Evaluation of Fluid Behavior in Spinning Toroidal Tanks

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An experimental study was conducted to evaluate propellant behavior in spinning toroidal tanks that could be used in a retropropulsion system of an advanced outer-planet Pioneer orbiter. Information on propellant slosh and settling and on ullage orientation and stability was obtained. The effects of axial acceleration, spin rate, spin-rate change, and spacecraft wobble, both singly and in combination, were evaluated using a ⅛-scale transparent tank in 1-*g* and low-*g* environments. Liquid loadings ranged from 5 to 96% full. The impact of a surface-tension acquisition device was assessed. Testing simulated the behavior of F_2/N_2H_4 and N_2O_4/MMH propellants. Results are presented that indicate no major fluid behavior problems would be encountered with any of the four propellants in the toroidal tanks of a spin-stabilized orbiter spacecraft.

Introduction

A previous study[1] investigated the feasibility of developing a toroidal tank system for use in a spin-stabilized, Pioneer-type orbiter for outer planet missions. The results indicated the toroidal tanks employing surface-tension propellant management devices could be fabricated and employed to advantage in the spinning spacecraft. Another study[2] indicated certain advantages in weight, packaging, and structural mounting for a system using two toroids in place of either two or four spherical tanks. However, these analytic studies lacked experimental confirmation of the fluid behavior characteristics associated with a spinning toroidal tank. Before considering a full-size tank development program, a scale-model assessment of propellant slosh and settling and of ullage orientation and stability characteristics of propellants in a spinning toroidal tank was desired.

The objective of this program was to evaluate photographically the effects of axial acceleration, spin rate, spin-rate change, and spacecraft wobble on fluid behavior. The tank was to contain a simulated propellant management device as defined in the initial study (Fig. 1). Liquid propellants to be simulated in the test were nitrogen tetroxide/monomethylhydrazine and fluorine/hydrazine. Dynamic conditions to be simulated singly and in combination were: axial acceleration – 0 to 0.1 g; spin rate – 0 to 20 rpm; spin rate change 1 rpm/sec; and wobble (nutation of spin axis) 1.6° minimum.

Test System

Testing was conducted primarily under low-*g* environmental conditions in the Martin Marietta Drop Tower. As a result, design of the test equipment was defined by the limitations of this low-*g* test facility, which provides a free-fall distance of 22.9 m (75 ft) resulting in a usable low-*g* test duration of 2.1 sec.

The drop system consists of an outer capsule (drag shield), and a smaller inner capsule (test cell) that contains the experiment, power supply, and instrumentation. The instrumentation includes a high-speed movie camera capable of film speeds up to 200 frames per sec. For zero-*g* tests, the test cell falls unguided and independent of the drag shield. Air drag on the test cell and piston effect between the two capsules are reduced to an acceleration level of less than 10^{-5} *g* by evacuating the drag shield to absolute pressure levels of 5 mm Hg. The relative travel distance between the two capsules permits a free-fall duration for the test cell of 2.1 sec. The entire capsule assembly is decelerated in a wheat bin. Peak deceleration is less than 25 *g* and the deceleration time interval is less than 0.15 sec.

To simulate low-*g* environments, the test cell is accelerated relative to the drag shield during the drop by a NEG'ATOR§ spring motor assembly and cable arrangement. The motors provide a near-constant force with linear deflection. The average acceleration applied to the test specimen is calculated by dividing the applied spring force by the test cell mass.

The design of the toroidal test tank evolved from considering the following four factors: fluid reorientation time during the drop test; optical characteristics of the tank; test cell envelope; and scaling relationship between the test tank model and full-sized tank. An evaluation of these factors resulted in the selection of a minor radius of 1.91 cm (0.75 in.) and a major radius of 5.72 cm (2.25 in.), providing a ⅛-scale model of the full-size tank.[1] This model provided acceptable optical characteristics for data recording and was compatible with test cell envelope limitations. Estimates of the time for the test liquid to reorient from the 1-*g* to the zero-*g* configuration in the toroidal tank model were obtained from methods developed for spherical tanks and cylindrical annuli.[3,4] The calculated times were 0.22 and 0.14 sec for the sphere and annulus, respectively. It was believed that these times would be representative for the toroidal tank and, therefore, the selected tank dimensions would be reasonable for the drop test duration of 2.1 sec.

