EXPERIMENTAL INVESTIGATION OF LIQUID IMPACT IN A MODEL PROPELLANT TANK

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SUMMARY

An experimental investigation was conducted to assess the problem of liquid impact in booster and space-vehicle propellant tanks. A partially filled cylindrical tank with hemispherical ends was subjected to sudden reversals in axial acceleration. The liquid behavior was observed, the structural loads were measured, and methods of impact attenuation were evaluated. Variables included: tank acceleration, initial condition of the liquid free surface, baffle configuration, and a range of liquid viscosity, vapor pressure, and surface tension.

The liquid response was found to be highly dependent upon the behavior of the free surface just prior to the change in acceleration. A "geysering" action was observed when the surface was initially quiescent whereas a continuous flow around the walls and bulkhead was observed in cases where a slosh mode was present. The magnitude of the impact was attenuated appreciably by screen baffles but was insensitive to changes in liquid viscosity, vapor pressure, and surface tension. The impact loads observed in these tests, however, do not appear to be of sufficient magnitude to pose a significant structural problem.

INTRODUCTION

The dynamic behavior of liquid propellants has been the subject of numerous investigations. In general, efforts have been concentrated on the oscillatory behavior of the liquid surface (slosh) and the effects of this motion on the control and structural response of the vehicle. Recently, however, concern has developed over a somewhat different type of problem, that of liquid impact. The problem of interest involves the impulsive movement or surge of the propellant mass from the aft end of the tank to the forward bulkhead due to an effective "thrust reversal." There are several conceivable situations which could constitute such a thrust reversal. These range from maneuvering or docking in deep space to a termination of thrust in the atmosphere. At present, attention has been centered on the latter case of thrust termination either intentionally (abort) or unintentionally (engine failure or premature ignition during staging). Upon removal of the thrust, the predominant force acting on the vehicle is that of the aerodynamic drag which opposes the vehicle motion. This reversal of force occurs over a very short period of time and thus the vehicle experiences a rapid change in magnitude and direction of acceleration.

The liquid, however, has a tendency to proceed forward during deceleration of the vehicle and impact the forward bulkhead. Such an impact may rupture the upper dome, cause a structural break-up, and, in the case of hypergolic fuels, may result in a fireball.

Although no comprehensive study of liquid impact phenomena has been conducted, certain aspects of the problem have been examined either analytically or experimentally. The initial effort in this area (ref. 1) was an experimental investigation of the impact pressures resulting from decelerations (ranging from 10g to 50g) of a small model. The model design was based upon the results of a dimensional analysis in which an attempt was made to simulate conditions in a 6-foot-diameter (183 cm), 12-foot-long (366 cm) prototype tank. Results indicated that peak pressures were approximately proportional to tank deceleration and were greater for cases wherein the tank and "thrust vector" were inclined to the vertical. Since the general extrapolation of these results to large vehicles was questionable, an attempt was made (ref. 2) to examine the problem analytically. A preliminary analysis utilizing an assumed spring mass model indicated that damaging stress levels could result from thrust termination over certain portions of a flight trajectory. In view of these results, the present investigation was initiated in an attempt to obtain a better definition of the phenomena and the associated problem areas.

A partially filled cylindrical tank with hemispherical ends was subjected to sudden reversals in axial acceleration. The liquid behavior was observed, the structural loads were measured, and the methods of impact attenuation were evaluated. Variables included: tank acceleration, initial condition of the liquid free surface, baffle configuration, and a range of liquid viscosity, vapor pressure, and surface tension. The results of this investigation are reported herein.

A motion-picture film supplement illustrating the behavior of the liquid is available on loan. A request card and a description of the film are included at the back of this document.

SYMBOLS

The units used for the physical quantities defined in this paper are given both in U.S. Customary Units and in the International System of Units (SI) (ref. 3). The following table presents factors relating these two systems of units:

U.S. Customary Unit	Conversion factor (*)	SI unit
ft	0.3048	meters
lbf	4.448	Newton
slug	14.594	kilogram
centipoise	0.001	Newton second/meter^2
$^{\circ}$Fahrenheit + 459.67	5/9	$^{\circ}$Kelvin

*Multiply value in U.S. Unit by conversion factor to obtain equivalent value in SI unit.

a	acceleration, ft/sec^2 (m/sec^2)
N_{Eu}	Euler number
F	force, lb (N)
g	gravitational acceleration on earth, ft/sec^2 (m/sec^2)
l	length, ft (m)
n	integer
p	pressure, lb/in^2 (N/m^2)
P	period, sec
N_{Re}	Reynolds number
t	time, sec
V	liquid volume, ft^3 (m^3)
v	velocity of tank, ft/sec (m/sec)
N_{We}	Weber number
μ	kinematic viscosity, centipoise (Ns/m^2)
ρ	liquid density, slug/ft^3 (kg/m^3)
σ	surface tension, (N/m)
ω	circular frequency, radians/sec

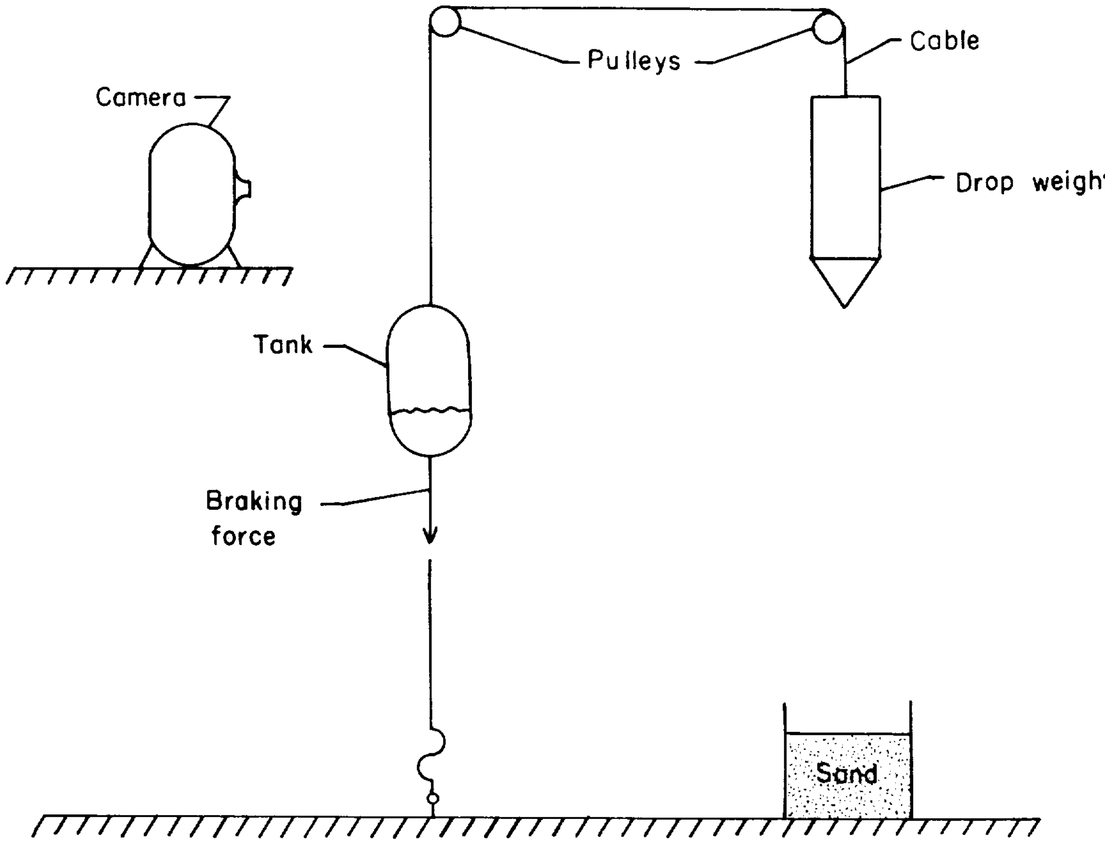
Subscripts:

f	full scale
m	model
rel	relative
0,1,2	denote specific times

APPARATUS AND TEST PROCEDURE

Impact Simulator

The apparatus used to simulate the liquid impact conditions is shown schematically in sketch (a). Basically, it consisted of an 8.5-inch-diameter



