Feasibility Study of Developing Torodial Tanks for a Spinning Spacecraft

J. E. Anderson* and D. A. Fester†
Martin Marietta Corporation, Denver, Colo.

and

D. W. Dugan‡
NASA Ames Research Center, Moffett Field, Calif.

The use of toroidal tanks in an advanced Pioneer, spin-stabilized Jupiter orbiter was investigated. Fluid behavior in spinning toroids was evaluated and the need for a propellant acquisition system was established. A common surface tension acquisition system design was selected from four candidates for gas-free liquid feed to a single outlet in both MMH and N_2O_4 tanks. Fabrication of toroidal tanks using either titanium or aluminum alloys is feasible. Integration of two toroidal tanks with surface tension systems in place of four spherical tanks provides spacecraft weight, packaging, structural mounting, thermal control, and stability advantages.

I. Introduction

SUCCESSES with spin-stabilized Pioneer vehicles in solar orbits and flyby missions to outer planets such as Jupiter (Pioneers F and G, now known as Pioneer 10 and Pioneer 11 since their successful launches) have led to contemplation of the use of such vehicles for orbiter missions to the outer planets. Accordingly, a study[1] was made of modifications required of the basic Pioneer F or G vehicle to enable it to accomplish an orbiter mission to Jupiter, and possibly to Saturn. TRW Systems Group, who made this study, designed an earth-storable (N_2O_4/MMH) propulsion stage so integrated with the derived payload vehicle that the dynamic constraints imposed by the resultant spin-stabilized spacecraft were met, although with some weight penalties. The dynamic problems were solved in part by using four spherical tanks to contain the propellant, two interconnected tanks each for oxidizer and fuel, arranged in a plane about the longitudinal axis of the vehicle. Bladders and standpipes, used for propellant management in each of the four tanks made the propellant system particularly heavy. An alternate system, consisting of two toroidal tanks equipped with surface tension propellant acquisition devices, one each for oxidizer and fuel, was proposed by Ames because of the inherent axial symmetry of such tanks and because of the apparent feasibility of attachment of the tanks around the aft cylindrical structure of the vehicle. However, experience with the fabrication and use of toroidal tanks was sparse and limited to nonspinning applications. Hence, a study of the feasibility of developing toroidal tanks to supply gas-free propellants in a propulsion system designed for spin-stabilized vehicles such as the proposed Pioneer Jupiter orbiter was undertaken by Martin Marietta Corp., Denver Div. under contract to Ames Research Center.[2] Results of the study, if favorable, were to be used in assessing the impact upon the Pioneer Orbiter spacecraft of using two toroidal tanks rather than four spherical tanks in the propellant system. This assessment was made; a brief summary of the results is included in the present paper.

Presented as Paper 74-1154 at the AIAA/SAE 10th Propulsion Conference, San Diego, California, October 21-23, 1974; submitted October 30, 1974; revision received January 30, 1975. This work was sponsored by NASA-ARC under Contract NAS2-7489.

Index categories: Electric and Advanced Space Propulsion; Spacecraft Propulsion Systems Integration.

*Staff Engineer.

†Section Chief. Member AIAA.

‡Aerospace Engineer. Associate Fellow AIAA.

The objectives of the Martin-Marietta study were: 1) to determine the feasibility of developing toroidal tank/surface tension propellant acquisition systems capable of supplying gas-free propellants to the engine of the spin-stabilized Pioneer Jupiter orbiter under all mission conditions; 2) to assess the feasibility and cost of fabrication of toroidal tank/surface tension device systems for interplanetary missions of long duration; and 3) to compare the weight and cost of two toroidal tanks with those of four spherical tanks of the same total volume.

Several guidelines and constraints were observed in the feasibility study. The mission operational sequence stipulated for the Pioneer Jupiter orbiter mission is shown in Table 1. Propellant requirements for the six burns of the main engine are summarized in Table 2. The mixture ratio of 1.65, combined with the ratio of the densities of oxidizer and fuel, makes the volume of each propellant the same. Propulsion system criteria specified for the study are given in Table 3. Spacecraft accelerations experienced during the mission, including the launch phase, are summarized in Table 4. All the foregoing guidelines and constraints affected the approaches followed in the study to be described.

II. Fluid Behavior Problems in a Spinning Toroidal Tank

The propellant distribution resulting from both steady-state and varying spin rates can, in addition to possibly influencing propellant acquisition system design, also impact on tank design and spacecraft performance and control. Therefore, an analytical investigation of fluid behavior in the spinning toroidal tank was performed for different phases of the baseline mission.

To define steady-state propellant orientation, a Martin Marietta computer program, developed under a company-funded research task, "Low-g Fluid Behavior and Control," was used to calculate the actual liquid-gas interface shape in the toroidal tank for different propellant volumes. This program takes into account the liquid-solid contact angle, angular spin rate, axial acceleration, liquid volume, liquid density, and surface tension, and the tank dimensions in determining the interface shape. The angle of inclination of the interface, with respect to the tank under the combined effects of axial and centrifugal acceleration was the most significant information provided by the program.

