Space Shuttle Reaction Control Subsystem Propellant Acquisition Technology

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In this supporting technology program, a surface tension propellant acquisition/expulsion configuration was selected for the Space Shuttle Reaction Control Subsystem tankage. The RCS requirements are unique and could not be met by existing tankage. The acquisition system must supply gas-free propellant at high flowrates during the low- and high-*g* operational environment (10^{-5}-3.3*g*) plus the numerous omnidirectional intermittent (pulse) demands of each mission. The high-*g* operations, boost abort and re-entry, have acceleration vectors separated by up to 119°. Candidate concepts to meet these stringent requirements were identified; this was followed by analysis and design sensitivity evaluations. A trade study resulted in the selection of a compartmented tank with individual flow channels as the preferred concept.

Introduction

THE Space Shuttle Orbiter employs three propulsion systems: the primary propulsion system, supplied by the External Tank, which accomplishes boost operations; the Orbital Maneuvering Subsystem (OMS) for the larger velocity changes in space; and the Reaction Control Subsystem (RCS). Docking maneuvers and attitude corrections while on-orbit and during the initial phase of re-entry are performed by the RCS. The RCS also augments the other propulsion systems during certain boost abort modes.

Passive surface tension propellant acquisition systems were baselined for both OMS and RCS applications due to reusability requirements. The acquisition system must provide 100-mission life with minimum servicing. Because RCS propellants must be supplied to the engines under a broad spectrum of conditions, extremely demanding requirements are placed on the propellant acquisition system. All-metal surface tension systems with their long-life, low-weight and high-reliability characteristics provide the best means of meeting these stringent requirements. A new design is required for this unique application, however. The purpose of this technology program is to select, design, fabricate, and test the surface tension device that will best accomplish propellant acquisition for the Space Shuttle RCS. Selection of the preferred concept is discussed in this paper.

RCS Description

The Orbiter RCS bipropellant propulsion system, using N_2O_4 and MMH, performs attitude control and small ΔV translational maneuvers. It consists of a single forward module and two aft modules, as depicted in Fig. 1. The forward module contains one oxidizer and one fuel tank and a pressurization system; it supplies a total of 22 thrusters (eight primary and three vernier on each side) in the nose of the Orbiter which are used for on-orbit operation only.

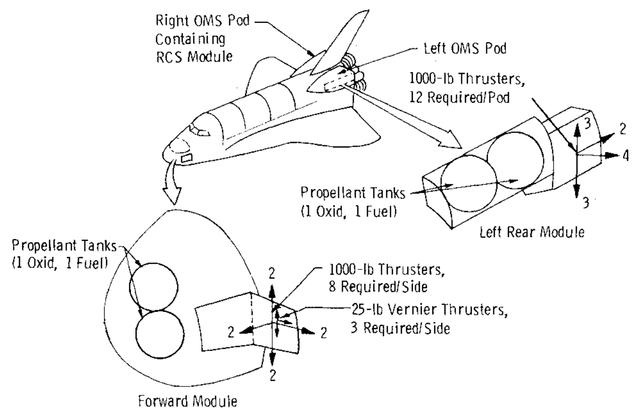

Fig. 1 Orbiter reaction control subsystem modules.

A total of 12 thrusters are supplied by each aft module at the rear of the Orbiter. These thrusters are used on-orbit, provide all RCS accelerations in the $+X$ direction, are used in the event of boost abort, and supply all RCS demands during re-entry. Each aft module also contains one oxidizer and one fuel tank.

Table 1 RCS tankage requirements

Tanks		
38-in. diam. spherical (16.63 ft^3)		
N_2O_4 and MMH ($MR = 1.65$)		
Temperature 40°F-125°F		
Flowrate/thruster (lb_m/sec)		
$N_2O_4 = 2.19$		
$MMH = 1.32$		
Tank pressure 280 ± 10 psia regulated helium		
Propellant loads (lb_m)		
	N_2O_4	MMH
Maximum	1343	840
Minimum		
forward	800	500
aft	880	550
Boost abort	463	290
Re-entry		
maximum	Full tank	Full tank
minimum	175	109

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Index categories: Liquid Rocket Engines; Spacecraft Attitude Dynamics and Control; Spacecraft Propulsion Systems Integration.

