Space Storable Propellant Aquisition System

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A program was conducted to select the best surface tension propellant acquisition concept for an advanced 3-axis spacecraft propulsion system having a 10-year life. Fabricability, performance capability, and spacecraft compatibility of various candidate concepts were assessed and compared. The results showed the sheet-metal vane low-*g* systems to be preferred for these interplanetary applications. They can be adapted to a broad spectrum of low-*g* applications and can be tailored to specific missions with the desired operational margin. A preliminary standpipe with vanes design was accomplished based on analysis and testing of the more significant factors influencing fabrication and operation.

Introduction

CERTAIN space storable propellant combinations, with their high specific-impulse values, are being considered for future spacecraft propulsion subsystems to obtain improved performance over the commonly used earth-storable propellants. A particular case is the NASA/JPL Space Storable Propulsion Module (SSPM) advanced development program to provide a high-energy, liquid propulsion system.[1] For the SSPM program, "space storable" denotes high-energy, liquid propellant combinations in which: 1) at least one of the propellants is a cryogen; and 2) both propellants can be maintained as a liquid, onboard the spacecraft in flight, with only passive thermal control. Example propellant combinations are Flox/MMH, F_2/N_2H_4 and OF_2/B_2H_6.

Propellant management and control are required for successful propulsion system performance. For long-duration interplanetary missions, the propellant acquisition subsystem must provide gas-free liquid on demand for many long and short engine firings. In addition, space storable propellants, particularly fluorine-containing oxidizers, require special consideration in the design of a propellant acquisition system because of their toxicity, reactivity, temperature, and physical properties. This case was the subject of a study conducted for JPL in 1971 and 1972 to provide the propellant acquisition system technology needed for the SSPM program.[2] The objectives of the advanced technology program were to select and design the best surface tension propellant acquisition system for this application.

Surface tension devices were previously shown (1970) to be the best acquisition method for Mars Orbiter and Grand Tour missions.[3] The utility of all current propellant acquisition devices was investigated for advanced spacecraft applications and surface tension systems were found to be clearly preferred. An earlier study (1968) of various acquisition methods also concluded that the surface tension technique is preferred.[4] Following these general selection studies, other programs have now been conducted to select the best surface tension device configuration for specific applications. Examples are the Viking Orbiter[5,6] the Space Shuttle Orbital Maneuvering System,[7] and the Space Shuttle Reaction Control System.[8] These studies have primarily employed the selection process developed for the first two programs[3,4] and have followed the study reported here, which also used this general selection process. Since surface tension device design details are mission-dependent, each application requires re-evaluation of the applicability of any particular concept. However, all configurations operate on the same basic principle using the liquid/gas surface tension and ullage pressure to passively support the liquid in the desired location.

The baseline mission for the study was that for the Jupiter Orbiter; it consists of ground hold, launch into Earth orbit, Earth-Jupiter transfer, and Jupiter-orbit phases. Ground hold could be as long as 60 days. Maximum coast time of the 3150 lb spacecraft, including propellants, in a 100-nm parking orbit is 1 hr. Five engine burns occur during the 25-month Jupiter-transfer phase which includes a two-year period with no engine burns. This is then followed by another year in Jupiter orbit with at least 22 short burns of variable duration.

Adverse spacecraft accelerations range from $10^{-7}g$ during coast, arising from factors such as solar wind or planetary atmosphere drag, to $10^{-4}g$ during attitude control maneuvers. The settling acceleration due to main engine burn varies from $0.19g$ to $0.32g$ at the beginning and end of the mission, respectively.

The Space Storable Propulsion Module consists of three major subassemblies: engine; pressurization; and propellant feed. The propellant acquisition subsystems are part of the propellant feed system; however, their design is affected by the impacts on the operation of the other assemblies. Both in-line and side-by-side tank configurations were considered. The tanks in the two-tank system were spherical, but cylindrical tanks were also of interest. The propellant combinations considered were Flox (88:12)/MMH and F_2/N_2H_4 (dual-mode system). A more detailed description of the system is given in Ref. 1.

The nominal initial ullage volume to be controlled in the 6Al-4V titanium fuel tank was 5% (at 530°R); that for the 2219 aluminimum oxidizer tank was 20% (at 155°R). Tank diameter was 2.40 ft for MMH, 2.94 ft for Flox and 2.70 ft for both N_2H_4 and F_2. Each tank included 4% residual propellant, had an operating pressure of 260 psia and was pressurized from a separate stored helium tank to which it was thermally connected.

Preliminary Design Study

A number of surface tension concepts were formulated that appeared capable of accomplishing the required propellant acquisition. These concepts included advanced systems, such as the Martin Marietta "Fruhof"[3] and other promising methods or combinations. An initial screening was conducted

Presented as Paper 74-1151 at the AIAA/SAE 10th Propulsion Conference, San Diego, California, October 21-23, 1974; submitted October 30, 1974; revision received May 7, 1975. This work was accomplished under NASA Contract NAS2-6548.

Index categories: Liquid Rocket Engines; Spacecraft Propulsion Systems Integration.

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to identify the more promising concepts for detailed evaluation. Concepts which change or modify the tank internal geometry to accomplish propellant positioning were of primary interest. Also, it was desirable that the device be amenable to modular installation through a 9-in. diam tank access port.