Computer-generated plots of the resulting oxidizer tank interface shapes are shown in Fig. 1 for the first, fifth, and sixth

Table 1 Mission operational sequence

Event and time from launch	Operation	System
Midcourse correction 5 days	Spin spacecraft to 10 rpm	Attitude control
	Orient spacecraft	Attitude control
	ΔV firing	Toroidal tank
	Reorient spacecraft	Attitude control
	Despin to 4.8 rpm	Attitude control
Orbit entry at 1st Periapsis 820 days	Spin spacecraft to 10 rpm	Attitude control
	ΔV firing	Toroidal tank
	Despin to 2.0 rpm	Attitude control
Plane change 834 days	Spin spacecraft to 10 rpm	Attitude control
	Orient spacecraft	Attitude control
	ΔV firing	Toroidal tank
	Reorient spacecraft	Attitude control
	Despin to 2.0 rpm	Attitude control
Orbit trim at 2nd Periapsis 870 days	Spin spacecraft to 10 rpm	Attitude control
	ΔV firing	Toroidal tank
	Despin to 2.0 rpm	Attitude control
Apoapsis reduction at 3rd Periapsis 909 days	Spin to 10 rpm	Attitude control
	ΔV firing	Toroidal tank
	Despin to 2.0 rpm	Attitude control
Orbit time trim at 4th Periapsis 925 days	Spin to 10 rpm	Attitude control
	ΔV firing	Toroidal tank
	Despin to 2.0 rpm	Attitude control

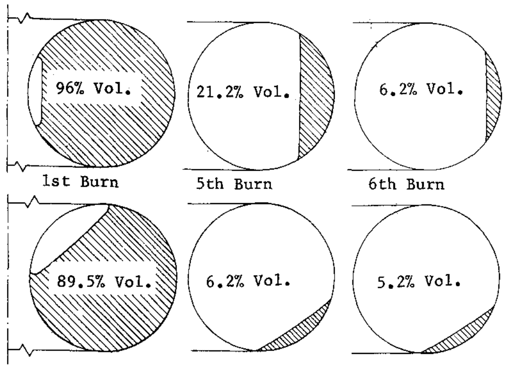

Fig. 1 Oxidizer tank liquid orientation during first, fifth, and sixth burns.

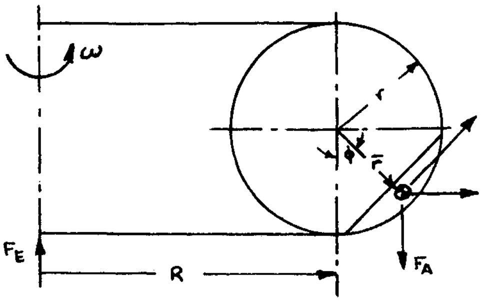

Fig. 2 Slosh model.

burn periods. Similar results were obtained for the fuel tank. The top row of plots indicates the orientation of the propellant just prior to the burn. At this time, the propellant is subjected to the accelerations resulting from the spacecraft spinning at 10 rpm. The bottom row of the plots indicates the orientation of the propellant just prior to terminating the burn. At this time, the acceleration field imposed upon the propellant is a combination of the 10-rpm spin acceleration and the axial acceleration produced by the ΔV engine. All interface shapes are essentially flat; the greatest interface curvature appears to exist during the first burn where the ullage volumes are the smallest.

A problem of locating the tank outlets is immediately apparent from the liquid orientation plots. If the outlets are located in the tank bottom, they will be uncovered during spin-only phases of the mission after approximately 50% of the propellant has been consumed. If the outlets were placed on the outer tank surface at an angle of approximately 45°, a gas-free engine start-up would be marginal if the remaining propellant quantity were approximately 20% and impossible for quantities less than 20%. Thus, regardless of the location of the outlets, some means of communication between the propellant bulk and the outlets must be provided.

Another problem arising from the liquid orientation analysis was that of propellant slosh resulting from the ΔV engine firings. Just prior to engine ignition, the propellants are distributed on the outer wall of the torus due to spacecraft spin. After the engine is ignited, the axial acceleration of the spacecraft tends to move the propellant to the bottom of the tank and on up the inner wall. To evaluate the slosh problem, a simple two-dimensional pendulum model was developed, as shown in Fig. 2. The propellant mass M was assumed to move as a solid mass along the torus wall in response to the centrifugal force due to spin and the axial force due to spacecraft acceleration (ΔV firing). These forces are designated as F_R and F_A, respectively (Fig. 2). In addition, a retarding or drag force due to skin friction F_D was assumed to act on the propellant mass. The centroid of the propellant mass was assumed to rotate about the center of the torus cross-section with radius $\bar{r}$ which is the pendulum arm. It was also assumed that the length of $\bar{r}$ did not change with the position angle, ϕ. Other symbols used in Fig. 2 are: ω = spacecraft spin rate, R

Table 2 Toroidal tank propulsion system—propellant requirements for Jupiter orbiter mission[a]

Event	ΔV required m/sec	(fps)	Burn time sec	Propellant consumed, kg (lb_m): Total kg	Total (lb_m)	Oxidizer kg	Oxidizer (lb_m)	Fuel kg	Fuel (lb_m)
Midcourse correction	85	(279)	190	27.7	(61)	17.3	(38)	10.4	(23)
Orbit entry at 1st Periapsis	900	(2953)	1684	246.1	(542)	153.3	(337.7)	92.8	(204.3)
Plane change	350	(1148)	522	76.3	(168)	47.6	(104.7)	28.7	(63.3)
Orbit time trim at 2nd Periapsis	80	(262)	112	16.3	(36)	10.2	(22.4)	6.1	(13.6)
Apoapsis reduction at 3rd Periapsis	400	(1312)	513	74.9	(165)	46.7	(102.8)	28.2	(62.2)
Orbit time trim at 4th Periapsis	30	(98)	34	5.0	(11)	3.1	(6.9)	1.9	(4.0)
Total required	1845	(6053)	3055	446.3	(983)	278.1	(612.5)	168.2	(370.5)
Spare	155	(509)	177	25.9	(57)	16.1	(35.5)	9.8	(21.5)
Total loaded	2000	(6562)	3232	472.2	(1040)	294.2	(648)	178.0	(392)

[a]Initial spacecraft mass = 938.5 kg (2069 lb_m); specific impulse = 2860 n-sec/kg (292 lb_f-sec/lb_m); thrust = 418 $_n$ (94 lb_f).

