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Propellant Vortexing in a Spinning Spacecraft

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The use of high thrust engines on the LEASAT (a communications satellite leased by the Navy) Liquid Apogee Motor (LAM) subsystem, with their associated high flow rates, stimulated a discussion of the possibility of vortexing phenomena within the LAM propellant tanks. Previous liquid propulsion systems were not vulnerable to this phenomena due to either low flow rates or the use of a bladder which eliminated the free surface required for vortex formation. A literature search showed that although a certain amount of qualitative testing has been done, there is no analytical treatment which can be applied with confidence. Therefore, as with previous approaches to the problem, full scale and model testing were done, using the appropriate scaling equations derived from dimensional analyses. The tests were divided into two categories: extensive testing at 1 *g*, which indicated vortex formation, and limited centrifuge testing which showed no tendency to form vortices in this design.

Nomenclature

g = acceleration, ft/s/s
L = length, in.
r = radial distance, in.
V = velocity, ft/s
w = angular velocity, rpm
Z = vortex axis of symmetry
μ = dynamic viscosity, lb/ft-s
ν = kinematic viscosity = μ/ρ, ft^2/s
ρ = liquid density, lb/ft^3

Subscripts

m = model
p = prototype
R = ratio of model property to prototype property; e.g., $L_R = L_m/L_p$

Introduction

THE LEASAT Liquid Apogee Motor (LAM) subsystem has been described in detail in Ref. 1. Summarizing those parameters of interest in a study of vortexing, the subsystem is located on the spinning side of the spacecraft and incorporates four tanks (two oxidizer and two fuel) holding approximately 4000 lb of propellant which is fed to two engines, each of 100 lb thrust. Since the centrifugal force supplied by the rotating structure settles the propellants at the tank outlets, no positive expulsion devices are required, and the free liquid surface would allow the existence of a vortex if other important parameters were favorable.

Problem Statement

The ingestion of pressurant into a bipropellant system is serious in that it can cause flame-out, leading to overheating, chugging, and possibly explosion. For a monopropellant system chugging could go unnoticed and probably would not be serious. It has been observed that ingestion often is self-healing; i.e., its result temporarily stops vortexing until enough time has evolved to reestablish the vortex.

In considering vortexing in LEASAT, there are three factors:

1) A mechanism which provides some propellant angular momentum around a radial vector normal to the spin axis.

2) The time required for circulation buildup during or prior to draining from a very low angular rate to one sufficiently strong to cause a large vortex to form.

3) The time required for a small vortex to build up to sufficient height to cause ingestion.

In examining the literature,[2-8] one notes significant activity in the late 1950s and early 1960s when the problem appeared in launch vehicles, and very little thereafter. The early efforts produced one significant theoretical approach[2] and several empirical approaches resulting from full and part scale tests. These efforts all led to the conclusion that antivortexing baffles were an obvious solution to the problem, and these were universally adopted. As a result of zero and partial g operation, some interest in vortexing was renewed in the late 1960s and early 1970s.[3]

Conclusions from these efforts are still not sufficient to quantify the problem. It is possible, with some confidence, to arrive at specific figures in answer to query 3. Here, as applied to LEASAT parameters, theory and empirical results are capable of being compared and do include all vital parameters (i.e., g level, tank pressure, flow rate, viscosity, drain size, and drain size to tank size ratios, etc.). Agreement is within an order of magnitude, and clearly indicates that sizable (of the order of 1 ft in height) vortices can be formed in 2 min or less if starting swirls are on the order of 4 rpm or more. No real information is available to indicate times necessary to increase swirl rates which start as infinitesimal to get up to values of the order of 4 rpm (query 2), although it is suggested that once draining starts, this time is also short in comparison to our typical 10-min runs.

The weak link in this discussion is the provision of a satisfactory answer to query 1 above. Most likely generating functions are described by Dodge[4] (amplification due to boundary layer interactions associated with curved streamlines) and Abramson et al.[5] (irrotational in-phase sloshing, driven by spin axis nutation, turning into reversing-periodically rotational flow). In addition, it can be argued that a coriolis-type moment produced by an interaction of fluid motion moving radially inward towards the drain combined with the spin angular rate could be a driver—but this is difficult to quantify.

Other possibilities of swirl initiation are "left-over" angular rates (damping would be very slow in view of the low viscosity of the propellants) from the preapogee burn reorientation maneuver, and random inputs caused by a series of RCS system pulses.

Analytical Treatment

The vortexing of a fluid in an emptying tank under 1 g conditions is a phenomenon in which the free surface pressure condition is met by a balance between the gravitational effect

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and the local velocity. In steady state conditions on the vortex surface, this becomes:

$$\rho g Z = -\tfrac{1}{2}\rho V^2 \quad (1)$$

For most vortices which have been observed, the velocity due to exit flow is not sufficient to support this configuration. For nearly steady flow, such a geometry can be achieved by superposition of a single vortex flow in which the angular momentum is along the Z axis, and where the azimuthal velocity component is proportional to $1/r$ (e.g., see Lamb's *Hydrodynamics*, p. 29).

Consider next the tank which rotates about an offset axis (X axis), with the drain along the Z axis and with Y axis perpendicular to the X, Z plane. The local free surface pressure condition is quite similar to the preceding, i.e.,

$$\tfrac{1}{2}\rho V^2 = \tfrac{1}{2}\rho w^2 (r^2 - r_0^2) \quad (2)$$

where $r^2 = Z^2 + Y^2$, and r_0 corresponds to the equilibrium no flow condition.

These conditions are analogous to the 1 g case, while the corresponding acceleration is effectively $w^2 r_0$. Suppose a vortex were aligned with the Z axis, with a velocity field defined by:

$$U = -CY/(X^2 + Y^2) \quad (3)$$

$$V = CX/(X^2 + Y^2) \quad (4)$$

The coriolis acceleration becomes:

$$\frac{2wCX}{X^2 + Y^2}\bar{k} \quad (5)$$

This is antisymmetrical about the YZ plane. The maximum coriolis acceleration occurs at $Y=0$ and becomes $2wC/X$.

If the vortex has a depth Δr, the pressure condition would be:

$$r^2 = w^2 2 r_0 \Delta r \quad (6)$$

and, at $Y=0$, $V=C/X$.

Hence, the maximum coriolis acceleration becomes:

$$2w(2w^2 r_0 \Delta r)^{1/2} = 2(2)^{1/2} w^2 (r_0 \Delta r)^{1/2} \quad (7)$$

The ratio of coriolis to centripetal acceleration then becomes $2(2)^{1/2}(\Delta r/r_0)^{1/2}$.

