Design and Development of a Passive Propellant Management System

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This paper describes the design, fabrication, and verification of a passive propellant management system. The objectives were to design and develop a hydrazine propellant acquisition system which will acquire propellant in low- or zero-*g* environments and also retain this propellant under high axially directed accelerations that may be experienced during launch and orbit-to-orbit transfer. The system design requirements were established to generally satisfy requirements for a large number of potential NASA and military applications such as orbit-to-orbit shuttles and satellite vehicles. The resulting concept is a multicompartmented tank with independent surface tension acquisition channels in each compartment. The tank is designed to provide greater than 98% expulsion efficiency when subjected to the simultaneous requirements of acceleration, vibration, and outflow usage. The system design has the unique capability to demonstrate low-*g* performance in a 1-*g* test environment and the test program was structured around this capability. The performance of the system was verified by test.

Introduction

ORBITING space vehicles require propulsion systems with propellant acquisition devices which provide a continuous liquid propellant supply to the attitude control and/or maneuvering thrusters in on-orbit acceleration environments. The Space Shuttle will service many of these propulsion systems in orbit, and, to be compatible with these operations, the acquisition device must be reusable. Definition of system requirements and development of a reusable acquisition system design with versatility in terms of its applicability to future spacecraft was a key issue in this effort.

Many spacecraft provide propellant acquisition with positive expulsion devices primarily by the use of bladder-type tanks. Bladder-type tanks were used on the Mercury, Gemini, and Apollo spacecraft and on many unmanned satellites. Because of cost considerations it is desirable to reuse these systems, and the Space Shuttle will provide the opportunity to utilize that capability. With the advent of the Space Shuttle and its related capabilities of resupply, repair/refurbishment, and replacement, orbiting spacecraft propulsion systems can be reused and thereby reduce costs. Typically the bladder acquisition tank will be the component limiting the propulsion system reusability for Space Shuttle payloads. For bipropellant systems the only bladder material compatible with nitrogen tetroxide is teflon, which has a severely limited cycle life. The requirement for multiple-use propulsion systems dictates the use of acquisition systems which are passive; have no moving parts, and are thus not life limited. Candidate systems include surface tension and/or capillary propellant acquisition devices. These have been employed in the past for some space vehicles, however, each design was customized for its particular application. To satisfy the requirement for up to 100 reuses, the Space Shuttle Orbiter will use surface-tension-type acquisition devices to supply propellants for both maneuvering (OMS) and attitude control (RCS) propulsion systems. These acquisition systems are optimized for their particular requirements. The thrust of this effort was to develop a configuration which has the versatility to be used for various space transportation system applications, not be life limited, and utilize the existing experience of reusable acquisition systems. Further design requirements were to develop a configuration which is simple and relatively inexpensive to fabricate.

The passive propellant management system (PPMS) configuration defined to satisfy these requirements is shown in Fig. 1. It is a compartmented, spherical tank separated into two equal volume compartments by a flat bulkhead mounted between the tank halves. Each compartment has four similar screened galleries located in the principal vehicle axes. This assures that bulk propellant will contact at least one gallery during vehicle maneuvers. The forward compartment galleries collect propellant and feed it into the aft compartment through the communication screens which protrude into the aft compartment. This propellant is then collected by the screened galleries in the aft compartment and supplied to the propellant outlet.

The acquisition system requirements for advanced spacecraft were defined and system design requirements selected which encompassed the requirements of reusable and nonreusable spacecraft. With these requirements, various concepts were investigated for applicability and led to definition of the selected concept which could satisfy all reusable system requirements. This system was then designed, its operation defined, and performance estimated. The system was fabricated and acceptance tested by in-tank bubble point

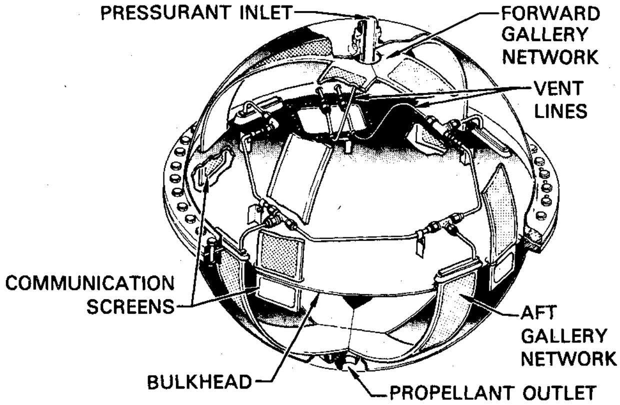

Fig. 1 Passive propellant management system.