The test tank was fabricated by casting polyester resin in a mold. This method produced symmetrical halves of the torus, which were then cemented together to form the complete tank. The test apparatus used for both bench and drop tower testing is shown in Fig. 2. The toroidal test tank was supported on a shaft over a hole in a housing containing two Sun

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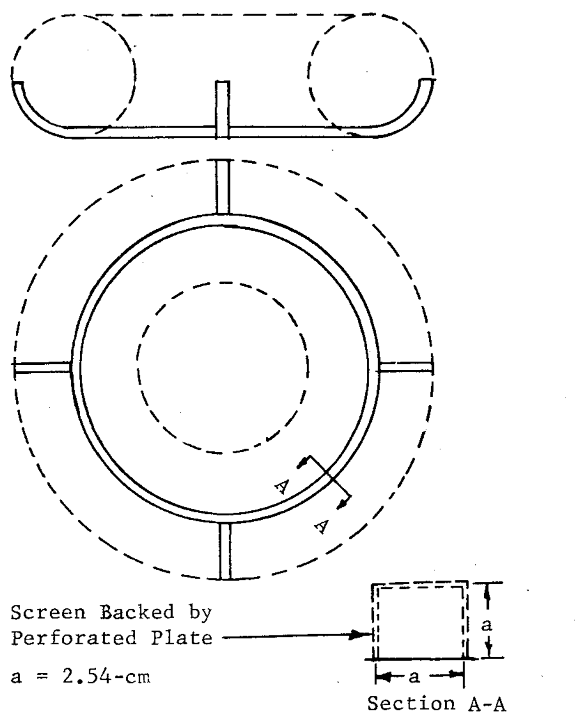

Fig. 1 Propellant acquisition system for use in a spinning toroidal propellant tank.

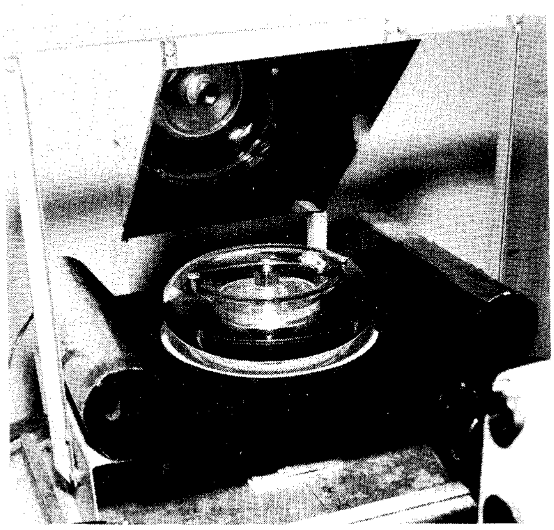

Fig. 2 Test equipment assembly.

Gun lamps that illuminate the tank from the underside. A mirror mounted above the toroidal tank allowed photographing the front and top of the tank simultaneously.

Spinning of the tank was provided by a high-speed drive motor and gear box combination positioned under the lamp housing. During drop tests, the motor speed was controlled remotely by a rheostat connected through a landline to the motor. A sensing switch mounted on the gear box was connected by landline to a tachometer located near the power control rheostat.

The shaft used to support and spin the test tank was a solid, straight rod for all tests except those simulating spacecraft wobble. For the wobble tests, the geometric axis of the test tank was displaced by an angle from the instantaneous spin axis. Two approaches were employed to provide the required minimum displacement of 1.6°. The first employed a solid shaft bent at an angle of 2°, producing a wobble effect in the toroidal tank during spinning. The second approach used a helical spring as a flexible coupling in the spin shaft with a mechanical stop to limit the geometric axis travel to ±2°. This latter method was used to ascertain whether perturbations and unsymmetrical liquid distributions would tend to increase the wobble effects. The helical spring used in the flexible coupling had an axial spring rate of 98.1 N/cm (56 lbf/in.). A lateral force of approximately 0.556 N (0.125 lbf) was required to hold the coupling against its mechanical stop.