If the offset r_0 is very large compared to Δr, this ratio is small, and a behavior similar to the 1 g case might be expected.

However, for the case under consideration, $r_0 \sim 61$ in., Δr is proportional to the tank radius. Here $r_t = 19$ in. If the depth of the vortex is to be of the order $\tfrac{1}{2}r_t$, then $(\Delta r/r_0) \sim 9.5/61 = 0.151$. The ratio of coriolis to centripetal acceleration would be 1.1. It is expected that since the coriolis accelerations are antisymmetric, they would tend to disrupt vortex formation. When the coriolis acceleration becomes significant compared to the centripetal acceleration, such vortex formation would appear to be unlikely.

Modeling

Due to the theoretical difficulties associated with vortex phenomena, it was decided to conduct a series of tests both at 1 g and using a centrifuge to simulate the acceleration field seen on a spinning spacecraft. Dimensional analysis was used to scale the test equipment to realistically simulate the applicable spacecraft parameters.

The Froude number is defined as:

$$Fr = V^2/Lg \quad (8)$$

and the Reynolds number is:

$$Re = VL\rho/\mu = VL/\nu \quad (9)$$

For dynamic similarity, the model physical characteristics and the prototype characteristics as defined by the Froude number are:

$$Fr_m = V_m^2/L_m g_m \quad \text{and} \quad Fr_p = V_p^2/L_p g_p \quad (10)$$

or, defining

$$Fr_R = \frac{Fr_m}{Fr_p} = \frac{(V_m/V_p)^2}{(L_m/L_p)(g_m/g_p)} = \frac{(V_R)^2}{L_R/g_R} \quad (11)$$

Correspondingly, for the Reynolds number:

$$Re_m = V_m L_m/\nu_m \quad \text{and} \quad Re_p = V_p L_p/\nu_p \quad (12)$$

and defining

$$Re_R = \frac{Re_m}{Re_p} = \frac{(V_m/V_p)(L_m/L_p)}{(\nu_m/\nu_p)} = \frac{V_R L_R}{\nu_R} \quad (13)$$

Therefore, for dynamic flow simulation during 1 g testing, the Froude number, which ratios the inertial forces to the gravitational forces, was judged a more important parameter with regard to the vortex phenomena than the Reynolds number, which ratios the inertial forces to the viscous forces. Consequently, setting Eq. (11) equal to unity, the velocity ratio is:

$$V_R = (L_R g_R)^{1/2} \quad (14)$$

Hence, for a given model size at 1 g, the flow velocity is stipulated by the above equation.

Substituting into Eq. (13),

$$Re_R = (L_R g_R)^{1/2} L_R/\nu_R = (L_R^3 g_R)^{1/2}/\nu_R \quad (15)$$

Therefore, for a below full scale test a 1 g with a fluid with properties similar to the propellants, the resulting Reynolds number ratio could be either above or below unity depending on the spacecraft (prototype) rotational speed selected to be simulated.

However, by using a centrifuge to simulate the g level, the Reynolds number ratio can also be set equal to one, and from Eq. (15),

$$g_R = \nu_R^2/L_R^3 \quad (16)$$

Hence, for model dimensions significantly below the prototype, high g levels could be required for simultaneous simulation of both Froude and Reynolds numbers.

Testing

The various parameters investigated during the testing included the effects of:

1) Flow rate variations.
2) Fraction fill variations.
3) Direction of initial fluid rotation.
4) Tank pressure variations.
5) Variations in outlet tube diameter.
6) Stopping flow during vortexing.
7) No initial fluid motion.
8) Slosh only, no rotation.
9) Different fluids.
10) Uniform 1 g field vs a rotational field.
11) Different diameters of tanks.
12) Alternate baffle design scaled to the appropriate tank dimensions.

13) Rotation of the outlet port about the vertical tank centerline to interfere with the vortex dynamics.

14) Variations in initial fluid rotation speeds.

15) Perforations in baffles on vortex suppression.

Due to the limited number of nontoxic fluids available to simulate the oxidizer (nitrogen tetroxide) and fuel (monomethylhydrazine), complete satisfaction of both the Reynolds and Froude numbers is not possible in a 1 *g* environment.[9] (Freon-TF and water were selected to simulate oxidizer and fuel, respectively.)

12.7-In. Metal Tank Testing

Initial testing was performed on an existing 12.7-in.-diam conispherical tank while plastic tanks were being prepared for testing. The flow rate, corresponding to the flight tank diameter of 36.7 in., was approximately 0.7 lb/min based on a Froude number correlation.

The test setup is shown schematically in Fig. 1. The presence of vortexing was detected by both the presence of bubbles in the sight glass and a "crackling" sound emanating from the tank as bubbles were exhausted.

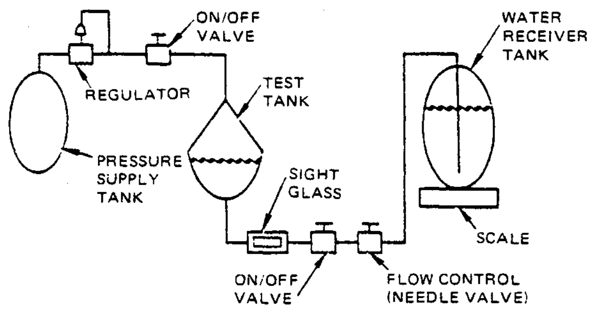


Fig. 1 Vortex test setup schematic for 12.7-in.-diam conispherical tank.

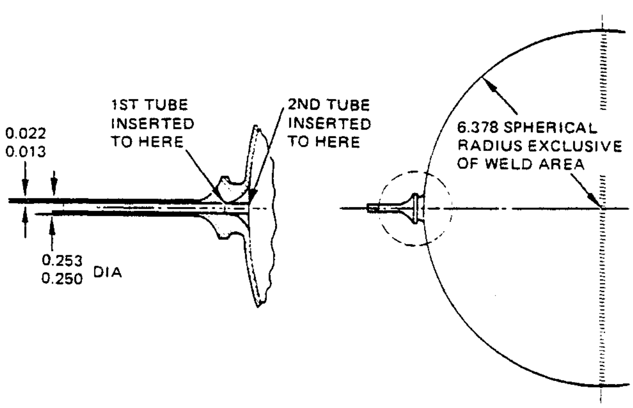


Fig. 2 3/16-in.-diam tube locations in tank outlet.