Each of the selected candidates fell into one of three general categories based upon its configuration, as shown in Fig. 1. Category A devices retain some liquid over the outlet by using capillary barriers, such as perforated plate, to compartment the tank and form one or more propellent trap areas. Category B devices extend from the bottom to the top of the tank, contacting both and orienting some of the liquid over the outlet and some in a columnar fashion above the outlet. Category C devices, the Fruhof class of systems, contact only the bottom of the tank over the outlet and orient a large fraction of the liquid at this location. Communication channels, which allow liquid to flow under surface tension forces into preferential contact with the device, are employed with the Category C devices.

Analyses and evaluations were conducted on each candidate concept to assess its practicality, performance capability, and compatibility with the spacecraft. Operational considerations included static interface shape, ullage positioning and interface stability, slosh, and settling dynamics, pressurization/venting, suction dip, bubble ingestion, and communication channel operation. Interaction with the pressurization and thermal control systems was assessed, and fabrication, assembly, and tank installation were considered. In addition, an experimental drop-tower program was conducted to support, verify, and complement the analytical evaluation of candidate concepts.[2]

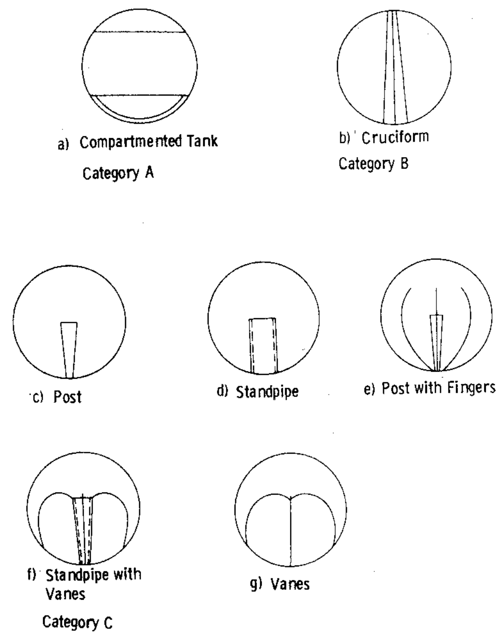

Fig. 1 Candidate devices.

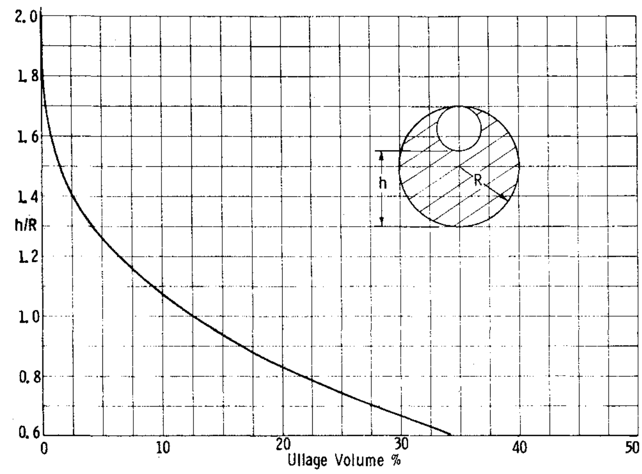

Fig. 2 Post height vs ullage volume.

Compartmented Tank

The compartmented tank (Fig. 1a) is best representative of the Category A devices. It consists of a trap plus additional barriers. The trap maintains a reservoir of liquid at the tank outlet which is always available for engine start. As the engine starts, liquid outside the trap settles over the coverplate, feeds into and through the trap, and out of the tank. A barrier above the trap coverplate is positioned so that liquid will remain below it and gas above it throughout the mission. This allows the tank to be vented and pressurized through the ullage above this second barrier. Performance of this type device has been previously characterized.[3,9] It provides good liquid/gas interface stability and ullage control.

Cruciform

Category B and C devices use capillary pumping to position liquid at the desired outlet location. Their shape determines how the liquid will orient about the device in low-g. Therefore, these devices are configured to provide an equilibrium liquid orientation biased toward the outlet. Some achieve this better than others. A capillary pressure difference exists across any curved liquid/gas interface; its magnitude is given by the Young-Laplace equation:

$$\Delta P = \sigma[(1/R_1) + (1/R_2)] \qquad (1)$$

where ΔP = capillary pressure differential; σ = surface tension of the liquid; and R_1, R_2 = radii of curvature of the interface. In zero-g, pressures within the liquid are determined solely by the Young-Laplace equation. Pressure equilibrium within the liquid is reached and the static interface configuration is established when the surface curvature $(1/R_1 + 1/R_2)$ is everywhere the same.

The Category B cruciform shown in Fig. 1b takes advantage of the capillary pumping phenomena. With a wider base, more liquid collects over the outlet than at the top. Communication of liquid from the top of the tank to the outlet is provided by the device itself. In low-g, sufficient liquid is oriented over the outlet to permit engine start. Once started, all liquid is settled so that a supply of propellant can be maintained for the duration of the engine burn. At low liquid volumes (~20%), liquid collects symmetrically about the cruciform. For large liquid volumes, however, an offset unsysmmetrical kidney-shaped bubble can form. When this device was tested in the drop tower, the formation of the offset ullage bubble from the less-stable toroidal bubble was demonstrated. Since the ullage location is indeterminate at the smaller ullage volumes, neither venting nor pressurization could be reliably accomplished with this device. Also, a considerable portion of the liquid is held within the device and at the top of the tank in low-g, rather than close to the outlet. This liquid holdup aggravates settling, slosh, and suction dip problems during engine start.