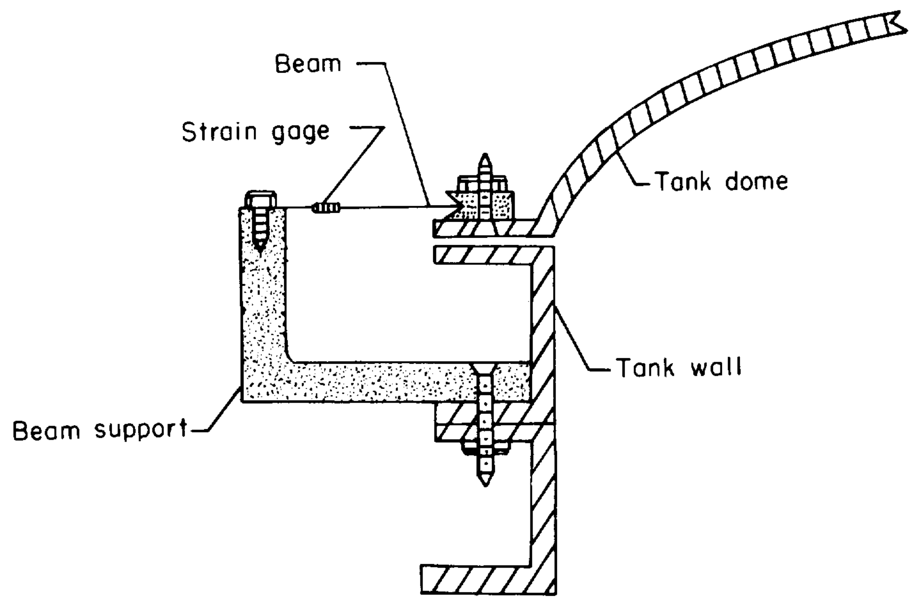
Sketch (a).- Schematic representation of impact simulator.

(21.6 cm) tank partially filled with water (36 percent by volume). The tank was attached to a 100-pound (45.36 kg) drop weight by means of a steel cable passing over a system of pulleys. The forces were applied to the tank through support rings (fig. 1(a)) which were attached to the cylindrical section; thus, the upper bulkhead loading was due to the liquid impact and dome inertia only. Upon release of the drop weight, the tank was accelerated upward and reached a velocity proportional to the release height of the weight. Upon impact of the drop weight, an arresting force was applied to the tank with an elastic cable and caused the tank to decelerate with respect to the liquid. Because of the elastic nature of the arresting cable, which remained slack until impact of the drop weight, the deceleration started from 0 g and was a function of the tank displacement. A short period of time existed between the upward acceleration and the maximum deceleration and simulates to a degree the acceleration time history of a vehicle experiencing a thrust termination.

Tank and Instrumentation

Details of the tank and instrumentation are shown in figure 1. The tank, 8.5 inches (21.6 cm) in diameter and 15.5 inches (39.4 cm) in overall length, was constructed of 1/8-inch-thick (0.3 cm) transparent plastic to facilitate visual observations and high-speed motion-picture studies of the fluid motions. It is made up of four flanged cylindrical sections and two flanged hemispherical ends. This type of construction facilitated the installation of baffles at the section interfaces as shown in figure 1(b). Baffle configurations consisted of flat rings having a 0.15-inch (0.4 cm) internal protrusion and screen baffles of 1/4-inch (0.6 cm) mesh that completely spanned the tank cross section.

The instrumentation consisted of an accelerometer rigidly attached to the base of the tank frame, a pressure cell mounted flush in the center of the upper dome, and six force transducers located around the circumference of the tank. The force transducers consisted of thin strain gaged beams fixed to the cylindrical section. These beams supported the dome as shown in sketch (b).



Sketch (b).- Force transducer.

In its equilibrium position, a slight clearance existed between the dome and cylinder to allow freedom in pitch as well as vertical translation. The stiffness of the beam springs was such that the dome displacements were relatively small and the frequency high. The data from the transducers were recorded on an oscillograph and supplemented with high-speed motion pictures of the liquid.

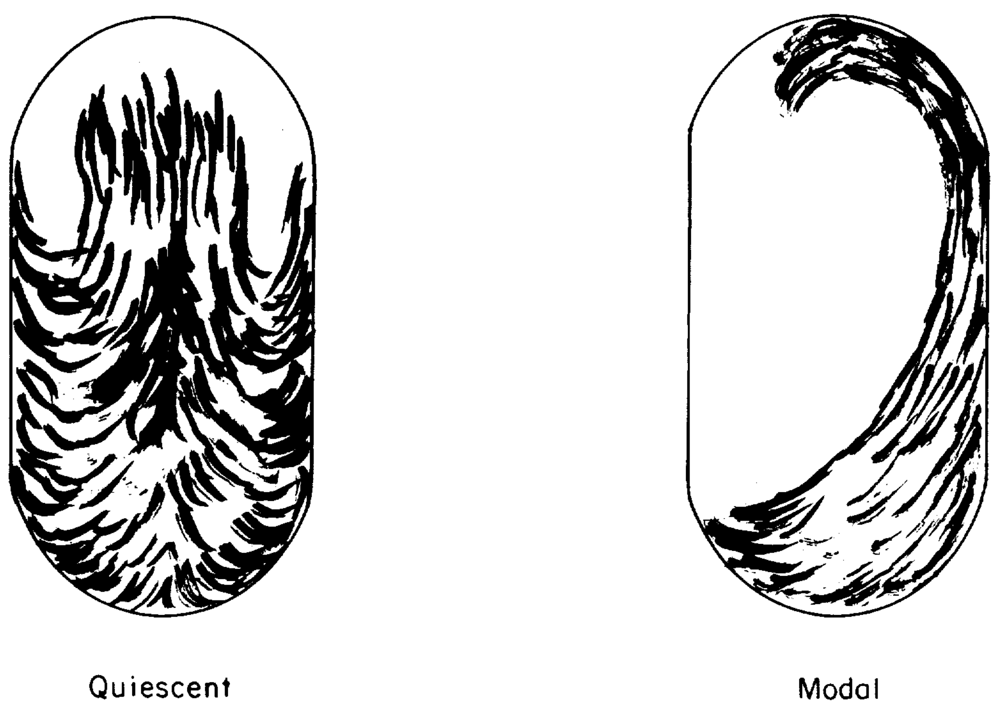
Procedure and Measurements

The sequence of events and the type of data recorded are illustrated with the schematic time history (fig. 2). Shown is the accelerometer trace and one of the six recorded force outputs. The acceleration trace, with time running from left to right, reveals the release of the drop weight and vertical ascent of the tank which results in the level of acceleration existing prior to t_0, the time of impact of the drop weight. At time t_0, both the tank and liquid experience 0g, and, in addition, the tank has the deceleration resulting from the elastic cable superimposed. In subsequent discussions, the difference between the tank acceleration level and the 0g or "free-liquid acceleration level" is called the relative acceleration. It is not implied or assumed that all the liquid is in free fall or 0g during the time interval prior to its contact with the dome, but it is believed that the liquid particles in transit between the surface and the dome prior to impact are essentially in free fall.

The impact force corresponding to the acceleration trace is also shown in figure 2. The slight rise in force at t_0 is due to the inertia of the dome. With a further increase in time, particles reach the dome and a gradual increase in force is noted, the increase reaching a maximum at t_1. The force then decreases rapidly and approaches zero at t_2, the time of "zero" relative acceleration and the conclusion of the test. Further details of the time history are presented and discussed with the presentation of the data.