The first series of tests attempted to determine whether a vortex would be self-generating or whether an initial fluid rotation was required. There was no evidence of vortex formation until 90% of the fluid had been expelled (the rate of bubble ingestion from this point to depletion was small compared to that seen during strong vortexing so that this effect may be due to normal fluid surface depression discussed in Ref. 10 rather than actual vortexing action). The initial swirl input, as produced by a technician holding the tank and moving it in a circular path, had to be above a certain unknown rate to initiate the vortex condition. The tests started at a high flow rate, and as soon as vortexing was noted, the on/off flow control valve was closed, the needle valve closed a certain number of turns, and the flow restarted. The flow rate which was found to prevent vortexing (except near depletion) was approximately 1.8 lb/min. This flow rate was found to be independent of tank pressure or fraction fill. (Fraction fills of 25%, 50%, and 75% were tested in addition to tank pressures of 220, 55, and 15 psig.) Clockwise initial rotation was found to be as effective in initiating vortexing as counterclockwise rotation.

Tubes were inserted into the tank outlet on the hemisphere to more closely simulate the LAM configuration which has the outlet tube flush with the tank wall (see Fig. 2). The smaller flow area resulted in an area ratio (LAM outlet tube to test tube) of 3.1 which is close to the 2.9 ratio based on the tank diameters. No discernible differences in critical flow rates or vortex action were noted (reorganizing the limitations of the simple test setup in use).

As had been noted earlier during the tests with a small plastic hemisphere, a rotation of between 5 and 15 deg of the outlet port about the tank center stopped the vortexing action. These test results were confirmed by rotating the tank slightly after vortexing had begun. To extend this data, the tank was inverted to produce flow at the cone outlet port, a vortex was begun, and then the tank outlet rotated until the vortexing stopped. As before, the vortexing stopped around 10 deg tilt. An attempt was also made to initiate vortexing with the tank cone 45 deg to the vertical (standard conisphere installation in other Hughes spacecraft). If any central surface depression was induced by the initial rotation, there was no indication of a deep vortex as would be exhibited by bubbles reaching the outlet port.

With the tank oriented hemisphere down and without initial rotational input, the tank was oscillated perpendicular to the vertical axis to produce a sloshing action in one axis during the entire expulsion period. No vortex or gas ingestion was noted until the slosh wave began to unport the outlet port.

An experiment was also run to determine the effects of flow termination on vortex reappearance. As soon as vortexing

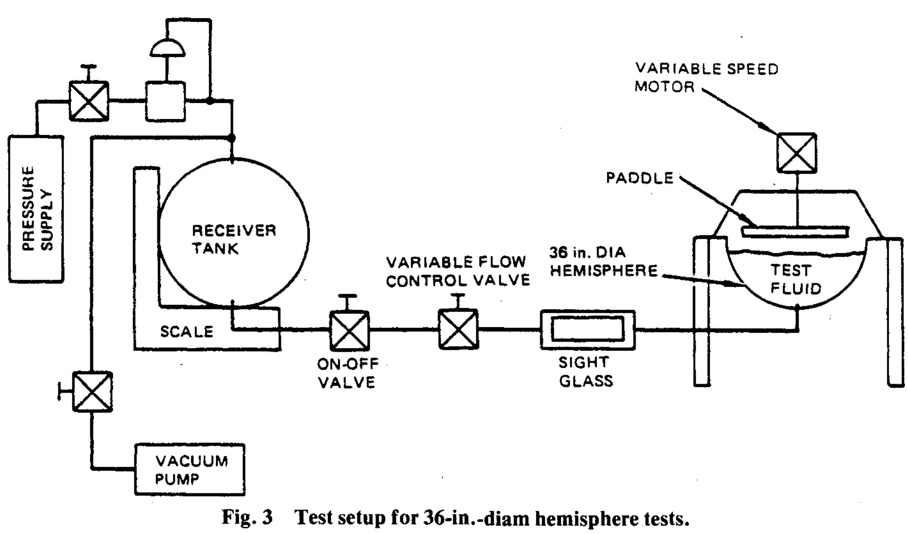


Fig. 3 Test setup for 36-in.-diam hemisphere tests.

