly different lines from each other and from the 50 percent case. Therefore, it appears that Se is a suitable correlating parameter for relating reorientation performance from small-scale to full-scale geometrically similar tanks, containing the same fluid and with the same volume fraction of liquid.

## SUMMARY OF RESULTS

The ECLIPSE Code has been used to model the process of impulsive reorientation. The accuracy of computational predictions was evaluated by comparison to experimentally obtained data for reorientation in small-scale tanks with shapes typical of spacecraft propellant tanks. The model correctly predicted the extent of geyser formation and the elapsed time required to accomplish settling. Based on the comparisons, ECLIPSE was judged to be a suitable tool for studying impulsive reorientation in cryogenic propellant tanks.

Reorientation of liquid hydrogen in flight experiment tanks was analyzed. These tanks have elliptical heads connected by a cylindrical barrel section and are representative of vehicle propellant tanks. ECLIPSE was able to model the reorientation without difficulty and provided significant insight into the process. For one tank, it was demonstrated that if the existing design was



replaced with one producing an optimal acceleration environment, propellant expenditure could be reduced by a factor of almost 20. For the other tank a range of acceleration environments was investigated and a summary of the results is reported.

Reorientation in a full-scale OTV tank was modeled for three different tank fillings across a range of acceleration environments. A summary of the results for these cases is presented.

A dimensionless parameter called the Settling number,  $Se$ , is proposed for correlating the reorientation process between geometrically similar tanks with the same liquid volume fraction. To test the proposed parameter, computational predictions of vehicle delta-v acquired during settling for a full-scale spacecraft tank and for a 0.215-scale model were plotted against  $Se$ . All data points fall into a single straight line, supporting the validity of  $Se$  as the appropriate correlating parameter.

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TABLE I. - I.E. SUMNER'S TEST CONDITIONS MODELED USING ECLIPSE

Test	R, cm	FR	Fluid	FL, percent	a, cm/sec <sup>2</sup>	Bo	Geyser
1	1.65	4.00	TCTFE	71	16.7	3.9	Small
5	2.00	2.25	Ethanol	62	29.4	4.2	Small
6	2.00	2.25	Ethanol	29	29.4	4.2	Large
7	2.00	2.25	Methanol	51	29.4	4.1	Moderate
8	2.00	2.25	Methanol	33	29.4	4.1	Large
12	3.22	2.14	Ethanol	71	10.8	4.0	None

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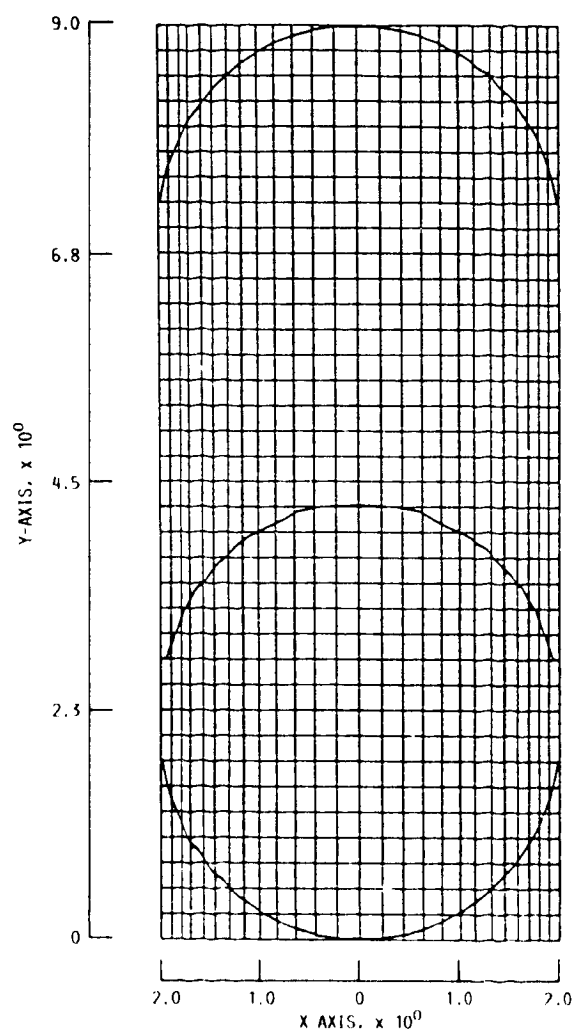


FIGURE 1. TYPICAL COMPUTATIONAL MESH FOR SMALL  
SCALED TANKS.

