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SUMMARY

An investigation of vapor ingestion during liquid outflow was conducted in a 1/3.67 and 1/38 scale-model Centaur liquid hydrogen tank at the Lewis Research Center. The purpose of the investigation was to establish the height above the concave oblate ellipsoidal tank bottom at which vapor ingestion would occur for two tank outflow rates at various acceleration levels in order to define Centaur propellant residuals.

Experimental values of the liquid height at which vapor ingestion occurs were obtained at normal gravity. A Froude number simulation was then used to relate the normal gravity experimental data to other acceleration levels. The experimental values were correlated with an analytical expression based on Bernoulli's equations. The analytical expression correlated well with the experimental values over the entire range of tank outflow rates.

INTRODUCTION

As a liquid is drained or pumped from a tank, a depth is reached at which the surface of the liquid experiences a "suction dip" in the vicinity of the tank exit. The surface distortion grows rapidly until the vapor above the liquid surface is ingested in the tank exit and reduces the liquid outflow rate. Vapor ingestion or vapor "pull through" occurs at some critical height above the tank exit. In a space vehicle employing liquid propellants, the ingested vapor could result in pump cavitation and a subsequent loss in engine performance. This critical height, then, established a limit on the amount of usable propellants.

An experimental program was conducted at the Lewis Research Center in order to establish the critical liquid height at which vapor ingestion would occur in the Centaur liquid hydrogen tank at various acceleration levels and tank outflow rates for both main engine thrusting and engine restart after a coasting period. For the purposes of the program it was assumed that the liquid height at which vapor ingestion occurs will depend on the acceleration field. It should be noted, however, that this assumption

has not been verified experimentally.

The Centaur liquid hydrogen tank possesses a unique outflow configuration since the tank outlet is very near the concave oblate ellipsoidal tank bottom. Outflow tests were conducted in a 1/3.67 and 1/38 scale model of the Centaur liquid hydrogen tank with water and alcohol as the test liquids. All tests were conducted at normal gravity. The scale-model tank outflow rates were varied such that a Froude number (ratio of inertia forces to gravity forces) simulation of the Centaur outflow rates was provided. The Froude number simulation was then used to relate the 1-g experimental data to other acceleration levels. The model test data were correlated with an analytical model based on Bernoulli's equations and one data point from a test using a full-sized Centaur hydrogen tank.

EXPERIMENTAL APPARATUS AND PROCEDURE

An experimental investigation of the vapor ingestion phenomenon was conducted in a 1/3.67 and 1/38 scale model of the Centaur liquid hydrogen tank. Two scale-model tank sizes were needed to employ properly the Froude number simulation over the entire range of Centaur liquid hydrogen tank outflow rates and acceleration levels. A schematic of the full-size Centaur liquid hydrogen tank is shown in figure 1. A liquid hydrogen