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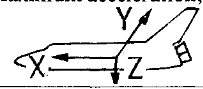
Table 2 Acceleration environment and RCS flow rate requirements



		Maximum acceleration, g			RCS flowrate, (lbm/sec)	
Mission phase	Acceleration source	X	Y	Z	N_2O_4	MMH
Boost						
normal insertion	Solid rocket motors Main engines	3.0	0	0.5	0	0
RTLS abort	Main engines, OMS, RCS	3.3	0	0.5	26.2	15.9
AOA abort	Main engines, OMS, RCS	3.0	0	0.5	4.4	2.7
On-orbit						
unpowered coast	Drag	-3.0×10^{-6} axial (0° angle of attack) -1.6×10^{-5} lateral (90° angle of attack)				
ΔV translation	OMS	0.077	0	0	0	0
random, omnidirectional maneuvers	RCS forward	+0.027 −0.035	0.231	0.231	21.9	13.2
	RCS aft	+0.047 −0.039	0.117	0.117	19.7	11.9
Re-entry	Aerodynamic drag	−0.68	0	−2.1	19.7	11.9

System and Mission Requirements

The basic requirement placed on the propellant acquisition system is that it provide gas-free propellant to the thruster as required throughout the operational mission, which includes normal boost operations, boost abort, on-orbit operation, and re-entry. The Space Shuttle concept places emphasis on reusability; the acquisition device for the RCS must provide 100-mission life over a 10-year period with minimum servicing. Man-rated reliability must be maintained. Also, the propellant acquisition device must be compatible with operations involved in servicing the orbiter before and after each flight. Loading of the tanks will occur when the orbiter is vertical, but the tanks must be capable of being drained in either the vertical or horizontal orientation.

A description of the RCS tankage requirements is presented in Table 1 and maximum expected flowrates and accelerations, due to all sources, are listed in Table 2. A specific mission duty cycle was not specified for the RCS due to the diverse acceleration/flowrate requirements of each mission, including boost abort and re-entry. Worst-case values were used for this reason. The random, omnidirectional accelerations produced on-orbit were obtained by assuming the maximum number of possible thrusters firing with a minimum Orbiter mass of 156,000 lb.

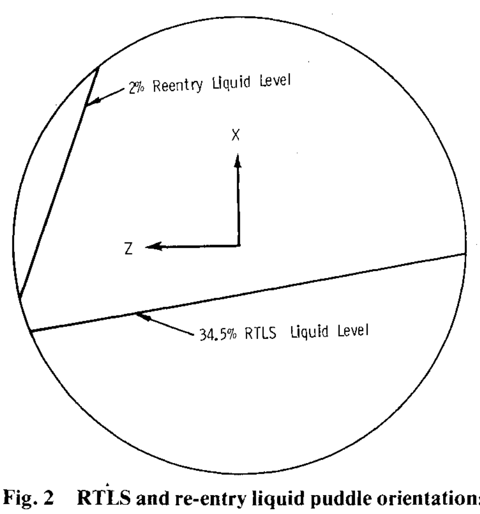


Fig. 2 RTLS and re-entry liquid puddle orientations.

RCS operation is not required during a normal boost sequence. However, all aft module engines are fired during the return-to-launch site (RTLS) boost abort operations to deplete all but 750 lb_m of propellant (463 lb_m oxidizer, 290 lb_m fuel as noted in Table 1) which is required for re-entry. Only the $+X$ thrusters on the aft pads are burned during abort-once-around (AOA) to help the orbiter achieve orbit. This is the abort mode used during later phases of boost operation. RTLS abort imposes the worst conditions of high outflow rates and accelerations up to 3.3 g. Re-entry imposes another high-g, high outflow condition which tends to conflict with the RTLS requirements, having an acceleration vector up to 119° from the RTLS vector. The propellant required for re-entry is between 13 and 34.5% of the tank capacity, depending on the particular mission and trajectory flown, and high expulsion efficiency is desired. Further, re-entry must be accomplished without relying on surface tension acquisition when accelerations are greater than 0.05g. RTLS and re-entry liquid orientations are shown in Fig. 2 to display the difficulty of locating a tank outlet with the high-g vectors separated by up to 119°. The most desirable location for the outlet is toward the $+Z$ side of the tank at the edge of both puddles. High outflow rates are required at relatively high acceleration levels during on-orbit operations (Table 2). In addition, the OMS engines produce random vibrations of 1.93 g RMS which act on the aft RCS tanks. If one OMS engine fails, four aft RCS thrusters will be operated to maintain orbiter attitude while using the remaining OMS engine.