Test Program

"Quiescent" force and pressure measurements as well as "modal" force and pressure measurements were taken for a series of drop heights and arresting-cable spring constants. The term quiescent refers to cases where the liquid surface was essentially undisturbed prior to arrest and modal refers to cases where the liquid was oscillating in its fundamental antisymmetric sloshing mode



Sketch (c).- Liquid behavior following thrust reversal for quiescent and modal initial surface conditions.

at the time of tank arrest. These two initial conditions and their associated flow patterns following tank deceleration are clearly visible in the motion pictures which were obtained during the tests. The basic fluid motions are also shown in sketch (c). Tank and liquid variables included: the smooth-wall or unbaffled condition; tank fitted with simulated "Z-ring" baffles; the 1/4-inch (0.6 cm) screen or mesh baffles; and a range of liquid viscosity, vapor pressure, and surface tension.

PRESENTATION AND DISCUSSION OF RESULTS

Impact Force

Impact-force data obtained with the smooth-wall tank are shown in figure 3. The peak forces associated with modal and quiescent impacts are presented along with the relative acceleration which existed at the time of maximum impact force. It is noted that the force increases with acceleration and, presented in this manner, forces associated with the modal and quiescent impacts show essentially the same relationship to acceleration. The liquid behavior, however, is very different in the two cases. If the surface is initially quiescent, a series of particles and streamers leave the surface and travel to the dome, but if the surface is oscillating as in the modal case, the liquid travels up one wall around the dome and back down the opposite wall as illustrated in sketch (c).

The force data points presented in figure 3 were obtained by averaging the peak outputs of the six transducers. This technique was used since the force output of each gage was approximately the same and no measurable time difference existed between the force peaks. Preferably, the value of acceleration would be measured directly from the records; however, the resolution at t_1 was such that much discretion was required in selecting an acceleration value. The relative acceleration a_{rel} at the time of impact was therefore calculated from the recorded acceleration time histories by using the relationship:

$$a_{rel} = v_0\omega \sin \omega\left(t_1 - t_0\right)$$

where

v_0 upward velocity of tank at time of application of arresting force t_0 (fig. 3)

$\omega = \frac{\pi}{P}$

P period of acceleration pulse (fig. 2)

t_1 time of peak impulse

This relationship was used to obtain the relative accelerations since ω, t_0, and t_1 could be very accurately determined from the records, and the acceleration pulse closely resembled a half sine wave as would be expected in the case of an ideal linear mass-spring system. The use of relative acceleration as the prime variable followed limited attempts to correlate the data with peak acceleration, peak velocity, and velocity at the time of fluid impact, none of which exhibited a consistent effect on the dome pressures and forces.

Impact Presssure

Impact-pressure measurements at the center of the dome in the smooth-wall tank are shown in figure 4. The magnitude of the peak pressure is presented as a function of the relative acceleration. Although the peak pressure appears to increase with acceleration, the trend is not as consistent as the corresponding force increase with acceleration. However, inspection of the data showed that the pressure impulse or area under the pressure time curve also exhibited an acceleration dependence similar to that associated with the force. Pressures associated with modal and quiescent impacts appear to be similar in magnitude for a given relative acceleration. It is interesting to note that if the recorded peak pressure is multiplied by the projected area of the dome, the resulting force is about twice as high as the measured peak force. This relationship indicates the existence of a pressure distribution which is probably a maximum in the center of the dome.

Baffle Effectiveness

The effectiveness of the screen type of baffle for the suppression of the impact forces is shown in figure 5. The quiescent and modal impact forces are shown by the circles and squares, respectively, and for comparative purposes, the faired curve which represents the data obtained with the smooth-wall tank is also shown. The data shown were obtained from the tank fitted with four screen baffles at the locations shown in figure 1(b). The data exhibit a reduction of impact force by approximately 30 percent. It is probably possible to reduce the impacts to much lower levels by controlling the mesh size of the screen. No significant reductions in force were observed when the tank was fitted with ring baffles only.

Effect of Liquid Properties

Up to this point, all the results discussed were obtained with water at room temperature as the test liquid. In extrapolating the results of these tests to full-scale vehicles, an understanding of the effects of the liquid properties is of fundamental importance since rigorous scaling was not attempted in these tests, nor does it appear to be generally feasible. Dimensional analysis of this problem incorporating variables such as vapor pressure, surface tension, and viscosity yields dimensionless groups which may be impossible to satisfy in the model and prototype with available liquids. (See ref. 4.) Thus, a phase of this study was devoted to the examination of the effects of several of the fluid properties, namely, viscosity, surface tension, and vapor pressure. To accomplish this phase of the study, impacts were made with water ranging in temperature from 38° F (276.48° K) to 175° F (352.59° K). The results of these studies are presented in figure 6. The measured force data, normalized on the room-temperature force curve of figure 3 are shown as a function of temperature. For convenience, the variations of viscosity and vapor pressure are also presented as a function of the temperature to indicate the range covered in the tests. Within this range, no significant variation of force response could be detected. The data shown by the solid symbols were measured after the addition of a detergent and an antifoam agent to the liquid to reduce the surface tension. No change was noted in behavior or force response with this approximately 3 to 1 reduction in surface tension.

Although no particular similitude was maintained, a wide variation of Reynolds, Weber, and Euler numbers resulted from these temperature and surface-tension variations. This range is illustrated in table I where the ratios of the parameters for a typical full-scale launch vehicle to those of the model are presented.

TABLE I.- VARIATION OF RATIOS OF PARAMETERS ACHIEVED BY VARYING

WATER TEMPERATURE AND SURFACE TENSION

Parameter	Ratio	Ratio of variables	Propellants	
			Fuel	Oxidizer
Euler number	$\frac{(N_{Eu})_f}{(N_{Eu})_m}$	$\frac{\rho_m}{\rho_f} \frac{p_f}{p_m} \frac{l_m}{l_f} \frac{a_m}{a_f}$	0.15 to 46.7	0.0369 to 11.63
Reynolds number	$\frac{(N_{Re})_f}{(N_{Re})_m}$	$\frac{\rho_f}{\rho_m} \frac{\mu_m}{\mu_f} \left(\frac{l_f}{l_m}\right)^{3/2} \left(\frac{a_f}{a_m}\right)^{1/2}$	7.41 to 76.9	23.0 to 238.0
Weber number	$\frac{(N_{We})_f}{(N_{We})_m}$	$\frac{\rho_f}{\rho_m} \frac{\sigma_m}{\sigma_f} \left(\frac{l_f}{l_m}\right)^2 \frac{a_f}{a_m}$	15.0 to 300.0	41.2 to 820.0

Since no variation of force was observed for the range of surface tension, vapor pressure, and viscosity, it may be possible to scale the results based only upon the inertial characteristics of the liquid such as density, volume, and acceleration. The validity of this assumption can be determined, at least to a degree, by correlating or comparing results obtained from several models of different size. At the present time, the only experimental results available for comparison are those presented in references 1 and 4 in which a tank was partially filled with carbon tetrachloride and accelerated vertically downward along the longitudinal axis. The results of this comparison are shown in figure 7. The nondimensional parameter $F/\rho Va$ is presented as a function of acceleration g. The parameter $F/\rho Va$ is obtained by dividing the measured force F by the "hydrostatic force," ρVa, where ρV is the total mass of liquid at the time of impact and a is the acceleration, that is, ρVa is the load that would result if the acceleration was applied to the tank for a sufficient period of time to allow all the liquid to reach an equilibrium state in the upper dome. It is probable that this hydrostatic force would ultimately result when a vehicle experiences a thrust termination in the atmosphere. Thus, the parameter $F/\rho Va$ is a measure of the relative severity of the impact or degree of overshoot possible. Presented in this manner, the relative severity of the impact appears to decrease with an increase in acceleration. The ratio exceeds 1 only in the acceleration range below 1g. This condition indicates that the hydrostatic loads will be more severe than the impact loads when a vehicle is subjected to decelerations greater than 1g. Furthermore, a vehicle designed to withstand hydrostatic loads proportional to ng (where $n > 1$) will be able to withstand the impact forces resulting from decleration ranging from 0 to ng. Thus, it appears that a launch vehicle having identical ends, for example, is capable of withstanding impact loads of much greater magnitude than those observed in these tests and represented by the data presented in figure 7.