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Table 1 Candidate spacecraft and expulsion environments

Spacecraft	Weight,[a] lb_m	Acceleration, g	Maximum N_2H_4 flow rate, lb_m/s	Random vibration power spectral density at 60 Hz, g^2/Hz	Response acceleration, g_{rms}	Reusable
Space Tug	5755	2.61	1.18	15×10^{-4}	0.84	Yes
Interim upper stage (IUS)	10,704	4.25	0.48	8×10^{-4}	0.61	No
Multimission	2000	0.093	0.91	...	...	Yes
Space test program standard spacecraft	1510	0.19	1.39	0.33×10^{-4}	0.125	No
Laser communication satellite (LCS)	1400	0.02	0.11	...	...	No
Space infrared radiation experiment (SIRE)	2000	0.003	0.004	...	...	No
High-altitude large optics (HALO)	2500	0.002	0.004	...	...	No

[a] Weight at maximum vehicle acceleration.

verification. The performance verification testing described herein was completed in Nov. 1977.

Design Requirements

The advanced spacecraft investigated to define acquisition system requirements and the design environments for each are shown in Table 1. The primary factors influencing design are: acceleration, vibration, propellant outflow rate, and the propellant type. Monopropellant hydrazine was selected as the propellant because of extensive usage in spacecraft propulsion systems. The acceleration vectors imposed on the system represent the primary design requirement and dictate capillary or screen size in conjunction with tank compartment size. The screened acquisition device can satisfy the acceleration requirements of all the reusable spacecraft investigated as shown in Fig. 2. Because the Space Tug requirements were the best defined at program initiation and represented the highest on-orbit acceleration requirements for a reusable system, it was selected as the baseline to define system requirements. These and other system design requirements are shown in Table 2.

The maximum vibration levels that exist after the spacecraft has separated from the launch vehicle occur during spacecraft main engine firing. This orbital vibration environment is a complex function of engine thrust, vehicle mass, and location in relation to the engine. For design purposes a level equal to the Apollo SPS vibrational environment was used. This environment (Fig. 3) was measured on the aft bulkhead adjacent to the engine. Shown for comparison in Fig. 3 are the Space Shuttle OMS and RCS tank design vibration environments. These vibration environments are lower in relation to the Apollo SPS because the thrust is lower, the vehicle mass higher, and the tanks are located further from the engine. The RCS tank is located forward of the OMS tank and would approximate the location of the hydrazine tank in the Space Tug. The use of the more severe Apollo SPS environment provides a more versatile design, which is also adaptable to other space vehicle requirements. Other requirements and/or criteria not specifically defined by the candidate vehicles but which were applied to the PPMS are to provide for 1) vertical fill and drain, 2) gaging installation, 3) verification of installed acquisition assembly, 4) interconnection of multiple tanks, 5) flow transients, and 6) launch or refill with a partial propellant load.

Analysis and Concept Definition

The candidate acquisition assembly concepts considered for the PPMS were capillary pumping, refillable trap, and full and compartmented tank surface tension devices. These concepts are shown in Fig. 4.

Capillary pumping devices require closely spaced surfaces which reduce the propellant radius of curvature and pump propellant into the device. Capillary pumping devices were considered impractical for this application because of fabrication difficulties. The tolerance control of closely spaced surfaces required to satisfy the high acceleration environment (<0.01 in.) was not considered economically achievable.

A refillable trap does not allow mission flexibility since high acceleration is required at definite intervals to replenish the trapped propellant which had been used during the low-g periods. Although high-g acceleration environments occur with orbit transfer vehicles, their scheduling is indefinite and would severely limit system versatility. The sacrifice of mission flexibility was inconsistent with program goals, and the refillable trap system was also eliminated from consideration.