Table 3 Propulsion system criteria

Engine system		
Thrust, newtons (lb_f)	418 (94)	
Specific impulse, n-sec/Kg (lb_f-sec/lb_m)	2860 (292)	
Propellants fuel	Monomethylhydrazine	
oxidizer	Nitrogen Tetroxide	
Mixture ratio (oxidizer to fuel)	1.65	
Flow rates Kg/sec (lb_m/sec)		
oxidizer	0.091 (0.200)	
fuel	0.055 (0.122)	
total	0.146 (0.322)	
Propellant tanks	**Fuel**	**Oxidizer**
Shape	Torus	Torus
Total volume, m^3 (ft^3) $V=2\pi^2r^2R$	0.214 (7.58)	0.214 (7.58)
Dimensions, m (ft)		
Major toroidal radius, R	0.458 (1.505)	0.458 (1.505)
Minor toroidal radius, r	0.154 (0.505)	0.154 (0.505)
Operating pressure, n/cm (psia)	155 (225)	155 (225)
Temperature, °C (°F)		
Range	7-32 (45-90)	7-32 (45-90)
Nominal	21 (70)	21 (70)
Ullage volume % (at maximum temperature)	4	4
Propellant mass, Kg (lb_m)	178 (392)	294.2 (648)
Spare propellant, %	5.5	5.5

Table 4 Acceleration environment

Function	Acceleration (g)
Boost	
Axial	+9.3, -3.5
Lateral	+3.9, -3.9
Spin ($\omega=60$ rpm)[a]	1.85
Steady-state spin (Centrifugal)[a]	
Cruise ($\omega=4.8$ rpm)	0.012
During attitude and ΔV changes ($\omega=10$ rpm)	0.0515
During imaging operations ($\omega=2$ rpm)	0.0021
Spin/design operations (tangential)[a]	4.9×10^{-4}
Precession maneuvers[b]	
(Maximum rotation of tank about vehicle center of gravity)	0.03 per thruster pulse[c]
ΔV Corrections (axial)	0.045-0.091

[a]Based upon a radius from the vehicle spin axis to the center of the torus cross-section.
[b]Based upon a radius from the vehicle center-of-gravity to the center of the torus cross-section.
[c]Thruster pulse duration is 0.125 sec.

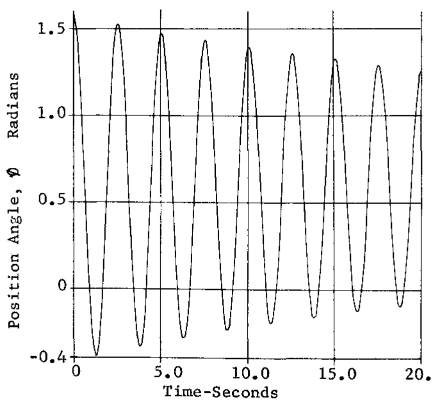

Fig. 3 Propellant displacement during sixth burn—no baffles.

=torus major radius, and F_e = thrust produced by ΔV engine along spacecraft spin axis. Applying Newton's second law, a force balance was developed to describe the motion of the mass, M

$$Mr\frac{-d^2\phi}{dt^2}=F_D+F_R\cos\phi-F_A\sin\phi$$

where t = time. This differential equation was solved numerically on the CDC 6600 digital computer for the oxidizer tank during the sixth burn period. F_A was calculated from the engine thrust, F_e, and the spacecraft and propellant masses. The propellant mass M was assumed to be oriented initially at position ϕ of $\pi/2$ rad (90°). Values of ϕ vs time t were plotted by the computer system and are presented in Fig. 3. From this plot, it is obvious that the effect of skin friction alone is not sufficient to adequately damp fluid oscillations during the sixth burn and that some form of baffling is required.

Prior to the ΔV engine firings, changes in spacecraft spin rate are required. Because of the low viscosity and high inertia of the propellants, the propellant mass may accelerate at a lower rate than the tank surface during these spin rate changes. The resulting velocity differences between the propellant bulk and the tank surface can induce a transient wave motion upon the propellant liquid/gas interface. Baffles could also be installed to reduce or eliminate this wave motion.

III. Propellant Acquisition System Selection and Design

Selection of a preferred surface tension type of propellant acquisition system for use in a spinning toroidal tank was accomplished in two steps. First, four candidate concepts were identified and then evaluated and compared on the basis of fluid control in the spinning torus. The selected concept was then further analyzed and modified to improve its operation in the toroidal tank system.