Candidate Systems

Fine-mesh screen surface tension devices utilize liquid surface tension and ullage pressure to passively provide gas-free liquid expulsion on demand. The surface tension of the liquid stabilizes the liquid/vapor interface at the screen pores and the ullage pressure supports the liquid in the controlled region. The screen retention capability or pressure differential which can be supported across the wetted screen pores is commonly termed the screen "bubble point." This is the pressure differential at which gas just begins to bubble through the screen. The situation when the bubble point is exceeded and gas begins to enter the controlled liquid region is known as screen "breakdown."

The screen retention capability ΔP_c or bubble point BP must offset all pressure differentials involved in the flowing system in order to prevent gas ingestion

$$\Delta P_c = BP \geq \Delta P_h + \Delta P_e + \Delta P_v + \Delta P_f + \Delta P_t$$

where ΔP_h = hydrostatic head supported by the screen system, ΔP_e = entrance loss due to flow through the screen into the flow annulus, ΔP_v = change from pressure head to velocity head, ΔP_f = friction loss due to flow in annulus, ΔP_t = transient losses due to vibration, pulsed flow, etc. For more detailed description of the theory and design considerations for surface tension systems see Ref. 1.

The relatively high acceleration levels coupled with the 38-in. diam tanks produce large hydrostatic heads. The high flowrates tend to result in high viscous losses, and transients add to the total system ΔP. The retention capability provided by fine-mesh screen is needed to meet these ΔP requirements and provice high expulsion efficiency.

Screen devices fall into two general categories: 1) propellant reservoirs (traps) which hold a supply of propellant at the tank outlet and depend on propellant settling over the device to continue feeding gas-free liquid; and (2) total communication devices which always contact the bulk propellant, regardless of its location, and provide a flow path to the outlet. Because of the omnidirectional nature of the on-orbit accelerations, variations in the total communication concept were considered as candidates for RCS application.

Total Communication Devices

A screen liner concentric with the tank wall forms the basic device (Fig. 3). The annular gap, formed by the screen and the tank wall, is kept full of liquid and acts as a flow passage to transfer propellant from the bulk region to the tank outlet. When the volume of liquid in the tank is small, the screen must be capable of supporting the hydrostatic head, maintaining the annulus full of liquid. While this is not a problem in the relatively low-*g* environment on-orbit, the accelerations experienced during boost with a partial propellant load, pose a problem. As shown in Fig. 4, a single layer of the finest mesh screen cannot retain the liquid under such conditions, and some means of increasing the retention capability of the liner device is needed.

It has been shown[2] that screens can be layered to increase their retention capability such that the bubble point increases directly with the number of screen layers. Another method is to add a gas buffer annulus[1] between the liquid flow annulus and the bulk liquid region by spacing the screens apart to decrease the number of screen layers required (Fig. 5). The device is not stable under a high, steady acceleration and the buffer annulus ingests (and traps) gas at a finite rate. After some period of time, the flow annulus breaks down and gas is ingested from the gas buffer annulus. During this time interval which can be composed of one or more increments, however, the gas buffer protects the flow annulus from gas ingestion with only liquid feeding into the flow annulus. The time interval can range from seconds to minutes depending on system geometry, acceleration level and flowrate. A combination of screen layers and a gas buffer annulus is also possible. Details of these systems are beyond the scope of the paper, see Ref. 1.

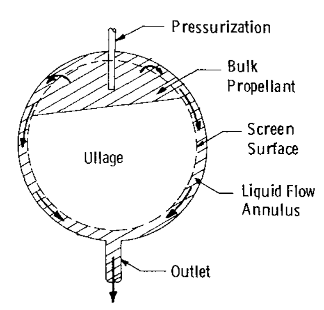


Fig. 3 Total communication device.