Experimental Program

Four types of tests were conducted during the experimental program to evaluate fluid behavior in a spinning toroidal tank. These were ullage orientation, liquid settling, wobble, and spin-rate change. The results are discussed in the following paragraphs.

Ullage Orientation

The results of the previous study[1] indicated that the liquid-gas interface would be flat and the ullage uniformly distributed in the propellant tanks during all mission phases because of the radial acceleration resulting from spin stabilization of the spacecraft. However, previous work performed[5,6] indicated that, at liquid volumes of 50% or greater and under zero-*g* conditions without spin, the ullage in toroidal tanks tended toward an unsymmetrical orientation, forming one or more bubbles. Therefore, two aspects of the ullage behavior in toroidal tanks were investigated in the Martin Marietta Zero-G Facility. First, it was necessary to corroborate ullage-bubble breakup under zero-*g* conditions; then, the stabilizing effect of spin on the ullage orientation was evaluated. Liquid volumes of 5, 25, 50, 75, and 96% of tank volume were used with a simulated propellant acquisition device in the test tank.

Two drop tests were conducted for each liquid volume. The first test was conducted without spin under zero-*g*. In the second test, the tank was spun at a given rate prior to and during the test. Both tests were conducted without axial acceleration. During each test, ullage behavior was recorded on high-speed color film.

The spin rate for the test tank was established by maintaining Bond number similarity between the full-size tank and the test model. The Bond number is defined as the ratio of acceleration to capillary forces acting at the liquid-vapor interface. At low Bond numbers, the capillary forces predominate so that the liquid/vapor interface is strongly curved with a high possibility of the ullage separating into two or more segments. At high Bond numbers, the hydrostatic forces predominate so that the liquid/vapor interface is flat with essentially no possibility of forming or maintaining multiple bubbles. Mathematically, the Bond number was defined for the toroidal tank as follows

$$B_O = (\rho/\sigma) r^2 R\omega^2$$

where ρ = liquid density, σ = liquid surface tension, r = minor toroidal tank radius, R = major toroidal tank radius, and ω = spin rate.

The variation of Bond number with spin rate for each of the four specified propellants in the full-size tank is shown in Fig. 3. For the minimum spin rate of 10 rpm employed during main engine firings, the Bond number varies from 180 to 1200. For axisymmetric containers such as spheres or cylinders, the liquid/vapor interface is essentially flat at Bond numbers of approximately 50.[7] Thus, the hydrazine tank Bond numbers were used to define test tank spin rates since they present the worst case condition.

The test fluid selected for the ullage orientation tests was methanol, primaily because its wetting characteristics are similar to the candidate propellants. Bond numbers for the test tank using methanol were calculated and are also shown in Fig. 3 as a function of spin rate. Simulating hydrazine tank Bond numbers at 10 rpm require spinning the test tank at 150

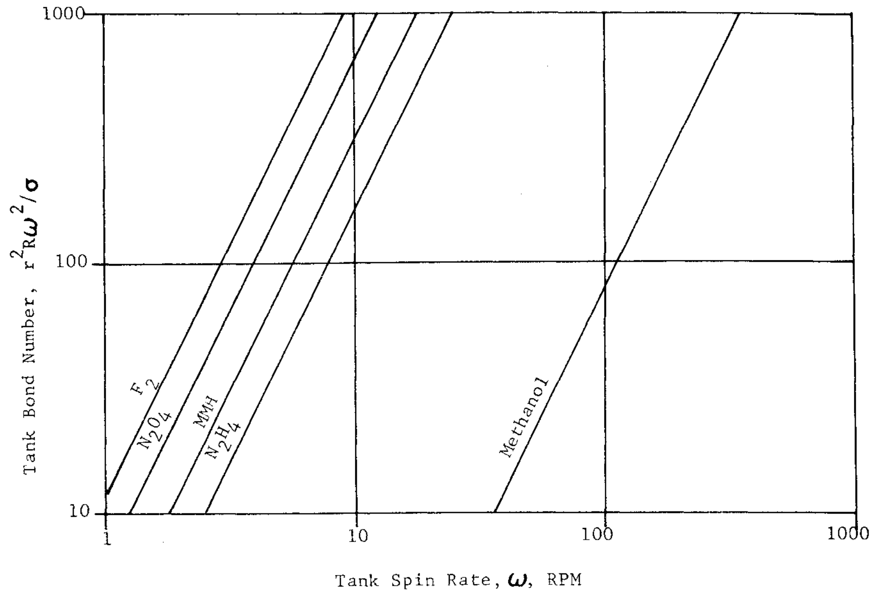

Fig. 3 Variation of tank Bond number with spin rate.

