Selection of a Surface-Tension Propellant Management System for the Viking 75 Orbiter

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For the Viking 75 mission, the midcourse trajectory corrections, Mars orbit insertion, and Mars orbit adjustments of the spacecraft are performed by the Orbiter propulsion system. A surface-tension propellant management system was chosen because of 1) its passive reliability and light weight, 2) its lower projected cost, and 3) the propellant quantity and resultant slosh loads. Based on the propellant management system requirements of the Viking 75 mission, a series of surface-tension design concepts was evaluated. The chosen concept is identified and its mission operation is described. Ullage bubble and bulk liquid positioning characteristics, pressurization and venting considerations, and liquid communication provisions are discussed. The nucleus of a development plan is established, and the results of some preliminary design and testing are presented.

Introduction

THE Viking 75 mission includes boost, the approximately 12 month transit time to Mars with necessary midcourse corrections, Mars orbit insertion, release of a Lander vehicle, and periodic orbit adjustments of the Orbiter. The midcourse corrections, Mars orbit insertion, and Mars orbit trims are performed by the Orbiter propulsion system.

The propulsion system consists of a 1334.4 N (300 lbf) bipropellant engine using monomethylhydrazine (MMH) and nitrogen tetroxide (N_2O_4) propellants, tankage to accommodate approximately 1360.8 kg (3000 lbm) of propellant, helium pressurant tank, and other feed system components. A comprehensive mission optimization study was conducted and a surface-tension propellant management system was chosen to be developed for the Orbiter. The primary factors leading to the selection of a surface-tension system were the propellant to ullage volume ratio, which produces slosh loads that could be detrimental to a bladder, and the passive reliability, potential light weight, and lower projected cost of a surface-tension system. This selection represents the first time that a complete surface-tension propellant management system has been applied to interplanetary flight.

This paper covers a portion of the work done to select a surface-tension propellant management system for the Viking 75 Orbiter. Additional details of the work can be found in Ref. 1. Some preliminary design, fabrication, and testing were done to answer questions regarding the basic structural integrity of the selected concept, materials compatibility, fabricability, ease of cleaning, and ease of installation and removal.

Systems Design

The Viking 75 Orbiter propellant management system begins operation after boost into an Earth-Mars transfer orbit, and must perform satisfactorily until propellant depletion. It must provide propellant upon demand for Earth-Mars interplanetary trajectory corrections, insertion into Mars orbit, and orbit trims around Mars. In addition to supplying gas-free propellant to the engine, the propellant management device must also position propellant symmetrically about each tank centerline to keep the spacecraft center of mass within the tolerances necessary to maintain acceptable pointing accuracy for velocity change maneuvers. In the event of a pressure regulator failure, the device must position propellant to permit venting of the ullage gas with a minimum loss of propellant, thus avoiding vehicle torques and contamination of critical surfaces. As a result of the propellant tank design, the propellant management device must be designed for installation and removal through a 22.9-cm-diam (9-in.) access hole. To meet these requirements, development of a surface-tension system must be preceded by specification of the system requirements. Since the system is passive, it must be designed to a specific set of requirements. Some of the specific environments, vehicle constraints, and functional requirements are listed in Table 1.

Design Concepts

A number of surface-tension propellant management system design candidates were generated that meet the requirements. Several are shown in Fig. 1. These candidates were evaluated to define performance weaknesses sufficient to introduce mission sensitivity, degraded off-design capability, increased development cost and risk, and reduced statistical reliability. The objective of the evaluation was to evolve a candidate that, within the constraints of weight and ease of installation, eliminates marginal characteristics, and consistently exceeds mission requirements.

Concept selection criteria were identified with an approximate numerical index of their relative importance. Some of the selection criteria were cost, weight, reliability, system operation, and development risk. All design concepts were evaluated against these weighted criteria, and the selection rapidly narrowed to a choice between the truncated central cross and the central baffle concepts. The two concepts are of the same basic family. Both position propellant over the tank outlet, drive the ullage bubble radially outward and forward, locate the propellant center of mass on the tank axis, stabilize the ullage bubble on the tank centerline at the forward end of the tank to reduce the disturbance during

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Table 1 Viking propellant management requirements

Functional requirements	
Number of burns	12–35
Time between burns	1–320 days
Minimum time between maneuver and burn	128 sec
Minimum propellant quantity at start of final burn	8.52 kg (18.8 lbm) N_2O_4, 5.89 kg (13.0 lbm) MMH
Minimum ullage volume (initial)	6.1% MMH, 11% N_2O_4
Minimum ullage volume (after Mars orbit insertion)	70% MMH
Flowrates	0.193 kg/sec (0.42 lbm/sec) MMH 0.29 kg/sec (0.64 lbm/sec) N_2O_4
Pressurization	
Pressurant	Regulated helium
Liftoff pressure	68.9 N/cm² (100 psia) at 294°K (70°F)
Flight pressure at first burn and after	167.5 N/cm² (243 psia) nominal
Time from flight pressurization to first burn	24 hr
Regulator flowrate	400 std m³/hr (250 scfm) He max per tank
Bulk temperature of stored propellant in flight	286–297°K (55 to 75°F)
Feed quality	Greater than 99%
Ullage bubble eccentricity and liquid loss during venting	Minimum practical
Materials and compatibility	Referee fluids (Freon TF and isopropyl alcohol) and propellants
Physical constraints	
Weight	66.6 N (15 lb) per device
Tank material	6A14V titanium alloy
Tank outlet end configuration	22.9-cm-diam (9-in.) access hole
Environmental constraints	
Steady boost	5 g forward, 2 g lateral
Steady coast	1×10^{-7} g max in any direction
Spacecraft attitude maneuver (up to 360° at 0.001 rad/s)	
Steady (due to angular accel)	0.0002 g for 0.6 sec
Steady Orbiter Engine burn	0.04 g min, 0.15 g max
Slosh	See Fig. 9