Figure 5, relating vehicle acceleration, hydrazine properties, screen containment capability, and hydrazine column height was used for assessment of the full tank gallery, full tank liner, and series gallery acquisition concepts. The finest screen in common usage is the 325×2300 mesh twill dutch double weave (TDDW) which is used in Space Shuttle tank applications. With a 22.5-in.-diameter tank at the required 3.3 g, the hydrostatic head alone exceeds the ideal containment capability of 325×2300 TDDW screen. Thus, full tank acquisition concepts would require multilayer screen. This would significantly increase fabrication difficulty and was considered inconsistent with the goals of simplicity and inexpensive fabrication.

The series gallery approach in a compartmented tank reduces the effective liquid column height such that requirements can be satisfied with a single layer screen. Hydrazine liquid columns for an equally compartmented tank

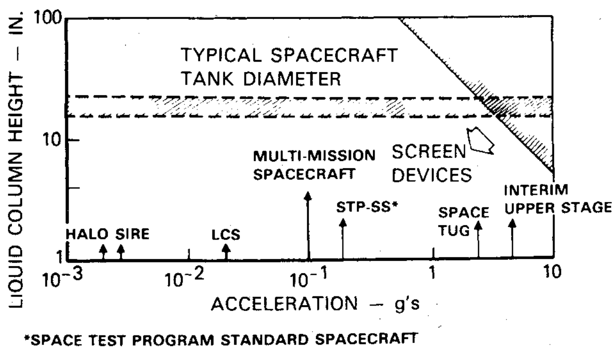

Fig. 2 Acquisition device retention capabilities.

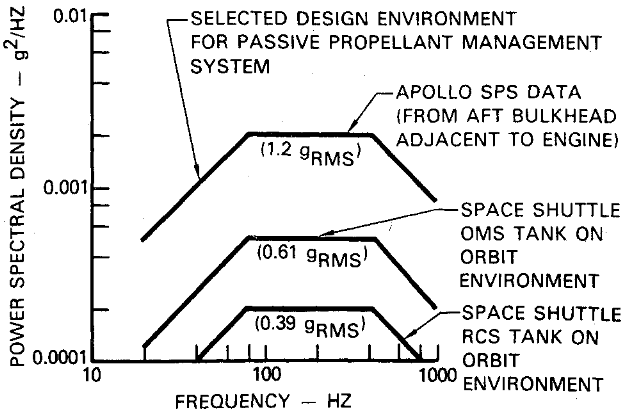

Fig. 3 On-orbit random vibration.

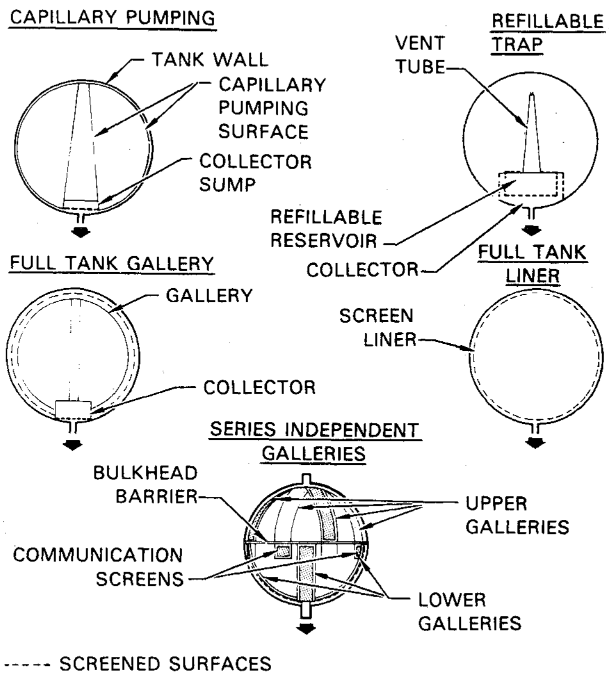

Fig. 4 Candidate acquisition concepts.