Candidate Concepts

In selecting candidate concepts for the spinning toroidal tank system, a variety of surface tension devices were considered. These ranged from open sheet-metal structures, which position and hold liquid at the desired tank outlet location for very low acceleration applications (on the order of $10^{-3}g$ or less for most tank systems), to fine-mesh screen systems, which can operate over a much broader acceleration range (from 0 to $3g$, or higher, depending on the application). The primary concern in the selection process was the ability of the device to retain liquid against the adverse acceleration conditions and provide gas-free liquid feed to the engine. Since the acceleration environment ranged from $2\times 10^{-3}g$ to $0.1g$ during the mission, devices using fine-mesh screen were considered to offer the best practical approach for this application. Additional details on the functioning and operational range of these devices are contained in Ref. 2.

Four different fine-mesh screen flow-channel and liner propellant acquisition concepts were established as candidates, as shown schematically in Fig. 4. Configuration 1 consists of a fine-mesh screen liner located in the lower half of the toroidal tank along the outer wall and provides a continuous communication path between the propellant bulk and one or more tank outlets. Configuration 2 consists of a ring of semicircular cross-section in the tank, supplying propellant to one or more outlets. Four feeder-arms are connected to the ring at four equally-spaced locations forming continuous flow path between the propellant bulk and one or more outlets. For both configurations 1 and 2, the tank outlets were located 0.524 rad (30°) from vertical.

Configuration 3 employs a conical propellant sump at a single tank outlet displaced 0.524 rad (30°) from vertical. Propellant is retained in the sump by centrifugal forces during spinning. A fine-mesh-screen cover prevents gas ingestion. A ring-channel and four feeder-arms of square cross-section provide communication between the propellant in the tank and the sump. Configuration 4 employs a modified toroidal tank geometry and single or multiple outlets. Orientation of the tear-drop cross-section, as shown, allows centrifugal forces to move the propellant to the outlet region. A fine-mesh screen prevents gas ingestion and also forms a flow channel in the tank.

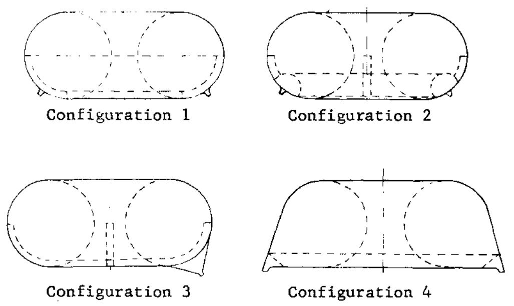

Fig. 4 Candidate propellant acquisition concepts for a toroidal tank.

System Evaluation and Selection

Criteria used in the system comparison were propellant distribution provided by the system, potential slosh control, expulsion efficiency, estimated mass, and relative impact on tank design. The results of the evaluation are shown in Table 5. Based on these results, configuration 2 was selected as the preferred concept since it provided: 1) Uniform propellant distribution during all mission phases; 2) Good slosh damping; 3) High expulsion efficiency; 4) Low mass; and 5) No need to modify tank geometry.

Selected System Design

Following selection of configuration 2, modifications were made to improve performance and ease of fabrication. The cross-sectional shape of the retainer ring and communication channels were changed from semicircular to square. This simplified the fabrication requirements by eliminating the need for screen surfaces of compound curvature. Also, the tank outlets were relocated to the bottom of the tank, from the original 0.524 rad (30°) displacement to allow complete tank draining on the launch pad.

The final acquisition system design is shown in Fig. 5. It consists of four communication channels, spaced $\pi/2$ rad (90°) apart, feeding a propellant-retaining ring in the bottom of the tank. The cross-section for both the ring and the communication channels is 2.54-cm (1.0-in.) square. The ring and channels are fabricated from 325×2300 mesh, Dutch-twill weave stainless steel screen supported by perforated stainless

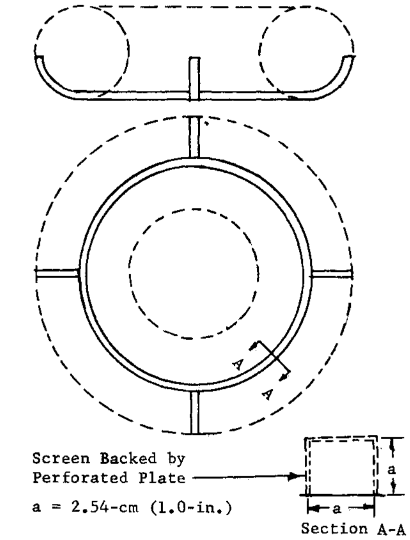

Fig. 5 Selected propellant acquisition system for use in a spinning toroidal propellant tank.

Table 5 Candidate concept evaluation and comparison

Criteria	Candidate Configuration 1	2	3	4
Propellant distribution	Symmetrical	Symmetrical	Unsymmetrical	Symmetrical
Slosh control	None	Flow channel ring & feeder arms act as baffles.	Flow channel ring & feeder arms act as baffles.	Not a problem due to tank geometry.
Estimated expulsion efficiency	99% based on gap of 0.254 cm (0.1-in.) between liner & wall.	99.5% based on 2.54 cm (1.0-in.) ring & feeder arm cross-section diameter	98.5% based on 2.54 cm (1.0-in.) square ring & feeder arm cross section	99% based on assumption dropout occurs at propellant level of 2.54 cm (1.0-in.).
Estimated mass	1.18 kg (2.6 lb_m).	0.45 kg (1.0 lb_m).	0.95 kg (2.1 lb_m).	Not estimated.
Relative impact on tank shell design	None	None	Addition of sump complicates design.	Noncircular cross-section has greater impact.

steel plate, having a 50% open area. The design is applicable to both the oxidizer and the fuel tanks, since the tanks are identical and other considerations such as flow losses, slosh, and propellant properties do not indicate the need for different designs. An expulsion efficiency of 99% is provided.