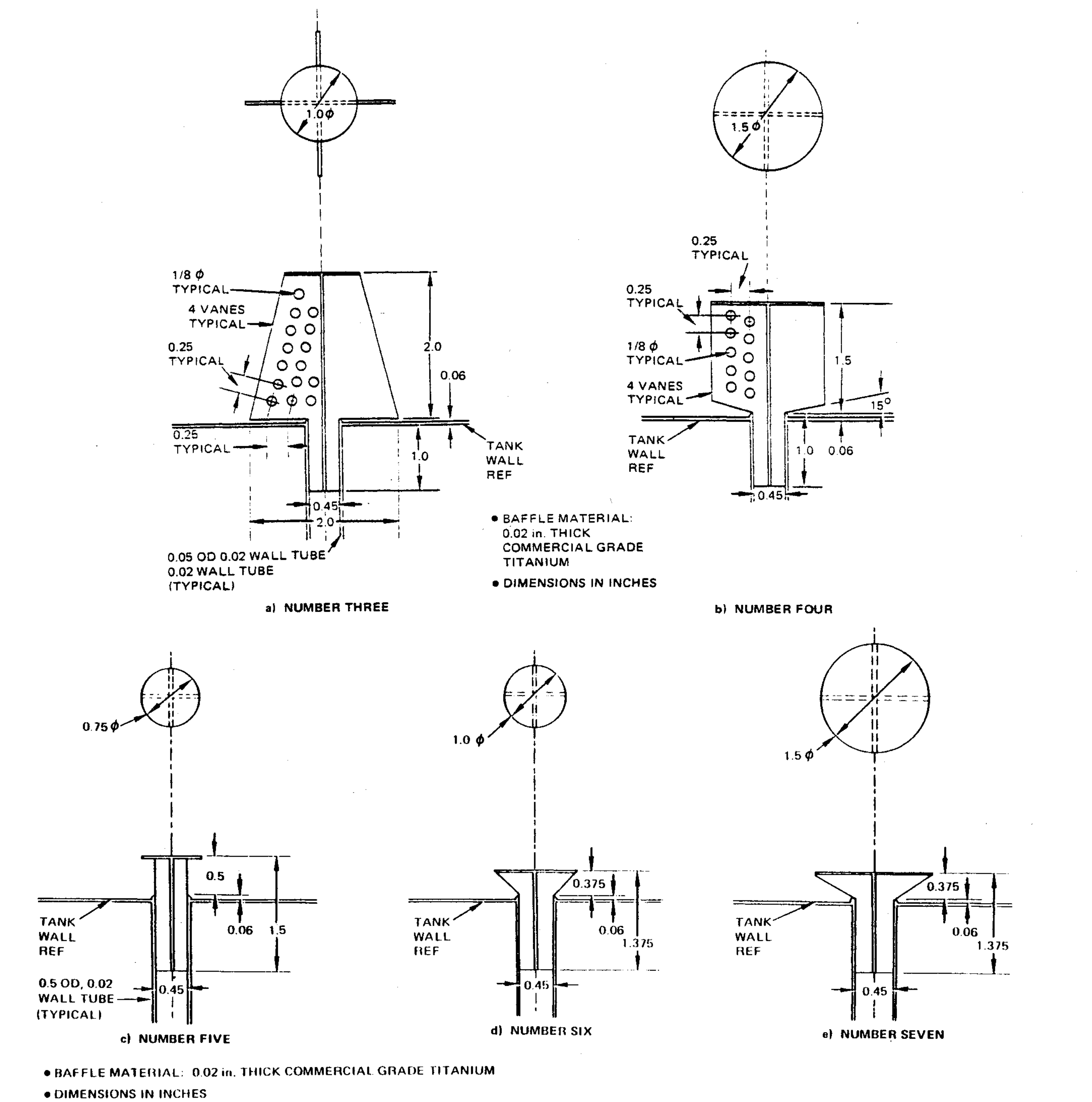


Fig. 4 LEASAT LAM baffle designs.

appeared, the flow control valve was turned off for 5 s and then reopened. The vortex reappeared shortly thereafter. This "off" time interval was progressively increased to 90 s; the vortex always reappeared albeit at somewhat longer time intervals as the "off" times increased. This result was anticipated since the vortex flow pattern takes longer to reform after an extended period of dissipation during no flow conditions.

36-In. Plastic Tank Testing

The next set of tests were performed using a plastic hemisphere, 36 in. in diameter. This size hemisphere was very close to the 36.7-in.-diam tank used in the flight spacecraft.

Test objectives were to:

1) Verify the results of the 12.7-in.-diam tank testing.
2) Determine degree of dynamic flow variations between water and Freon which were used to simulate fuel and oxidizer, respectively.
3) Determine efficiency of alternate baffle designs in reducing vortexing.

A schematic of the test setup is shown in Fig. 3.

The variable speed motor attached to the paddle allowed a known amount of fluid rotation to be induced. Although the degree of rotation potentially induced during various mission phases was unknown, an upper limit of 40 rpm, corresponding to the maximum rotational speed of the spacecraft, was established, with the intent of determining sensitivity of vortexing to this parameter. The sight glass provided positive indication that vapor was being ingested. This was required due to the lens effect of the fluid which distorted the image of the fluid leaving the hemisphere. The flow control valves allowed flow rates to be regulated to desired levels, and the

Table 1 Vortex test parameters simulating 30 rpm spacecraft spin speed

Propellant simulated	Test fluid	ν_R	g_R	V_R Desired	V_R Actual	Fr_R, actual	Re_R, actual
1-g test with 36-in.-diam hemisphere							
MMH	Water	1.07	0.50	0.697	1.23	3.11	1.12
N_2O_4	Freon	1.58	0.50	0.697	0.841	1.45	0.518
1-g test with 19-in.-diam sphere							
MMH	Water	1.07	0.50	0.510	4.20	67.8	2.04
N_2O_4	Freon	1.58	0.50	0.510	3.27	41.2	1.08
Spinning test with 19-in.-diam sphere							
MMH	Water	1.07	8.14	2.06	3.90	3.59	1.90

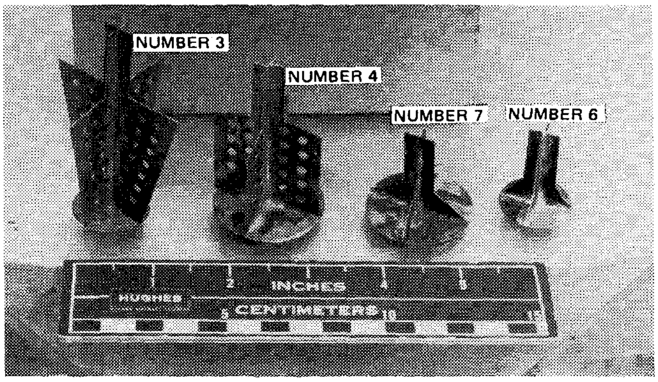


Fig. 5 Alternative baffle designs.

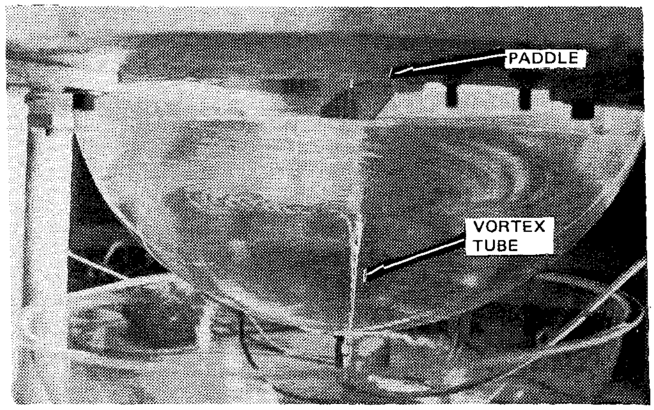


Fig. 6 Freon at 0 deg tilt—no baffle.

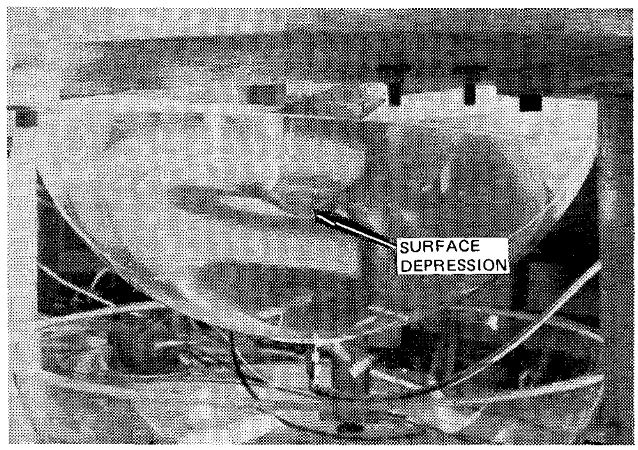


Fig. 7 Freon at 5 deg tilt—no baffle.

receiver tank/scale assembly allowed measurement of flow rates. The pressure supply allowed fluid to be returned to the hemisphere for the next test and the vacuum pump provided the suction required to obtain the required test flow rates.