Table 2 General design requirements

Item	Requirement
Propellant	Hydrazine as per MIL D-26536 C, dated May 23, 1969
Operating pressure	360 psia
Propellant quantity,	
Minimum	3300 in^3
Maximum	5600 in^3
Propellant flowrate,	
Minimum	0.118 lb/s
Maximum	1.18 lb/s
Expulsion efficiency,	
Minimum	98%
Service life,	
Minimum	50 mission cycles
Flight temperature environment	+40°F to +175°F
Flight acceleration environment,	
On orbit, maximum	$3.3\,g+X$ axis $0.035\,g-X$ axis pitch $0.0009\,g$ yaw $0.0053\,g$ roll $0.015\,g$ drag $1\times10^{-4}g$

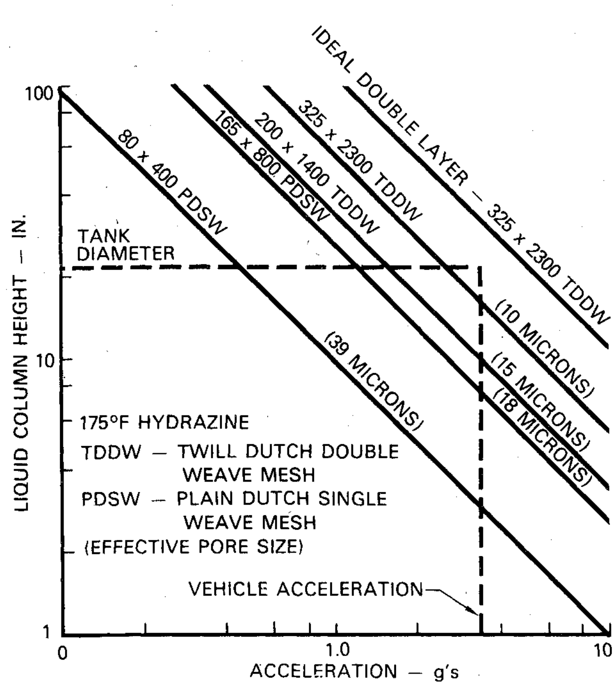

Fig. 5 Hydrazine screen retention capability.

with two independent gallery assemblies would be approximately 11-in. Figure 5 shows that with this liquid height and 3.3-g acceleration, 325×2300 TDDW screen containment capability is adequate. This design also allows low-g testing to be accomplished in 1 g by proper tank orientation. This configuration (shown in Fig. 1) was selected for detailed design. It satisfies all requirements, provides mission duty cycle flexibility, and is within the state-of-the-art of surface tension screen systems.[1-3]

Design and Performance

The passive propellant management system uses two independent gallery assemblies to acquire propellant through screens located on the outer surface of each gallery leg. A flat internal bulkhead divides the tank into two compartments. The forward and aft gallery networks are assemblied to this bulkhead as shown in Fig. 1.

The forward galleries acquire propellant from the forward tank compartment to replenish the aft compartment on a one-for-one basis. After the forward tank compartment is depleted, outflow continues from the aft compartment until the aft galleries break down. Communication between tank compartments is provided by the screens located in the lower end of each forward gallery channel. These protrude through the internal bulkhead into the aft compartment. These communication screens are the only flow path between the forward and aft tank compartments. The forward gallery network is manifolded near the pressurant inlet and welded to the internal bulkhead.

The aft compartment propellant is expelled from the tank by the aft gallery network consisting of four screened channels which are manifolded at the tank outlet. Each aft gallery leg is welded to the internal bulkhead and the aft gallery manifold is connected to the propellant feedline by a 1.0-in.-diameter outlet tube.

Vent lines for filling are routed to the forward and aft gallery networks and the aft compartment ullage. The forward compartment is vented through the pressurization inlet. These vent lines are required for complete loading of the propellant tank galleries and for in-tank verification of the acquisition assembly capillary retention capability during system acceptance tests and maintenance checks.