Since multiple tank outlets increase weight and fabrication cost, reduce reliability, and require flow balancing, the possibility of using only one tank outlet was investigated. A single outlet can be used with the selected acquisition system, provided that the total pressure difference from ullage to tank outlet does not exceed the screen bubble point. If the bubble point is exceeded, gas could be ingested into the engine feedline. A pressure drop analysis was performed on the acquisition system for both fuel and oxidizer tanks, employing only a single tank outlet. The following worst case assumptions were also made: 1) Maximum propellant flow was established before ΔV engine thrust started; 2) All of the propellant flow was supplied through the communication channel farthest from the outlet; 3) Spacecraft spin rate was 10 rpm; and 4) Propellant conditions were those at the start of the last burn (6% propellant remaining). The calculated pressure differences for both the oxidizer and fuel systems are tabulated together with the screen bubble points. A safety factor defined as the ratio of the bubble point, ΔP_c, to the pressure difference, $P_G - P_L$, is included in Table 6. These results indicate a reasonable safety factor with only a single tank outlet.

An evaluation of the slosh-damping characteristics of the selected system was made using the analytical model previously discussed. The model was modified to include the drag effect of the propellant retaining ring in the tank bottom. The slosh-damping effect of the propellant acquisition device is shown by comparing the result obtained with the device (Fig. 6) with that obtained without the device (Fig. 3). It is seen that the propellant acquisition system produces a significant reduction in propellant slosh. The four communication channels will act in a similar manner to reduce liquid motion resulting from spacecraft spin-rate changes.

The effect of unintentional spacecraft over-spin on acquisition system performance was of interest. An estimate was made of the spacecraft spin rate required to produce static pressure across the screen sufficient to exceed the bubble point of the screen. The results indicated that an oxidizer tank spin rate of 76 rpm and a fuel tank spin rate of 110 rpm would be required to produce liquid loss from the acquisition system during spacecraft operation. Since the maximum spacecraft spin rate is 10 rpm, there is a significant safety factor in the selected system design to follow for accidental over-spin.

Table 6 Comparison of calculated pressure differences and screen bubble points

	Oxidizer		Fuel	
Pressure difference $P_G - P_L$, n/cm^2 (psi)	0.317	(0.46)	0.626	(0.91)
Bubble point, ΔP_c n/cm^2 (psi)	0.757	(1.1)	0.964	(1.4)
Safety factor $\Delta P_c/(P_G - P_L)$	2.39		1.54	

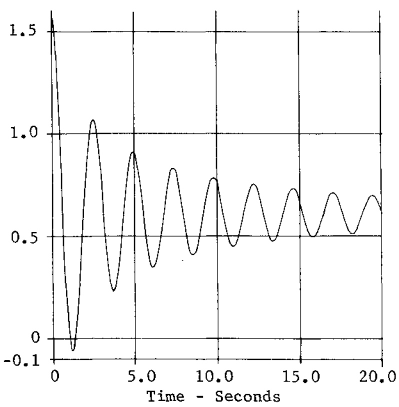

Fig. 6 Effect of propellant retaining ring on propellant displacement—sixth burn period. Ordinate represents position angle, ϕ rad.

IV. Torodial Tank Fabrication

Fabrication of a toroidal tank using the selected surface tension propellant acquisition system was evaluated as part of the study. To support the evaluation, various tank manufacturers were contacted in regard to methods, problems, and costs associated with toroidal tank fabrication. A weight comparison between the two-toroidal-tank system and a four-spherical-tank system was also made.

Previous Experience

A review of previous industrial experience in the fabrication of toroidal tanks was made. A report prepared by the Illinois Institute of Technology Research Institute under Contract NAS7-388[3] summarized tank development programs in the aerospace industry. This report identified four toroidal-tank programs, two of which contain information applicable to this study. One of these two programs concerned the fabrication of a titanium toroidal tank by Fansteel Inc., for the Hibex system. Although information regarding the Hibex tank was not published in the report, Fansteel was contacted and pertinent information regarding fabrication of the tank was obtained. The other program was conducted by the Baltimore Div. of Martin Marietta Corp. for the NASA Langley Research Center under Contract NASw-913.[4] During this program, a toroidal tank was fabricated from 2219 aluminum by explosive forming. In addition, the Titan III solid rocket motor thrust vector control system utilizes a toroidal-shaped manifold for injection of nitrogen tetroxide into the solid motor nozzle. This torus is fabricated from 6061-T6 aluminum forgings.

Material Selection

Three candidate tank structural materials were selected on the basis of their availability, propellant compatibility, and fabricability. These were 2219 aluminum, 6061 aluminum, and 6Al-4V titanium, which are generally nonmagnetic and are, therefore, satisfactory for the proposed Jupiter-orbiter mission. In addition, these materials have sufficiently high annealing temperatures to allow sterilization, if required. The following minimum handling gages were used for the candidate materials: 2219 and 6061 aluminum, 0.064-cm (0.024-in.), 6Al-4V titanium, 0.038-cm (0.015-in.).