Impact Pulse Shape

Selected force and pressure pulses are shown in figure 8 for quiescent and modal impacts. These time histories were traced directly from the records and are shown with the appropriate force, pressure, and time scales. The values of acceleration apply to the peak values of force and pressure. In general, the force and pressure shapes are similar for a given impact; however, the area under the curve is slightly larger in the modal cases.

CONCLUSIONS

An investigation has been conducted to assess the problem of liquid impact in booster and space-vehicle propellant tanks. The results of the investigation are as follows:

1. The liquid exhibits one of two flow patterns depending upon the condition of the surface prior to arrest, that is, (a) if the liquid surface is undisturbed or quiescent, it travels in a series of streamers; (b) if the surface is oscillating in its fundamental antisymmetric mode, a portion of the liquid travels up one side of the tank, around the dome, and down the opposite side.

2. The impact force is dependent upon the relative acceleration of the tank at the time of impact.

3. For a given acceleration level, there appears to be no significant difference in the magnitude of the modal and quiescent impact force.

4. The pressure in the center of the dome is about twice as high as the value obtained by dividing the average force by the projected area.

5. The force level is not significantly altered by the inclusion of ring baffles; however, a reduction in force of approximately 30 percent was observed with the inclusion of 1/4-inch (0.3 cm) screen baffles.

6. For the range covered in this investigation, no dependency of the force or pressure on the vapor pressure, surface tension, or viscosity was observed.

7. The ratio of impact force to hydrostatic force is less than 1 for all values of tank deceleration greater than 1 g. Therefore, a tank designed to withstand the hydrostatic loads resulting from tank deceleration (greater than 1 g) should not experience excessive liquid impact loads.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., June 29, 1965.

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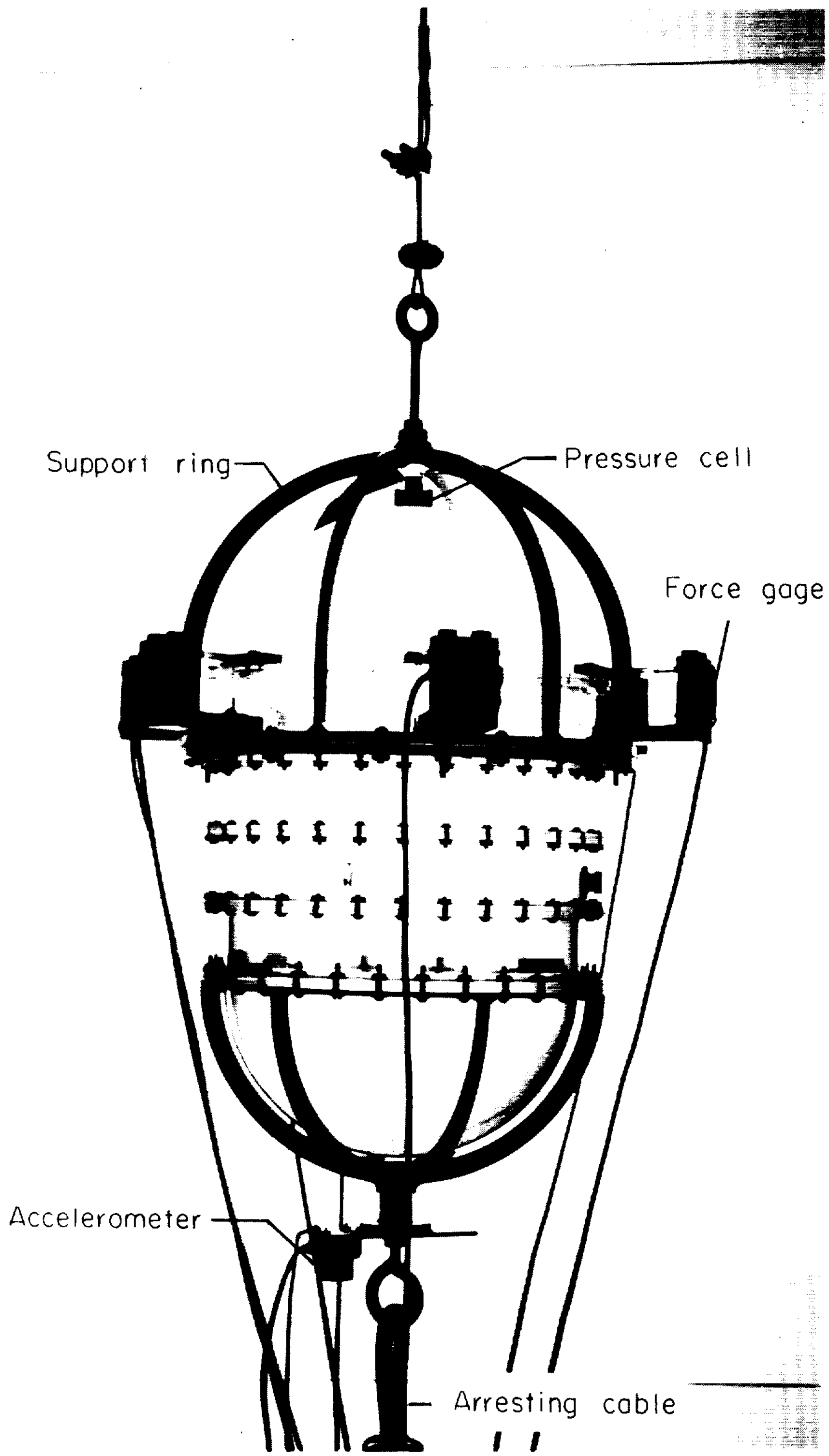

(a) Tank and instrumentation.