All forward and aft gallery screens and communication screens are 304L stainless steel, 325×2300 wires per inch

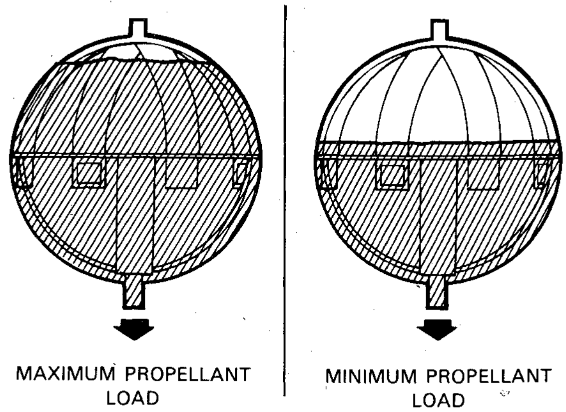

Fig. 6 Propellant load levels.

(TDDW). The communication screens are mounted on both the interior and exterior of the gallery legs to minimize the pressure differential across the bulkhead. The flow area of these communication screens determine the bulkhead pressure differential, and they have been sized to produce a maximum of 4.4 psid.

The flat internal bulkhead location was determined to satisfy the off loading requirement and the high axial acceleration. The internal bulkhead also serves as a mounting plate for the forward and aft gallery networks and vent lines. All eight gallery legs are welded to the bulkhead through intermediate gallery pans. These pans are used to increase the screen surface of each gallery so that if propellant is oriented in the minus or plus X directions at tank depletion, residuals will meet the 98% expulsion efficiency requirement. The pans are sized to insure that the welding operation will not affect the screen pore size or screen to frame weld. The gallery vent lines are welded into the galleries and attached to the bulkhead by stainless steel brackets and clamps. A bulkhead access panel is used to mate the vent lines with the flange ports during tank assembly.

Figure 6 depicts the maximum and minimum initial propellant loads. For loading, the propellant tank is completely filled in the vertical position and then drained to the level required for mission propellant usage. Complete filling insures the initial wetting of the acquisition screens. The tank is never off loaded below the internal bulkhead level so that the aft gallery network is completely covered and filled during launch. The forward gallery network is allowed to break down during launch environments. This may allow two-phase flow out of the forward compartment during initial propellant usage, but since the aft compartment galleries are separate, the gas thus entrained cannot be supplied to the engines. After this initial purging into the bulk region of the aft compartment, the flow from the upper galleries will be completely liquid until depletion of the forward compartment. Once the forward compartment has been depleted, the communication screens will break down and dry out during further usage. However, when the propellant in the aft compartment is reoriented during subsequent maneuvering or zero-g periods the screens rewet and prevent back flow into the upper compartment. Gas free propellant flow to the engines will continue from the aft compartment throughout usage.

Figure 7 defines the propellant orientations under the operating mission phases: launch, $\pm X$ translation, transverse acceleration, and zero gravity propellant orientation. For launch, the propulsion system is quiescent and there are no outflow requirements. As discussed previously, the aft compartment galleries are covered by propellant during this phase so that the gallery's screen is not exposed to the launch environments. For $+X$ axial acceleration, the propellant is oriented over the outlet. Propellant is supplied through the