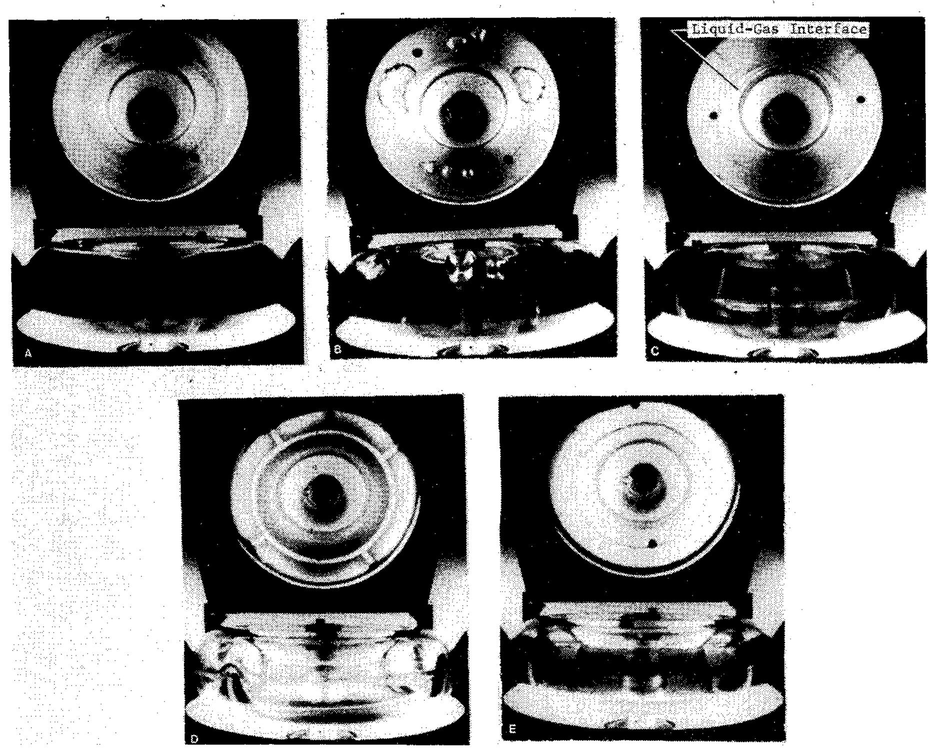

Fig. 4 Experimental ullage orientations. a) 96% liquid volume, 1-*g* axial acceleration, zero rpm spin rate; b) 96% liquid volume, zero-*g* axial acceleration, zero rpm spin rate; c) 96% liquid volume, zero-*g* axial acceleration, 150 rpm spin rate; d) 5% liquid volume, zero-*g* axial acceleration, zero rpm spin rate; e) 5% liquid volume, zero-*g* axial acceleration, 150 rpm spin rate.

rpm. This spin rate represents the conditions just prior to firing the main engine. If the ullage was unstable or unsymmetrical at this time, center-of-gravity shift might occur and application of the main engine thrust could create an attitude control problem.

In general, the test results were in agreement with the previous investigations.[5,6] For liquid volumes of 50% or greater under conditions of zero-*g*, the ullage tended toward an unsymmetrical distribution and, in some cases, broke up into several bubbles. Applying a spin rate of 150 rpm to all volume conditions produced a stable, symmetrical ullage under zero axial-*g* conditions. The ullage orientation for a 96% liquid volume, no-spin condition with 1-*g* and zero-*g* axial acceleration are shown in Figs. 4a and 4b. In Fig. 4a, the system is subjected to a normal 1-*g* environment prior to the drop test and the ullage is distributed symmetrically in the top of the tank. A picture taken near the end of the 2.1-sec, zero-*g* drop test is presented in Fig. 4b. The ullage volume has divided into seven distinct bubbles which are nonsymmetrically distributed in the tank. Ullage orientation with 96% liquid volume subjected to a spin rate of 150 rpm and zero axial acceleration is shown in Fig. 4c. For these conditions, the liquid-gas interface should be oriented vertically or parallel to the spin axis, since only radial acceleration is present. The ullage should also be uniformly distributed. These were the observed conditions as shown in Fig. 4c taken from the film strip near the end of the drop test. In the tank top view, the liquid-gas interface appears as a circle near the toroidial tank inner wall. Similar results were obtained for 75 and 50% liquid volumes. Unsymmetrical ullages were present under conditions of zero axial acceleration and zero spin rate. Application of spin, however, always produced a symmetrical ullage distribution.