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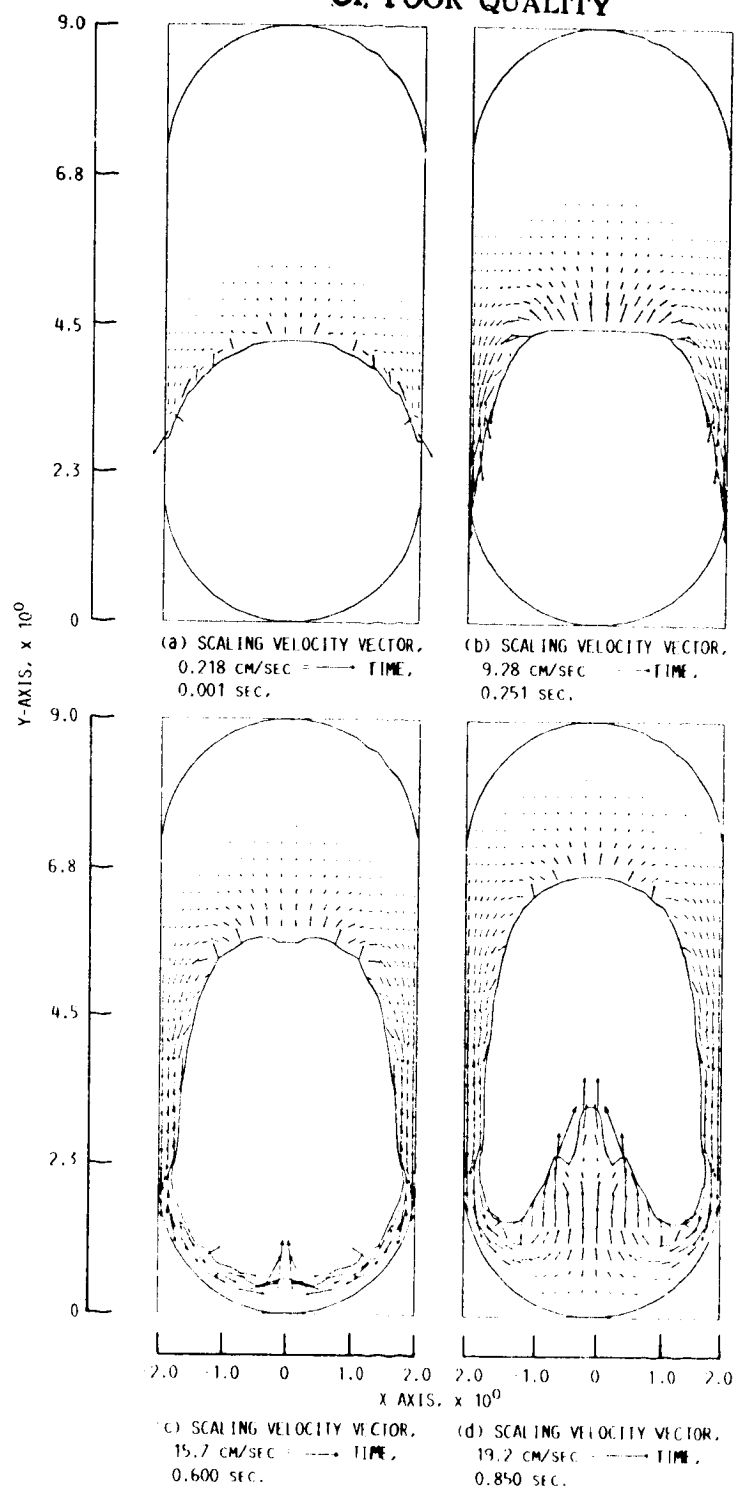


FIGURE 2. PROPELLANT MOTION FOR TEST 5; NOTE: VELOCITY VECTORS  
SCALED TO MAXIMUM VELOCITY IN FIELD.

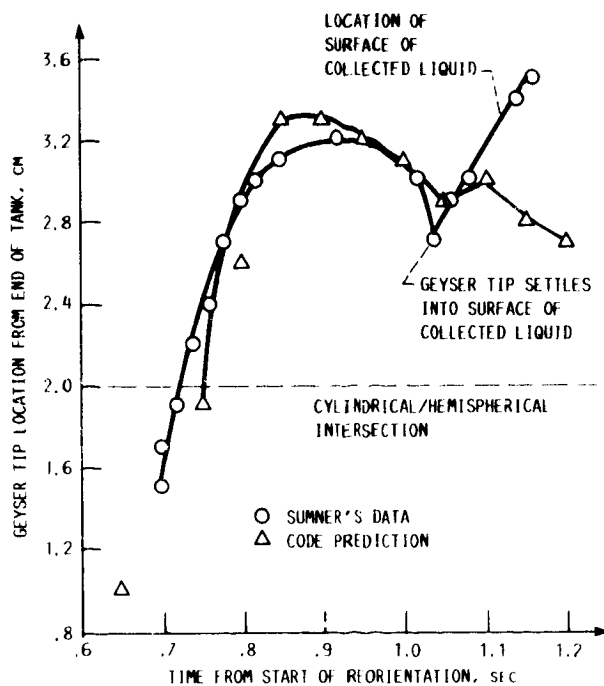


FIGURE 3. - GEYSER TIP LOCATION VERSUS TIME FOR TEST 5.

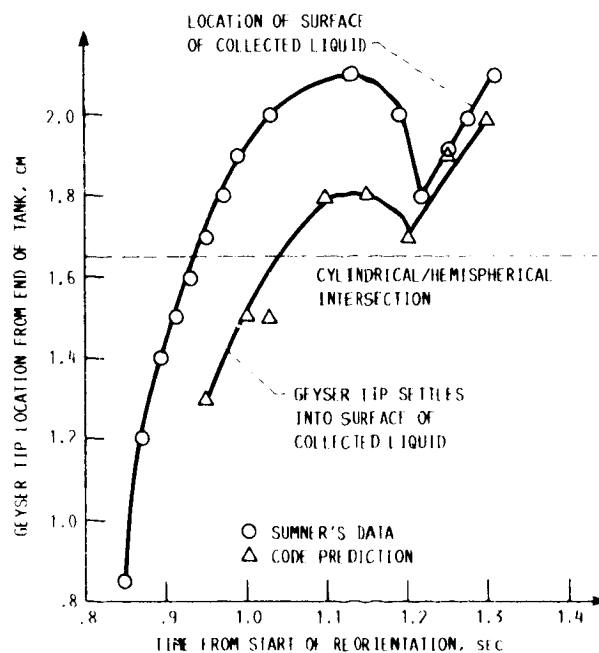


FIGURE 4. GEYSER TIP LOCATION VERSUS TIME FOR TEST 1.