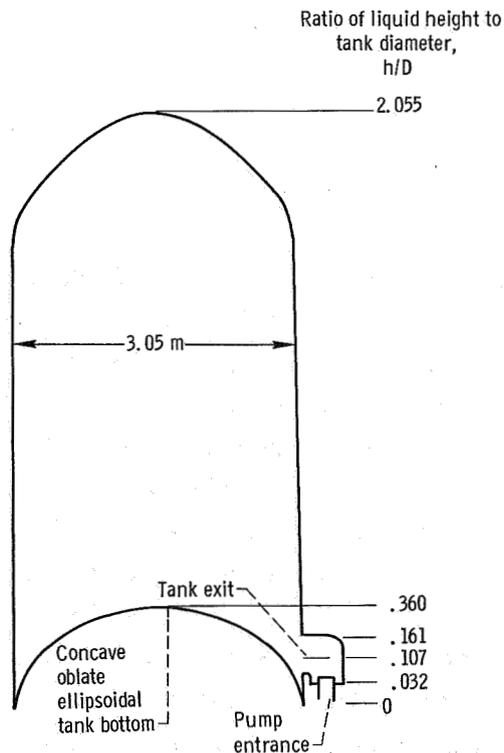
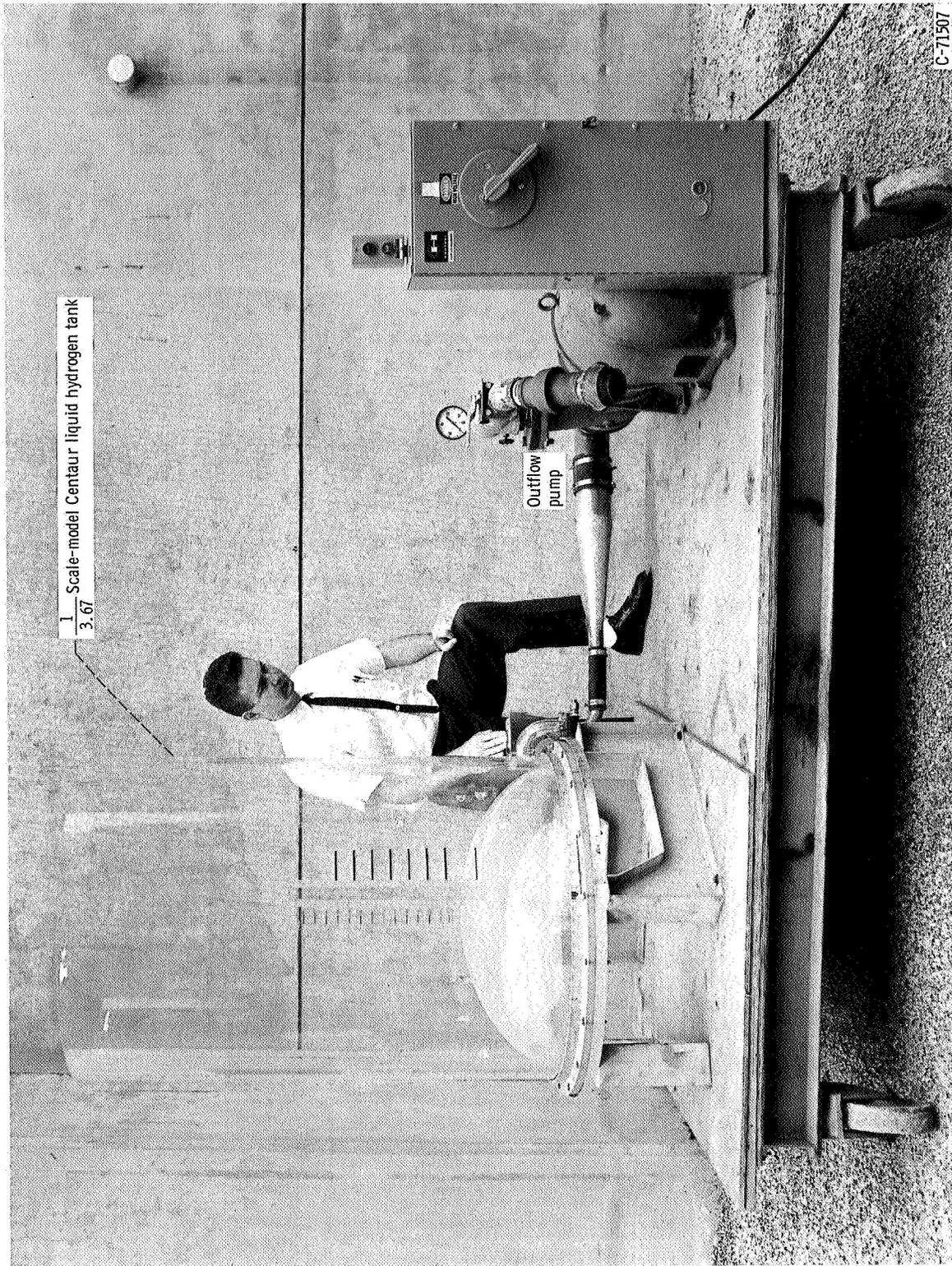


Figure 1. - Centaur liquid hydrogen tank.



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Figure 2. - 1 - 3.67 Scale-model Centaur liquid hydrogen tank.