Axial and lateral stability refers to the ability of the device to hold liquid about itself (over the tank outlet) under the effect of an adverse system acceleration. A stable liquid interface implies no liquid flow. With this type of system, however, liquid flow occurs under the influence of a new acceleration until a new stable configuration is formed. For any given axial or lateral acceleration, the cruciform would hold a larger volume of liquid over the outlet than the post or post with fingers, but it would be less stable than the vaned devices of Category C.

Post

Because of their varied operation and performance, five Category C devices were selected as candidates. Each includes a communication channel. A variety of analyses were conducted to configure and evaluate these candidates. Height of the devices are determined by the initial ullage volume, since the acquisition device should be capable of uniquely positioning the ullage bubble so that venting, pressurization, and center-of-mass (c.m.) control can be accomplished. In zero-g, the equilibrium ullage configuration is spherical. If only the near zero-g conditions are considered, the curve in Fig. 2 shows height as a function of ullage volume for a spherical tank with radius R.

A post height h provides one location between the top of the post and the top of the tank at which the ullage bubble can be positioned. For the simple post shown in Fig. 1c, this is a unique location only if the volume of the gas bubble is greater than 12.5% ($h/R = 1.0$). When the volume is less than 12.5% and the diameter of the post is small, there are other locations around the side of the post where the bubble can be spherical. For a 20% ullage volume, a post height of $0.83R$ would uniquely position the ullage. The height of the post would be 1.26 R for a 5% ullage, but this post will not guarantee the positioning of the bubble and will only interfere with the positioning of a larger ullage bubble. For this reason, the height of the post for the fuel tank was limited to $1.0R$. When the ullage volume is less than 12.5%, the location of the bubble is indeterminate.

Axial stability of the post was analyzed mathematically. The results show that increasing the post diameter and the taper to the outlet increased stability. This was verified by the results of the test program. The analysis also showed that if the liquid interface is in contact with the top edge of the post, this "stuck" interface is less stable than one that intersects the post elsewhere. This should be considered in device design. If interface stability is critical for a given range of liquid volume, and dimensions of the device should be increased to provide a point at which the interface becomes stuck beyond the range of concern. The post has little lateral stability and any lateral disturbance produces an offset ullage (verified experimentally); however, recentering would occur after cessation of the perturbation. It was concluded that the post has the least capability of the candidate devices, with its most significant weaknesses being: 1) the device for the fuel tank is not capable of positioning the ullage bubble at volumes less than 12.5%; 2) the stability of the device is lower than that for any of the other candidates; and 3) communication channels will not function with the post at contact angles greater than two degrees (discussed later). Because of these weaknesses, the post was eliminated from further consideration.

Standpipe

The standpipe is essentially a large-diameter, hollow post (Fig. 1d). Openings are provided around the base so it can fill with liquid. Height of the standpipe is determined in a manner similar to that used for the post, but larger diameters may be employed. Centering of the ullage cannot be accomplished for volumes less than 12.5%. Analysis of the ullage centering capability of the standpipe showed that equilibrium ullage bubble positions exist in the centered position above the standpipe and offset to the side. The drop tower tests demonstrated the existence of these other stable offset states for the standpipe. At low liquid volumes, most of the liquid will be oriented inside the standpipe. Based on a $0.4R$ (R = tank radius) diameter standpipe, the critical Bond number is 21 and a very stable reservoir of liquid (high axial stability) is provided. At low ullage volumes, the lateral stability of the standpipe is much like that of the post. As a result of the configuration of the device, liquid located inside the standpipe is very stable under the effect of lateral accelerations.

Post with Fingers

A post with fingers device, Fig. 1e, is slightly better than the post alone. By increasing the post height to $1.26R$, it can hold a 5% ullage in the centered position, but other stable bubble locations are possible due to the weak positioning effect of the fingers. If the ullage is initially centered, the fingers assist the post in maintaining the bubble in that position against a lateral disturbance. This was verified in the drop tower tests. Stability of the device in the axial direction is the same as the post.

Vanes

A number of vanes radiating outward from a small central post comprise the vane device shown in Fig. 1f. Only two of the six vanes are shown for clarity. The post serves as a structural member and has little operational effect. Primary variables in the design are the vane number and profile; height is established by Fig. 2. The objective in designing the vane profile is to make the centered position the only ullage equilibrium location. Elsewhere, capillary forces must pump it to the uniquely centered position. To provide this condition, the vane radius r_V, measured from the tank center, must increase with displacement angle ϕ (Fig. 3). However, if the vane profile exceeds an outer limit, a phenomenon called 'bubble breakup" is possible. This limit, defined in Ref. 2, varies with the number of vanes.

Breakup of the ullage bubble was demonstrated with vaned devices in the drop tower tests, as shown in Fig. 4. This resulted when the vane device tanks were inverted and small ullage volumes (5% to 20% ullage) were used. At the beginning of the test, the ullage was located at the base of the device. Once the system entered low-g, liquid filled the gap between the edge of the vane and tank wall, splitting the ullage into a number of bubbles before the whole bubble could be pumped away from the outlet. These small bubbles can be spherical and still fit within the vanes, so that no capillary forces act to move them further from the outlet. They would be buoyed away from the tank outlet and would not be ingested when the engine starts. However, there would

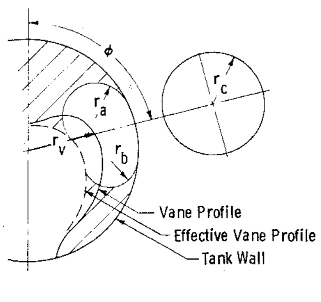

Fig. 3 Vane and bubble geometry.