The initial test series utilized water with the vertical tank axis parallel to the gravity field and showed that a vortex would form independent of the initial paddle rotational speed, with longer formation times associated with slower initial rates of rotation. (After allowing time for the fluid to achieve paddle rotational velocities, the paddle was lifted out of the fluid simultaneously with the initiation of fluid flow from the outlet.) The times for vortex formation after fluid rotation at 40 rpm and 10 rpm were approximately 5 and 25 s, respectively.

Tests were then repeated with the tank axis tipped 5 deg from the vertical, and although a surface depression approximately 2 in. in diameter and 1-in. deep formed as soon as the paddle was removed and flow started, no vortex was formed and the depth of the depression decreased as the fluid level approached the outlet, corresponding to the dissipation of the rotational motion.

Tests were then begun to determine the effectiveness of various baffle designs in inhibiting the vortexing. The designs were based on types used historically incorporating vanes to damp local swirl velocities and a disk to prevent vortex penetration to the tank outlet port. The tests were to determine the effects of variations in vane and disk size. The alternate baffle designs tested are shown in Fig. 4 (baffle designs 3-7). A photograph of baffle designs 3, 4, 6, and 7 is shown in Fig. 5.

The test results indicated:

1) Increasing the size of the disk on top of the baffle causes a shallower and larger diameter depression on the liquid surface.

2) The vortex never reached below the baffle disk, even with the smallest diameter tested (design 5, Fig. 4).

3) Gas was consistently ingested once the liquid level fell below the top of the disk, indicating that the disk should be as close to the outlet as possible.

4) Holes in the vanes reduced the level at which gas ingestion occurred. This may be due to greater liquid-to-liquid surface tension relative to that at the liquid-to-vane metal interface.

5) The baffle designs caused a pressure drop (measured with a manometer) at the tank outlet of approximately 0.1 psi. This was attributed primarily to the reduction in cross sectional area of the outlet tube caused by the baffle supporting structure.

Tests were repeated with Freon since, as seen from Table 1, its fluid properties were closer to the oxidizer's (water properties approximate the fuel). Flow dynamics were similar with the Freon appearing to produce a somewhat smaller diameter vortex.

A photograph of the vortex in Freon-TF without baffle and 0 deg tilt, is shown in Fig. 6. Corresponding surface indentation at 5 deg tilt is shown in Fig. 7. Figure 8 shows the surface indentation with baffle 6 (1-in.-diam disk), whereas Figs. 9 and 10 show the surface indentation with baffles 7 and 4 (1.5-in.-diam disks).

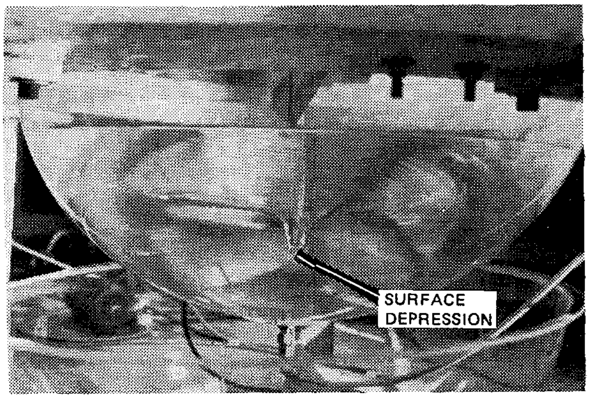


Fig. 8 Freon with baffle number 6—in.-diam disk.

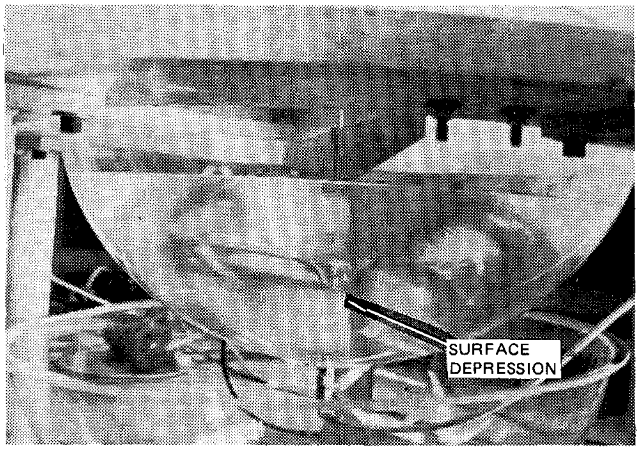


Fig. 9 Freon with baffle number 7—1½-in.-diam disk.

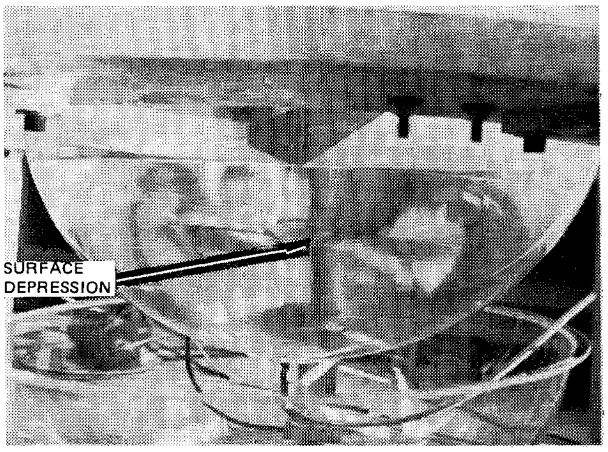


Fig. 10 Freon with baffle number 4—1½-in.-diam disk.

As a result of uncertainties as to whether a vortex forming under 1 g conditions is dynamically feasible in a radial acceleration field as seen on a rotating spacecraft, it was decided to do a centrifuge test. However, since the 36-in.-diam plastic hemisphere in use was not capable of the high stress loads required, an existing 19-in.-diam plastic tank with the desired strength was used.