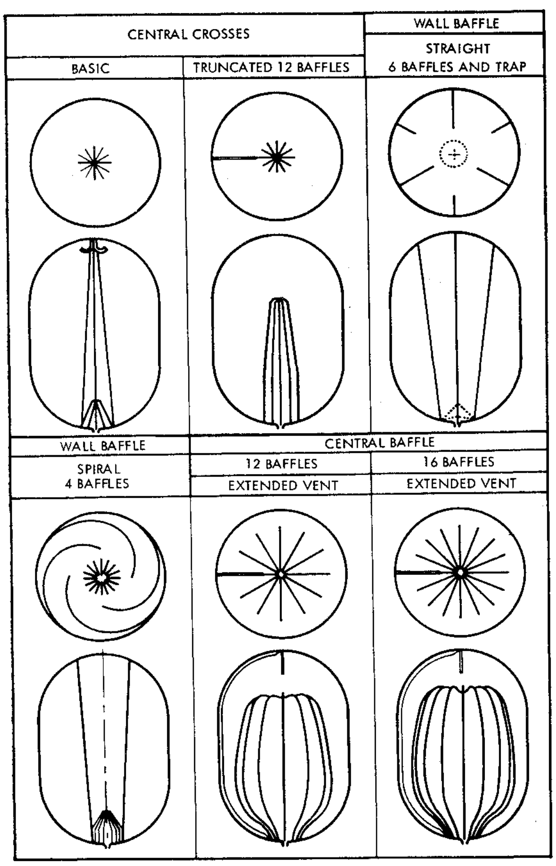


Fig. 1 Candidate concepts.

pressurization, and provide vent port access to the vapor for relief valve depressurization of the tanks. An optimal 12-element truncated cross design and 12- and 16-element central baffle designs were chosen for comparison. Analyses were conducted to determine the quantitative performance of the three candidates against specific mission requirements.

The minimum ullage capability equals the volume of a bubble, expressed in percent of tank volume, which is just large enough in dimension, in its low-g form, to span across the greatest distance existing between the propellant management baffles and the tank wall. The determination of allowable adverse acceleration and maximum time for bubble centering are discussed under the heading Bubble Positioning.

As shown in Table 2, the required performance under venting conditions cannot be satisfied with the truncated cross but is met satisfactorily by both versions of the central baffle. If the minimum ullage were increased to 10%, and if the other requirements were relaxed, analyses showed that there would

Table 2 Comparison of truncated cross and central baffle

	Concept capability		
		Central baffle	
Requirement	Truncated cross	12	16
Minimum ullage capability, 6.1%	6.1%	3.5%	2%
Allowable adverse acceleration during venting, 10^{-5} g	1×10^{-7} g	1×10^{-5} g	1.5×10^{-5} g
Maximum time for bubble centering, 4 min	10 min	1.25 min	1.0 min

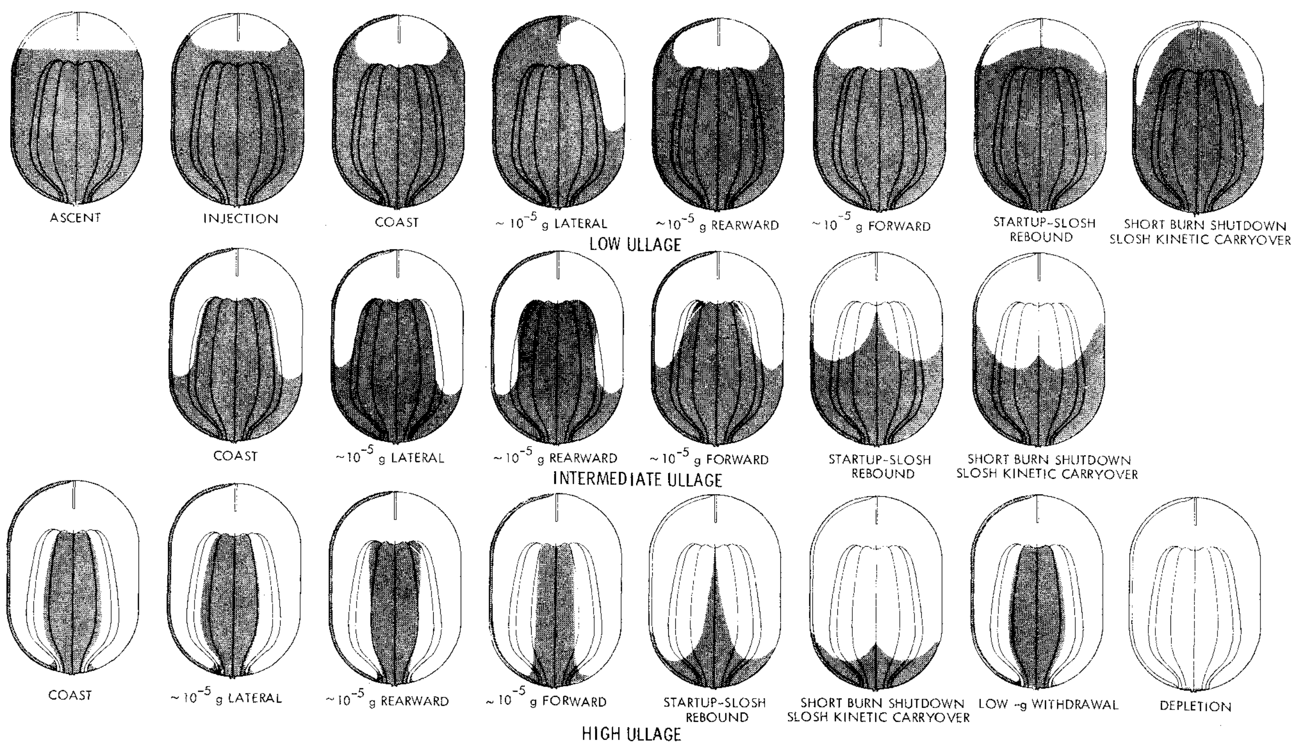


Fig. 2 Typical operating sequence of Viking propellant management.

still be limitations to the truncated cross associated with slosh damping and kinetic carryover. Slosh disturbances to spacecraft guidance would be much larger and longer lasting with the truncated cross. Kinetic propellant carryover would be much stronger which would result in a high probability of ullage breakup, and a wider range of conditions would have to be examined. Also, long prototype response times correspond to long low-g test times and require complex and high-cost test techniques. Based on these data, the central baffle design concept was chosen. As shown in Table 2, the performance of both the 12- and 16-element design is similar and each meet the requirements. Thus, the 12-element design was chosen for its simplicity and light weight.

Performance of Selected Concept

Introduction

Figure 2 depicts a typical mission sequence of operation for the central baffle propellant management system. The shaded and unshaded areas denote liquid and vapor, respectively. The various views portray the propellant behavior under various designated mission situations.