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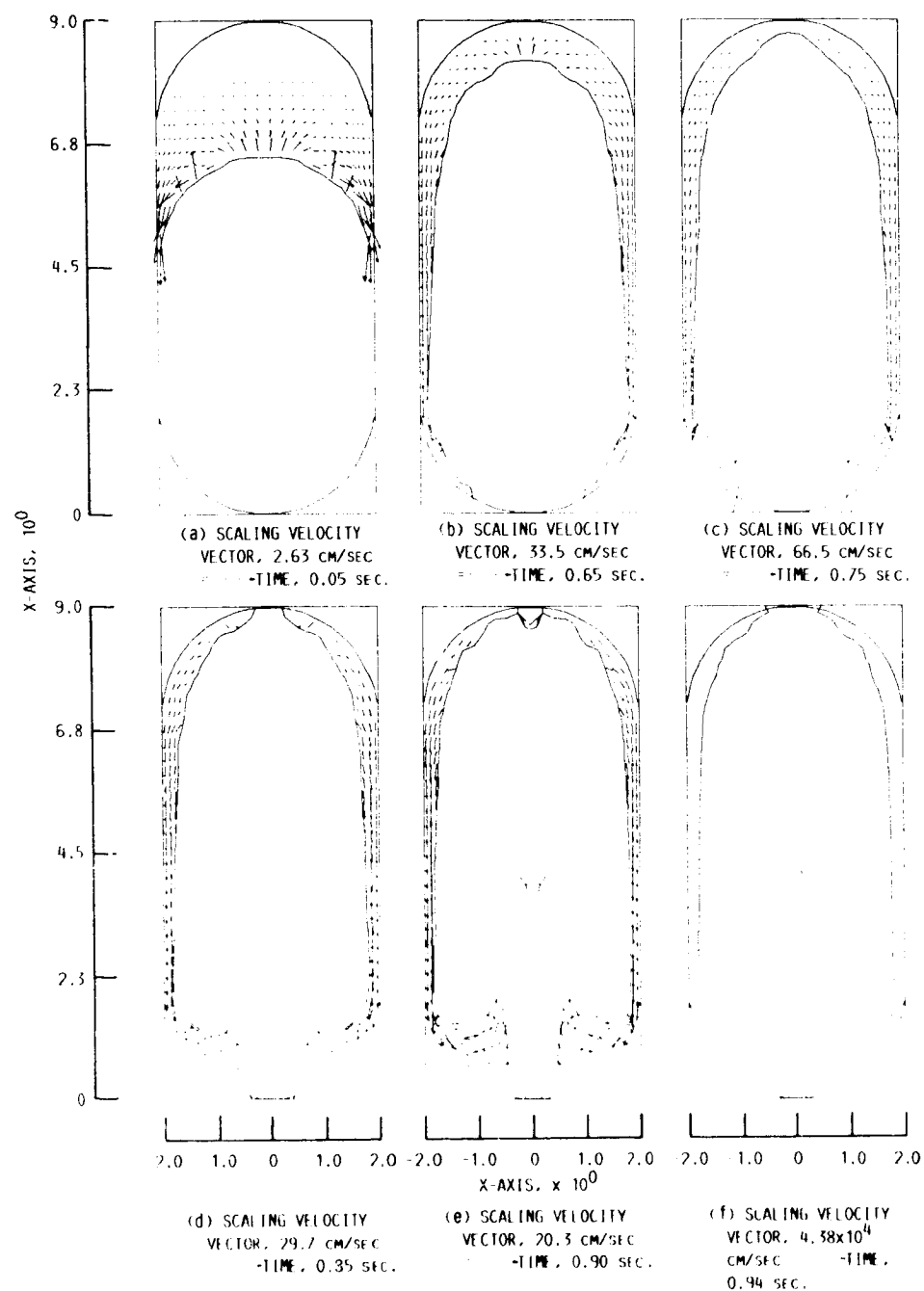


FIGURE 5. - PROPELLANT MOTION FOR TEST 8.

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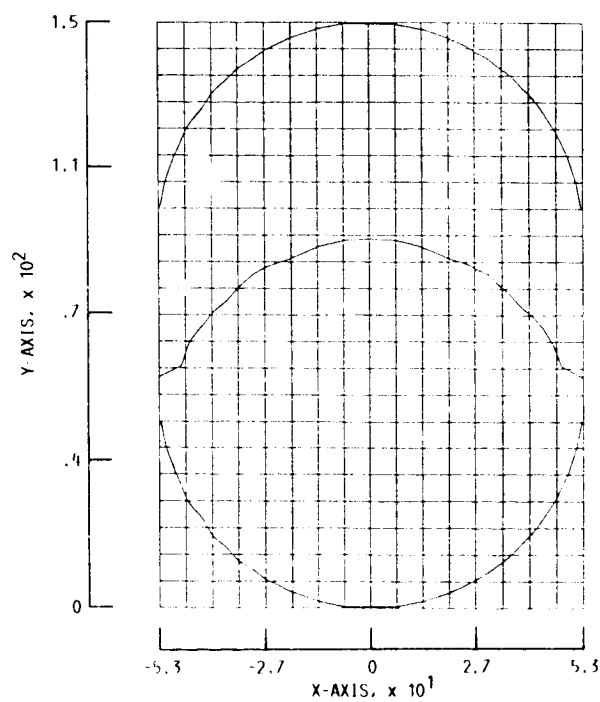


FIGURE 5. - BOEING SB OTV PROPELLANT TANK, 0.25 SCALE.