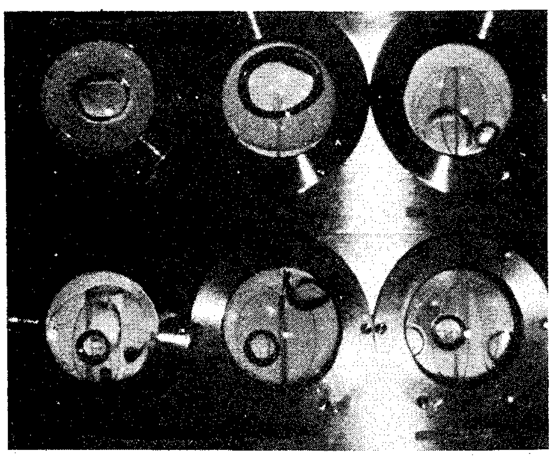

Fig. 4 Models of 5 different vane devices in spherical glass. Tanks show ullage breakup in drop tests.

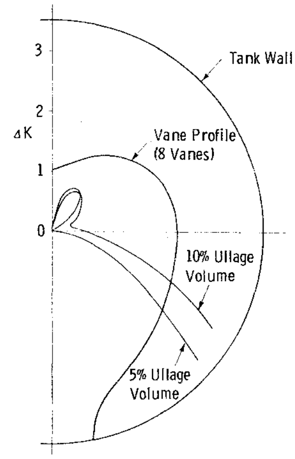

Fig. 5 Pumping capability vs ullage volume.

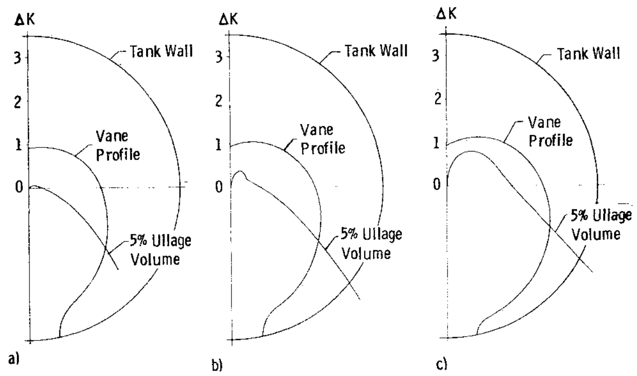

Fig. 6 Effect of number of vanes on pumping capability: a) six vanes; b) eight vanes; c) twelve vanes.

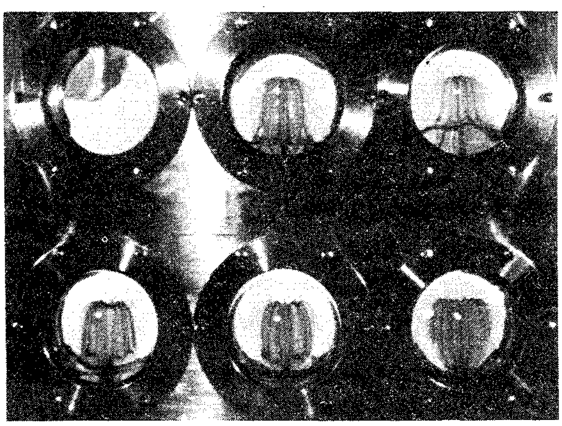

Fig. 7 Orientation of small liquid volumes by various vane configurations (drop test).

no longer be a centered ullage for the purposes of venting and pressurization. Vanes designed with profiles within the outer limit were tested in the drop tower and no breakup of the ullage bubble occurred.

Vane profiles were analyzed by calculating the capillary forces acting on a bubble of a specified volume as the bubble is displaced. The force acting on the bubble is proportional to the difference in curvature at opposite ends, see Fig. 3. It was assumed that the effective vane profile determines bubble configuration within the vanes. The capillary pressure difference across the bubble is determined from Eq. (1) as:

$$P_b - P_a = \sigma[(1/r_b) - (1/r_a)] = \sigma\Delta K \tag{2}$$

The difference in curvature ΔK was calculated as a function of the displacement ϕ for a given vane profile, number of vanes and ullage volume. An example is shown in Fig. 5 where the pumping capability ΔK is superimposed on the profile using polar coordinates.

When the bubble is centered, ΔK is zero and the bubble is in its stable state. As the bubble is displaced, ΔK increases, indicating the existence of a centering force. With a 5% ullage, this vane profile has another stable state at a displacement of 80°; this is a region in which the radius decreases slightly. Increasing the ullage to 10% eliminates this condition. The centering force reaches a minimum, but the force is always present.

A computer program was used to provide the optimum vane profile. Through a process of specifying the effective vane profile and calculating the actual vane profile, the desired centering capability can be obtained. Vane profiles using this approach for 6, 8, and 12 vanes are shown in Fig. 6. In each case, the bubble breakup outer limit was used as a design criterion.

Another significant factor in determining the vane profile is the positioning of small liquid volumes over the tank outlet. The drop tower tests showed that more liquid is held up within the vanes away from the outlet when the outer profile limit is respected. The 12-vaned device on the lower right in Fig. 7 has a profile within the outer limit while the upper center one, also with 12 vanes, does not. The lower center vane device has the same profile as the lower right device, but has only eight vanes. Decreasing the number of vanes and exceeding the outer limit toward the outlet end of the tank both tend to maintain liquid close to the outlet at low liquid levels.