The approach used to assess the performance of the surface-tension propellant management system consisted of generating a particular baffle profile and determining its capability to drive an ullage bubble. The small ullage bubble is generally more difficult to drive, more important to position for venting, and more susceptible to adverse bubble breakup effects due to liquid kinetics resulting from body accelerations. A small ullage bubble is also the size present early in the mission when mass centering is especially important from the standpoint of maintaining an accurate spacecraft trajectory.

A typical central baffle design and its bubble driving capability profile are shown in Fig. 3. Bubble driving capability is expressed in terms of an equivalent buoyant acceleration acting on the bubble as a function of bubble center location. This form of expression is chosen since the buoyant force on the bubble during vehicular maneuvers or disturbances opposes the surface-tension driving force of the central baffle. In the absence of accelerations on the tank, the bubble will always stabilize in static equilibrium with its center on the forward centerline of the tank. The only other place the bubble can be in static equilibrium is where its center is on the aft centerline of the tank; however, this

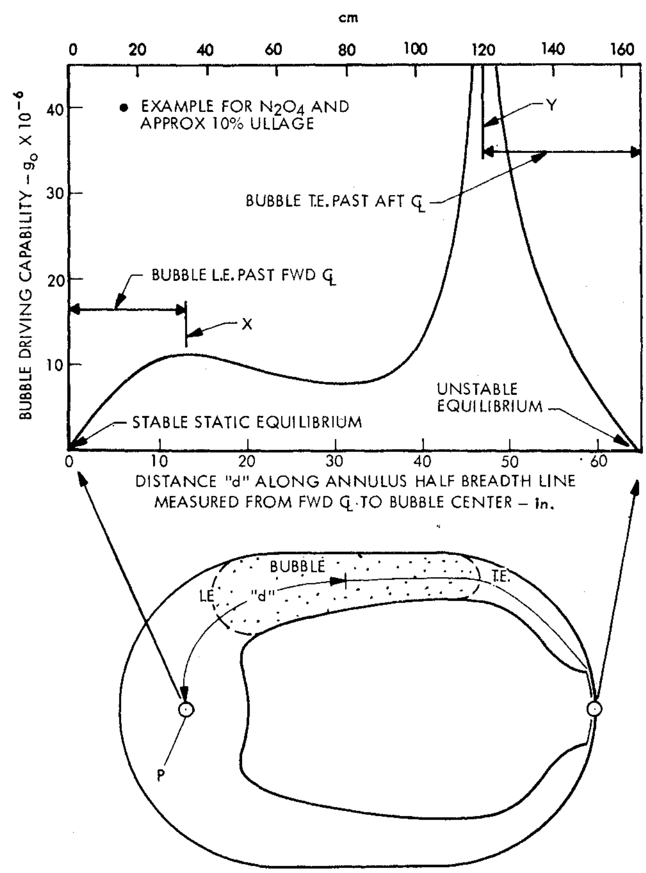


Fig. 3 General profile of baffle driving capability.

equilibrium is unstable, so the bubble resides there only momentarily. If displaced from the forward centerline position, the bubble will be forced to return there by surface-tension forces created by the shape of the baffle elements.

In moving to the equilibrium bubble location, there will be a bubble position, which is designated by the line X in this 10% ullage case, where the bubble leading edge passes the tank forward centerline. Forward of this point the strength of the meniscus at the leading edge no longer decreases with forward progress. Instead it starts to increase and begins approaching the strength of the trailing edge meniscus. When the bubble center arrives at the tank centerline, the leading and trailing edge menisci are of equal strength, the bubble is in static equilibrium, and the driving force goes to zero as shown.

If a vent tube is placed with its port at point P in Fig. 3, the port will retain access to ullage vapor until the bubble center moves rearward past the position of line X. The driving capability corresponding to position X then represents the body acceleration that could be imposed on the tank before loss of vent communication with the ullage, assuming the body acceleration is acting in a direction directly opposing the bubble driving force. Other vector directions of body acceleration result in larger allowable acceleration levels.

When the bubble is moving toward a centered position in the tank, the maximum resistance to the centering offered by the vent tube also occurs with the bubble at position X. The resisting force is the line force of the bubble meniscus intersection with the vent tube. The driving force tending to overcome the resistance is equal to the surface-tension centering force produced by the baffles.

The maximum driving capability of the bubble occurs when its center is at the position denoted by line Y; however, the designation of line Y is of little significance. The higher driving capability in this region is a result of the greater strength of the bubble trailing edge meniscus when the bubble is in this location.

Characteristically, in setting up the baffle profiles, it is important that they be far enough away from the tank wall so that the centers of the smallest ullage bubbles do not lie radially inward from the baffle chord lines. If this should occur, the strength of the meniscus formed between the baffle edges and the tank wall can exceed that of the meniscus between baffle elements. This can result in the subdivision of the ullage bubble and loss of bubble contact with the tank wall. In that case, the bubble would no longer have access to the annulus taper formed between the baffles and the tank wall, and would result in a loss of bubble driving capability. It would probably produce mass eccentricities, and result in a loss of vent port access to vapor during coast.

Evolution of Selected Concept

Figure 4 shows several of the central baffle arrangements that were analyzed. Figure 5 gives the bubble driving

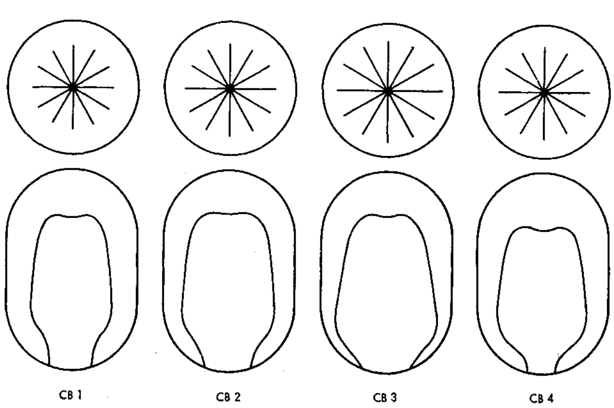


Fig. 4 Evolution of central baffle concept.