Testing with 25 and 5% liquid volumes resulted in uniform propellant distribution and a symmetrical ullage under conditions of zero axial acceleration and zero spin rate. Liquid distribution for the 5% volume tests is shown in Fig. 4d and 4e. For a zero spin rate, nearly all of the liquid is retained around the edges of the propellant acquisition device (Fig.

4d). This indicates that, although the propellant acquisition device was designed to function under the influence of a radial acceleration with periodically imposed axial acceleration, it will also retain some propellant under the resulting zero-*g* condition if it were necessary to completely despin the spacecraft. When the 150 rpm spin rate was applied to the tank, the liquid was distributed on the outer tank surface as shown in Fig. 4e. The liquid mass was still in contact with the communication channels of the propellant acquisition device.

Results of the ullage-orientation tests are applicable to any of the four specified propellants in the full-size tank spinning at 10 rpm since the test Bond number was equal to or less than those of the four propellants. In the absence of perturbing forces, the propellants simulated in these tests can be expected to be distributed symmetrically in the toroidal tank about the spacecraft spin axis prior to engine ignition.

Liquid Settling

When the main engine is started, the propellant mass moves in response to the axial acceleration component from its distributed location on the outer tank wall toward the bottom of the tank, past the equilibrium position, up the inner tank wall, and then back in a cyclic fashion. A simplified slosh analysis conducted during the previous study[1] showed that significant damping of the propellant motion was provided by the recommended propellant acquisition device. To verify these analytic results, the liquid settling process was simulated in the drop tower. Test conditions employed were a) liquid volumes of 5, 25, and 50%; b) axial acceleration of 0.034 *g*; c) spin rates of 15, 20, 25, and 50 rpm; and d) methanol as the test fluid.

The liquid volume range tested was selected on the assumption that sloshing forces arising from liquid settling in the toroidal tank would increase to a maximum at liquid volumes of 50%, as is the case in spherical tanks.[4] The axial acceleration specified above is the maximum value that could be readily applied in the drop tower facility with available equipment.

In order to maintain similarity between scale model and full-size system operation, the ratio of axial to radial acceleration of the full-size tank was used to establish test model spin rates. An estimate of this ratio was made from mission data of the original study.[1] The result is plotted vs percent liquid volume in Fig. 5. It was also desired to extend the coverage of the test program. A second acceleration-ratio variation based on increased propellant mass, spacecraft spin rate, and engine thrust was also estimated and is plotted as the growth curve in Fig. 5.

The spin rates for the test program were selected to bracket the two acceleration lines. Tests were performed with 5, 25, and 50% liquid volumes at spin rates of 15, 20, and 25 rpm, as indicated in Fig. 5. A test was also run for the 5% liquid volume case at a 50-rpm spin rate. The constant axial acceleration was applied to the test cell at the start of the test and continued until the test cell bottomed in the arrestor inside the drag shield near the end of the drop period. Prior to and during the drop test, the desired spin rate was applied to the toroidal tank. An additional test was conducted without a simulated propellant acquisition device to allow a comparison of the settling and slosh damping in the toroidal tank with and without a propellant acquisition device. This test was conducted at a 25% liquid volume and a spin rate of 20 rpm.

For the bare-tank test, an oscillatory or sloshing motion of the liquid occurred. Since the drag force along the walls, the liquid internal friction, and the capsule total acceleration are all small, this motion would continue for some time. The 2.1-sec drop test time was not sufficient for these forces to completely damp this motion. An estimate of the frequency of the oscillation was made by observing the liquid-gas interface movement along the tank surface as shown by the film record. A natural frequency of 0.77 cps was obtained for liquid sloshing in the bare spinning toroidal tank by averaging several readings.