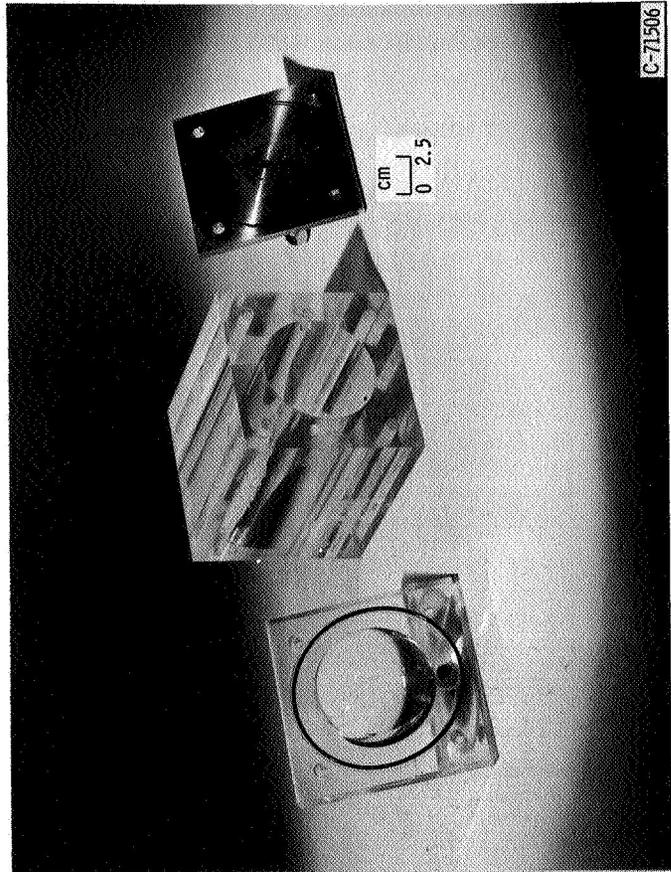
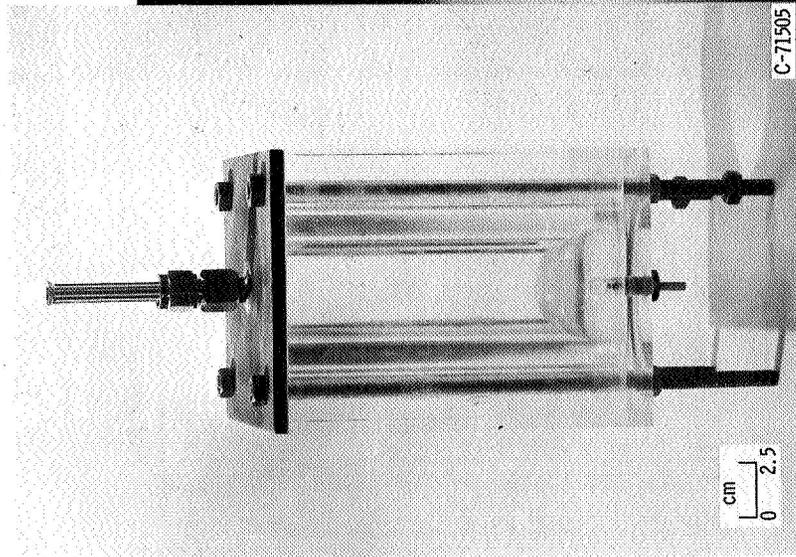


Figure 3. - $\frac{1}{38}$ Scale-model Centaur liquid hydrogen tank.

pump is located in the elbow at the bottom of the tank. The pump entrance is shown at the end of the elbow.

The 1/3.67 scale-model tank is shown in figure 2. The tank was constructed by forming and gluing sheets of lucite to form the proper configuration. The fluid was expelled by use of a pump. The pump is shown attached to the tank in figure 2. The test liquid used in the 1/3.67 scale-model tank was water.

The 1/38 scale-model tank is shown in figure 3. The tank was machined from a block of lucite. The fluid was expelled from the tank by high-pressure air within the tank. The pressure tank volume was large enough with respect to the amount of liquid removed from the model tank that no appreciable pressure decrease resulted, while the liquid flowed from the model tank. Two test liquids were used in the 1/38 scale-model tank, water and ethyl alcohol.

The liquid outflow velocity from the scale-model tanks was varied to simulate the Froude number (ratio of inertial to gravitational forces V^2/Da) of the Centaur liquid hydrogen tank outlet at various acceleration levels. The liquid heights at which vapor ingestion occurred were obtained from motion pictures taken of the tank outflow.