19-In. Plastic Tank Testing

To confirm the 1 g test results seen on the 36-in.-diam hemisphere, a series of tests were conducted which, by scaling, simulated on the 19-in.-diam tank the flow fluids tested on the 36-in. hemisphere. This sphere, with fluid paddle installed, is shown in Fig. 11.

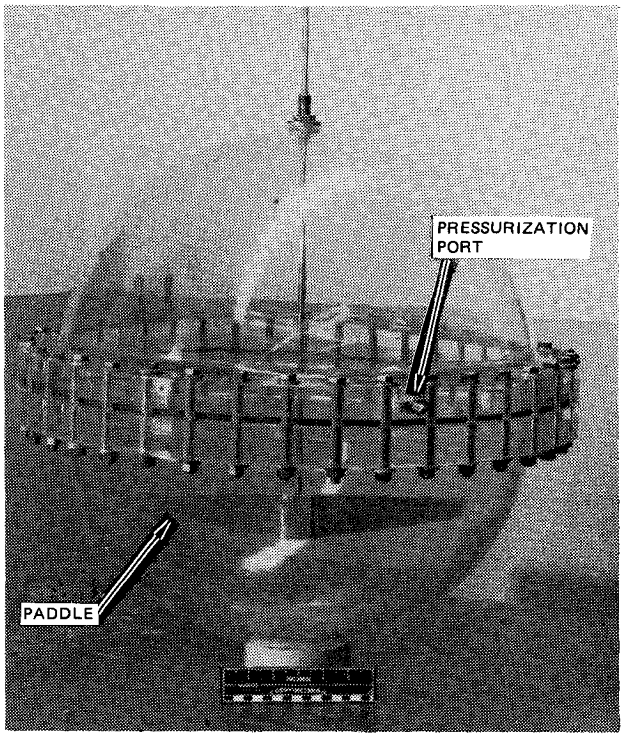


Fig. 11 19-in.-diam plastic tank.

The test setup was similar to that shown in Fig. 3 except that provisions were made to pressurize the tank to get the desired flow rates. The resulting Froude and Reynolds number ratios are shown in Table 1. The higher obtainable flow rates allowed both dimensionless ratios to be greater than 1. Tests were conducted with and without tilt and baffles with generally the same conclusions as from previous testing. The one difference was the appearance of a fluid slosh which was excited and amplified during fluid expulsion with a baffle.

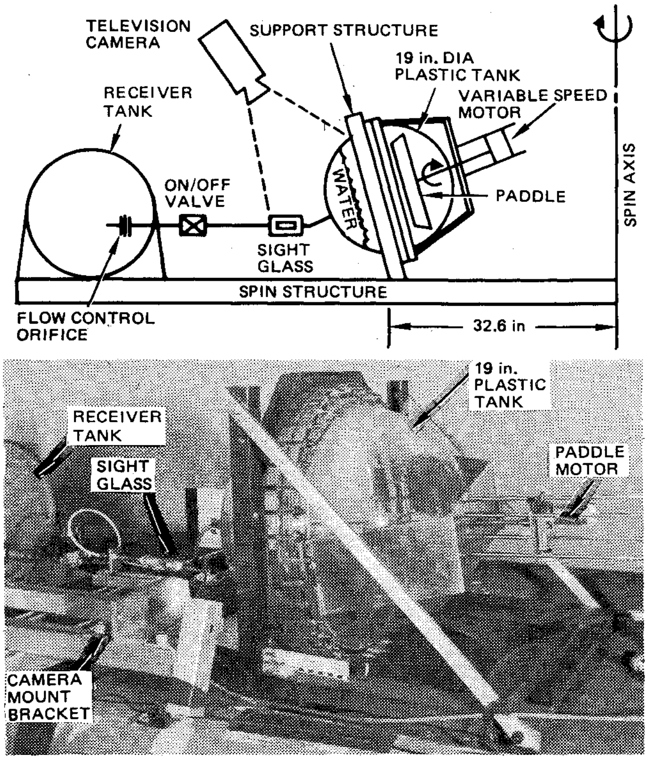
The slosh frequency was approximately 1.2 Hz and the amplitude was large enough to cause unporting and gas ingestion well before fluid depletion. No similar oscillations were seen in the 36-in.-diam hemispherical tests perhaps because the scaled flow rates on the 19-in.-diam tank tests were larger than in the 36-in. hemisphere tests (see Table 1).

Centrifuge Testing

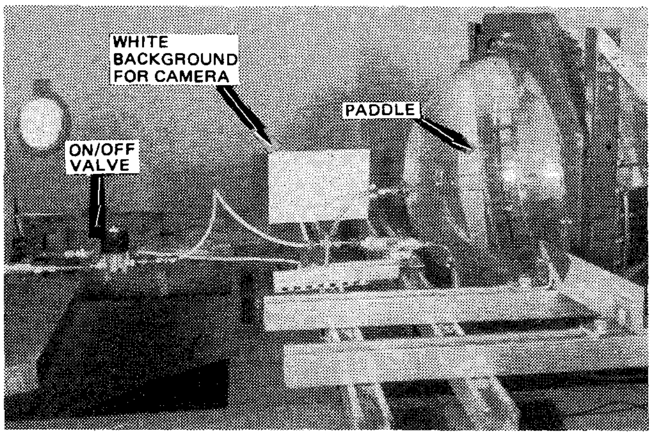
At this point the 1 g testing had indicated that rotating the tank outlet 5 deg or more about the tank center was a more effective vortex suppressant than the incorporation of baffles and also was a much simpler design change. Consequently, the decision was made to rotate the flight tank centerline through the outlet port 10 deg relative to the spacecraft radius through the tank centerline, assuming that the vortexing phenomena would exist in a spinning spacecraft.

Subsequent centrifuge testing was therefore limited to a primary test of the flight design with the 10-deg rotation and a secondary test with the tank centerline through the tank outlet coincident with the radial acceleration vector (0 deg rotation) to determine whether a vortex would form with this particular environmental/geometrical combination.

The test setup (Fig. 12) consisted of the 19-in.-diam plastic tank mounted 32.6 in. from the spin axis (as required by the scaling equations). The outlet was tilted 3.9 deg down from the horizontal to compensate for the vertical 1 g field. This geometry aligns the axis of any potential vortex tube with the tank outlet. The 10-deg angular offset is shown in the schematic (Fig. 13). The tests were run at 118 rpm, which, through scaling, corresponds to the 30 rpm on the spacecraft and provides an effective acceleration of 16.5 g as opposed to approximately 2 g on the spacecraft. The use of the sight glass



a) forward section.



b) Aft section.