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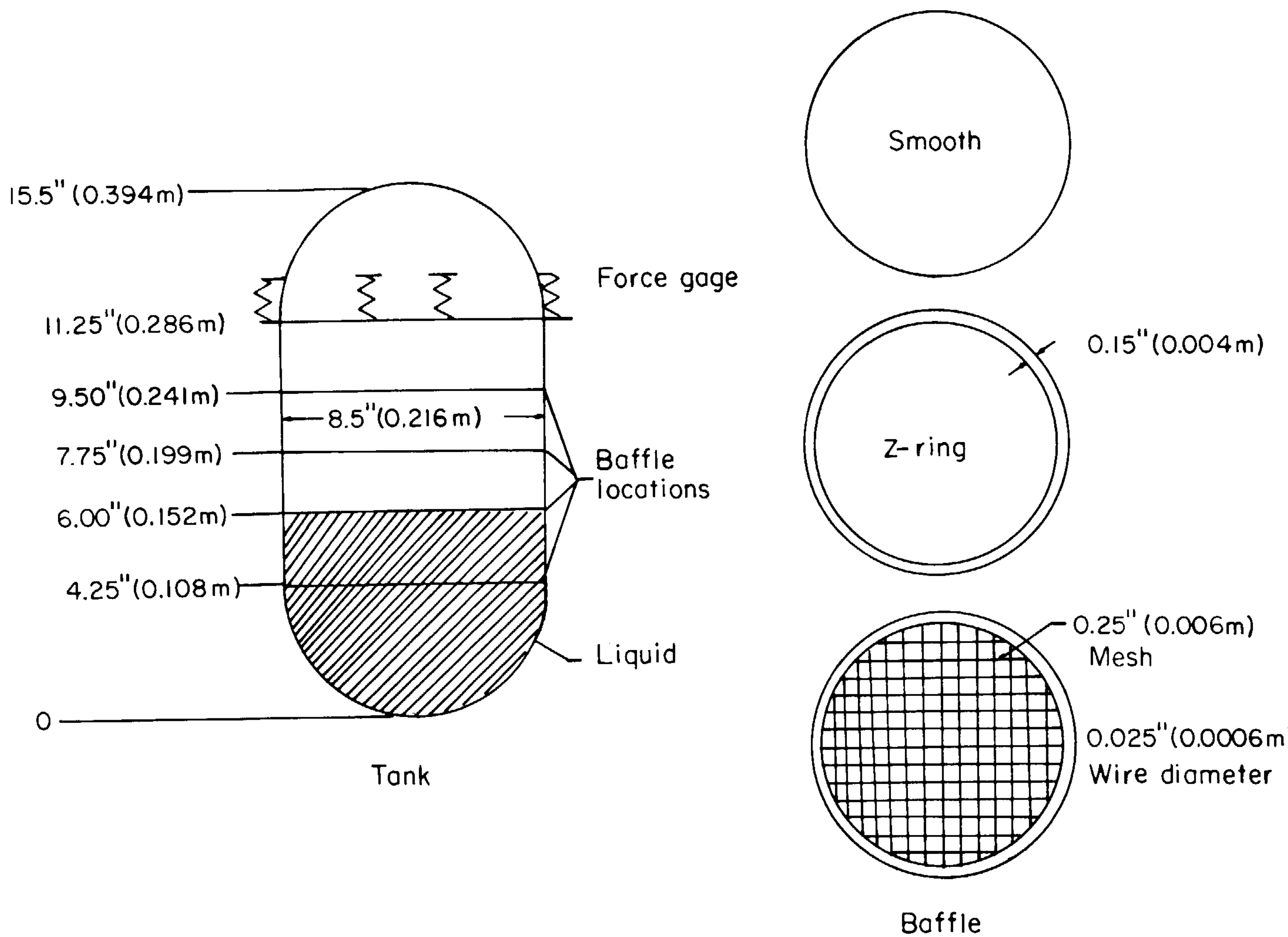
Figure 1.- Model propellant tank and baffle configurations.



(b) Tank and baffle details.

Figure 1.- Concluded.

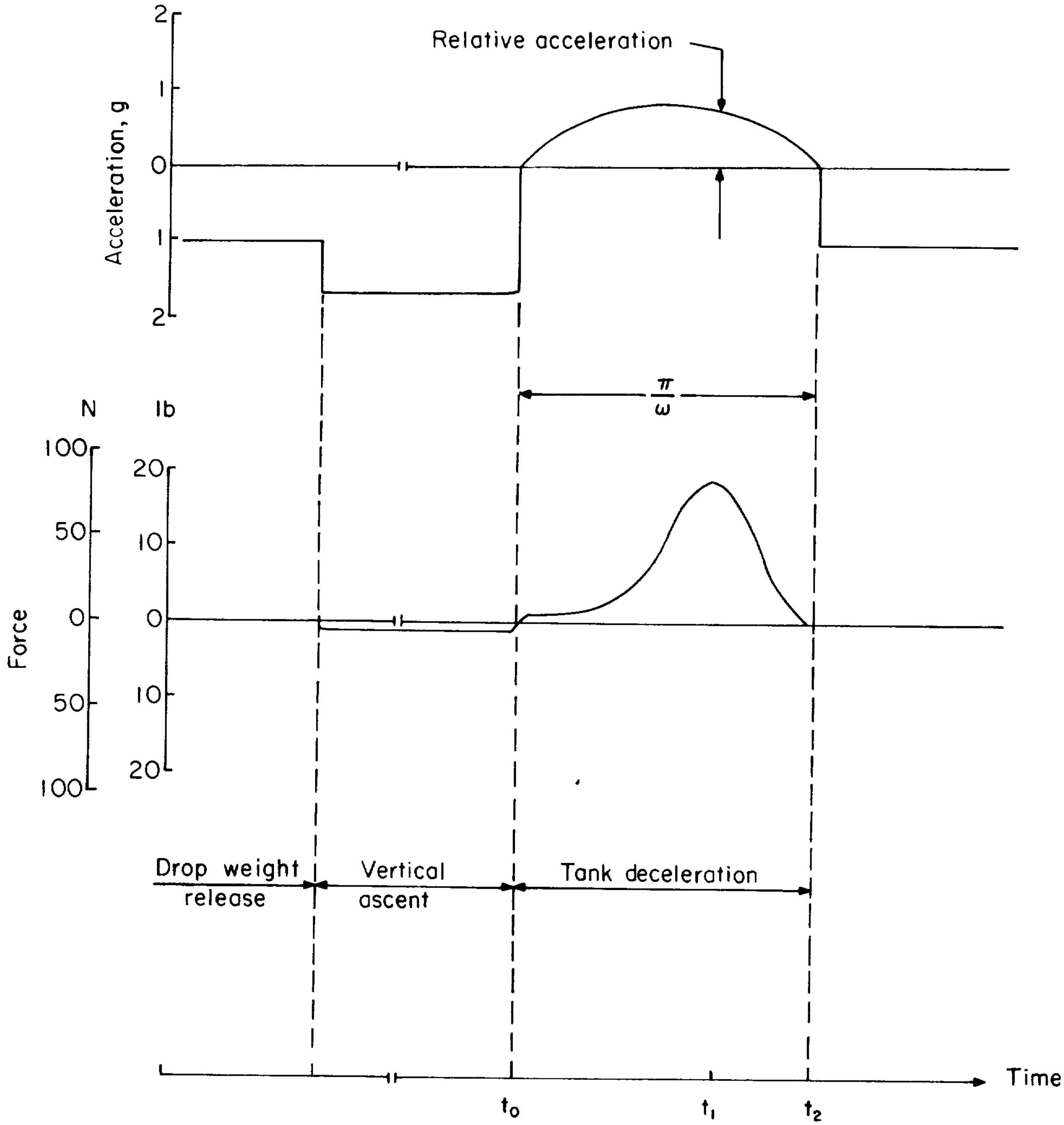


Figure 2.- Schematic force and acceleration record.