ANALYSIS OF THE CRITICAL LIQUID HEIGHT FOR VAPOR INGESTION

At the acceleration levels of the Centaur vehicle, prior to, and during the second main engine start, the inertial forces predominate over the viscous and surface tension forces. The use of a Froude number V^2/Da as a scaling parameter to simulate fluid behavior in a flow regime dominated by gravitational and inertial forces has been indicated by various sources (refs. 1 to 3). A definite relation between the critical liquid depth and the Froude number can be shown from Bernoulli's equations applied at the

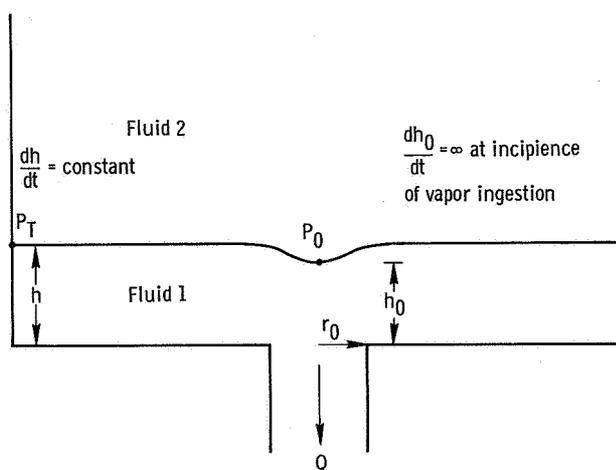


Figure 4. - Incipience of vapor ingestion.

incipience of vapor ingestion. The relation is derived in the following analysis which closely follows the work of reference 2 and is presented here with minor alterations. For a rigorous derivation of the equations describing the free surface shape during vapor ingestion, see reference 4. At the incipience of vapor ingestion, shown in figure 4, the liquid height above the perimeter of the tank outlet h_0 decreases at an infinite rate

$$\frac{dh_0}{dt} = \infty \quad (1a)$$

whereas the liquid height at the tank wall decreases at a constant rate corresponding to the tank outflow rate

$$\frac{dh}{dt} = \text{constant} \quad (1b)$$

The criterion for the incipience of vapor ingestion can then be expressed mathematically as

$$\frac{dh/dt}{dh_0/dt} = \frac{dh}{dh_0} = 0 \quad (2)$$

This criterion assumed that the fluid flow is irrotational and inviscid. Since the inviscid assumption breaks down at the tank exit because of the high velocity gradients, the analysis is conducted at some surface away from the tank exit. If a hemispherical surface is constructed over the tank exit as shown in figure 5 such that the surface will intersect the falling interface at a circle of radius r_0 , then the surface area in contact with fluid 1 is the area of a hemispherical section given by $2\pi h_0(h_0^2 + r_0^2)^{1/2}$. The stream velocity U_0 is assumed to be everywhere normal to this surface.

Assuming fluid 2 in figure 5 to be stationary, the Bernoulli equation for fluid 2 is

$$P_T = P_0 - \rho_2 a(h - h_0) \quad (3)$$

Neglecting the effects of surface tension between the two fluids, the Bernoulli equation for fluid 1 is