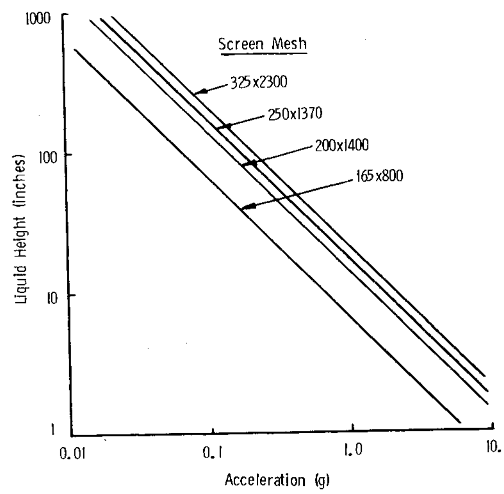


Fig. 4 Retention capability of various screen meshes with N_2O_4.

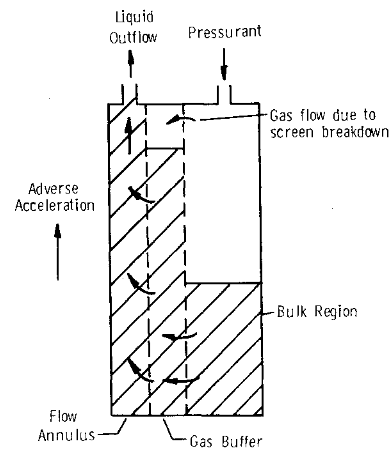


Fig. 5 Gas buffer system.

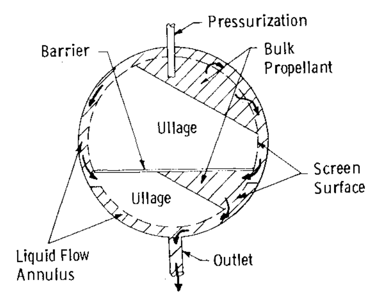


Fig. 6 Compartmented tank device.

Compartmented Tank Devices

If barriers are added to a total communication device, the tank is divided into compartments (Fig. 6). The compartments feed from one to another, bringing the propellant to the tank outlet. By adding the barriers, the length of the annulus and resultant hydrostatic heads are reduced, making it easier to retain liquid in a high-*g* environment (Fig. 4). The number of barriers used and the relative size of the compartments are variables in the design.

Variations to the Concepts

Numerous variations exist in the total communication and compartmented tank devices. The liquid flow annulus can be formed by either a complete or partial screen liner. A partial liner is usually composed of screen-and-plate flow channels connected to the tank outlet. These channels can be positioned along the tank wall, through the center of the tank, or on the barriers of a compartmented tank device. Their cross-section is usually rectangular and one or more of the surfaces is formed by fine-mesh screen. Variables include the number and size of channels and location of the tank outlet with respect to the vehicle coordinate axes. There are many other more subtle variations such as variable channel geometry, addition of bubble filters and tailoring to mission details that can be considered in the final design of a surface tension device; however, these variations do not significantly impact the selection of the best overall concept.

Concept Analysis

Numerous candidate concepts were analyzed to provide comparative information for selection of the best concept. In general, a channel system provided advantages over a full liner because a liner is heavier and retains a larger volume of residual liquid at tank depletion (lower expulsion efficiency) than the channels.

Since the properties of the fuel and oxidizer are different, the performance of a given surface tension device will vary with the propellant. A device designed for the fuel could be different than one designed for the oxidizer, e.g., different screen mesh size and different annulus flow area. After analyzing the candidate concepts, it was found that there was little difference between fuel and oxidizer performance for this application, however. Commonality of design for the foward and aft tanks was another consideration. Since the forward RCS thrusters are not operational during RTLS or re-entry while the aft thrusters are, a somewhat simplified device could be used in the forward tanks. Again, the slight improvement in performance would not warrant the cost of developing and qualifying two different surface tension devices. As a result, the same device should be used in all six tanks, forward and aft, fuel and oxidizer, of the RCS.