A review of previous slosh analysis and testing in toroidal tanks was made for comparison. All previous work was performed under nonspinning conditions; however, two methods[4,8] for calculating natural frequencies showed

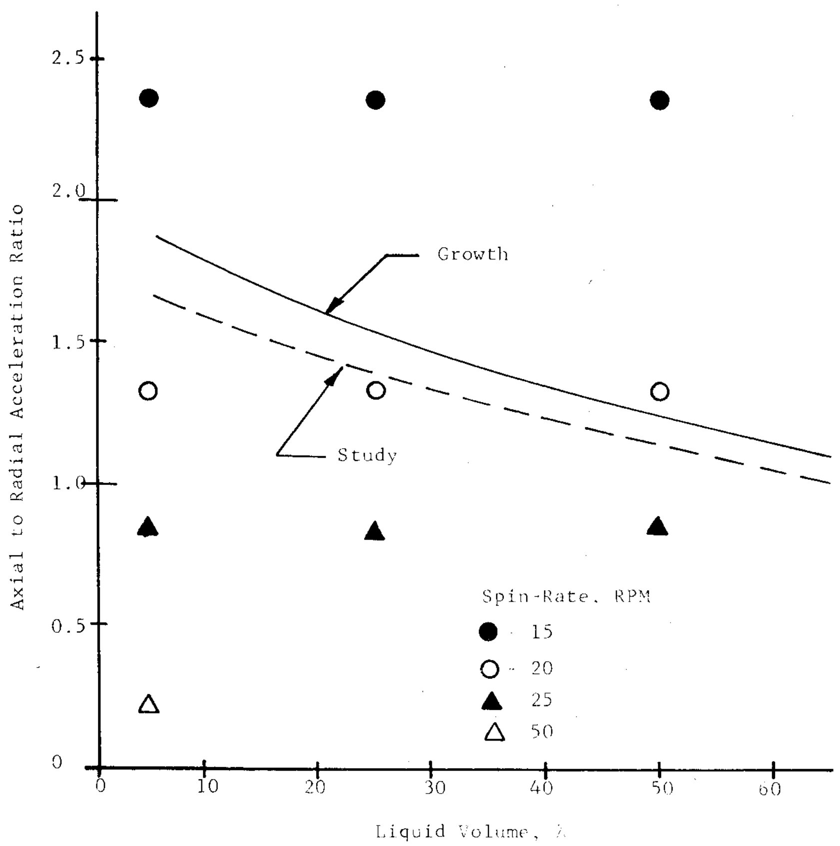

Fig. 5 Axial to radial acceleration ratio for liquid settling and slosh analysis.

remarkable agreement with the experimental results. More testing is required to justify use of these methods, however.

With the simulated propellant acquisition device installed in the tank, considerable damping of the fluid motion occurred. For the 5% liquid load spinning at 20 rpm, the liquid moved along the outer tank wall and impacted on the retaining ring of the acquisition device in the tank bottom after 0.76 sec. The size of the ring was sufficient to retain the small quantity of liquid in this position and no further liquid movement past the ring toward the inner tank wall occurred.

For 25% liquid at 20 rpm, liquid contacted the retaining ring at 0.36 sec. Sufficient liquid accumulated at 0.75 sec so that overflow toward the tank spin axis began. At 1.0 sec, a small quantity of liquid had accumulated inside the ring. After 1.5 sec, all significant liquid movement was damped and the orientation was stabilized.

At 50% liquid and 20 rpm, only 0.27 sec was required for the liquid to contact the retaining ring because of the larger quantity of liquid. After 0.5 sec, a significant amount of liquid had spilled over the ring. At 1.0 sec, the liquid was uniformly distributed over the tank bottom but the liquid was still moving. After 1.5 sec, the liquid had moved to an area between the retaining ring and the tank outer diameter. Near the end of the test at 2.0 sec, some of the liquid had moved back toward the spin axis with some fluid motion still present.