$$P_T + \rho_1 a h = P_0 + \rho_1 a h_0 + \frac{\rho_1 U_0^2}{2} \quad (4)$$

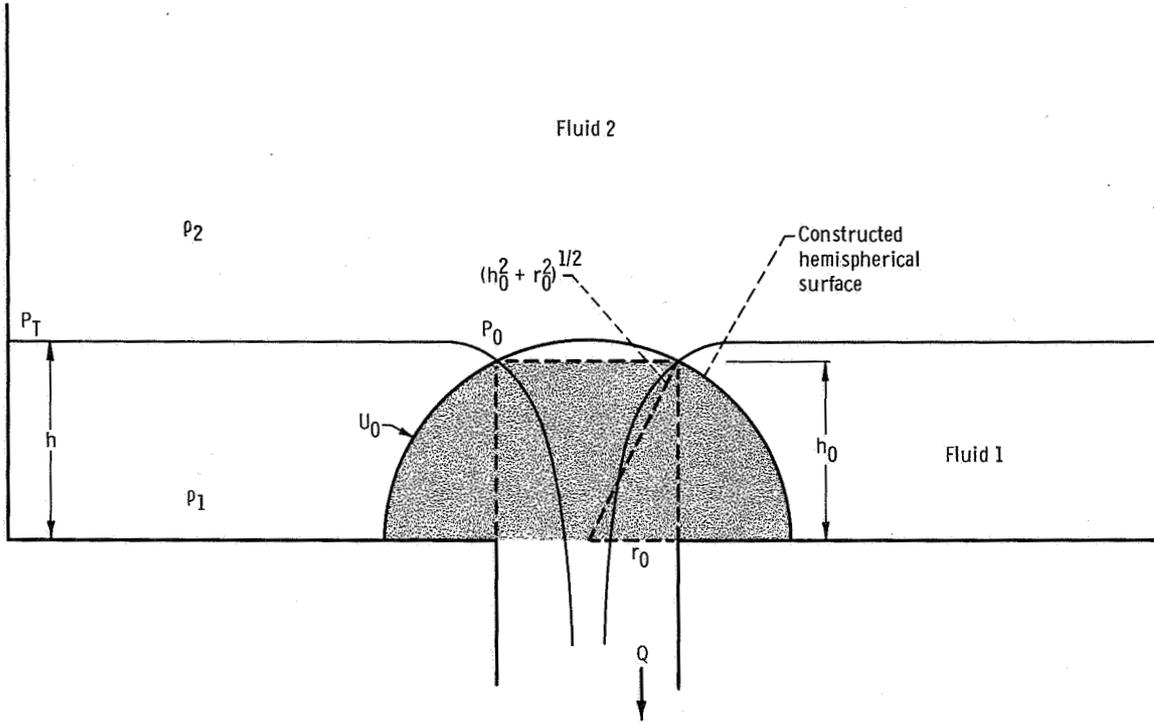


Figure 5. - Hemispherical sector constructed over tank exit used to formulate vapor ingestion analysis.

Subtracting equation (3) from equation (4) yields

$$(\rho_1 - \rho_2)ah = (\rho_1 - \rho_2)ah_0 + \frac{\rho_1 U_0^2}{2} \quad (5)$$

The volumetric flow rate through the hemispherical section is given by

$$Q = U_0 \left[2\pi h_0 (h_0^2 + r_0^2)^{1/2} \right] \quad (6)$$

Substituting equation (6) into equation (5) for U_0 results in

$$h = h_0 + \frac{\rho_1}{8\pi^2(\rho_1 - \rho_2)a} \left[Q^2 h_0^{-2} (h_0^2 + r_0^2)^{-1} \right] \quad (7)$$

Applying the vapor ingestion criterion of equation (2) to equation (7) yields

$$\frac{dh}{dh_0} = 1 - \frac{\rho_1 Q^2}{8\pi^2(\rho_1 - \rho_2)a} \left[\frac{2}{h_0^3 (h_0^2 + r_0^2)} + \frac{2}{h_0 (h_0^2 + r_0^2)^2} \right] = 0$$

and upon rearranging

$$\frac{Q^2}{4\pi^2 (\rho_1 - \rho_2)a} = \frac{h_{0c}^3 (h_{0c}^2 + r_0^2)^2}{(2h_{0c}^2 + r_0^2)} \quad (8)$$

where h_{0c} is the critical liquid height above r_0 . The critical height h_c at the tank wall is obtained by substituting Q^2 from equation (8) into equation (7); that is,

$$h_c = h_{0c} \left[1 + \frac{(h_{0c}^2 + r_0^2)}{2(2h_{0c}^2 + r_0^2)} \right] \quad (9)$$

Equation (8) can be written in terms of the Froude number, based on the tank outlet flow velocity and diameter, as follows:

$$\frac{2h_{0c}^3 (h_{0c}^2 + r_0^2)^2}{(2h_{0c}^2 + r_0^2)r_0^5} = \frac{2Q^2 \rho_1}{4\pi^2 r_0^5 a (\rho_1 - \rho_2)} = \frac{v^2}{Da} \frac{\rho_1}{(\rho_1 - \rho_2)} = F_r \left(\frac{\rho_1}{\rho_1 - \rho_2} \right) \quad (10)$$

The usefulness of equations (8) and (9) to establish the critical liquid height h_c in a flow regime dominated by gravitational and inertial forces has been established by low viscosity liquid-liquid and liquid-vapor experiments (ref. 2).

RESULTS AND DISCUSSION

Outflow tests with the scale-model tanks were conducted to provide a Froude number simulation of various Centaur vehicle acceleration levels at two Centaur liquid hydrogen tank outflow rates of 2.5×10^{-2} and 7.6×10^{-2} cubic meter per second, which correspond to outflow velocities of 1.1 and 3.3 meter per second, respectively. The flow rate of 2.5×10^{-2} cubic meter per second is employed when the pump operates in a "deadhead" condition (zero flow to the engine) after a coasting period prior to Centaur second main engine start. The vehicle acceleration at this time is approximately 7.5×10^{-3} g. The flow rate of 7.6×10^{-2} cubic meter per second is obtained when the pump is operating during main engine firing. During the second main engine firing, the Centaur vehicle acceleration level increases from 7.5×10^{-3} g to approximately 4 g's.