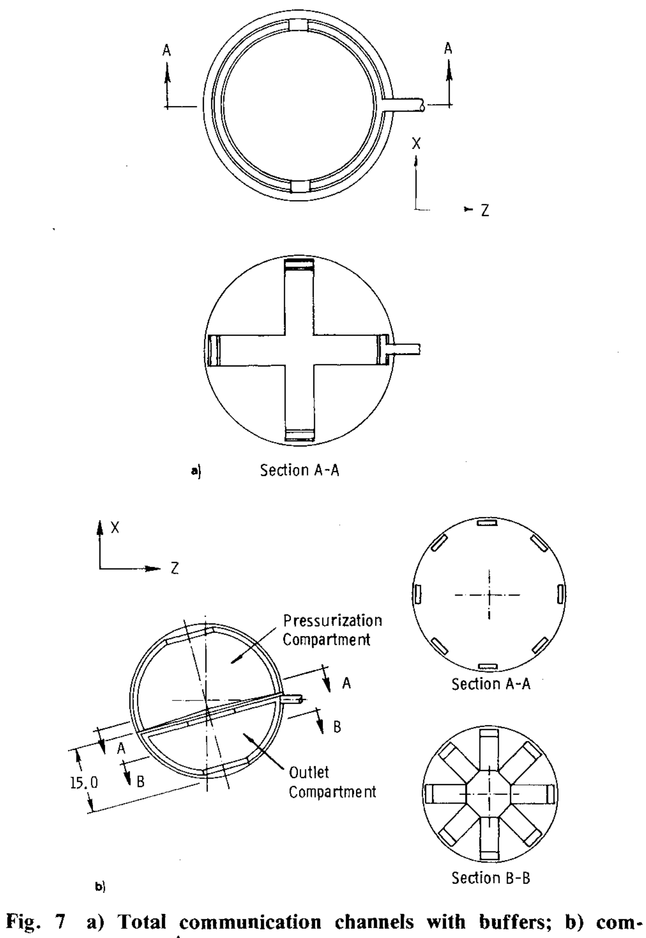


Fig. 7 a) Total communication channels with buffers; b) compartmented tank device.

Two concepts, illustrated in Fig. 7, were selected for further evaluation. These were the total communication device composed of channels with gas buffers and the compartmented tank device using channels in both compartments. For both concepts, the outlet was positioned on the $+Z$ axis in the re-entry puddle.

The primary advantage of a total communication device, is that it maintains direct contact with the bulk propellant. Buffers are preferred as the means of increasing the retention capability of the flow annulus since fewer layers of screen are required. Just stacking screen layers to provide stability against the highest accelerations results in more screen layers and a system which is more costly. The buffer enables the flow channels to remain stable, full of liquid, throughout the boost phase of the mission, including the abort modes. The capability exceeds that required on orbit considering combined acceleration, vibration and flow effects. During re-entry, the propellant is positioned over the outlet so that it will feed independent of the surface tension device.

The boost phase imposes the most stringent requirements on the channel with gas buffer systems, especially the aft tanks. The system must remain stable under the high boost acceleration with off-loaded tanks and must supply propellant during the aborts. It is this phase that establishes the mesh size of the screen material and the number of screen layers required on the flow annulus and on the gas buffer annulus (high ΔP_h and moderate flow losses). Conversely, on-orbit operation determines the channel flow area and geometry (aspect ratio) required for high expulsion efficiency with the high outflow rates at tank depletion during this mission phase (very high ΔP_e with other losses moderate). Re-entry has a lesser impact since the tank outlet can be positioned so as to take advantage of the propellant orientation; gas pull-through into the outlet must be precluded, however.

For the compartmented device, a single barrier divides the tank into two compartments, designated the pressurization and outlet compartments. A tank with three or more compartments was eliminated because of increased cost and mass and reduced expulsion efficiency. The outlet compartment is located at the aft end of the tank since a forward outlet complicated the structure, fill and drain was more diffucult, and expulsion efficiency was lower. Propellant is fed through the channels of the pressurization compartment to the bulk region of the outlet compartment. From here, it flows into the channels of the outlet compartment to the tank outlet. With this arrangement, the channels of the pressurization compartment can feed two-phase fluid to the outlet compartment. The only requirement is that the pressurization compartment be depleted prior to the outlet compartment, so that no liquid will be left behind in the pressurization compartment. This is required to maximize the on-orbit expulsion efficiency of the forward module.