Tank System Mass Comparison

The four-spherical-tank system was used for comparison since it was the system selected in the original study.[1] Materials used in the comparison were 6Al-4V titanium and 2219 aluminum. The 6061 aluminum was not considered because of its significantly lower strength.

Tank shell weights were obtained, assuming membrane stress theory for establishing wall thickness. For a toroidal tank, the meridional stress rather than hoop stress determines required wall thicknesses. The meridional stress is given by the following equation

$$S = (Pb/2t)\,(r+a)/r$$

where S is the meridional stress, P is the internal pressure, and t is the wall thickness. The dimensions a, b, and r are defined in Fig. 7. A toroidal shell possesses a unique characteristic in that, for a constant wall thickness, the working stress in the shell varies from a maximum at the innermost points to a minimum at the outermost points. The point of maximum

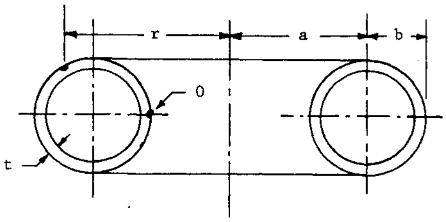

Fig. 7 Toroidal dimensions for stress calculations.

stress is designated "O" in Fig. 7. It is this point that determines the minimum wall thickness allowable in a torus of constant wall thickness. For each material, the minimum wall thickness calculated from the forementioned equation was greater than the minimum gage requirements defined previously. Calculations of spherical shell weights were based on the hoop stress formula. The required wall thicknesses for the spherical shells were also greater than the minimum handling gage for each material. Working stress for each material was based on the ultimate strength.

The mass of tank closure welds and 0.64-cm (0.25-in) diam inlet and outlet bosses was also included. For the spherical tanks, a 15.24-cm (6.0-in.) diam outlet flange, similar to that used on the Mariner Mars '71 tanks, was used. Material strength in the vicinity of the welds and bosses was assumed to be the annealed value.

Mass of the surface tension system, including the stainless steel perforated plate and a fine-mesh screen, was calculated as 1.23 kg (2.7 lb_m). The polymeric bladder weight used in each spherical tank was estimated as 2.95 kg. (6.5 lb_m).[5] The system mass is tabulated in Table 7. Both aluminum and titanium toroidal tanks are included. Comparison of the titanium toroidal system with the sphere/bladder system shows a significant 6.7 kg (15 lb_m) advantage for the toroids. This mass difference is primarily due to the lighter surface tension acquisition system. Even the aluminum toroidal system compares favorably with the sphere/bladder system; 26 kg (58 lb_m) compared with 25 kg (55 lb_m), respectively. The heavier aluminum toroidal-tank is again offset by the low-mass surface tension system. The spherical tank system mass presented in the table compares favorably with data from the TRW study[1] which lists a total tank system mass of 29.09 kg (64 lb_m). Data from the Mariner Mars '71 program[6] also support the system mass estimates presented here.

In evaluating system mass, the primary comparison was between a two-toroidal-tank system using surface tension propellant acquisition devices and an equivalent volume four-spherical-tank system using bladders. This comparison was extended to include a four-spherical-tank system using surface tension devices, as shown in Table 7. The surface tension acquisition device consisted of a single feeder-arm channel in each spherical tank, similar to those used in the toroidal tanks. The channel would be located on the tank wall farthest from the spacecraft spin axis and would extend from the outlet in the tank bottom to just below the tank equator. The weight of the surface tension devices would be only one-ninth of that for bladders, resulting in a 10 kg (23 lb_m) weight savings. Comparing the toroidal-tank system with the spherical-tank system on a completely equal basis (titanium tanks and surface tension acquisition devices with both systems), the spherical tank system provides a weight advantage of only 3.7 kg (8.1 lb_m).

Tank Fabrication

A toroidal tank could be fabricated from symmetrical halves, unsymmetrical halves, or bent tubing, as shown in Fig. 8. In assembling the torus from symmetrical halves, two identical parts are welded together at the mid-plane normal to the toroidal axis (Fig. 8a). Inner and outer weld joints are required. The method using unsymmetrical halves (Fig. 8b) has a center spool-section encompassed by a ring of semicircular cross-section. Circular closure welds are required at the top and bottom of the torus. The tank could also be made from bent tube sections, as indicated in Fig. 8c. Although four sections are shown, more sections could be used if desired. These sections would be joined by girth welds around the torus. Installation of the propellant acquisition device is simplified using symmetrical halves. The device could be installed in the lower half of the torus just prior to the final closure tank weld. Furthermore, symmetrical halves could be produced on similar if not identical tooling which would also tend to reduce manufacturing costs. However, this method involves welding at the points of maximum stress. With the other two methods, installation of the acquisition device would not be possible as a fixed or single unit. Joints and connections would be required which would greatly compound the difficulty of fabrication and could compromise performance. For these reasons, the assembly method employing symmetrical halves was selected.

In evaluating toroidal tank fabrication, the following companies were contacted: Pressure Systems, Inc. Los Angeles, Calif.; Fansteel Precision Sheet Metal Los Angeles, Calif., Beech Aircraft Corp., Boulder, Colo.; Explosive Fabricator Industries, Louisville, Colo. Fabrication techniques and budgetary cost information were of primary interest.