The experimental critical liquid height ratio for the scale-model tanks at various outflow velocities is shown in figure 6. The data of figure 6 were used to provide the Froude number simulation of the actual Centaur liquid hydrogen tank outflow rates and acceleration levels.

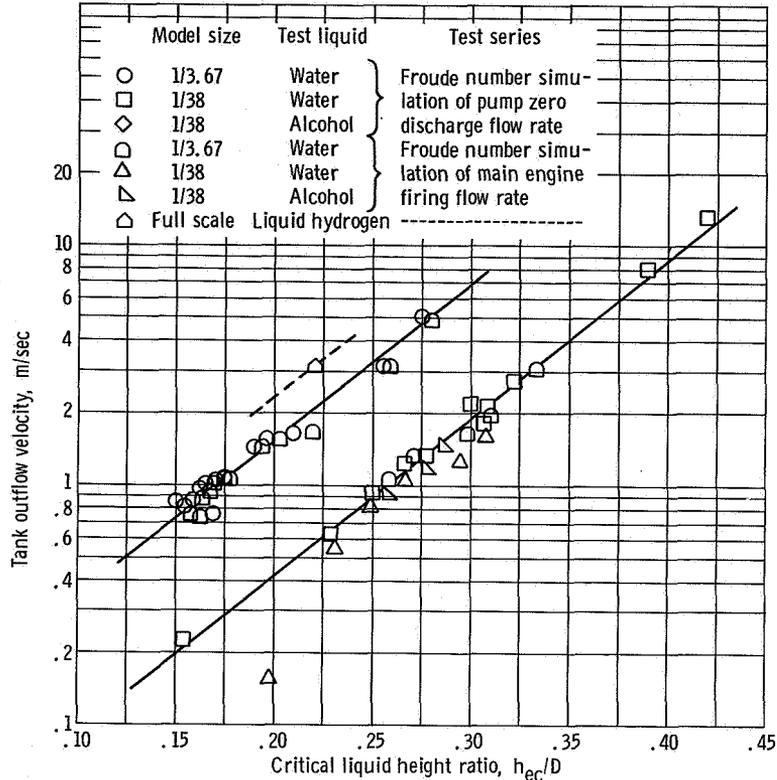


Figure 6. - Experimental tank outflow velocity as function of critical liquid height ratio.

The experimental critical liquid height ratio at Centaur liquid hydrogen tank outflow rates of 2.5×10^{-2} and 7.6×10^{-2} cubic meter per second at various acceleration levels is shown in figures 7 and 8, respectively. The distance h_{ec} is measured positively up from the bottom of the tank. Both figures contain data obtained from the 1/38 and 1/3.67 scale-model tanks. The variation in outflow velocities from the scale-model tanks provided a Froude number simulation of the Centaur vehicle flow rates under various vehicle accelerations. Figure 8 contains one data point obtained from a full-sized Centaur liquid hydrogen tank at normal gravity during an actual engine firing. This one data point correlates well with the scale-model tank data at 1 g.

A comparison of figure 7 with figure 8 indicates that the critical liquid height for the main engine firing flow rate 7.6×10^{-2} cubic meter per second are approximately 25 percent greater than the critical liquid height for the pump zero discharge flow rate of 2.5×10^{-2} cubic meter per second.