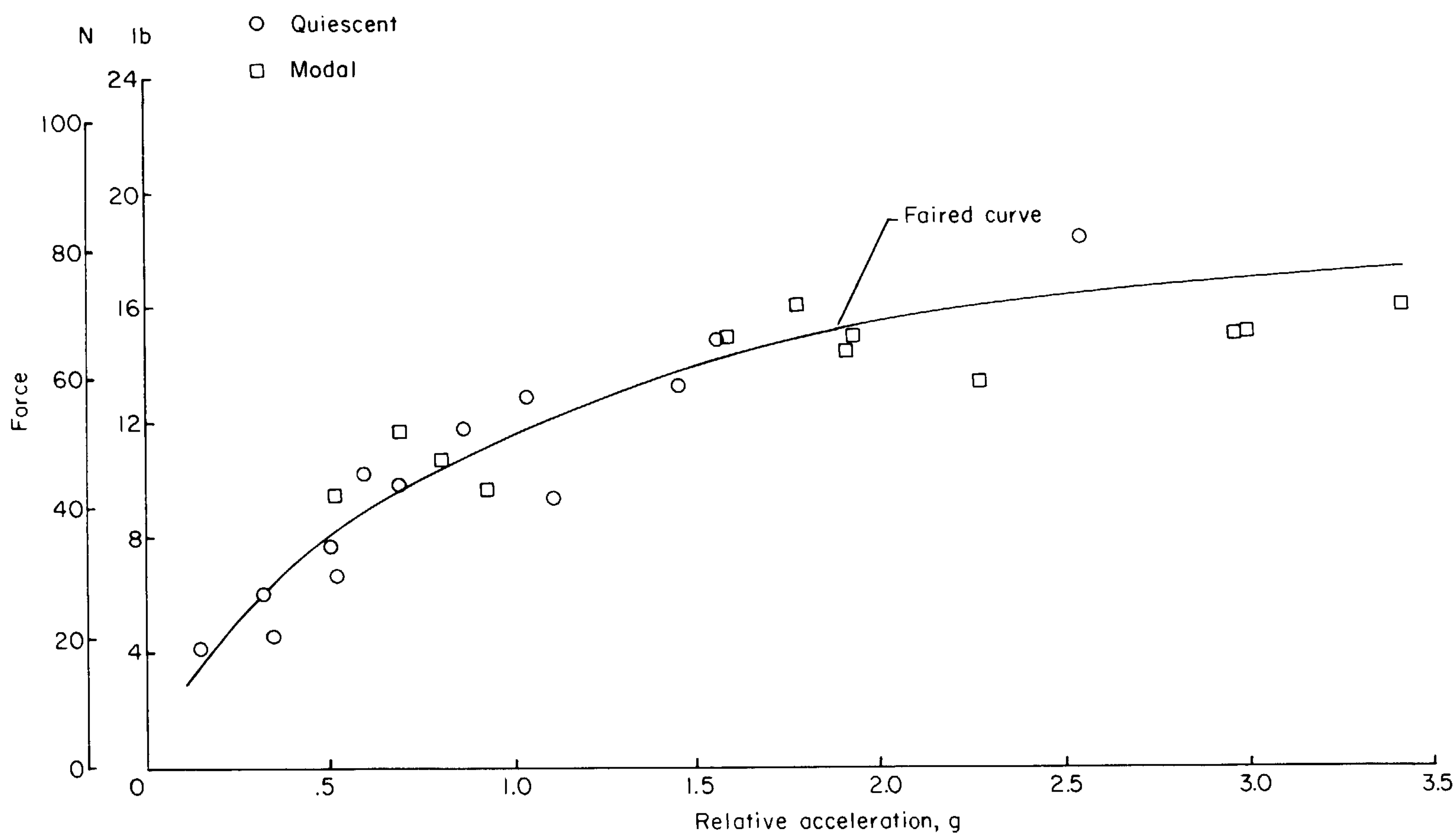


Figure 3.- Variation of impact force with tank acceleration. Smooth-wall tank.

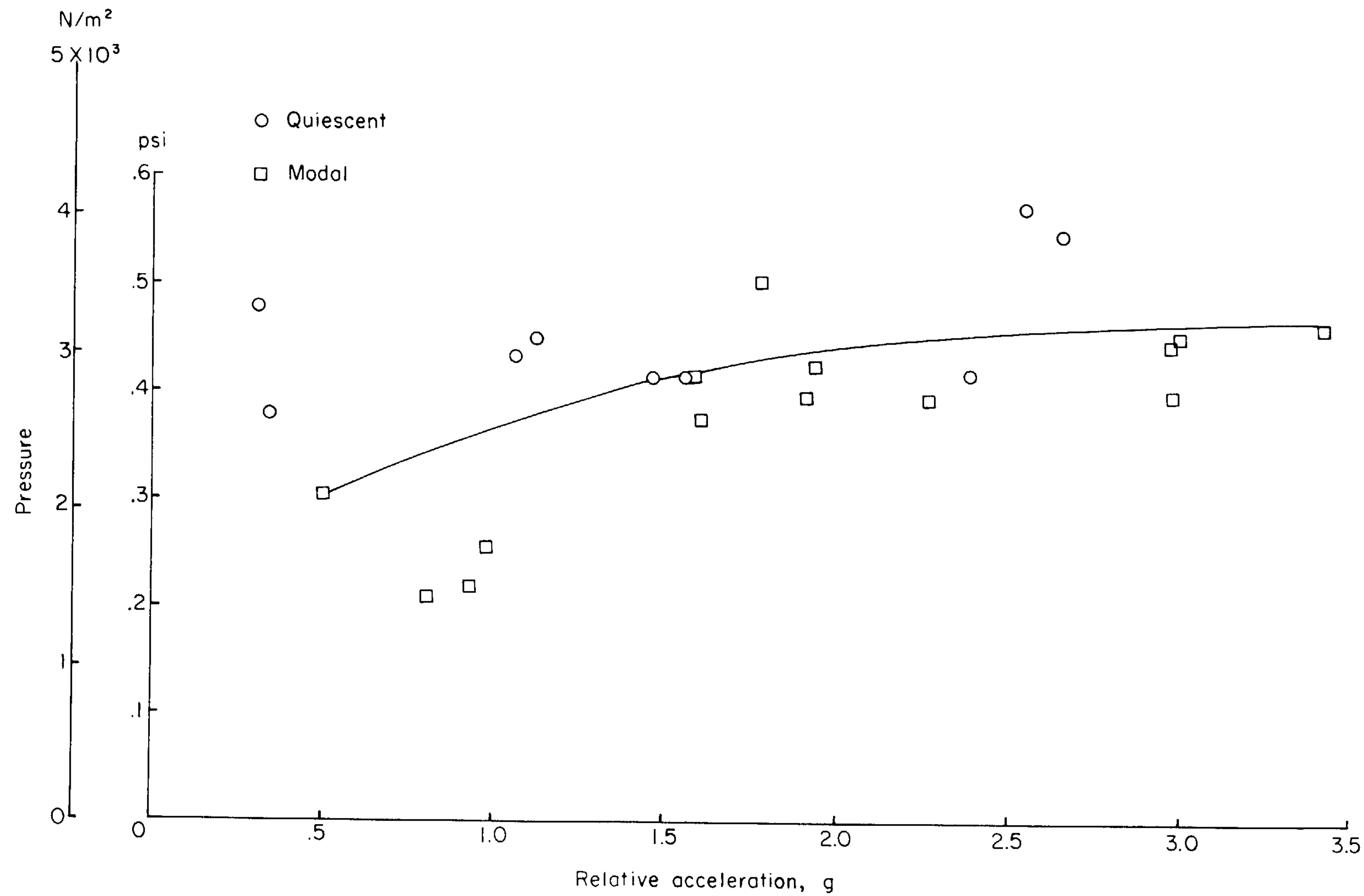


Figure 4.- Variation of impact pressure with tank acceleration.