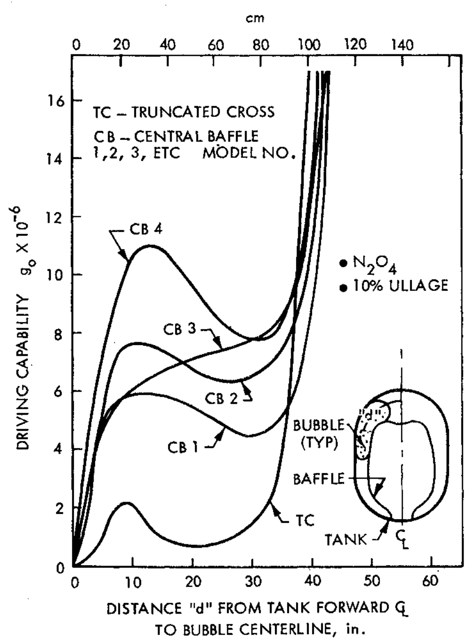


Fig. 5 Comparison of ullage bubble driving capabilities of various devices tested.

capabilities of the four configurations. The capability of the truncated cross concept is included as a point of reference. These plots are on an expanded driving capability scale relative to Fig. 3 and also omit the portions of the profiles near the aft end of the tank because of the small involvement of that region in subsequent performance discussions. The trend shown from the CB 1 device to the CB 4 device reflects the effort that has been made toward higher driving capabilities, particularly near the forward end of the tank, which is the region of primary interest.

Drop tower test results with configuration CB 3 illustrated the bubble subdividing effect which was discussed earlier. When the CB 3 configuration was dropped in an inverted position with the bubble initially in the aft end of the tank, the bubble subdivided due to surface-tension effects. Inspection of the aft region of the CB 3 baffle form shown in Fig. 4 suggests this possibility.

Bubble Positioning

Figure 6 shows the maximum allowable acceleration for the full range of ullages for both MMH and N_2O_4. Interesting items revealed here are the small variations in the allowable acceleration with ullage in the region above the minimum ullage and the infinite allowable acceleration above 94% ullage. The small variation in the lower ullage range reflects the geometry of the particular annuli tapers chosen. They cause the force differentials between the ends of the bubble to be proportional to bubble length, which makes the driving capability virtually independent of ullage volume. The infinite capability above 94% ullage reflects the effect of the extension of the vent tube into the tank cavity to the point that about 6% of the tank volume is forward of the vent tube ports. In this case the vent communicates with the ullage at any g loading with liquid quantities of less than 6% of the tank volume, since the liquid cannot reach the vent port.

The ullage will travel from any high-g position to an equilibrium low-g position soon after the beginning of a low-g environment, providing it does not become subdivided into bubbles with diameters less than the maximum annulus dimension. Subdivision of the bubble can be caused by two mechanisms. One is the strictly surface-tension-induced mechanism, which was described earlier. This mechanism can be avoided by controlling the relationship of the space

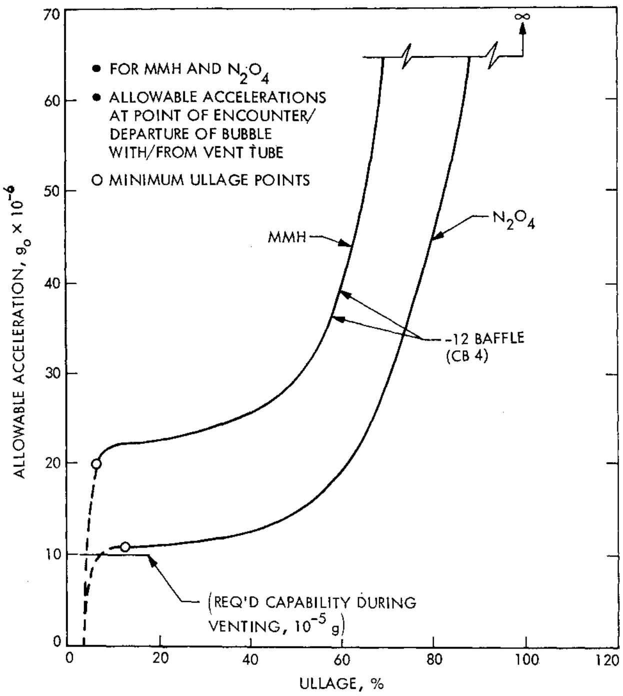


Fig. 6 Maximum allowable acceleration vs ullage for typical 12-baffle device.

between adjacent baffles to the space between the baffles and the tank wall. The other bubble breakup mechanism results from liquid kinetics and will be discussed later. This mechanism can be avoided by specific design provisions.

Sufficient testing and analyses were conducted to permit approximate prediction of bubble transient response times. Low-g drop test results with $\frac{1}{30}$-scale models using kerosene as the test fluid and having a 10% ullage show the model time required for a bubble to travel from any position in the model to the forward centered position to be a maximum of about 2 sec.

Prototype times can be estimated with the aid of model data. The transient bubble achieves a terminal velocity at which surface-tension driving forces are equaled by fluid dynamic drag forces. The driving forces were derived from the bubble meniscus dimensions and the surface-tension forces characteristic of the liquids involved. The drag force is composed of viscous shear skin-friction force and of pressure drag force. The viscous shear forces result from liquid flowing over the wetted tank walls and baffle surfaces during transition from upstream to downstream of the moving bubble. The pressure drag force results from the eddying incurred by the liquid flowing around the bubble. It was shown by Reynolds number calculation and isolation of the pressure drag force increment that the model flows were highly viscous dominated. Accordingly, the viscous force coefficients effective in the models were readily calculated from the driving forces and observed velocities of the model bubbles. Through some iteration, a prototype velocity was found which, with empirical values of pressure drag added to a Reynolds scaling of the model viscous force, resulted in a total drag force equaling the prototype bubble driving force. From the aforementioned velocity and the prototype dimensions, a prototype response time was determined. Prototype times were approximately 30 times the model times. Thus, the time required for the prototype to return a 10% ullage bubble from any position to the forward centered position is predicted to be of the order of 60 sec.