Similar results were obtained at the other spin rates, with the 50% liquid volume presenting a worst case for liquid settling and slosh than the other liquid volumes tested. Further testing should be conducted at liquid volumes above 50% to verify that the 50% volume does in fact produce the worst case for toroids as it does for spheres. The tests are considered conservative, since the transition from 1-*g* to low-*g* with the liquid initially located in the top of the tank induced more severe initial sloshing than would be expected in the actual tank where the propellant is distributed symmetrically along the outer tank wall prior to imposing the low axial acceleration.

On the basis of the observations, no major sloshing conditions should be encountered in the toroidal tank system of a spin-stabilized spacecraft. Most of the fluid oscillations in the model tank containing the propellant acquisition device appeared to be reasonably damped by the end of the test time. The propellant management device was designed to maintain contact with the propellant throughout the entire mission.[1] With the low outflow rates, the slosh will be damped before any significant change in liquid volume has occurred. The resultant effect of propellant withdrawl on slosh damping is minimal.

Wobble

Spacecraft wobble in a spinning spacecraft may be caused by a misalignment of the engine thrust vector with the spacecraft spin axis or a misalignment of the spacecraft spin axis and longitudinal axis owing to migration of the center-of-mass. It was believed that spacecraft wobble could induce propellant perturbations or sloshing that might impose unduly large requirements upon the spacecraft attitude control system. The third series of tests evaluated the effects of spacecraft wobble on fluid behavior in the spinning torus. Both bench and drop tower tests were used.

Bench testing was performed first using a flexible shaft, a liquid volume of 75%, and methanol as the test fluid. The shaft was forced against its 2° stop while the tank was spinning and then released. Spin rates of 50 and 100 rpm were used. No slosh magnification occurred. Instead, oscillations induced by releasing the shaft were damped out after 3.0 sec at a 50-rpm spin rate and 2.0 sec at a 100-rpm spin rate. The difference in damping time was attributed to the higher radial acceleration associated with the 100 rpm spin rate.

The second type of bench test with the flexible shaft involved a step change in the tank spin rate from an initial steady value to zero and back to the initial value. Initial spin rates of 50, 100, and 150 rpm were employed. A definite oscillation or wave pattern was induced on the liquid surface when the spin rate was reduced to zero. However, these oscillations were completely damped after 3.2, 2.7, and 2.8 sec for 50, 100, and 150 rpm spin rates, respectively. No major or continuous slosh problems were encountered.

Two types of bench tests were also performed with the solid, bent shaft. First, observations of fluid behavior were made with the tank rotating at constant rates of 50 and 100 rpm. Then, the step change in spin rate used for the flexible shaft tests was also applied to the solid, bent shaft. Initial spin rates of 50, 100, and 150 rpm were employed. Observations of the fluid orientation in the tank under steady-state spinning indicated no significant oscillations or sloshing. In general, the liquid tended to accumulate in that portion of the torus farthest away from the spin axis (i.e., in the direction the shaft was bent). This was more pronounced at higher spin rates because of the higher resultant centrifugal forces. Results of tests in which the spin rates were cycled were essentially the same as those noted with the flexible shaft, with one exception. It appeared that, with the solid, bent shaft, the induced slosh was amplified when the tank spin rate was increased from 0 to its initial value. This was especially evident for the 100- and 150-rpm spin rate tests. However, although the slosh problem appeared to be aggravated, the damping times did not change appreciably. After 3.4 sec in the test at 50 rpm, the liquid-gas interface was stable and nonoscillatory. Approximately 2.8 sec were required to reach corresponding conditions in the 100- and 150-rpm tests.

Three drop tests using the solid, bent shaft were performed using liquid volumes of 75, 50, and 25%. A fourth drop test using the flexible shaft and a liquid volume of 75% was also performed. All drop tests were performed under zero axial acceleration with a radial acceleration of 0.06 *g*.

The first drop test, using the solid shaft and 75% liquid volume, produced no large sloshing or fluid oscillations as a result of the simulated wobble. However, an unsymmetrical liquid distribution was established because of the tilted tank orientation. The liquid mass tended to move to the region of the tank farthest from the spin axis. The fluid displacement, together with a low Bond number (2.8), resulted in a corresponding displacement of the ullage bubble into a toroidal segment which appeared stable and quiescent.

In the second drop test with the solid shaft and a liquid volume of 50%, the ullage was not displaced to one side, although the liquid was distributed unsymmetrically. No significant oscillations of the liquid-gas interface were observed.