Positioning the liquid at low liquid volumes, to ensure gas-free expulsion during the terminal phase of the mission, was given precedence over the chance of ullage breakup. Vane profiles that exceed the outer profile limit near the outlet were selected for the candidate concepts. When the mission acceleration environment is considered, it is seen that conditions leading to ullage breakup are so unlikely that this factor should not influence system design for this application. When the outer profile limit is exceeded, as it was for the selected vane device profile, significant increase in the pumping capability of the vane device is obtained. This is another reason for not using the outer limit as a design criterion.

Vane profiles for the 5% fuel tank ullage and the 20% oxidizer tank ullage were determined using the same approach. A profile was designed to apply a centering force that continued to increase the further the ullage bubble was displaced from the centered position.

Drop tower tests were used to establish the axial stability of vane devices. Based on the results, the devices hold a significant amount of liquid over the outlet under axial accelerations equal to or greater than mission accelerations. Also, increasing the number of vanes increases the stability.

Lateral stability depends on the pumping capability of the vane device. As the bubble is laterally displaced, the capillary force increases until it balances the hydrostatic pressure of the liquid. For the given mission, lateral disturbances will result from attitude control system (ACS) thruster firing and from boom deployment. The pulsing ACS thrusters fire 0.1 sec every 1 to 4 sec as the spacecraft attitude is changed. Analysis showed that the 0.1-sec pulse only displaces the ullage about 0.001 in. which presents no ullage centering problem. Also, the resulting spacecraft rotation at a constant angular rate would not cause any significant liquid displacement.

Boom deployment produces disturbances up to $8 \times 10^{-5}g$ for 45 sec, making it difficult for a vane device to hold the ullage bubble in contact with the vent port. The lateral stability tests confirmed that the bubble will be displaced to the side of the tank for accelerations of this size. Analysis showed that ullage bubble displacement sufficient to cause breakup could not occur, however. When the acceleration is removed, the bubble will again be recentered.

A compromise is involved in designing vane devices for centering small ullage volumes. A tall device is required for centering the ullage bubble, but a short device would orient small liquid volumes in the preferential location over the outlet. Because of the height of the device, some liquid will be held up in the vanes, but this was minimized by using only six vanes and the selected profile. When the engine starts, this liquid will settle, causing some splashing at the surface. Liquid already oriented at the outlet will not be distributed, so it will isolate the outlet from the action of the settling liquid.

Standpipe with Vanes

The standpipe with vanes is a combination device that is better than each alone. The configuration for the fuel tank is shown in Fig. 1g. Vane number and profile are the same as for the vane device and the performance is similar. A tapered standpipe, smaller than the basic standpipe device, is used. Liquid outside the standpipe feeds directly to an annular outlet that surrounds the base of the standpipe. Large openings in the base allow liquid to enter and leave the standpipe.

The standpipe provides a highly stable reservoir of liquid that supplements the liquid held about the device. At all liquid volumes greater than about 5%, the standpipe will be completely full of liquid. At lower liquid volumes, the static interface shape will be reached with a partially full standpipe. During the critical engine start phase of operation, the standpipe will become unstable. While liquid outside the standpipe is being settled and collected over the outlet, the volume of liquid inside the standpipe is available to maintain flow to the engine, thereby reducing the possibility of gas ingestion and suction dip.

Communication

If some or all of the liquid is moved away from a Category C acquisition device, communication channels are provided for return of this liquid to the device. If the interface of the liquid that has been moved away is in contact with the device, the channels serve no purpose. But, when that interface does not touch the device or come into contact with the liquid about the device, the channels will interconnect the displaced liquid and the liquid about the device.

A capillary pumping pressure provides the driving force to cause the flow of liquid along the channels. The driving force is the difference in pressure between the two liquid volumes which is directly proportional to the difference between the curvatures, Eq. (1). The curvature of a given volume of liquid under zero-*g* is influenced by contact angle and the geometry of the surface containing the liquid. Liquid located in a sharp corner will have a higher curvature than liquid on a smooth, flat surface.

Considering a displaced volume of liquid in contact with a communication channel, the pressure of the liquid in the channel is less than that of the displaced liquid, and liquid will flow into and rapidly fill the channel. Scaling the drop tower test results showed that the time required to fill the channel would be about 25 sec for the Flox tank and 35 sec for the MMH tank.

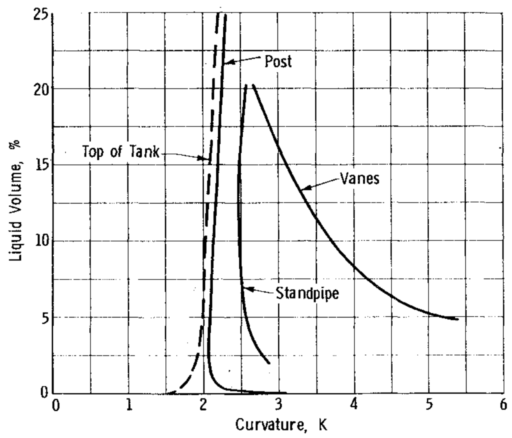

Fig. 8 Comparison of curvature for three devices at 5° contact angle.

Once the channel has filled, pressure is still not in equilibrium, so the liquid will flow about the sharp corners of the acquisition device. This capillary pumping of the liquid continues until the curvature, and therefore the pressure, is uniform everywhere.