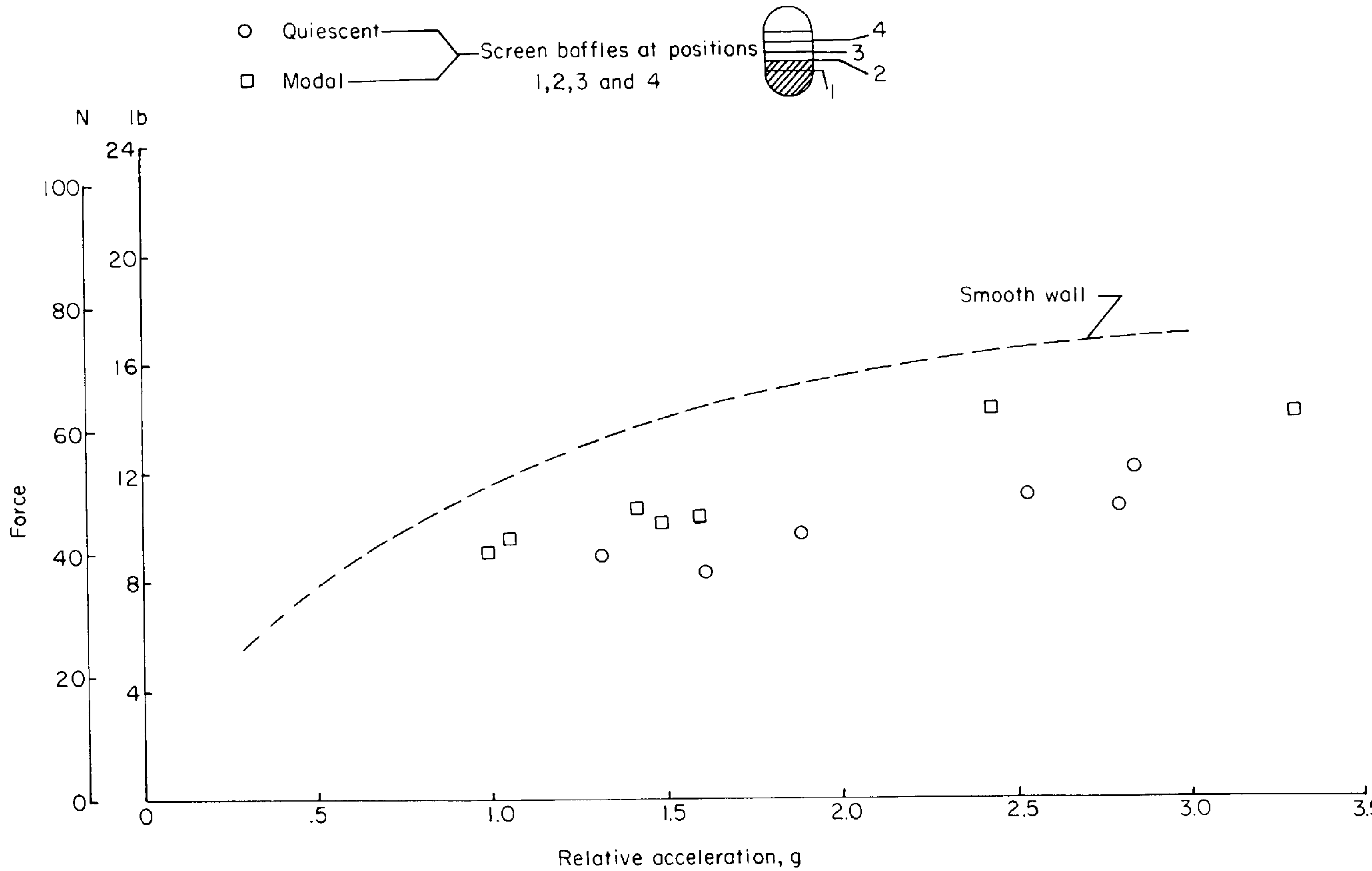


Figure 5.- Effectiveness of screen baffles for force attenuation.

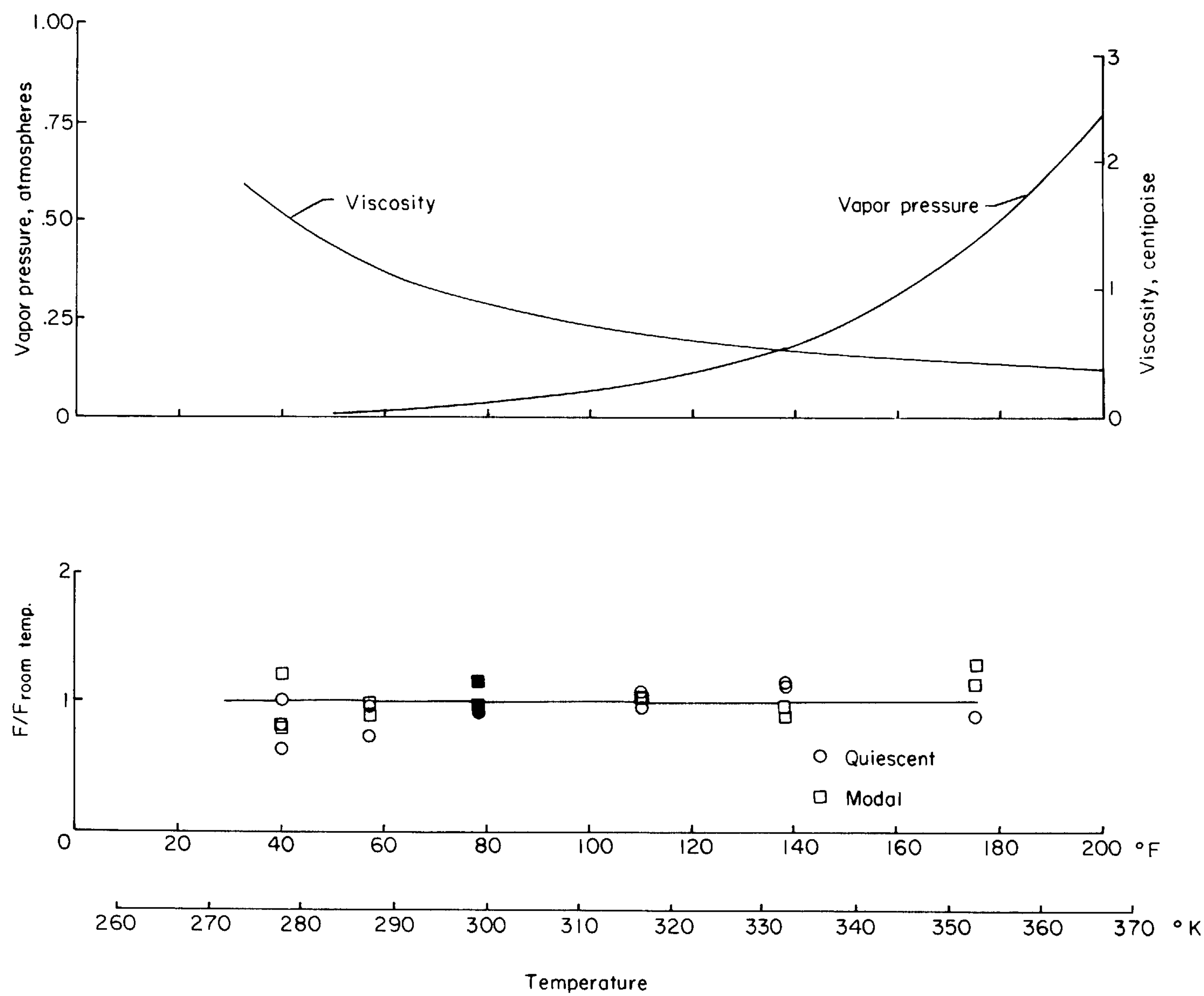


Figure 6.- Variation of impact force with liquid properties as achieved by varying the temperature and surface tension of water.