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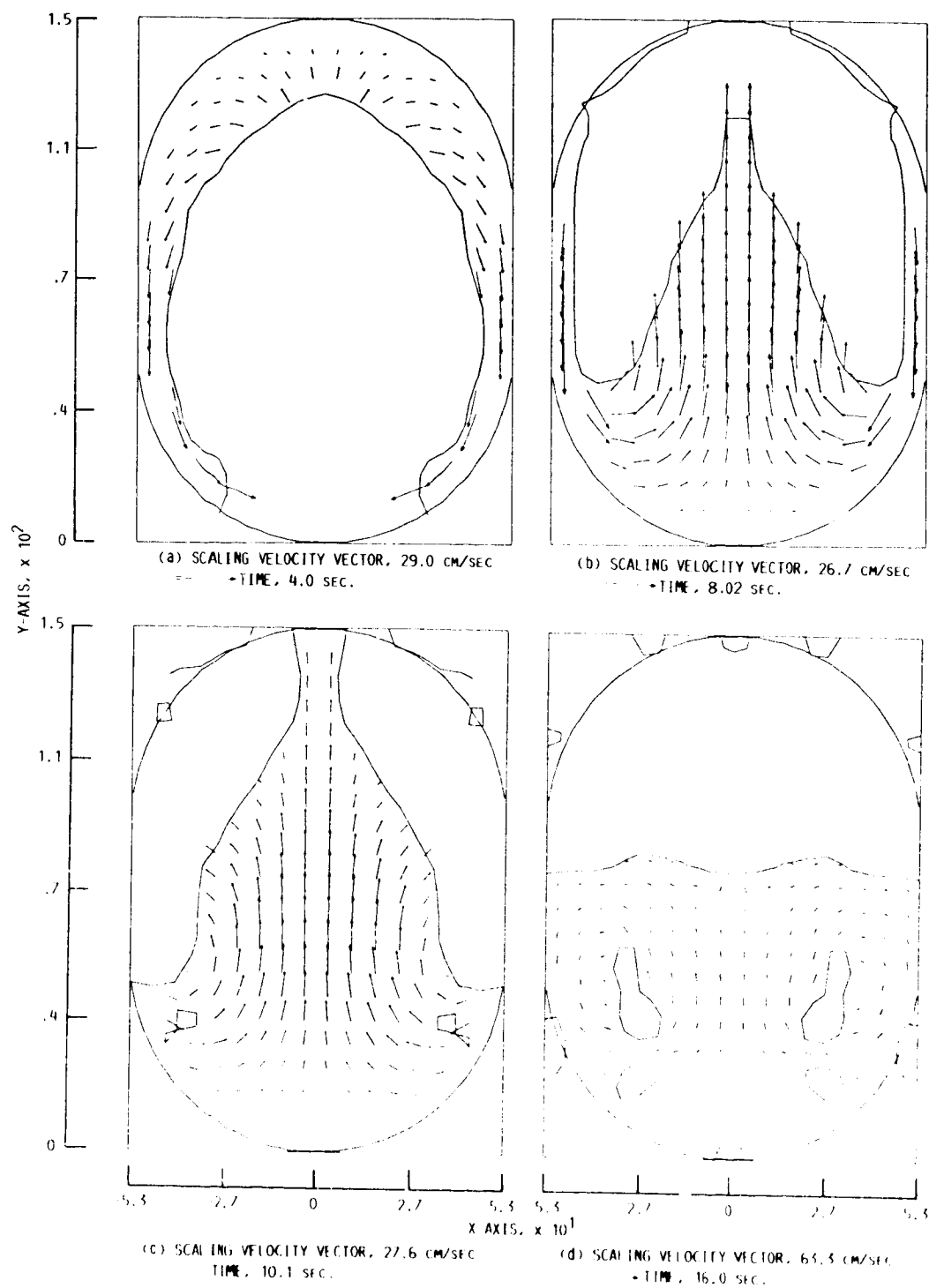


FIGURE 7. - PROPELLANT MOTION WITH A  $8.0 \times 10^5$ ; NOTE: VELOCITY VECTORS SCALED TO MAXIMUM VELOCITY IN FIELD.