Reorientation

Slosh due to propellant reorientation is generally important from the standpoint of spacecraft pointing and ΔV accuracy and from effects on propellant management resulting from liquid kinetics remaining after shutdown. The initial energy of slosh varies with the difference in propellant potential energy between the low-g and high-g propellant orientations. The distance traversed by the ullage bubble centroid before the slosh ceases varies with the initial kinetic energy of the bubble divided by the average damping force present during slosh. Figure 7 characterizes slosh for the truncated cross concept, the CB 4 model of the central baffle, and an undesignated, low-slosh model of the central baffle. A 10% ullage volume was chosen for the characterization because of the greater interest in slosh early in the mission when control of ΔV and direction is particularly important and because the chance of loss of vent port communication with vapor due to ullage bubble breakup increases as the ullage volume decreases.

The reverse occurs at engine shutdown. When a transition is made from high-g to zero-g, all potential energy due to g is lost. Only the potential energy difference between the surface-tension forces at high-g and a minimum free energy surface at a zero-g form remains. If at the time of the high-g to low-g transition, the slosh is at a peak amplitude in which all energy is of a potential form, only the potential energy from surface tension will remain after the transition to zero g. When a transition is made from a high-g to a zero-g environment at other than peak amplitude, both kinetic energy and the vector sum of momenta are conserved. The transport kinetic energy is the quantity of interest from the standpoint of ullage bubble relocation, mass shift, and immediate loss of vent access. The rest of the energy goes to turbulence, which does not cause the centroid of the ullage bubble to relocate from its forward central position, the mass center to shift, or the bubble to leave the vent tube region.

Figure 8 shows the calculated initial kinetic energy of the bubble, the distance it will travel before it is arrested, and the carryover index. The index is given a value of 1.0 for the model CB 4 baffle configuration as a baseline. The initial potential energy is equivalent to that resulting from the mass in the crosshatched region falling from A to B at the prevailing g.

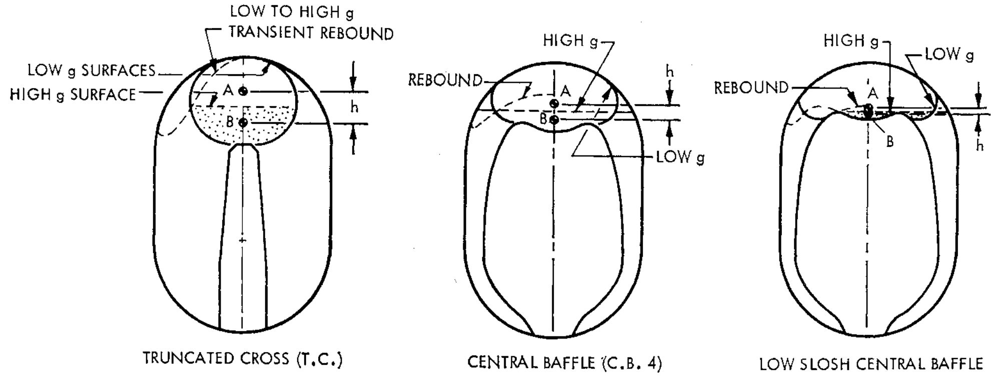
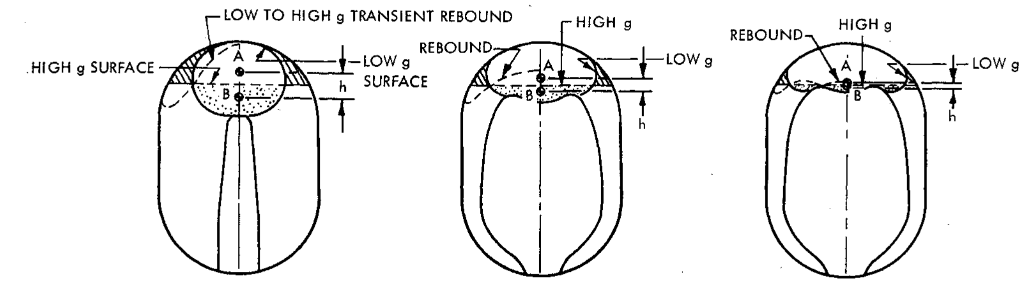


Fig. 7 Reorientation slosh modes.



	TRUNCATED CROSS (T.C.)	CENTRAL BAFFLE (C.B. 4)	LOW SLOSH CENTRAL BAFFLE
ULLAGE TRANSPORT KINETIC ENERGY	4.18 N-m (37 in.-lb)	0.339 N-m (3 in.-lb)	0.0282 N-m (0.25 in.-lb)
ULLAGE ARRESTING DISTANCE	127 cm (50 in.)	30.5 cm (12 in.)	7.62 cm (3 in.)
ULLAGE BREAK-UP INDEX	10.5	1.0	0.075

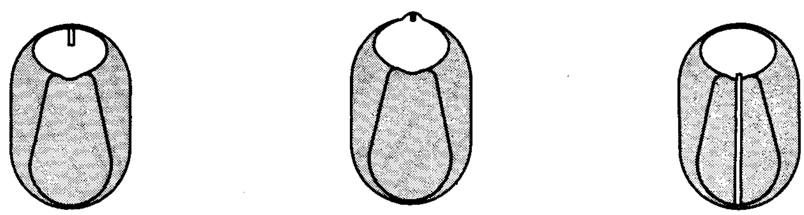
Fig. 8 Ullage shutdown—slosh kinetics carryover.

Pressurization and Venting

The effects of incoming pressurant gas are negligible during an engine burn since the nominal volume flow rates are small and the liquid surface is stabilized by the spacecraft acceleration. The pressurization period of interest is that taking place in the low-g environment prior to the first burn. At that time the launch pressure is less than the operating pressure, the rate of pressurization will be high, and no spacecraft acceleration will be present to help stabilize the propellant surface.