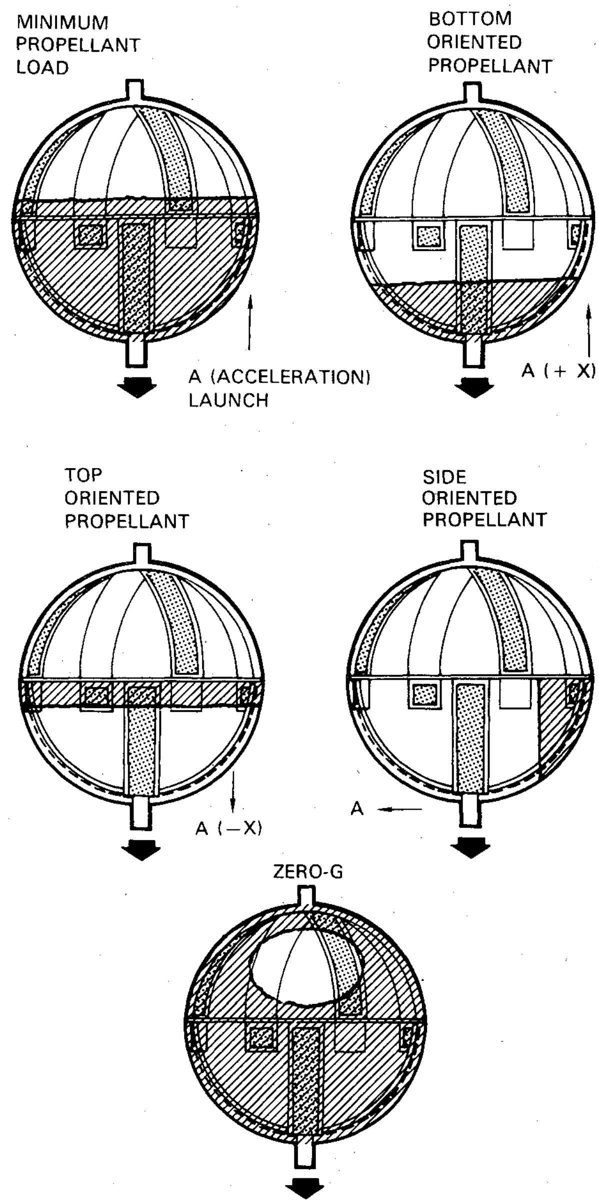

Fig. 7 Passive propellant management system operation.

submerged screens into the gallery networks while the gallery length exposed to the ullage retains propellant. For $-X$ accelerations, the propellant is oriented against the bulkhead in the aft compartment. The propellant is supplied through the submerged screen of each of the four galleries and flows along the galleries to the outlet. For lateral acceleration, the fluid is oriented against the tank wall. All galleries supply propellant when submerged. For large ullages, only a single gallery is submerged and that gallery supplies the propellant. All aft galleries remain full of propellant during all system operations until complete depletion of the tank. The preceding discussion described operation of the aft galleries. The forward galleries operate in a similar manner. For zero gravity, the propellant assumes a wallbound configuration as illustrated in Fig. 7, with the ullage located as a bubble in the center of the fluid.

The screen mesh chosen for the design is 325×2300 TDDW. This weave has the minimum pore size and greatest capillary retention capability of any screen used for propellant acquisition devices. Since the design to be demonstrated by this program should have the potential of being employed on vehicles and missions not yet fully identified, the maximum available retention capability was deemed most desireable.

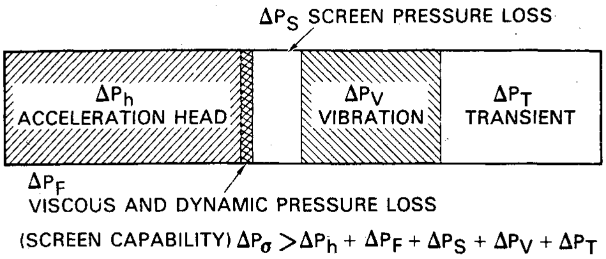

Fig. 8 Typical acquisition system pressure budget.

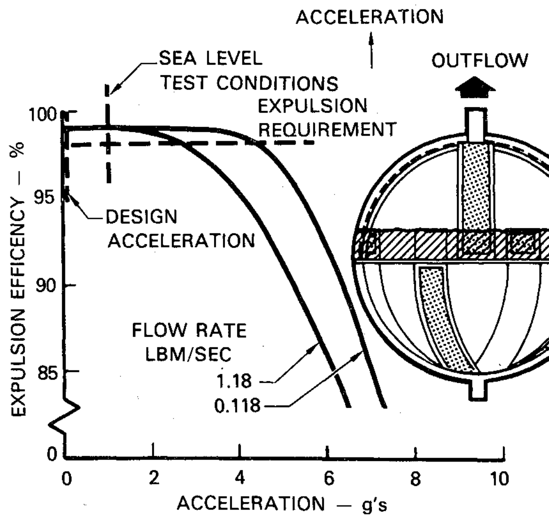

Fig. 9 Expulsion efficiency, top oriented propellant.

Analyses indicated that at the high acceleration and with the imposed random vibration environment, the 325×2300 TDDW was required for 98% expulsion efficiency. The minimum acceptable capillary retention capability to achieve that expulsion efficiency is 23.0 in. of water (H_2O). This allows approximately a 10% margin for degradation in the nominal screen capability during fabrication. The acquisition system was designed to satisfy the expulsion requirements in conjunction with the design environments when considering the actual surface tension/wetting properties of hydrazine. These properties were determined experimentally and agreed well with those reported in Ref. 4. As noted in Ref. 4, hydrazine exhibits a nonzero contact angle with the screen surfaces which reduces the capability of the liquid-gas interface at the screen to sustain imposed pressure differentials. This reduction in screen capability in hydrazine was accounted for in the system design.