Fig. 12 Test setup for vortex testing on centrifuge.

allowed the inception of vortexing to be detected rapidly since the lens effect of the test fluid and plastic tank restricted fluid visibility near the outlet. The orifice was used to control flow rates to the desired levels, the centrifugal force being used to drain the tank (desired flow rates were obtained without tank pressurization).

The desired water flow rate was 7.4 lb/min which is 50% above the nominal to demonstrate margin. Only water was used as a test fluid since it gave the most conservative results.

No vortexing was observed during testing in either tank orientation. A photograph of the videotape of the 0-deg test is shown in Fig. 14a. The bright disk near the center of the fluid surface is a mirror image of the tank outlet disk reflected from the underside of the water surface. The complete lack of distortion indicates there is no tendency to vortex as was seen during the 1 *g* testing (see Figs. 6-10). A repeat of the test at a different camera angle (looking down on the fluid surface) showed insignificant surface distortion until very near depletion. Figure 14b shows the bubbles in the sight glass at depletion.

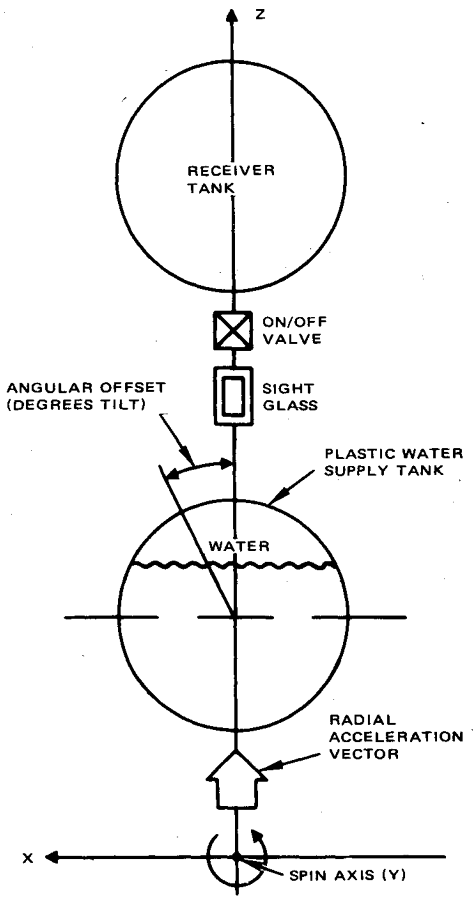


Fig. 13 Force vector system for centrifuge testing (top view).

The tests were repeated at the 10-deg outlet rotation corresponding to the spacecraft design. Again there was no perceptible surface distortion when the fluid surface was viewed from the liquid side (Fig. 15) or when viewed from the vapor side (Fig. 16a). The surface distortion caused by the forced paddle rotation is seen in Fig. 16b.

The results of the 1 *g* testing are shown in Table 1. The water flow rates obtainable in the 36-in.-diam tank allowed both Froude and Reynolds number ratios greater than unity when spacecraft rotational speeds of 30 rpm were simulated.

The flow rates obtainable in the 19-in.-diam tank allowed the Froude number ratio to be increased to the point that the Reynolds number was also above unity. (Note that the higher flow rates promote vortexing and make the test results more conservative.)

For the purposes of the centrifuge tests simulating the spacecraft application, the Froude and Reynolds number ratios were desired to be equal to or greater than unity, indicating that the viscous and gravity forces were being dominated by the inertial forces. The values obtained (Table 1) were 3.59 and 1.90, respectively, giving confidence in the test results as being highly conservative when applied to the particular design being simulated.

Conclusions

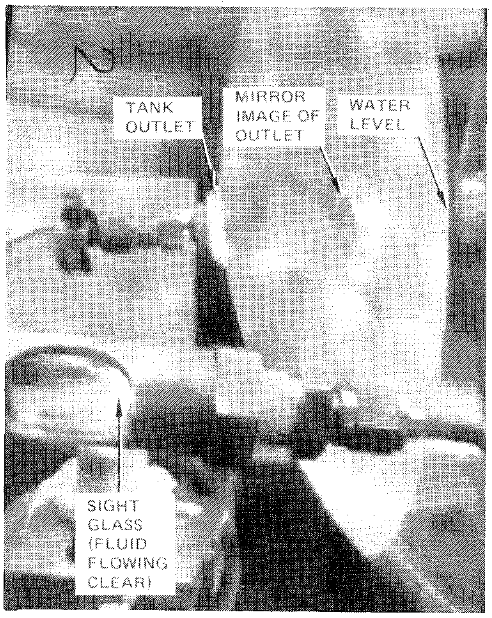
1) Either the rotation of the tank outlet about its centerline or the incorporation of baffles inhibit vortexing.

2) Higher flow rates produce stronger vortexing.

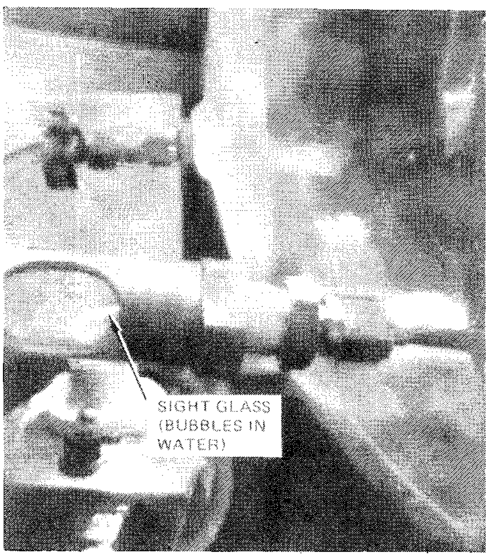
3) The vortexing phenomena were found to occur at all fraction fills, in both directions of initial fluid rotation, at various tank pressures, and with fluids exhibiting large differences in fluid properties.

4) Decreases in outlet tube diameter caused stronger vortexing due to increased flow velocity.

5) Stopping flow during vortexing would not prevent recurrence when flow was restarted.



a) Water at 0- degree tilt.



b) 0-deg tilt at water depletion.

Fig. 14 Test number 2.