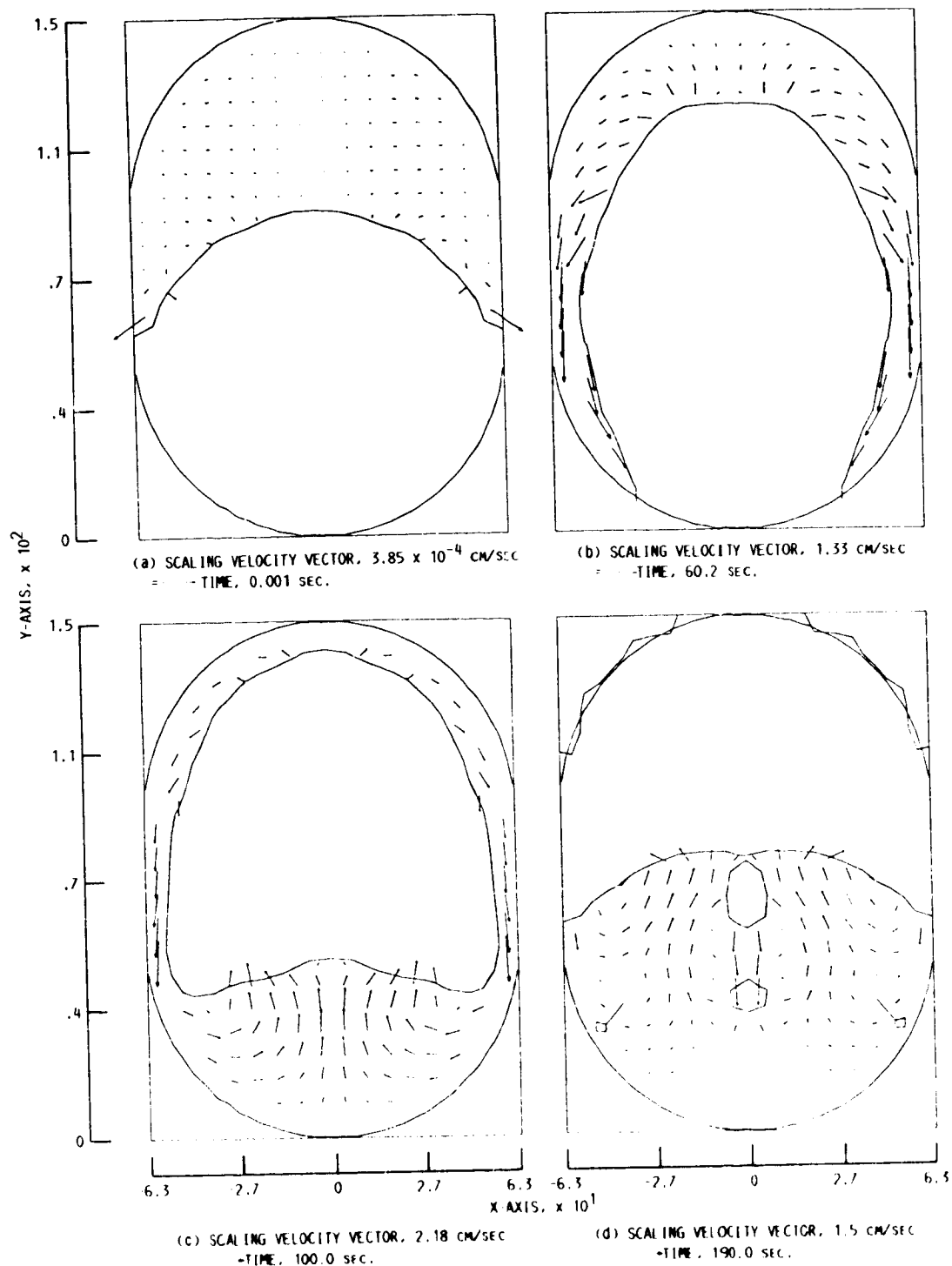


FIGURE 8. - PROPELLANT MOTION WITH  $A = 3.7 \times 10^5 G$ ; NOTE: VELOCITY VECTORS SCALED TO MAXIMUM VELOCITY IN FIELD.

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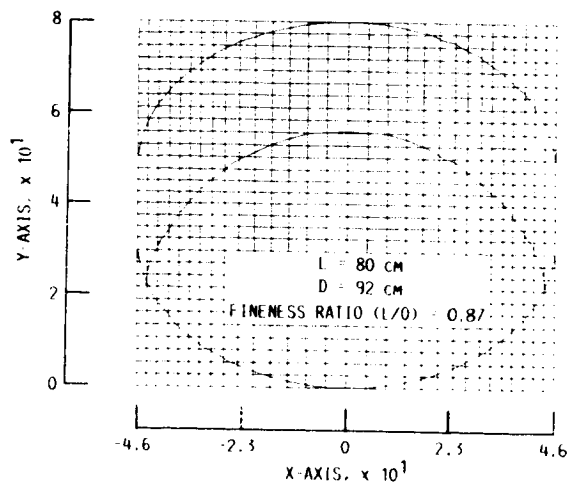


FIGURE 9. - BOXING SHORT SB OTV PROPELLANT TANK.  
0.215 SCALE.