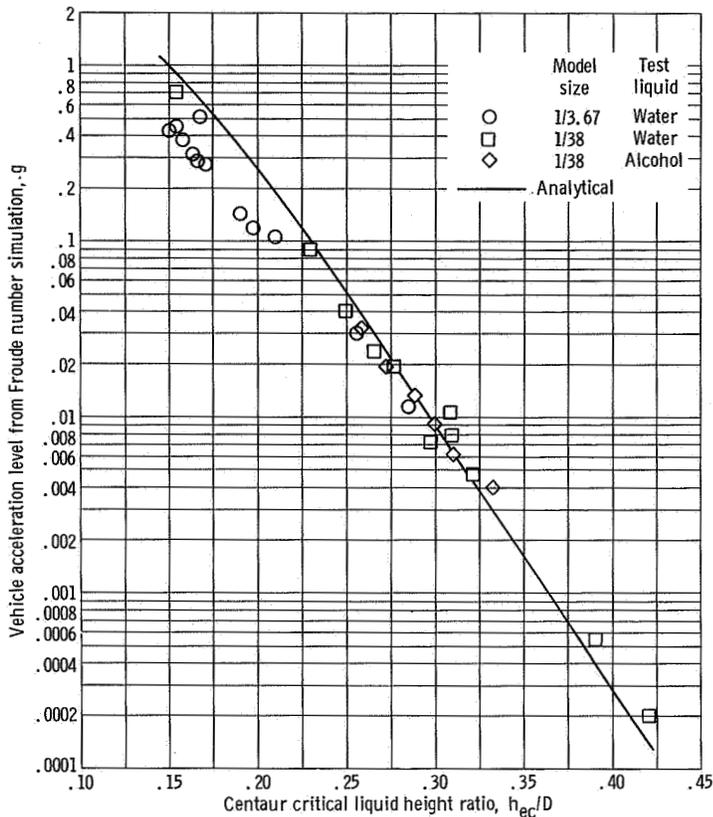


Figure 7. - Centaur liquid hydrogen tank critical liquid height ratio at pump zero discharge flow rate ($2.5 \times 10^{-2} \text{ m}^2/\text{sec}$).

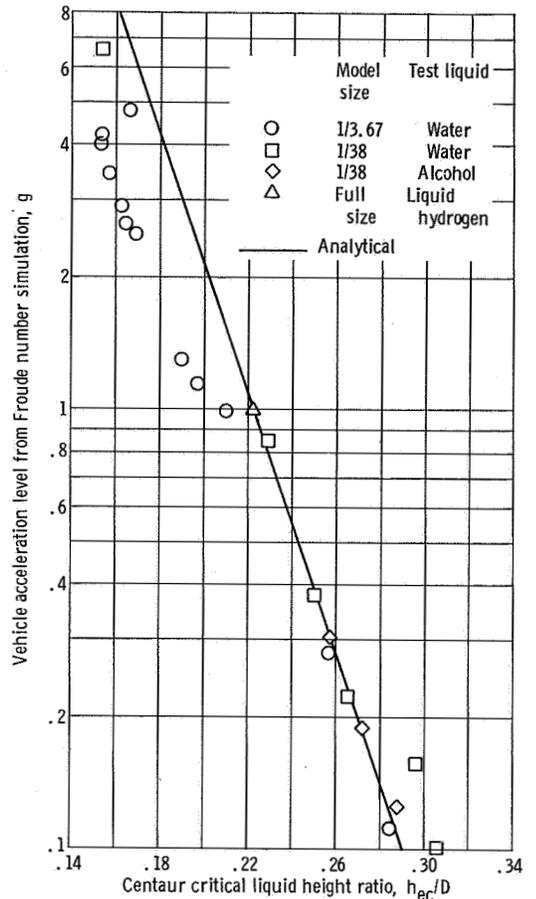


Figure 8. - Centaur liquid hydrogen tank critical liquid height ratio at main engine firing flow rate ($7.6 \times 10^{-2} \text{ m}^2/\text{sec}$).

The analytical expression obtained for the critical liquid height (eqs. (9) and (10)) is also plotted in figures 7 and 8. For the case of the Centaur liquid hydrogen tank, the vapor ingestion configuration is shown in figure 9. Since the Centaur liquid hydrogen tank contains a concave oblate ellipsoidal tank bottom very near the tank exit, the height h_c above the tank exit obtained from equations (8) and (9) had to be expressed as an "equivalent" height h_{ec} in the Centaur tank, where h_{ec} is the height at which the Centaur tank volume is equivalent to $\pi D^2/4h_c$. The analytical critical liquid height ratio h_{ec}/D correlated well with the experimental data obtained from the scale models. Both the analytical expression and Froude number simulation are only valid in a flow regime where gravitational and inertial forces predominate over the viscous and surface tension forces. The zero-gravity scale-model tests conducted by Derdul (ref. 5) indicate that vapor ingestion would occur at a finite liquid height ratio at zero gravity (actual critical liquid height measurements were not taken). The analytical expressions, equations (8) and (9), predict a critical liquid height ratio of infinity at zero gravity.