A single layer of screen was baselined for all components of the compartmented device due to structural design and fabrication, mass, cleaning, and reliability considerations. With this approach, the upper channels break down during boost, but the ingested gas will be purged into the bulk region of the outlet compartment once outflow is initiated. Since the channels in the lower compartment must remain stable and supply gas-free propellant to tank depletion, they must be protected from the combined boost (or RTLS) acceleration and vibration. This was accommodated by locating the barrier at the RTLS burn-down level (34.5% of load). In this manner, the outlet compartment is submerged during boost with minimum load and during abort. With the selected configuration, propellant is settled over the outlet during re-entry.

A prime factor in obtaining high on-orbit expulsion efficiency with the compartmented device is the minimizing of propellant residual in the pressurization compartment. A near-zero residual is possible because even after breakdown the pressurization compartment channels continue to

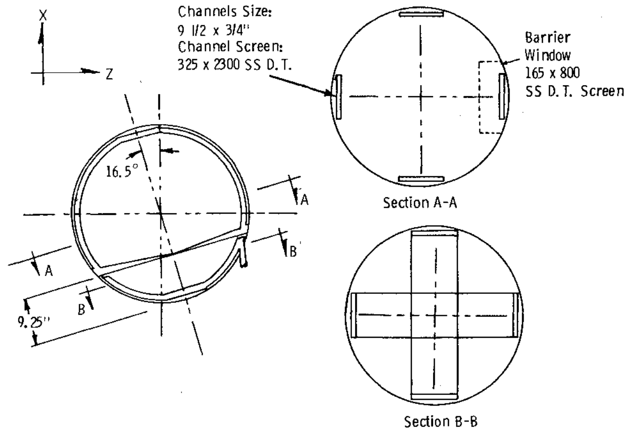


Fig. 8 Selected compartmented tank concept.

scavenge propellant, transferring a gas-liquid mixture to the outlet compartment.

The barrier location, and therefore, the relative volumes of the two compartments, is a significant factor influencing the needed capability to deplete the pressurization compartment prior to the outlet compartment. The average liquid quality that must pass through the barrier over the entire mission to insure that both compartments are depleted simultaneously is reduced as the barrier is raised (outlet compartment volume increased). The quality will be near 100% throughout most of the mission. After the screens in the pressurization compartment break down, the quality will begin to decrease. With the barrier located to provide 34.5% of propellant load in the outlet compartment, an average quality of only 60% is required. This should be easily attained, based on preliminary assessment.

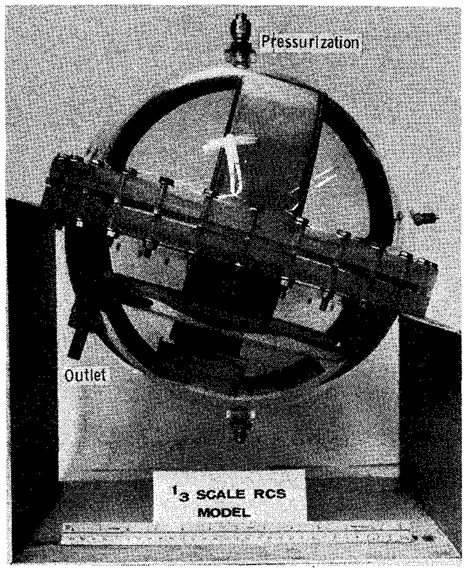


Fig. 9 Verification test model.

Since the pressurization compartment channels are allowed to break down during boost, this mission phase does not present the worst conditions for the compartmented device. On-orbit operation becomes the driver for determining screen mesh and channel area and geometry.