Performance of the system is defined as the expulsion efficiency that can be obtained under the various combinations of imposed environments and flow requirements. The system will allow gas to enter the propellant supply when the pressure drops resulting from any combination of acceleration head, screen flow pressure loss, viscous and dynamic pressure loss, vibration effects, and transient startup pressure, exceeds the screen retention capability. A typical acquisition system pressure budget is shown in Fig. 8. Calculated performance of the PPMS is shown in Figs. 9 through 11 for various propellant orientations. As shown, the design expulsion efficiency of 98% is exceeded for all orientations.

Random vibration environments are of concern during the on-orbit acceleration resulting from main engine operation (3.3 g max.). For launch, the aft gallery network is covered for all off loaded propellant levels so that consideration of vibration induced pressure differentials is not required for this flight mode. Thruster operations alone are not expected to cause any discernible structural response in the acquisition

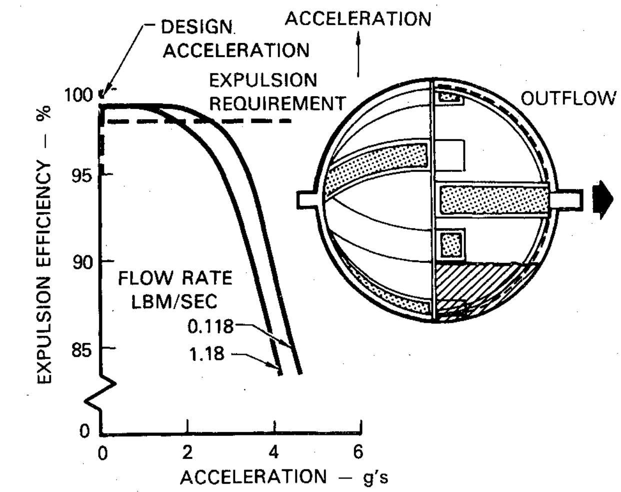

Fig. 10 Expulsion efficiency, side oriented propellant.

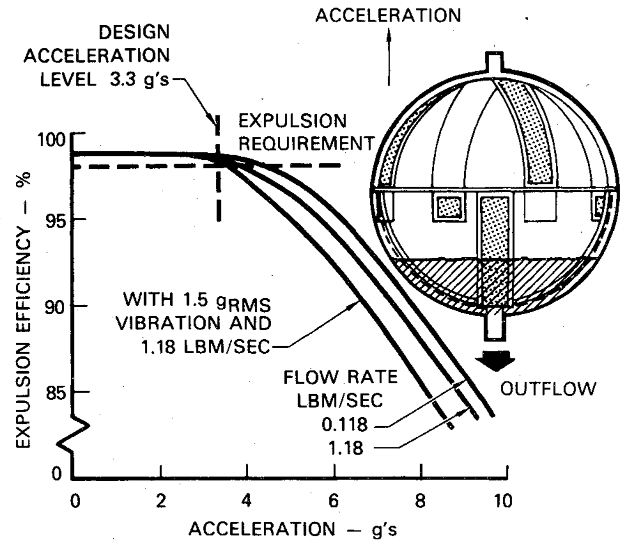

Fig. 11 Expulsion efficiency, bottom oriented propellant.

assembly. The effect of random vibration, as determined by a finite-element model analysis, is to reduce the expulsion efficiency as shown in Fig. 11. The assumptions used for the transient analysis are consistent with those recently published and verified in a study of the effect of vibration on screened acquisition devices.[5]

A transient flow analysis was conducted using a liquid propellant feed system dynamic analysis computer program. Typical thruster valve characteristics and line routings were established for a Space Tug type vehicle and formulated into a system model. This model, consisting of ten 25-lb_f thrusters and associated feedlines, was then coded into a dynamic analysis program and the transient pressure characteristics defined. The outflow initiation was the most critical transient condition. Outflow termination and its effect on acquisition system performance was not modeled, because it was not considered as the critical condition. This was verified by the results of transient outflow testing conducted by Cady.[6] In this testing a variety of screen meshes, screen backup structure, orientations, and fluids were used, and gas ingestion did not occur during liquid outflow termination. Gas ingestion during outflow initiation was predicted accurately in this work by the use of computer program H-672 Liquid Propellant Feed System Dynamic Analysis which was the same analytical design technique used for this system design.