Evaluation of the post device showed that a favorable capillary pressure differential will exist only if the contact angle is 2° or less. A device that has a greater effect on the curvature, such as a standpipe or vane device, would be suitable for use with liquids having much larger contact angles. Liquid interface curvature at the top of the tank is compared to that about the three devices at the tank outlet for a 5° contact angle (Fig. 8). The standpipe, with a diameter of 0.4 times the tank radius, will always have functional communication channels at this contact angle, i.e., the pressure about the device will always be less than the pressure of any displaced liquid. The vaned device will provide a much higher capillary pumping pressure. The curvature of the interface about the standpipe with vanes would be essentially the same as for the vane device except at low liquid volumes, where the standpipe would increase the curvature somewhat. This analysis indicates that unless contact angles very near to zero degrees can be guaranteed, communication channels will not always be functional with devices that do not significantly alter the curvature of the interface about the device. Conversely, a system, such as a standpipe with vanes, which has a high curvature will function properly over a wide range of contact angles (to 20° or more).

With the pressure differential between the ends of the communication channel established, the rate at which liquid will flow along the channel was determined using low Reynolds number, creeping flow equations. If all the liquid were displaced from the device, returning an amount equal to 5% of the tank volume would be adequate for engine start and settling the remainder. For the worst case Flox tank, the post would require 180 hr to transfer this quantity while a vaned device would reduce the time to 13 hr. Using four channels instead of one would reduce the time to about 3 hr. These results indicate that return of a significant amount of displaced liquid within a reasonable length of time is possible.

Comparative Evaluation

Acquisition System

Based on the information compiled in the preliminary design study, a comparative evaluation of the six remaining candidate acquisition concepts was performed and the best system for meeting the spacecraft and mission requirements was selected for further design study. This system was a standpipe with vanes, one of the Category C devices.

The evaluation process consisted of rating the ability of each candidate to satisfy various criteria that included both operational and assembly considerations. Following definition of the evaluation criteria, a weighting factor from 1 to 10 was assigned to each criterion where 1 is the least and 10 is most important. The resulting evaluation criteria and their corresponding weighting factors are listed in Table 1. The next step in this operations research process was to define rating factors for each candidate concept on a scale of 1 to 10, where 1 indicated the poorest and 10 the best compliance with each criterion. Finally, a figure of merit (FOM) was obtained by calculating individual rating-weighting factor products and summing the results for each concept.

The overall ranking with the accompanying FOM was: 1) standpipe with vanes (856); 2) vanes (812); 3) standpipe (762); 4) cruciform (509); 5) compartment tank (493); and 6) post with fingers (490). Strengths and weaknesses of the various candidate concepts are presented in Table 2.

Table 1 Evaluation criteria and weighting factors

Criterion	Weighting Factor
Operational considerations	
1) Gas-free liquid expulsion	10
2) Slosh control	7
3) Center of gravity control	8
4) Emergency pressure relief	9
5) Thermal gradient sensitivity	7
6) Pressurization sensitivity	8
7) Ground cooling integration	6
8) Operating flexibility	3
9) System flexibility	1
10) Relative development required	2
11) Relative weight	5
12) Relative reliability	10
13) Structural integrity	6
14) Loading and handling	4
15) Flight acceptance test constraints	2
Fabrication and assembly considerations	
1) Material limitations	3
2) Joining processes	3
3) Modular installation	7
4) Cleaning difficulty	5

Table 2 Comparison of candidate strengths and weaknesses

Concept	Strengths	Weaknesses
Compartmented tank	1) Good ullage control 2) Most development experience 3) Structurally sound	1) Lack flexibility 2) No modular installation 3) Sensitive to thermal effects 4) Lacks communication
Cruciform	1) Good communication 2) Easily manufactured & installed 3) Simple design	1) Lack ullage control 2) Poor slosh control 3) Liquid held up within device at low volume
Standpipe	1) High expulsion efficiency 2) High reliability 3) Easiest to manfacture & install 4) Structurally sound 5) Simple design	1) Poor ullage control 2) Poor slosh control
Post with Fingers	1) Lightweight 2) Minimum loading & handling problems 3) Easily installed	1) Lowest expulsion efficiency 2) Poor slosh control 3) Poor ullage control 4) Low liquid retention stability
Vanes	1) Stable liquid retention 2) Good ullage control 3) High expulsion ef- 4) High reliability	1) Complex design 2) Difficult to manufacture & install
Standpipe with vanes	1) Stable liquid retention 2) Highest expulsion efficiency 3) Good ullage control 4) High reliability	1) Complex design 2) Difficult to manufacture & install

Propellant Combination

The cryogenic space storable propellants considered, Flox, F_2, OF_2 and B_2H_6, have a strong influence on the design and fabrication of a spacecraft propulsion system in comparison to a system employing earth storables. Considering fabrication and assembly, selected materials must be compatible. The use of dissimilar materials within the tank is discouraged because this can increase the corrosion rate. All-welded fabrication is preferred; joints should not produce contaminant trap areas. Faying surfaces should be eliminated, and adequate clearance must be provided for cleaning and passivation. Stringent cleaning procedures must be used. External joints must be leak-tight.

The following apply to ground hold and launch operations. A clean and dry system is required for fluorine-based propellants. The propellant system must be passivated with gaseous fluorine before loading. Loading, transfer, and mating to the launch vehicle are all hazardous operations with fluorine propellants and stringent control is required. Any leakage is unacceptable. The vapor is too toxic to vent directly to the atmosphere; a charcoal burner should be employed. Cooling must be provided during ground hold due to the low storage temperature. Similar considerations apply to B_2H_6.