A computer model was developed to aid in concept analysis. It considers the tank and device geometry, acceleration environment and propellant outflow rate in determining the performance of a surface tension propellant acquisition system. Screen mesh, channel size and number of

Table 3 Device parameters

			Number of Screen Layers			Weight, lbm				
Design	Tank location	Number of channels	Channel	Buffer	Channel size, in.	Dry	Wet (N_2O_4)	Wet (MMH)	Explusion efficiency, %	Volumetric efficiency, %
Channels with	Forward	4	2	2	5.0×1.0	20.5	113.5	72.6	93.8	99.7
buffers	Aft	4	2	2	5.0×1.0	20.5	26.0	23.9	99.6	99.7
Compartmented	Forward	8	1	...	5.25×0.7	27.2	87.6	65.0	95.5	99.7
device	Aft	8	1	...	5.25×0.7	27.2	32.6	30.6	99.6	99.7

Table 4 Evaluation of concepts

		Rating		Figure of merit	
Evaluation factors	Weighting	Channels with buffers	Compartmented device	Channels with buffers	Compartmented device
Flexibility					
mission duty cycle	5	5	4	25	20
offloading, boost abort	4	4	5	16	20
Performance					
gas-free liquid on demand	5	5	5	25	25
expulsion efficiency	5	3	5	15	25
volumetric efficiency	2	5	5	10	10
System mass	5	5	4	25	20
Structural design & fab	4	4	5	16	20
Reliability	5	4	5	20	25
Compatibility	3	4	5	12	15
Loading and handling	4	3	5	12	20
Reusability	3	5	5	15	15
Development status	1	5	5	5	5
Cost	3	4	5	12	15
			Overall figure of merit	208	235

channels were evaluated to optimize the expulsion efficiency of the device while keeping weight to a minimum. The configuration of the device and the calculated parameters are listed in Table 3 for both forward and aft tanks. Both devices use 325×2300 Dutch-twill weave screen, since it was found to provide the highest expulsion efficiencies. Coarser mesh screens with their lower retention capability, result in a lower expulsion efficiency for this application. A design safety factor of 1.5 on screen bubble point was used in the analysis.

Concept Selection

Important factors influencing the development, fabrication and operation of the acquisition system were identified and used in the selection process. Each candidate device was evaluated with respect to the other (rating), considering each evaluation factor and its relative importance (weighting). This previously used technique[3,4] is summarized in Table 4. The concept comparison shows that the compartmented device is more sensitive to variations in mission duty cycle but can better accommodate offloading and boost abort. The total communication channel with buffer system must use two layers of screen on both the channel flow annulus and gas buffer annulus, which increases its cost, makes it more difficult to fabricate, clean, fill and inspect, and reduces its reliability.

The evaluation indicates that, while the two devices are both capable of meeting the RCS requirements, the compartmented tank device is the preferred system.

Following selection of the preferred concept, the computer model was used to perform further design analysis, resulting in the modified configuration shown in Fig. 8. It was found that an improved expulsion efficiency, with a significant weight savings, was obtained using four narrow cross-section channels. A minimum expulsion efficiency of 98% for an aft tank and 95% for a forward tank were predicted, based on the worse case accelerations and flow rates. Weight of the device was reduced to approximately 19 lb_m in going from eight to four channels.

The channels of the pressurization compartment are manifolded above the barrier and feed through a single barrier penetration to the outlet compartment. This opening or window in the barrier is kept small such that little hydrostatic head is imposed by the on-orbit acceleration. Yet, it is large enough to impose little loss (ΔP_e) during outflow. A coarser mesh screen (165×800) is used to minimize flow resistance and still provide sufficient support. In combination, the barrier window and the tank outlet permit the tank to be expelled during re-entry, independent of the surface tension device. The re-entry accelerations position or puddle the propellant toward the $+Z$, outlet side of the tank and tank pressurization causes the propellant to be transferred through the screen window to the outlet.

The development of this surface tension device continued under the technology program. Additional analysis, using the computer model, and tests, using subscale models to verify its operation, were conducted. These verification tests included fill and drain, expulsion, inspection and ground handling, pulsed-flow, slosh, centrifuge, and vibration evaluations. The 1/3-scale model used in this assessment is shown in Fig. 9. Results from this test activity were incorporated into detailed designs for full-scale ground test and flightweight hardware. A full-scale device and tank was built and tested with propellants to verify ground operations such as fill, drain, cleaning, and inspection. This design verification and ground demonstration program will be covered in a subsequent paper.

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