The results of the investigation have been used to determine the amount of required

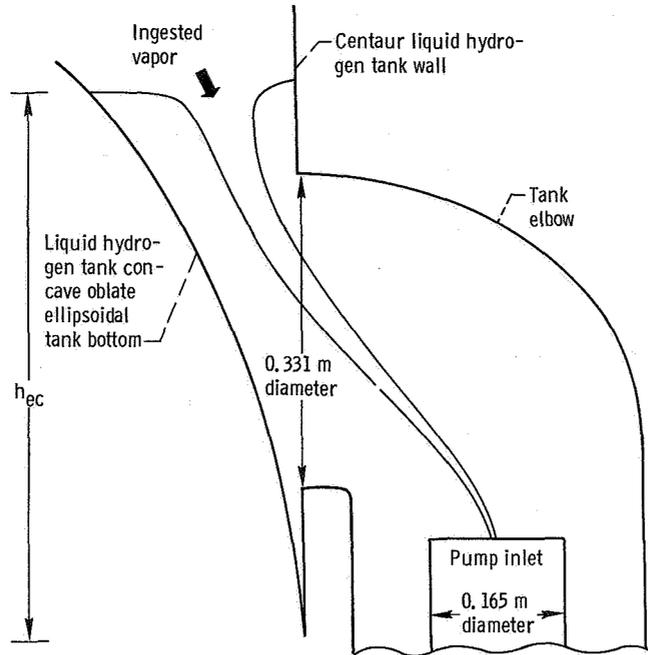


Figure 9. - Vapor ingestion configuration for the Centaur liquid hydrogen tank exit.

liquid residuals for the Centaur liquid hydrogen tank. For example, at a Centaur vehicle acceleration of $7.5 \times 10^{-3} g$, prior to second main engine start at the outflow velocity of 1.1 meter per second, vapor ingestion would occur at a liquid height ratio h_{ec}/D of 0.371 (from fig. 7), or 1.13 meters above the tank bottom. Therefore, the liquid height prior to second main engine start must be greater than 1.13 meters in order to achieve a successful engine start sequence.

SUMMARY OF RESULTS

An experimental investigation was conducted at the Lewis Research Center to establish the critical liquid height at which vapor ingestion would occur in the Centaur liquid hydrogen tank at various acceleration levels for two tank outflow rates. Scale-model tanks, 1/38 and 1/3.67, were used to conduct the investigation with alcohol and water as the test liquids. All tests were conducted at normal gravity. The outflow rates of the scale-model tanks were varied to provide a Froude number simulation of Centaur liquid hydrogen tank outflow rates and acceleration levels.

The critical liquid heights at which vapor ingestion would occur in the Centaur liquid hydrogen tank were established by Froude number simulation for acceleration levels from $2 \times 10^{-4} g$ to 4 g's for outflow rates corresponding to main engine firing and pump zero discharge conditions. The experimental critical liquid heights correlate well with an

analytical expression, based on Bernoulli's equations. A data point obtained from a test using a full-size Centaur liquid hydrogen tank correlates well with the scale-model data and the analytical results.

The critical liquid heights obtained from the investigation were used to establish the Centaur liquid hydrogen heights required for a successful engine restart sequence in space and to establish minimum propellant residuals at the end of the thrusting period.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 14, 1967,
891-01-00-06-22.

APPENDIX - SYMBOLS

a	fluid acceleration, m/sec^2
D	diameter of tank outlet, m
g	acceleration due to gravity, m/sec^2
h	liquid height at tank wall, m
h_c	liquid height at tank wall at which vapor ingestion occurs, m
h_{ec}	liquid height at Centaur tank wall at which vapor ingestion occurs, m
h_0	liquid height above tank outlet perimeter, m
h_{0c}	liquid height above tank outlet perimeter at which vapor ingestion occurs, m
P_T	pressure at liquid surface at tank wall, kg/m^2
P_0	pressure at liquid surface above tank outlet perimeter, kg/m^2
Q	volumetric tank outflow rate, m^3/sec
r_0	radius of tank outlet, m
t	time, sec
U_0	stream velocity normal to hemispherical surface constructed over tank outlet, m/sec
V	tank outflow velocity, m/sec
ρ	fluid density, kg/m^3

Subscripts:

1	fluid 1
2	fluid 2

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