Additional factors apply to acquisition system design and mission operation. Cryogenic space storable propellants possess lower surface tension σ, interfact stability σ/ρ, and capillary pumping $\sigma \cos \theta/\mu$ characteristics than earth storables. The sensitivity of these parameters to temperature variations is also greater for the space storables. Since stability decreases with temperature, the device should be designed for the maximum propellant temperature. The opposite is true for capillary pumping capability, where viscosity enters, and the communication channels should be designed for the minimum propellant temperature. The contact angle θ between the propellants and the metals of construction is essentially zero if the propellant is uncontaminated and the metal surface is clean. More problems are usually encountered with the higher surface tension fuels.[10]

The thermal implications presented by cryogenic space storable propellants can be greater than with an earth-storable system. Heat rejection may be needed in space, depending on the mission, heat leaks, method of pressurization, etc. With fluorine propellants, the probability of venting is greater and is also more difficult. Reliable relief valves are not now available. Some work on rupture disks was completed.[11] As discussed previously, pressurization presents some difficulties. Flightweight valves and regulators are problems. A worst-case situation is presented by the fluorine-containing oxidizers.

System Design

Further analyses were conducted in support of the selected standpipe with vanes and a system design was performed. Evaluation of the interaction of the propellant acquisition system with the other spacecraft subsystems was also continued. Details concerning the materials of construction, fabrication and installation of the device, testing, cleaning, loading and handling, and mission operation were considered. A complete survey of available data on the compatibility of the propellants of interest with various material was conducted. The design handbook[12] was used to select materials that would be compatible with the highly reactive space storable propellants for a period of 10 years. The result is a preliminary design of the surface tension propellant acquisition system for the baseline Space Storable Propulsion Module and the Jupiter mission. The basic design of this Fruhof-type system, however, is applicable to most envisioned 3-axis stabilized interplanetary spacecraft.

Sketches of the designs for the oxidizer and fuel tanks are presented in Figs. 9 and 10, respectively. (Detailed drawings can be found in Ref. 2). The devices will provide gas-free propellant to the engine on demand and will not hinder operation of other spacecraft subsystems, i.e., vent, pressurization, thermal control, ACS. An attempt was made to provide a design that is compatible with a 10-year life

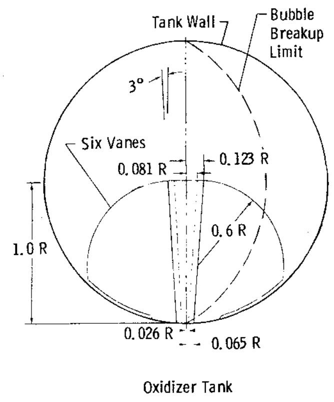

Fig. 9 Standpipe with vanes for oxidizer tank.

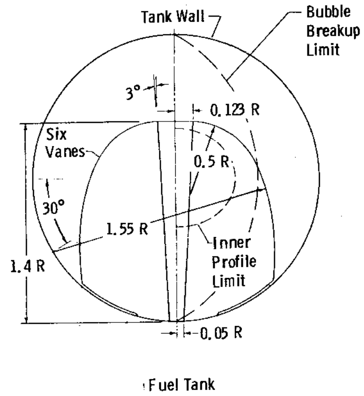

Fig. 10 Standpipe with vanes for fuel tank.

requirement and is capable of modular installation or removal through a 9-in. diam tank access port. A ground-hold cooling system was integrated into the design for the oxidizer tank propellant acquisition system.

Two alternative acquisition system designs were also accomplished for the oxidizer tank. (Detail drawings of these designs can also be found in Ref. 2). Rather than integrating the ground hold cooling system into the device, the coolant coils could be mounted on the internal tank wall. The cooling coils would be welded as part of the tank structure and would also serve as communication channels. The device, however, could still be modularly installed.

If the requirements for modular installation and internal cooling coils were not essential, the same device could be fabricated as an integral part of the propellant tanks. The device and the communication channel would both be welded to the tank wall during tank fabrication. This is the preferred approach from the standpoints of long life, F_2 compatibility, and acquisition system operation.

A height of $1.0R$, a 3° standpipe taper, and six vanes were selected for all three oxidizer tank designs. This provides good centering capability of the minimum 14% ullage which occurs at the maximum propellant temperature. In designing the primary and two alternate systems, emphasis was given to satisfying the fluorine-based propellant fabrication requirements of maximum system cleanliness with zero contaminant trap area joining processes.

The primary design satisfies the three major objectives of 1) modular installation; 2) ground-hold cooling integration; and 3) design for F_2 propellants. With a 2219 aluminum tank, all acquisition device components are constructed of aluminum alloys to avoid dissimular material problems. Rolling the vanes into a cylinder is used for device installation or removal with a special tool being employed. Vane thickness and material are dictated by the rolling requirement and the need to weld to the standpipe. Chemical milling from 0.063-in. plate is used to provice 0.009-in.-thick vanes. The vanes, standpipe, and communication channel are all constructed of 2219-T87 aluminum. The cooling capability is provided by a fusion-welded, hollow-wall standpipe through which LN_2 flows during ground hold. A mechanical attachment is used to join the standpipe to the tank access port cover. Internal volume of the standpipe is 0.24% of the tank volume, dictated by vane rolling requirements. The U-shaped communication channel is bolted to the tank at three points (equator and near poles).