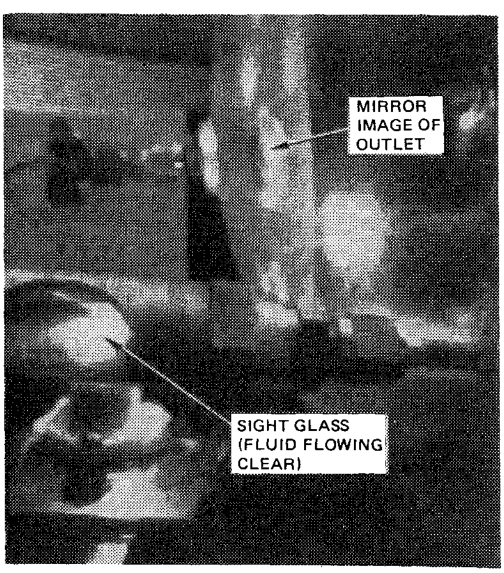
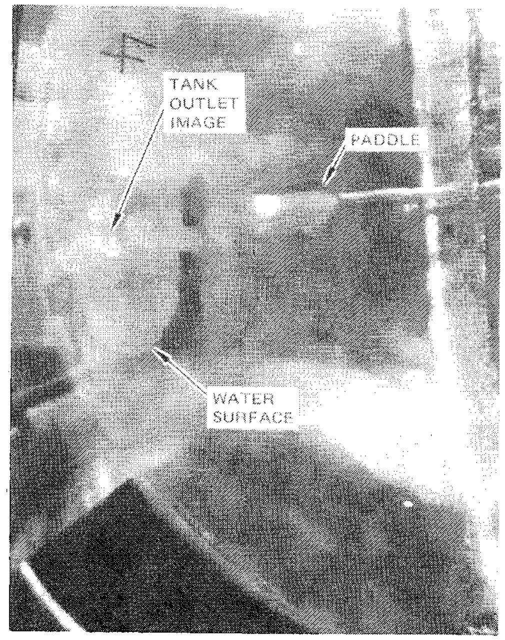
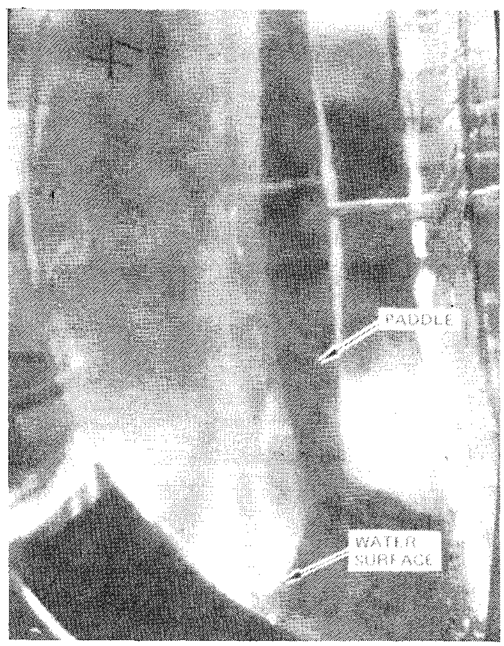


Fig. 15 Test number 3—water at 10-deg tilt.



a) Top view of 10-deg tilt with water near depletion.



b) 10-deg tilt—paddle out of water.

Fig. 16 Test number 4.

6) The time to form a vortex increased when there was no initial fluid rotation and was longer, in general, in water than in Freon.

7) A strong sloshing action inhibited vortexing by moving the vortex away from the tank outlet.

8) Similar vortex action was seen for the two fluids tested: water and Freon. The vortex formed more rapidly in Freon and tended to be thinner than that seen in water. These effects are attributed to the differences in kinematic viscosities of the two fluids.

9) While vortexing was easily induced in a 1-*g*, uniform acceleration field, no vortexing was observed in a rotating field scaled to the spacecraft dimensions.

10) Similar dynamic flow phenomena were seen when fluid flow parameters were scaled to conform to various tank and outlet tube diameters.

11) While the time to produce a vortex was influenced by the strength (velocity) of the initial fluid rotation, a vortex

consistently occurred independently of the rotational magnitude.

12) Although the baffles prevented vortexing, there was significant gas ingestion once the fluid level fell below the level of the disk. Holes in the vanes supporting the disk reduced the gas ingestion level, presumably due to the improved liquid-to-liquid surface tension interfaces provided by the holes.

Based on the author's study of vortexing phenomena, the following are new observations.

1) A small rotation of the tank outlet about its centerline effectively suppresses vortex formation.

2) No vortexing occurred in a radial acceleration field (as on a spinning spacecraft).

The remaining conclusions were expected from a knowledge of the fluid properties and previous work done on various baffle designs.

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References

[1]Pasley, G.F. and Donatelli, P.A., "LEASAT Liquid Apogee Motor Subsystem Design," *Journal of Spacecraft and Rockets,* Vol. 17, Sept.-Oct. 1980, pp. 396-399.

[2]Dergarabedian, P., "The Behavior of Vortex Motion in an Emptying Container," *Proceedings of the Heat Transfer and Fluid Mechanics Institute,* Stanford University Press, 1960, pp. 47-61.

[3]Gluck, D., "Vortex Formation, Free Surface Deformation, and Flow Field Structure in the Discharge of Liquid from a Rotating Tank," Space Division, North American Rockwell, S.D., 72-SA-0108, 1972.

[4]Dodge, F.T., "Liquid Rotation and Vortexing During Draining, Part II," Hughes Aircraft Company Accession N67 15896, source unknown.

[5]Abramson, H.N., Chu, W., Garza, L.R., and Ransleben, G.E., "Some Studies of Liquid Rotation and Vortexing in Rocket Propellant Tanks," NASA TN D-1212, 1961.

[6]Kawakubo, T., Tsuchiya, Y., Sugaya, M., and Matsumura, K., "Formation of a Vortex Around a Sink," *Physics Letters,* Vol. 68A, No. 1, Sept. 18, 1978.

[7]Martin, E., "Experimental Investigations on the Fuel Slosh of Dual Spin Spacecraft," *Comsat Technical Review,* Vol. 1, No. 1, Fall 1971.

[8]Slabinski, V.J., "Intelsat IV In-Orbit Liquid Slosh Tests . . .," *Comsat Technical Review,* Vol. 8, No. 1, Spring 1978.

[9]Bird, R.B., Stewart, W.E., and Lightfoot, E.N., *Transport Phenomena,* Wiley, New York, 1962.

[10]Saad, M.A. and DeBrock, S.C., "Simulation of Fluid Flow Phenomena in Propellant Tanks at High and Low Accelerations," *Journal of Spacecraft and Rockets,* Vol. 3, Dec. 1966, p. 1782.