Three possible methods of forming the torus halves, identified through these contacts, were spinning, forging, and explosive forming. Recommendations for forming of aluminum alloy tanks were generally a combination of hydroforming

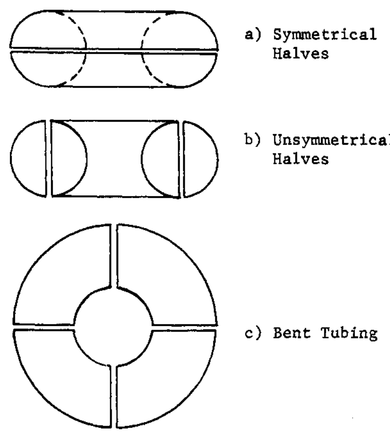

Fig. 8 Torus assembly methods.

Table 7 Mass comparison between a two-toroidal-tank system and a four-spherical-tank system

Tank system	Toroidal		Spherical	
Type acquisition device	Surface tension	Surface tension	Bladder	Surface tension
Number of tanks	2	2	4	4
Tank material	2219-T6 Aluminum	6Al-4V Titanium	6Al-4V Titanium	6Al-4V Titanium
Mass, kg (lb_m)				
Tank	23.7 (52.1)	15.7 (34.6)	13.1 (28.9)	13.1 (28.9)
Acquisition device	2.45 (5.4)	2.45 (5.4)	11.82 (26.0)	1.36 (3.0)
Total mass kg (lb_m)	26.15 (57.5)	18.15 (40.0)	24.92 (54.9)	14.46 (31.9)

Table 8 Toroidal tank manufacturing cost comparison

Tank system	Cost element	6061 aluminum	2219 aluminum	6A1-4V titanium
Toroidal	Nonrecurring	$14,200	$14,200	$14,200
(2 tanks)	Production	18,000	22,500	72,000
	Total	$32,200	$36,700	$86,200
Spherical	Nonrecurring	$12,000	$12,000	$12,000
(4 tanks)	production	20,000	24,000	48,000
	Total	$32,000	$36,000	$60,000

and spinning. Spinning was definitely not recommended for titanium; the low ductility of this material makes it extremely difficult to work. It was concluded that fabrication of titanium tanks can best be accomplished by forging. Following forging, however, machining and aging processes are also required; these increase the manufacturing costs.

Fabrication Costs

Estimates of the costs involved in fabricating toroidal tanks from 6061 aluminum, 2219 aluminum, and 6A1-4V titanium were made for comparison purposes. The estimates were based on information obtained from tank manufacturers, assuming production of two toroidal tanks. The cost comparison, presented in Table 8, clearly indicates a significant difference between aluminum and titanium tanks.. This difference is mainly because of the increased difficulty in working with titanium Use of 2219 aluminum instead of 6061 is justified by the reduction in tank weight gained with the 2219.

Cost of a four-spherical-tank system was compared with that of a two-toroidal system having the same total volume. Fabrication costs for the aluminum materials are about the same for the two systems. However, fabrication cost of titanium for the spherical-tank system is approximately 30% less than that for the toroidal-tank system, as indicated in Table 8.

This assessment shows that toroidal tanks can be fabricated with present technology using either titanium or aluminum alloys. The preferred material would be titanium because of its significantly higher strength. However, the titanium fabrication costs would be more than twice that required for an aluminum toroidal tank. Toroidal tank systems made from either aluminum or titanium and using surface tension propellant acquisition devices are competitive with an equivalent spherical/bladder tank system.

V. Use of Toroidal Tanks in Pioneer Jupiter Orbiter

The results of this feasibility study were used to assess the effects of substituting two toroidal tanks for the four spherical tanks in the baseline spacecraft design.[7] The results of a study by Jet Propulsion Laboratory[8] to assess the modifications of the Mariner '71 propulsion system required to make it compatible with the Pioneer Jupiter orbiter were also included. The effects of using the three propulsion stages (four spherical tanks, two toroidal tanks, and modified Mariner '71) on spacecraft design are compared in Table 9. Although the total ΔV and usable propellant loadings differ slightly from one stage to another, this does not invalidate the conclusions that can be drawn. The component and total weights of the three propulsion stages are compared in Table 10. From such data as presented in these two tables, TRW[7] concluded the following: 1) Weight and size, structural mounting requirement, and thermal interface advantages are offered by the toroidal tank configuration compared to the spherical tank configuration: 2) Mass properties of the toroidal tank configuration tend to reduce dynamic problems; analysis of propellant sloshing is required to assure stability under all operating conditions; 3) Integration and test of the