In the first alternative oxidizer design the LN_2 cooling tubes were welded to the inner tank wall instead of being incorporated in the standpipe. Vane thickness was increased to 0.010 in. by reducing standpipe o.d. and internal volume of the standpipe was increased to 0.45% of tank volume. The cooling tubes also provide communication, eliminating the separate channel. This design is attractive in that long-life capability is improved by increasing vane thickness and eliminating the communication channel mechanical attachment. The cooling coil is constructed of one continuous loop of 6061-T6 aluminum tubing while 2219-T87 aluminim is again used for the standpipe and vanes.

The primary objective of the second alternative oxidizer design was to obtain the least complicated system having maximum fluorine-propellant compatibility. Joining was limited to welding, resulting in an internal device/tank assembly. An externally mounted, ground-hold cooling system is employed, improving both safety and reliability by reducing tank penetrations and eliminating propellant contact.[13] Both the vanes and the 0.45% volume standpipe are constructed of 6061-T6 aluminum because this alloy is easily welded and high strength is not required. With the need for vane rolling eliminated, thickness was increased to 0.061 in. This value resulted from trading device weight, propellant compatibility, and welding considerations. The vanes are made from rolled stock. The U-shaped communication channel is welded to tabs on the tank at three points. Since a structural alloy is required in cold-forming the channel, it is made of 2219-T87 aluminum. The vanes are welded to both the standpipe and the tank wall and a simplified tank outlet is employed. Tank closure is accomplished with a girth weld. Because of the simplicity and greater propellant compatibility, this design is preferred for the oxidizer. Contaminant trap areas are minimized, resulting in increased reliability and long-life capability.

Based on the maximum fuel temperature, the initial ullage could be as small as 3.5%, in comparison to the 5% ullage at the nominal temperature. A height of $1.4R$ was selected for the fuel design, shown in Fig. 10, to bias the centering of the 3.5% bubble. Again, six vanes were selected for the device and a standpipe with a 3° taper and a volume of 0.84% was chosen, considering both operation and modular installation (vane rolling). Ground-hold cooling is not required by the fuel. Like the oxidizer designs, the fuel design satisfies the mission structural requirements.

The objective of the fuel design was to provide modular installation with minimum impact on 6Al-4V titanium tank fabrication. Considering vane-rolling and compatibility requirements, 6Al-4V titanium was also used for the vanes, standpipe and communication channel. The standpipe/vane assembly is joined by brazing and is bolted to the tank access port. Bolts are also used to attach the communication channel to the tank inner wall. Following brazing, the 0.061- to 0.064-in. thick vanes are chemical milled to the final 0.011-in. thickness.

Three small longitudinal grooves, 120° apart, are included along the inside wall of the standpipe for all designs. This insures that any bubble trapped between two portions of liquid within the standpipe will be expelled. The taper provides a difference in curvature and the grooves act as communication channels.

Operation of the oxidizer tank design is summarized in Fig. 11, showing liquid orientation during the mission. Considerable flexibility is inherent in the concept which is applicable to most interplanetary missions. System complexity decreases as the initial ullage volume increases, e.g., a

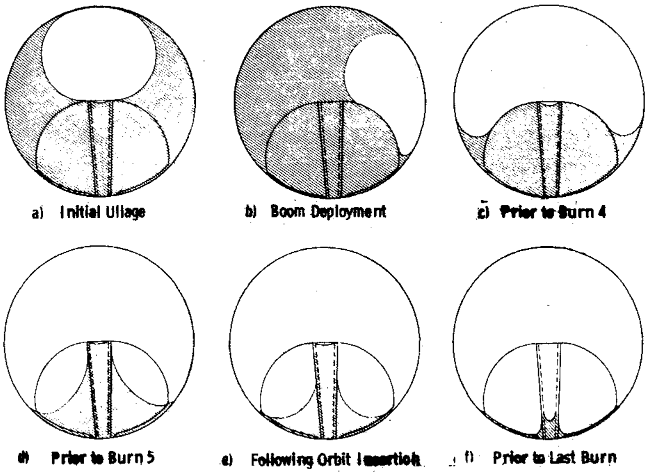

Fig. 11 Liquid orientation at various points in mission.

blowdown system. With the decreased height requirement, liquid will orient closer to the outlet. Increased stability is provided by increasing the number of vanes; a simple, triangular vane profile is adequate. For instance, liquid retention against $10^{-3}g$ can be provided in a 1-ft diam tank having 30% initial ullage.

The designs developed for the standpipe with vanes are applicable to both the Flox/MMH and F_2/N_2H_4 propellant combinations. Dimensions would be scaled according to tank size. Assuming that the spacecraft criteria would be essentially the same for an OF_2/B_2H_6 propulsion system, the same designs would apply to this propellant combination. Side-by-side tanks allow a 3-ft shorter envelope than in-line tanks; maximum c.m. shift is the same.

A device similar in concept to the one selected here, for use with earth storable propellants, has been designed, built and qualified, and will be flown on the Viking Orbiter in 1975.[6] This system uses N_2O_4/MMH earth-storable propellants.

Conclusions

Based on the analytical and experimental evaluations of a variety of candidate surface tension propellant acquisition concepts conducted under this program, the sheet-metal vane systems offer the best approach to a universal system for interplanetary spacecraft. These systems provide a wide operating band and can be tailored to specific applications with the desired operational margin. For the baseline spacecraft and mission requirements evaluated, the standpipe-with-vanes system is preferred for further design study.

Additional effort is necessitated by both fluid mechanics considerations and the use of space storable oxidizers, which present an order of magnitude increase in propellant acquisition difficulty over earth storables. Information is needed on the effect of both time and contaminants on propellant/tank system contact angle, and development of tank/acquisition system fabrication and assembly techniques is required.

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