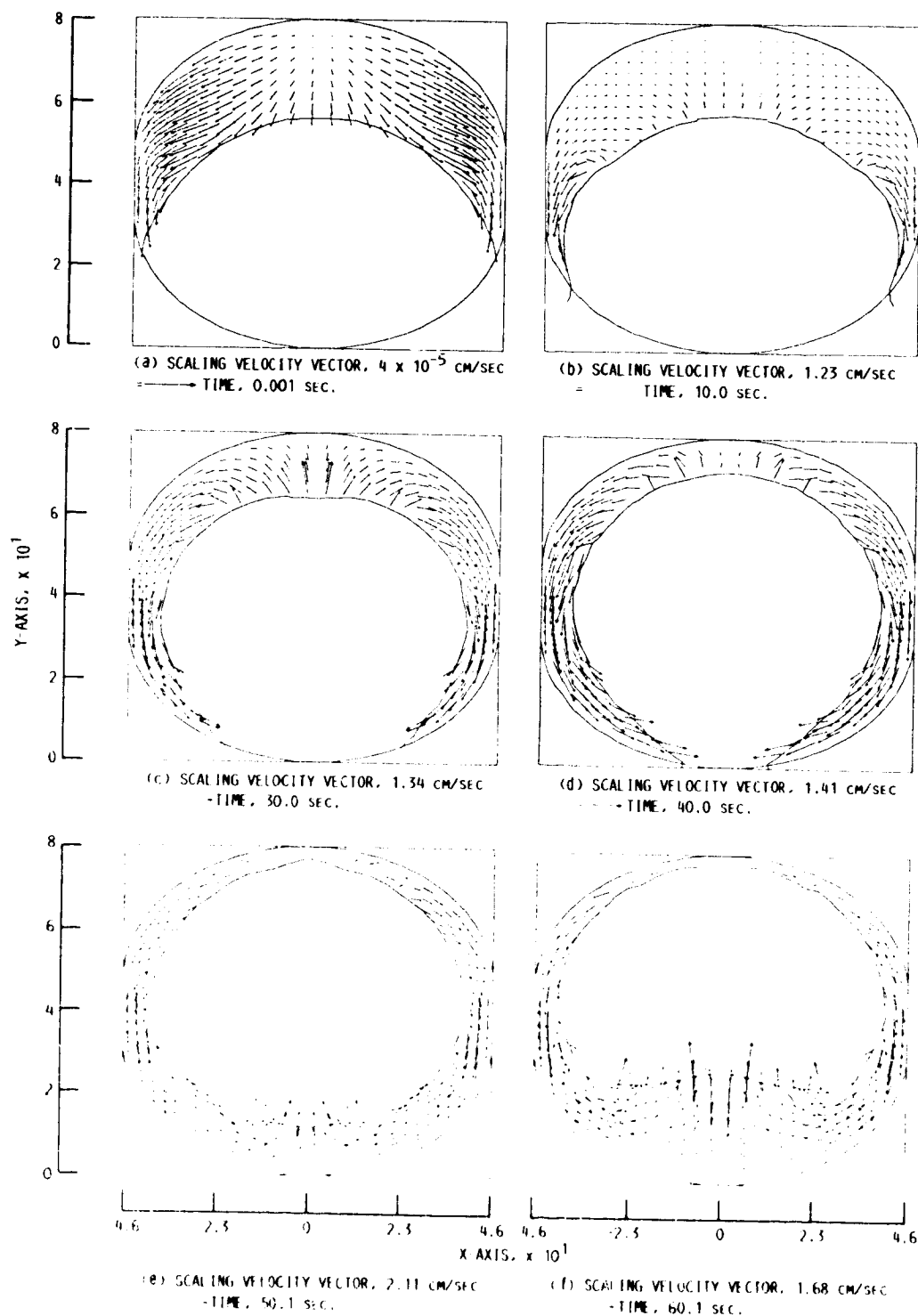


FIGURE 10. PROPELLANT MOTION FOR 0.215 SCALE BORING SB OTV (50% FULL, IMPOSED ACCELERATION IS  $5.32 \times 10^2$  CM/S<sup>2</sup>).

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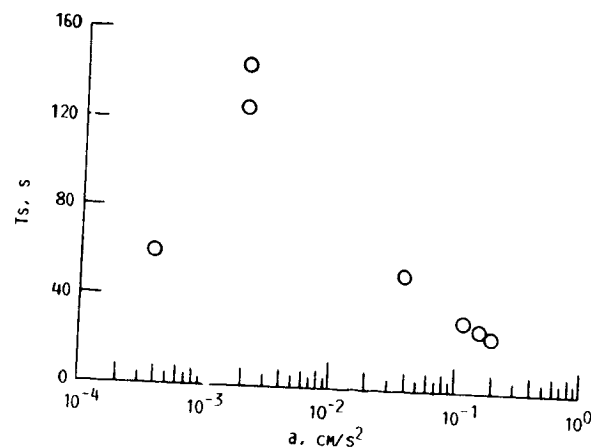


FIGURE 11. - SETTLING TIME VERSUS ACCELERATION, SMALL-SCALE TANK; FILL LEVEL = 50 PERCENT.

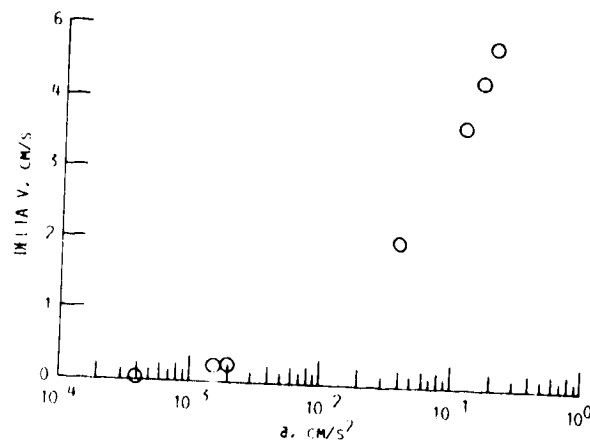


FIGURE 12. DELTA V VERSUS ACCELERATION, SMALL SCALE TANK; FILL LEVEL = 50 PERCENT.

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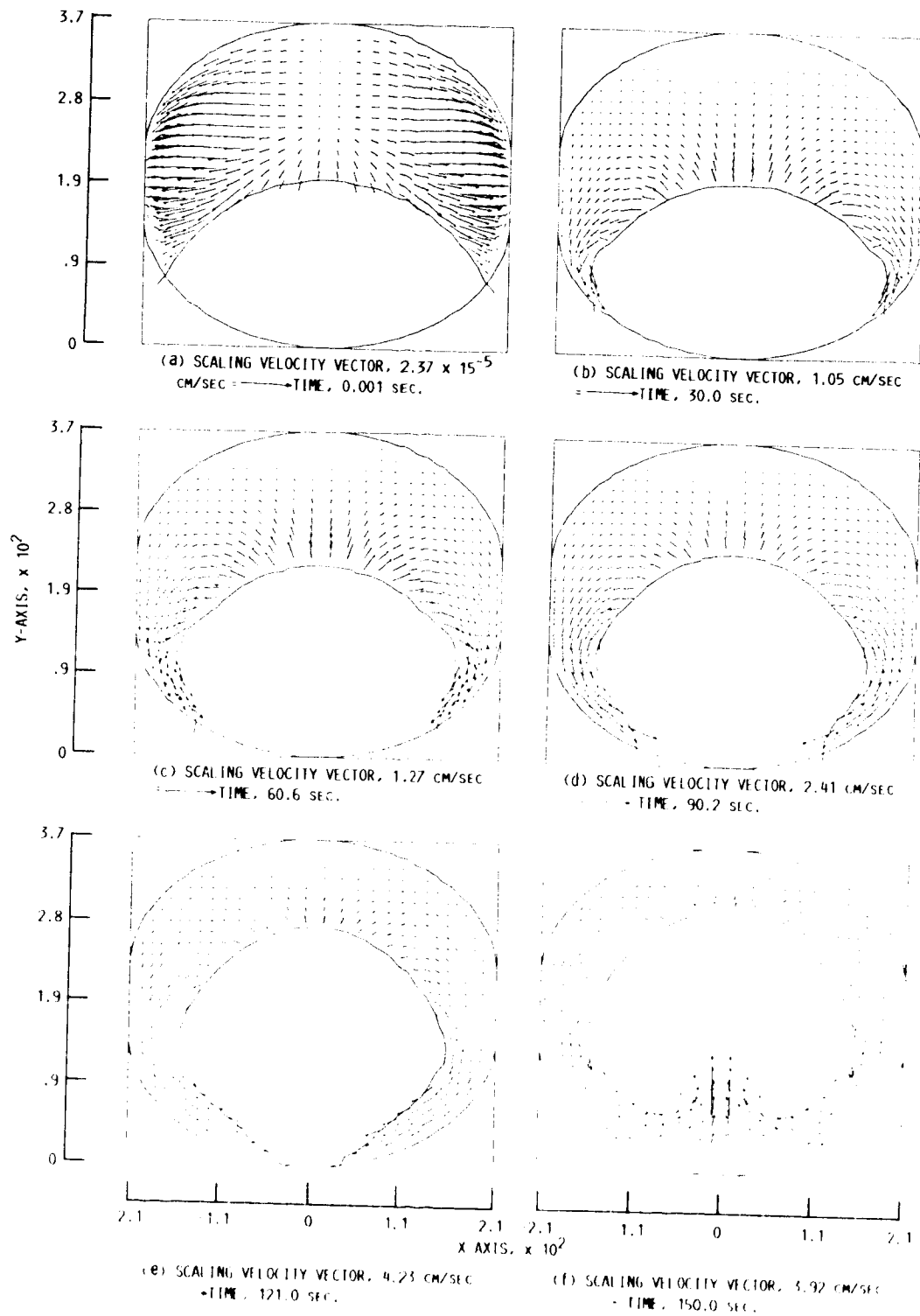