In a low-g environment the only forces available to statically stabilize the propellant surfaces are those of surface tension on the ullage bubble and those provided by the flow of the

Table 3 Venting concepts comparison



Comparison Factors	Extended Tube	Recessed Tube	Integral Tube
Description	Tube extends into ullage bubble	Tube submerged in recess in top of tank shell	Tube submerged in bubble positioning device, passes out tank bottom.
Effectiveness	Interferes with bubble positioning at small ullage volumes (cg location and venting effects) Longer tube has slightly more volume and potential for condensing more liquid for loss during venting Small liquid loss during gas venting	Tank shell design gives increase in stability of symmetric bubble Minimum liquid loss during gas venting except at high ullages and sustained rearward acceleration	Compatible with symmetric bubble positioning Longest vent tube, greatest potential for liquid condensation No liquid loss during gas venting except for condensate
Reliability	Confidence in bubble positioning has improved through additional analysis. Less sensitive to adverse vehicle acceleration than recessed tube.	High confidence in bubble placement prior to venting but not in maintaining during vent with high ullages and sustained rearward acceleration	Medium confidence in bubble placement prior to, and during venting
Cost/Weight	No significant cost or weight penalty	Requires special tank shell machining, but no special forgings.	Requires external plumbing to tie into pressurization system; requires separate provision for venting during pad fill/drain.
Installation	Installed after tank cleaning	Installed after tank cleaning, etc.	Installed integral with bubble positioning device. Plumbing connections more complicated than other approaches.
Development Risk	Decreasing as analytical confidence in concept improves. Test simulation of bubble positioning straightforward if concept functions properly.	Low risk. Concept demonstrated analytically. Straightforward test simulation of bubble positioning.	Medium risk. Concept not demonstrated. Straightforward test simulation of bubble positioning.

pressurant itself. The pressurant flow could aggravate local perturbations of the surface, but also, with appropriate pressurant port design, can be positively employed to aid surface-tension forces in stabilizing the bulk form and position of the ullage bubble.

One logical approach to the pressurization port design would be to distribute a series of holes to produce approximately equal static pressure everywhere on the bubble surface in its low-*g* form and to ascertain that any perturbation of the form or position results in a new pressure distribution that tends to restore the low-*g* configuration. Another approach would be to distribute holes in a manner that would produce, arbitrarily, a new bubble form of a kind easier to maintain during pressurization.

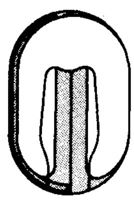
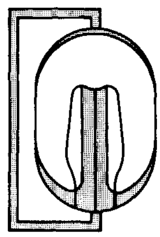
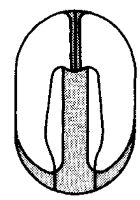
The primary concern in venting is the maintenance of communication between the vent port and the ullage vapor at all times. For communication to be maintained, the bubble driving capability of the baffle system must be sufficient to recover from perturbations of the ullage bubble position, force the ullage bubble to surround the vent tube, hold it in a venting position under spacecraft accelerations that may be present during venting, and preclude bubble breakup due to slosh kinetics.

Table 3 schematically illustrates three candidate pressurization/vent tube concepts and provides a tabulated comparison of the concepts. The extended tube arrangement is the tentative choice.

Liquid Communication Temperature Gradient

If the outlet end of the propellant tank becomes warmer than the forward end, propellant will evaporate from the bulk

Table 4 Communications concepts comparison

Comparison Factors	Internal	External	Integral
Description	Open channel communication device-channel shapes set by manufacturability, weight, installation ease.	Tube from top of tank to bottom outside tank shell	Open positioning device extends from bubble positioner to top of tank
Effectiveness	Establishes communication in ~10 sec after disturbance Slight biasing effect on ullage bubble location (within tolerance). Liquid pumping rate capability 100 times evaporation/condensation rate Good retention margins — liquid retreats to smaller radius as g increases.	Establishes communication in ~10 sec after disturbance Allows symmetric ullage bubble Liquid pumping rate capability 100 times evaporation/condensation rate Adequate retention margins — dumps liquid when critical g is reached unless tube has channel geometry inside.	Establishes communication in ~10 sec after disturbance Interferes with bubble positioning Liquid pumping rate capability 100 times evaporation/condensation rate Good retention margins — liquid retreats to smaller radius as g increases.
Reliability	Only failure mode is gross structural damage Some designs rely on a max allowable separation from wall Rapid recovery from adverse accelerations	External lines add leakage potential. Bubble in tube stops liquid communication unless tube has channel geometry. Recovers from adverse accelerations if no trapped bubble	Possible adverse effects due to eccentric bubble positioning Rapid recovery from adverse accelerations
Development Risk	Concept previously demonstrated Demonstration of all flow and acceleration conditions cannot be done simultaneously, but elements can be proven separately.	Exact modeling of dents, crimps, restrictions, etc., effects difficult	May not be compatible with central baffle concept based on earlier tests/analysis.
Fabrication/ Installation	Fabrication of curved angle stock may require special attention	May require extra tank ports or tubing interfaces. Welded joints decrease capability for removal if damaged.	No special effort for communication function
Weight/Cost	Small relative to positioning device recurring cost and weight. Development cost similar for all designs.	Cost to fabricate tube with internal channels will be high. Weight small relative to positioning device.	Small relative to positioning device

liquid surface and condense on the forward tank wall. Based on mission requirements, a 261°K (10°F) steady-state temperature differential in that direction may exist, so that the evaporation/condensation process must be considered. Unless means are provided to return such condensate to the bulk propellant located in the outlet end of the tank, substantial amounts of propellant could be eventually transported to the forward end of the tank, where it would not be accessible to the tank outlet for supply to the engine and where it would interfere with vapor venting. The transport rates for the maximum specified steady-state temperature gradient will be on the order of 10^{-6} kg/sec (10^{-2} lbm/hr). Some mission coast periods, however, are about 5×10^3 hr, so that, in spite of low rates, the total quantity that could be transported would become prohibitive unless means were provided to return it to the bulk propellant. The most convenient and reliable method for returning the condensate to the main body of propellant is to establish a liquid communication channel between the forward end of the tank and the region where the bulk propellant resides. The channel will perform the function passively by using the surface-tension properties of the propellants. A small channel of 6.45×10^{-2} cm^2 (0.01 $in.^2$) cross-sectional area is sufficient to meet condensate return requirements, so the size of the channel selected will be dictated more by good structural practice and by requirements for recovering propellants dislocated within the minimum specified time between burns.

Candidate concepts are shown schematically in Table 4 and comparisons of the candidates are made in tabular form. The integral arrangement is the simplest, lowest weight and most easily installed. Its main drawback is the inability of the baffle system to push the ullage bubble past a sufficiently large communication device under all conditions. This capability is essential for center-of-mass control and venting. Hence, the internal concept was chosen based on comparison of bubble centering analysis and test results.

Depletion

Depletion refers to the process of draining and scavenging the tank in final flight operation. The steady-flow velocity potential in the outlet region will be very uniform with the central baffle design. Also, the minimum propellant quantity required for restart will be small because of the efficient outlet design and because of the strong surface tension holding capability associated with the baffle elements in the central baffle configuration.