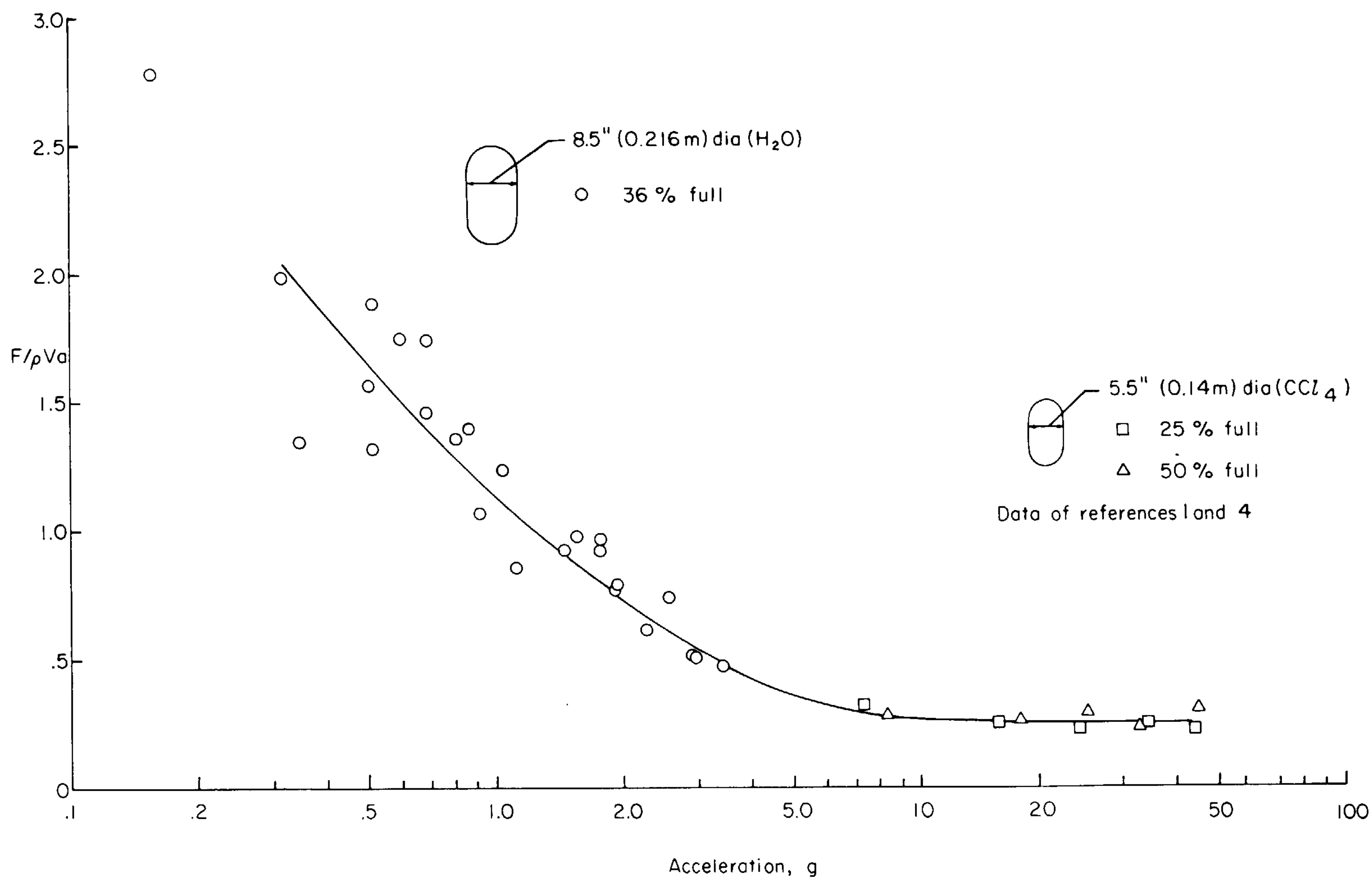
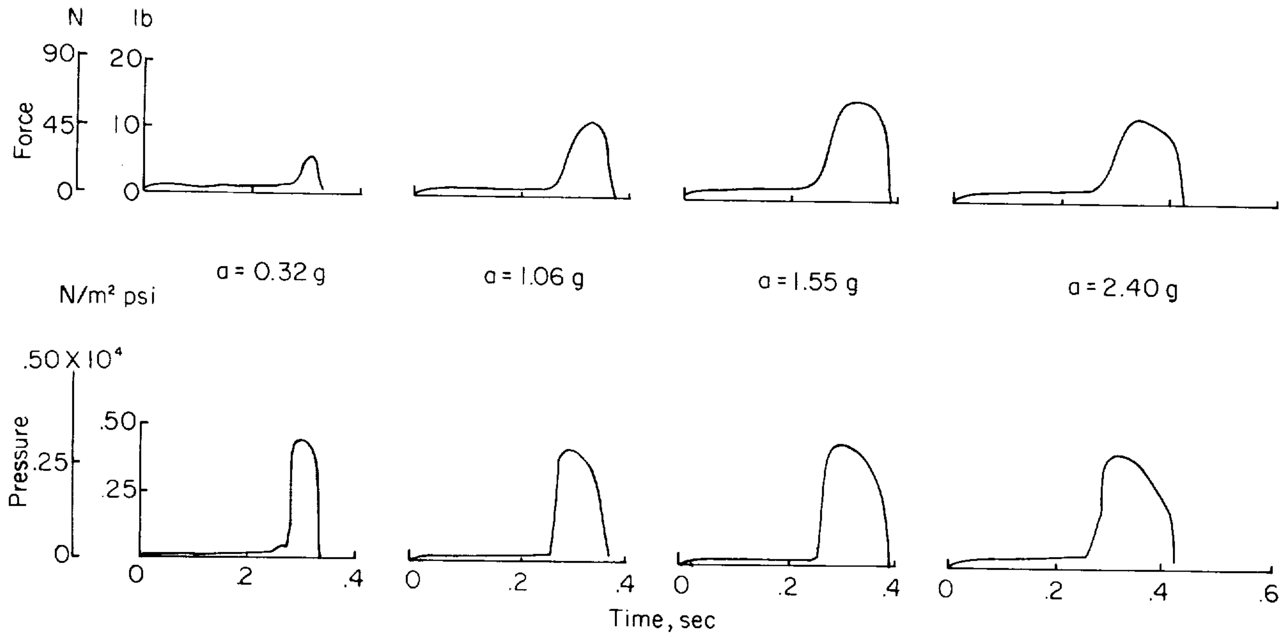
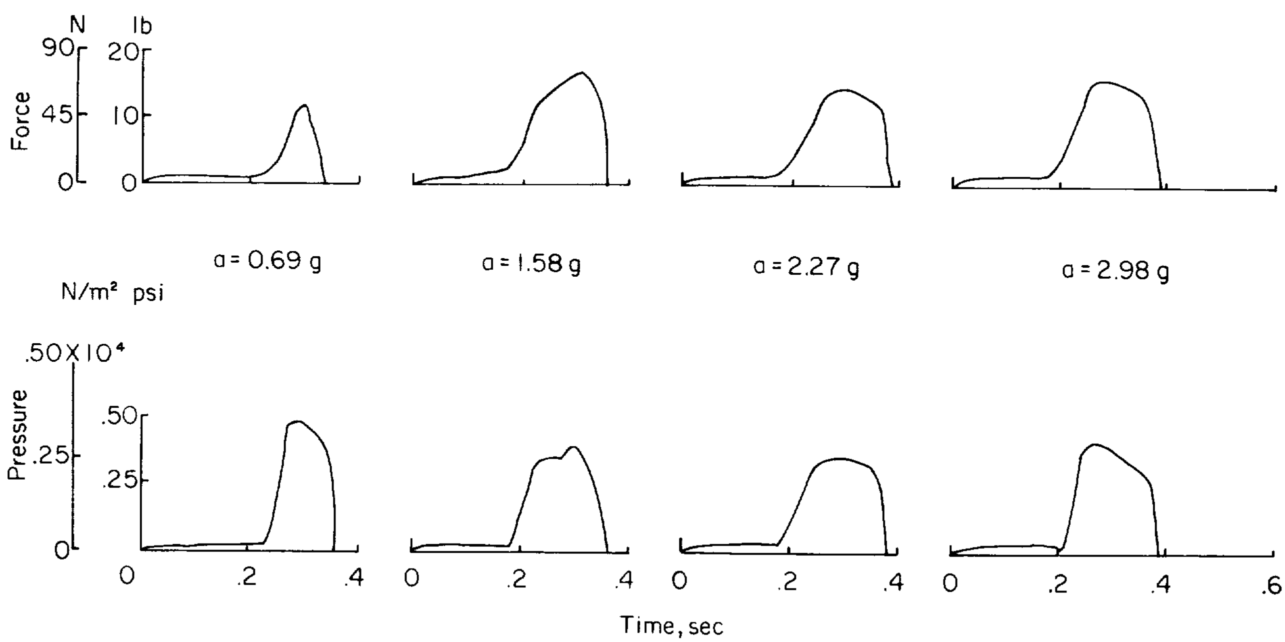


Figure 7.- Ratio of impact forces to hydrostatic forces.



(a) Quiescent.



(b) Modal.

Figure 8.- Force and pressure impact pulse shapes.

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The film (16 mm, 5 min, color, silent) presents the behavior of a contained liquid following a rapid change in tank acceleration for both quiescent and model surface conditions.

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