For the third test with 25% liquid volume, significant fluid displacement was noted. After 1.5 sec, the liquid was concentrated on the side of the tank in the direction of the bent shaft with definite fluid motion still occurring. This motion was not rapid or oscillatory in nature but did continue until the end of the test. Thus, a completely settled liquid condition, as observed in the two previous tests, had not been accomplished at the end of the drop test for this volume. Wobble effects appear to influence fluid behavior more at smaller liquid volume.

In the fourth drop test with the flexible shaft and a liquid volume of 75%, some fluid oscillations were observed at the start of the drop during reorientation from a normal 1-*g* environment to a near-zero-*g* condition. However, these oscillations were soon damped and a stable, uniform liquid-gas interface was observed. The fluid oscillations did not impose sufficient forces on the rotating tank wall to displace the tank against the 2° stop on the flexible shaft.

The tests indicated that no significant sloshing problems should be experienced in the full-size tank as a result of wobble. Artificially generated wave motions were damped rather than amplified by the tank spin rate. An unsymmetrical propellant distribution was obtained, however. The spacecraft in which the full-size tanks might be used is currently designed with four spherical tanks. Provision for wobble damping is included. Substituting two toroidal tanks can be expected to impose requirements for such damping no greater than, and probably less than, those currently provided. Depending on the frequency of the propellant motion in the spinning toroidal tanks, the wobble damping requirements could be reduced by propellant viscous effects.

Table 1 Spin rate change tests

Initial spin rate, rpm	Spin rate change, rpm/sec
50	10
50	40
100	10
100	40

Spin Rate Change

The spacecraft spin rates during cruise modes or during imaging at the planet are relatively low. However, when major velocity changes are made, higher spacecraft spin rates are required to minimize the effects of thrust misalignments. A major concern is that changing the spin rate might induce propellant sloshing or displacement that could affect spacecraft attitude and control. Spin rate change tests were conducted to investigate propellant orientation and behavior in the toroidal tank during this operation. A minimum spin rate change of one rpm/sec was simulated. All spin rate change tests were performed in the drop tower with zero axial acceleration. During the drop test, a ramp change in voltage to the spin drive motor was applied during the 2.1-sec test. This produced a linear change in spin rate during the drop.

Test conditions for the model tank were based on tangential velocities and accelerations to be expected with the full-size tank. For the model tank, an initial spin rate of 50 rpm and a spin rate change of 10 rpm/sec were approximately equivalent to five rpm and one rpm/sec in the full-size tank. These conditions were taken as a baseline. Additional testing was also performed at a higher spin rate change and a higher initial spin rate. A total of four tests were completed as in Table 1.

In general, the liquid-gas interface was oriented parallel to the tank spin axis with some oscillations and fluid motion occurring. Part of this motion resulted from the one-g to zero-g transition at the start of the drop test, making the motion more severe than would be expected for the actual tank. The observed motion was not amplified as time progressed.

The results of the spin rate change tests indicate that, for spin accelerations representative of the spacecraft, no major slosh problems should occur during spin-up and spin-down with the present propellant acquisition system design.

Conclusions

In general, no major fluid behavior problems in a spinning toroidal tank were identified during the bench and drop tower test program. Specific conclusions were as follows:

1) In the absence of perturbing forces during coast under zero-g conditions, propellant distribution should be uniform and the ullage should be stable and symmetrical in the tank because of the spacecraft spin stabilization. No breakup of the ullage bubble should occur for any of the specified propellants.

2) No major slosh problems are expected during liquid settling. Additional baffling can be easily incorporated, if desired. More experimental work is required to establish natural frequency and slosh force data in spinning toroidal tanks.

3) Unsymmetrical distribution of propellant resulting from spacecraft wobble appears to be the only significant fluid behavior problem in the spinning toroidal tank. Further evaluation is warranted.

4) During spin rate change tests, the liquid-gas interface was oriented essentially parallel to the spin axis. Fluid oscillations and perturbations on the interface were distributed fairly uniformly around the surface. No amplification of these oscillations was apparent and changing the spacecraft spin rate did not produce significant sloshing motion.

Acknowledgment

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