Proposed Development Phase Testing

Development of a surface-tension propellant management system is significantly different from the development of other types of systems. Development of most propellant management systems centers around mechanical testing of the system in a simulated flight environment to demonstrate mechanical integrity throughout the mission. Generally, it is assumed that if the systems remain intact, mission performance requirements will be fulfilled. However, a surface-tension device is passive in operation, contains no moving parts and is usually constructed from metallic components. Mechanical integrity is normally assured by means of conservative design and materials selection. Because the surface-tension system is passive, it depends upon natural phenomena for proper orientation of the propellant, and development testing is conducted primarily to demonstrate satisfactory orientation and expulsion of the propellant during the mission operating environment.

To assure satisfactory performance of the passive propellant management system, its operation must be evaluated completely and the associated phenomena, requirements, and design elements identified. To accomplish this, a mission functional matrix was prepared as the nucleus of the basic development plan. The functional matrix identifies the interactions between the various mission events, requirements, design elements, and surface-tension phenomena. The complete mission functional matrix is given in Ref. 1. The propellant management system for Viking 75 Orbiter was analyzed to generate a preliminary design. Performance verification of the design will be accomplished by means of similarity testing in conjunction with supporting analyses during the development program.

Numerous testing techniques have been developed to simulate the low-*g* propellant behavior in propellant tanks. A complete discussion of the available test methods is given in Ref. 2. These testing techniques were evaluated for their potential application in assessing the performance of the Viking 75 Orbiter propellant management system.

Mission operational events and the variables involved in each event have been identified. The dominant dimensionless groups were identified and then used to calculate model scale, test conditions, test equipment requirements, and test fluids for alternate test methods. These results were used to determine acceptable similarity test methods, model sizes, test times, test complexity, data precision, test cost, and schedule. The performance test matrix, shown in Table 5, summarizes the planned development test program. Detailed test analyses will be conducted to determine specific test objectives, test equipment, test plan and anticipated results for each category.

Preliminary Design and Testing

Prior to the final selection of the central baffle design as the propellant management system for the Viking 75 Orbiter, some preliminary design, fabrication, and testing were required. There were unanswered questions regarding the basic structural integrity of the baffle concept, materials compatibility, fabricability of the baffle concept, ease of cleaning, and ease of installation and removal of the baffle design. Since the Orbiter propellant tanks were being fabricated from 6Al4V titanium alloy, attempts were made to use the same material wherever possible on the propellant management device to avoid the potential compatibility problems associated with the use of dissimilar metals in propellant systems. Available data has established the compatibility of 6Al4V titanium alloy with MMH and N_2O_4, the propellants used on the Orbiter.

A spherical tank baffle device was designed and fabricated to obtain preliminary vibration data and installation and removal information. The choice of a spherical device was made to allow the vibration testing to be done in the 76.2-cm-diam (30-in.) spherical plastic tank available from the Mariner Mars 71 Project. The spherical device had baffle elements made in pairs from 2.54×10^{-2} cm (0.010 in.) thick sheet and spaced around the center tube using 1.27×10^{-1} cm (0.050 in.) gusset spacers. The baffle elements were mechanically attached to the center tube with screw fasteners. Pure titanium was selected rather than 6Al4V for this spherical device because of its availability.

Low-frequency slosh vibration of the spherical device was accomplished using water as the test fluid and with gas ullages from 6 to 40%. Sinusoidal vibration levels, given in Fig. 9, were selected to represent the on-pad wind environment that could be seen by the Viking Spacecraft. For each ullage condition, sinusoidal sweeps from 0.6 to 5 Hz were made at 1 octave/min and slosh resonances were identified. Dwells for 15 cycles were performed at each slosh resonance. Instrumentation consisted of strain gages mounted on the center tube, accelerometers located at the base and top of the center tube, and color motion pictures of each test. The thin baffle elements moved quite readily under the slosh loading, and strain gage readings indicated that only small loads were transmitted to the center tube. The rapid decrease in slosh motion observed at the termination of a test indicated that the baffles provided considerable damping to fluid motion. No

Table 5 Planned performance verification tests for Viking propellant management system

Mission event	Dominant variables	Dominant dimensionless groups	Scale ratio	Test fluid	Test method
Propellant retention characteristics	Surface tension, contact angle, gravity	Bond No.	1/1	Propellants	1-*g* bench
Low-*g* propellant configuration	Surface tension, acceleration, tank thermal characteristics	Bond No.	1/30, 1/3	Water, kerosene, CCl_4	Drop tower, immiscible liquid
Recovery from disturbances to equilibrium propellant configuration, slosh carryover	Surface tension, inertia, acceleration, viscosity	Weber No. Bond No. Reynolds No.	1/30, 1/18	Water	Drop tower
Propellant initial withdrawal transient, low-*g* venting propellant loss	Surface tension, inertia	Weber No.	1/4	Water	Drop tower
Propellant steady withdrawal and depletion	Inertia, acceleration, surface tension, viscosity	Froude No. Weber No. Reynolds No.	1/4, 1/3	Water	1-*g* bench
Propellant reorientation	Acceleration, inertia, viscosity	(Bond No. Regime) Froude No. Reynolds No.	1/4, 1/3	Water	1-*g* bench

cracking, galling, material permanent set, or other damage to the baffle device was observed as a result of the vibration testing. The low level of the structural loading of the baffle device permitted some weight saving features to be incorporated into the baseline propellant management device.

Although there were no major difficulties during the fabrication of the spherical tank device, several potential problems became apparent. The mechanically fastened baffle elements created numerous cavities that could trap particles and make cleaning of the assembled propellant management device difficult. The mechanically fastened design permits relative motion of metal surfaces in contact with other metal surfaces and could therefore lead to particle generation. Initially, a mechanically fastened baffle device was felt to be desirable from the installation and removal viewpoint. Variations of the fabrication technique used on the spherical tank baffle device would permit the assembly and disassembly of the device within the propellant tank. Although the introduction and removal of propellant management device elements through the propellant tank access hole becomes easier with this method, the chances of damage to a propellant tank by the baffle elements increases during this relatively uncontrolled assembly/disassembly process.