Table 9 Comparison of stage design options

Design option	A Reference configuration Pioneer orbiter	B Mariner stage adaptation	C Toroidal tank stage configuration
Tanks acquisition device	4 Spheres bladders	2 Spheres bladders	2 Toroids surface tension
Mass distribution and dynamics[a]		-Asymmetrical tank mounting required for balance. -Active balancing by deployable counterweight required.	-C.G. closer to spacecraft proper than in Case A. -Less C.G. shift in case A. -Moments of inertia smaller than in Case A.
	-All configurations have equally unfavorable inertia ratios prior to deployment (marginal stability).		
Thrust level	-94 lb_f retro engine (limited by structure integrity).	-300 lb_f Mariner engine to be replaced by 94 lb_f engine.	-Same engine as in Case A.
Thermal control	-Side louvers, requires attention to side-sun thermal load.	-Side louvers avoidable, smaller stage footprint.	-Aft louvers as in Pioneer retained. -Side-sun restriction to avoid re-radiation upon louvers.
	-Side-sun restriction may be preferred for all three configurations to avoid relocation of louvers.[b]		
Structural design	-Trusswork transfers load around 4 spherical tanks.	-Trusswork transfers load around 2 spherical tanks (modified from Mariner).	-Cylindrical column for direct load transfer; simple and lightweight, easy to integrate. -Attachment of toroid tanks by flanges or skirts (not provided in Martin Marietta design.
Usable propellant capacity (lb_m)	1152	988	1040
Total ΔV capacity[b] (m/sec)	2260	1900	2150
Estimated total stage weight[c] (lb_m)	1368	1298	1229
Development status of stage	-Tanks adapted from existing USAF program. -Existing 94 lb_f retro engine from USAF program.	-Tanks same as in Mariner '71. -Engine, valves and hydraulics modified (existing 94 lb_f retro engine repaces 300 lb_f Mariner engine).	-Tanks need new development and qualification. -Existing 94 lb_f retro engine from USAF program.

[a] Reference Pioneer Orbiter has 120-deg RTG separation.
[b] Similar to Saturn/Uranus mission.
[c] Assumes 739 lb_m spacecraft mass without stage (including 45 lb_m of monopropellant hydrazine).

Table 10 Stage weight estimates (lbs)

Configuration	A Pioneer Orbiter TRW-Design (4 Spheres)	B Mariner '71 Stage Adaptation[a] (2 Spheres)[a]	C Toroidal Tank Configuration (2 Toroids)
Propellant tanks	54.0	67.0	50.0[b]
Pressurant tank(s)	30.0	35.0	30.0
Retro engine assembly	8.3	8.3	8.3
Feed system, lines & fittings	12.5	52.0	18.5
Stage structure	58.6	44.0	46.2[c]
Micrometeoroid protection dry weight	15.0	12.0	6.0
	178.4	228.3	159.0
Propellant, total	1170.0	1050.0	1050.0
Pressurant	20.0	20.0	20.0
Total weight	1368.4	1298.3	1229.0

[a]JPL data based on Mariner '71 flight hardware.
[b]This includes 10 lbs for mounting flanges.
[c]Outer cylindrical shell includes micrometeoroid protection.

stage structure appears simpler for the toroidal configuration. Stage length is about equal.

VI. Conclusions

The results of this study indicate that a toroidal tank containing an effective, passive surface tension propellant acquisition device can be fabricated with available manufacturing methods and can be used interchangeably for either fuel or oxidizer. A two-toroidal-tank system is attractive for an advanced Pioneer spin-stabilized vehicle because of packaging, center-of-mass and spin control, mass and propellant outflow considerations. A single tank outlet satisfies the requirements for both normal propellant feed and emergency draining. The tanks can be stracked at the aft end of the spacecraft, centered about the spin axis. Propellant motion in the toroidal tanks tends to be balanced, e.g., propellant settling due to thrust acceleration is symmetrical. Because of this symmetry, a more balanced spacecraft requiring lesser control should result. In addition, a two-tank system is inherently more reliable and, with the single tank outlets, eliminates the need for outflow balancing from parallel fuel tanks and parallel oxidizer tanks. With titanium, the mass of two toroids using surface tension propellant acquisition devices is about 27% less than a system of four spheres using bladders. The cost of fabricating the toroids is about 30% more, however.

References

[1]*Study of Follow-On Pioneer Missions to Jupiter, Volume 2 Technical Pioneer Orbiter Mission,* 2046-6004-R0-00, Contract NAS2-6454, Aug. 13, 1971, TRW Systems Group, Redondo Beach, Calif.

[2]Anderson, J.E. and Fester, D.A., "A Feasibility Study of Developing Toroidal Tanks for a Spinning Spacecraft," MCR-73-223, Contract NAS2-7489, Sept. 1973, Martin Marietta Corp., Denver, Colo.

[3]*Aerospace Tanks,* Vol. I, Contract NAS7-388, Illinois Institute of Technology Research Institute, Chicago, Ill., Jan. 1969.

[4]Jordan, P.F., *Analytical and Experimental Investigation of Pressurized Toroidal Shells,* Research Rept. RR-64 Contract NASW-913, April 1965, Martin Marietta Corp., Baltimore, Md.

[5]Paynter, H. L., "Investigation of Space Storable Propellant Acquisition Devices, Final Report, Vol. I—Evaluation, Contract NAS7-754, MCR-70-171, Oct. 1970, Martin Marietta Corp., Denver, Colo.

[6]Brown, C. D., "Mariner Mars '71 Spacecraft Propulsion Subsystem Final Report, CPR-39-69-4, JPL Contract 952-460, Aug. 1970, Martin Marietta Corp., Denver, Colo.

[7]"Study of Alternate Retro-Propulsion Stage Configurations for the Pioneer Outer Planet Orbiter," 22303-6003-RU00, Contract NAS2-6859, Nov. 30, 1973, TRW Systems Group, Redondo Beach, Calif.

[8]Holcomb, L.B., French, R. L., and Kelly, J. H., "Final Report—Study of Orbit Insertion Propulsion for Spinning Spacecraft Condcucted for NASA-Ames," Oct. 18, 1973, Jet Propulsion Lab., Calif., Institute of Technology, Pasadena, Calif.