FIGURE 15. PROPELLANT MOTION FOR FULL SCALE BOILING SB OTV (75 PERCENT FULL,  $1.96 \times 10^{-2}$  CM/S<sup>2</sup>).

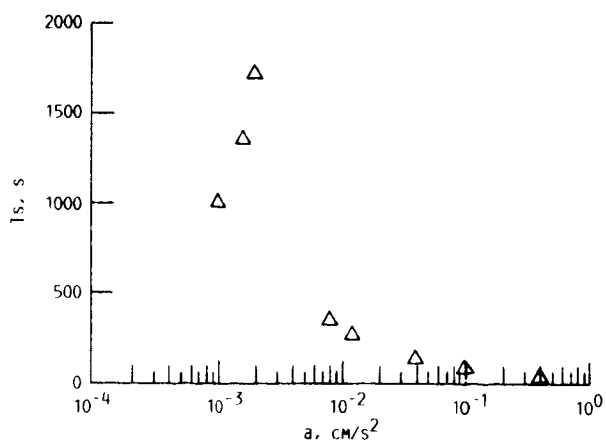


FIGURE 14. - SETTLING TIME VERSUS ACCELERATION, FULL-SCALE TANK; FILL LEVEL = 25 PERCENT.

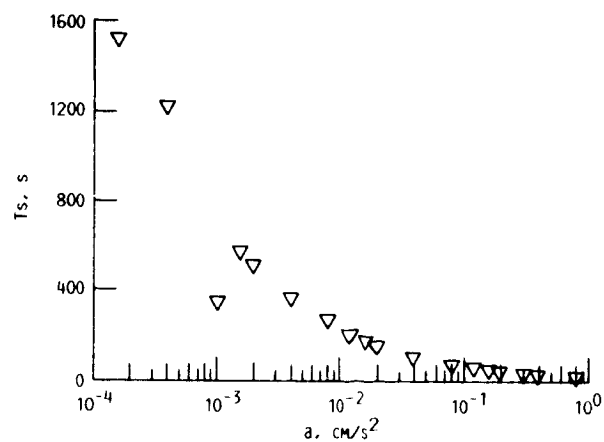


FIGURE 15. - SETTLING TIME VERSUS ACCELERATION, FULL-SCALE TANK; FILL LEVEL = 50 PERCENT.

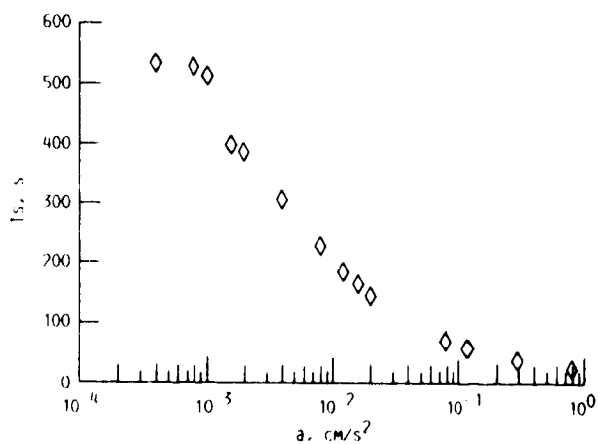


FIGURE 16. - SETTLING TIME VERSUS ACCELERATION, FULL-SCALE TANK; FILL LEVEL = 75 PERCENT.