To prevent possible damage to the propellant tank during propellant management device installation and removal and to promote a clean propellant tank assembly, a one-piece baffle assembly was desirable. To establish the feasibility of the installation and removal of a one-piece baffle assembly through the 22.9-cm-diam (9-in.) access hole in the propellant tank, a prototype installation and removal tool was designed and built. The tool provides 12 rods which furl the baffle elements when the baffle assembly is rotated within the tool. The furled baffle assembly can then be installed or removed through the propellant tank access hole. During installation, the tool provides a means for the controlled unfurling of the baffle assembly within the propellant tank. The spherical tank device and the prototype installation and removal tool

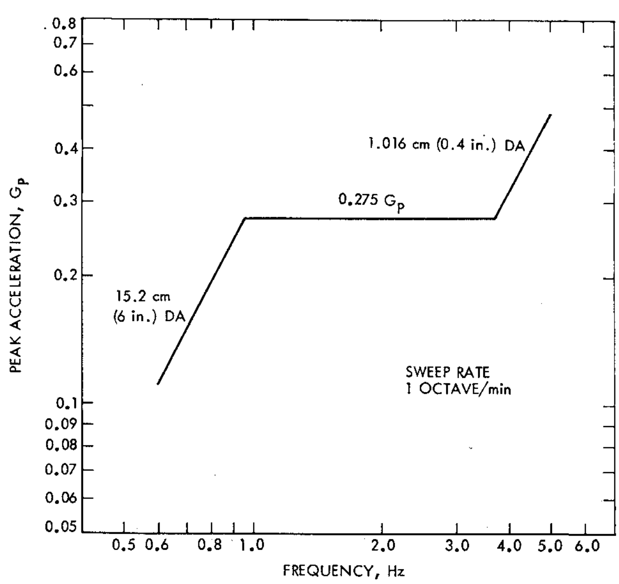


Fig. 9 Viking Orbiter propellant management device sinusoidal slosh environment.

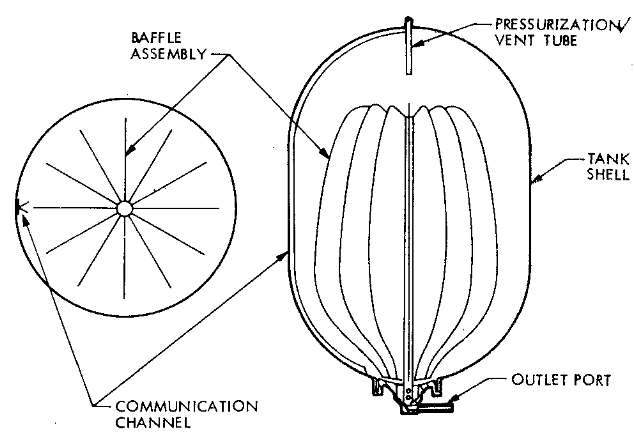


Fig. 10 Viking Orbiter baseline propellant management device.

established the feasibility of a one-piece baffle assembly. The furling concept does allow metal-to-metal contact between adjacent baffles when the baffle assembly is in the furled condition; however, metal-to-metal rubbing between adjacent baffles or between baffles and furling rods is minimized by supporting each rod on roller bearings.

As a result of the fabrication and testing of the spherical tank device, the baseline propellant management device for Viking 75 Orbiter was selected to have a one-piece, electron-beam welded baffle assembly. The selected baseline design, shown in Fig. 10, incorporates most of the recommendations of the concept selection phase of the Orbiter propellant management program.

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Verification of a Comprehensive Thrust Chamber Compatibility Model for Liquid Rocket Engines

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The objective of this effort was to assess the accuracy and validity of the Injector Chamber Compatibility model coupled with the Aerotherm Thermal/Chemical Ablation Analysis as a design tool for analyzing liquid rocket ablative or refractory thrust chamber durability. This evaluation consisted of analyzing and predicting chamber and/or throat erosion for five liquid rocket engine firings. The results demonstrated that the analysis can be used with a high degree of confidence to predict the amount of erosion and the location and depth of chamber and/or nozzle streaking.

Introduction

A CRITICAL aspect of liquid engine thrust chamber design is the relationship between the injector configuration and the durability of the chamber liner materials. Consequently, the Air Force Rocket Propulsion Lab. sponsored the development of a series of computerized models for predicting liner material performance. The main products of this effort were the Injector Chamber Compatability (ICC) Model[1,2] developed by Rocketdyne and the Aerotherm Thermal/Chemical Ablation Analysis.[3] When combined, these models constitute a design tool for analyzing: 1) the injector induced three-dimensional combustion and gas dynamic environment in the thrust chamber; 2) boundary-layer characteristics and subsequent heat transfer to the chamber wall; 3) the rate of material erosion and pyrolysis due to chemical and thermal attack. The purpose of the effort discussed herein was to assess the validity of this design tool through a systematic comparison of analysis and experiment.

This evaluation was accomplished by predicting chamber and nozzle liner erosion for five liquid rocket engine firings. In an attempt to ensure the objectivity of this evaluation, all but one of these predictions were accomplished before the experiments were conducted.

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Description of the Analytical Model

The ICC model was specifically developed to account for the effect of the injector configuration on the mass distribution and mixture ratio variation within the chamber. Consequently, this model is capable of relating the injector design to the performance of the chamber and nozzle liner materials.

Analysis of the combustion gas dynamics within the chamber is accomplished through a series of theoretical models which describe the progression of the liquid spray and exhaust gas from the combustion zone to the throat plane (Fig. 1). These calculations are usually accomplished for a wedge shaped portion of the chamber which has been selected upon consideration of symmetry.

The behavior of the liquid spray in the region immediately adjacent to the injector is calculated by the Liquid Injector

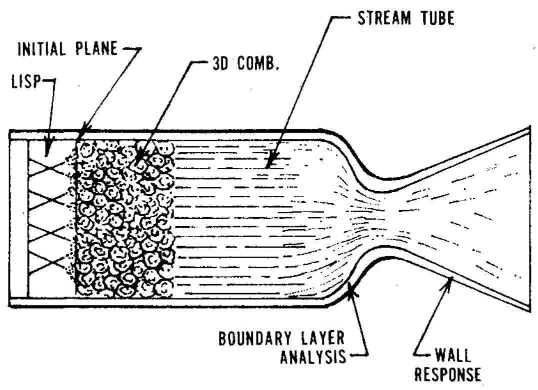

Fig. 1 Injector/Chamber Compatibility analysis.