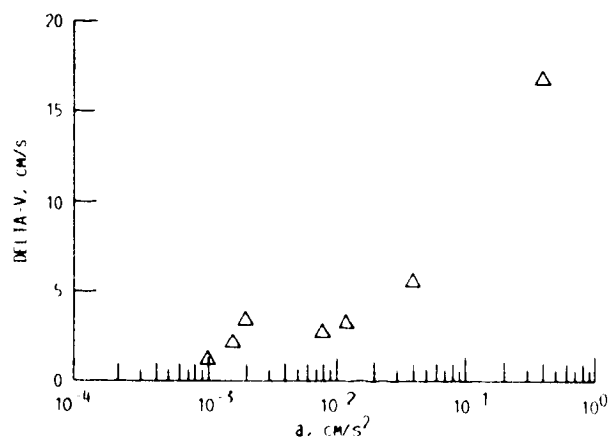


FIGURE 17. - DELTA V VERSUS ACCELERATION, FULL-SCALE TANK; FILL LEVEL = 25 PERCENT.

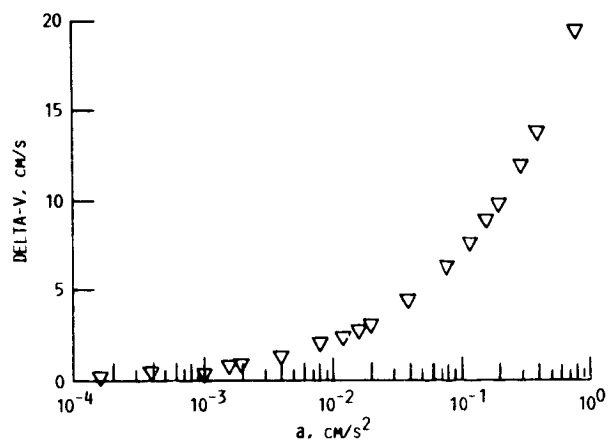


FIGURE 18. - DELTA-V VERSUS ACCELERATION, FULL-SCALE TANK; FILL LEVEL = 50 PERCENT.

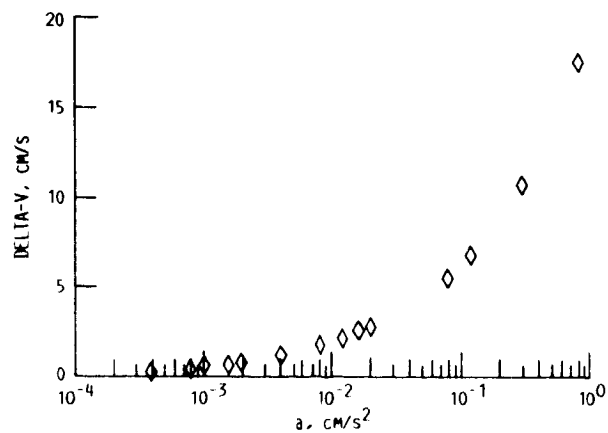


FIGURE 19. - DELTA-V VERSUS ACCELERATION FULL-SCALE TANK; FILL LEVEL = 75 PERCENT.

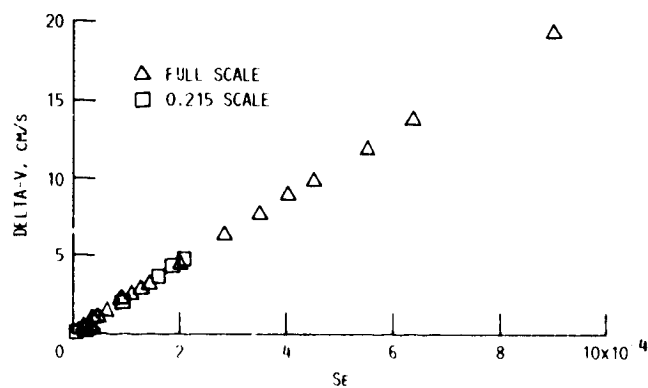


FIGURE 20. - DELTA-V VERSUS  $S_e$ , FILL LEVEL 50 PERCENT.

# Report Documentation Page

1. Report No. <b>NASA TM-101440 AIAA-89-0628</b>	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle <b>Modeling of Impulsive Propellant Reorientation</b>	5. Report Date	
	6. Performing Organization Code	
7. Author(s) <b>John I. Hochstein, Alfredo E. Patag, and David J. Chato</b>	8. Performing Organization Report No. <b>E-4545</b>	
	10. Work Unit No. <b>506-48-21</b>	
9. Performing Organization Name and Address <b>National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191</b>	11. Contract or Grant No.	
	13. Type of Report and Period Covered <b>Technical Memorandum</b>	
12. Sponsoring Agency Name and Address <b>National Aeronautics and Space Administration Washington, D.C. 20546-0001</b>	14. Sponsoring Agency Code	
15. Supplementary Notes <b>Prepared for the 27th Aerospace Sciences Meeting sponsored by the American Institute of Aeronautics and Astronautics, Reno, Nevada, January 9-12, 1989. John I. Hochstein and Alfredo E. Patag, Washington State University in St. Louis, Mechanical Engineering Department, Campus Box 1185, One Brookings Drive, St. Louis, Missouri 63130 (work funded under NASA Grant NAG3-578); David J. Chato, NASA Lewis Research Center.</b>		
16. Abstract <b>The impulsive propellant reorientation process is modeled using the ECLIPSE Code. A brief description of the process and the computational model is presented. Code validation is documented via comparison to experimentally derived data for small-scale tanks. Predictions of reorientation performance are presented for two tanks designed for use in flight experiments and for a proposed full scale OTV tank. A new dimensionless parameter is developed to correlate reorientation performance in geometrically similar tanks. Its success is demonstrated.</b>		
<div>17. Key Words (Suggested by Author(s))</div> <div>Propellant orientation</div> <div>Low gravity fluid mechanics</div>		
<div>18. Distribution Statement</div> <div>Unclassified - Unlimited</div> <div>Subject Category 20</div>		
19. Security Classif. (of this report) <b>Unclassified</b>	20. Security Classif. (of this page) <b>Unclassified</b>	21. No. of pages <b>24</b>
		22. Price <b>A03</b>