Due to the fast response of the thruster valves (8 ms), pressure disturbances in the propellant feedlines and in the

Table 3 Test conditions and results

Test	Tank attitude	Fluid	Temperature, °F	Outflow rate, lb_m/s	Expulsion efficiency, %
1	Vertical	N_2H_4	88	0.28	99.3
2	Vertical	N_2H_4	85	0.31	99.2
3	Vertical	N_2H_4	85	0.21	99.1
4	Vertical	N_2H_4	74	0.45	99.2
5	Side	N_2H_4	83	1.16	98.6
6	Side	N_2H_4	168	1.12	98.1
7	Side	N_2H_4	74	0.14	98.5
8	Inverted	N_2H_4	78	0.28	98.1
9	Inverted	N_2H_4	84	0.11	98.5
10	Side	N_2H_4	45	1.15	98.0
11	Vertical	C_3H_8O	75	0.55	99.2
12	Inverted	N_2H_4	62	1.10	98.1

tank acquisition assembly at outflow initiation can exceed screen capability. This transient pressure can be attenuated by techniques such as spring-loaded accumulators or line compliance. Since it is undesirable to achieve the necessary pressure attenuation by increasing feedline diameters or by reducing wall thickness, and since the use of accumulators increases propellant feed system complexity, the acquisition assembly was designed such that pressure wave attenuation was achieved within the propellant tank, i.e., the gallery compliance was made adequate for the worst-case startup condition of maximum outflow rate with the aft compartment bulk fluid located against the bulkhead. The pressure differential generated during this condition was 0.9 psid. The effect of the pressure transient is to reduce expulsion efficiency when the remaining propellant is less than 2.5% and can result in a 1% loss in expulsion efficiency to 97.5%. However, the expulsion performance can easily be improved by tailoring vehicle operating procedures to prevent a simultaneous 10-engine startup. This design possesses the capability to operate with other Earth storable propellants such as monomethyl hydrazine and nitrogen tetroxide, but axial acceleration capability is reduced because these fluids have a lower surface tension than hydrazine.

Fabrication and Acceptance Test

The acquisition assembly was fabricated using standard methods and techniques. All detail parts were weld assembled except for standard fittings in the vent lines. The gallery leg assemblies were built by resistance roll seam welding the acquisition screen to a curved frame which was, in turn, fusion welded to the gallery channels. The channels were formed using a sheet metal press brake and then stretch formed to the required contour.

After weld assembly of the eight gallery channels and screen/frames, bubble point testing of the assemblies, per Aerospace Recommended Practice 901, was accomplished. The criteria for acceptance was a bubble point of 23 in. of water. Teflon FEP powder was applied and cured on local screen areas which had low bubble point capability. After any necessary repair, the pressure at which the first bubble appeared on the screen ranged from 23.1 in. to 25.2 in. of water.

After bubble point test, the galleries were fusion welded to the gallery pans which had been previously welded to the bulkhead and also welded at the intersections of the four upper and the four lower legs. This completed the forward and aft gallery networks. The vent tubes were then welded to the assembly and all final assembly welds verified by bubble point testing of the assembly.

The acquisition assembly was then inserted into the tank shell which was fabricated by spin forming the stainless steel domes and weld assembly of the machined flanges. The bulkhead, to which the acquisition system is attached, is bolted between the two tank flanges, and the pressurant inlet and propellant outlet fittings attached. The final assembly was leak checked at the normal operating pressure of 360 psi.

Because of the development nature of this effort, the primary emphasis on the acquisition aspects, and the desire to examine the acquisition assembly after verification tests, the tank shells were designed to nonflight criteria. The bulkhead can be easily redesigned to interface with a flight weight tank shell instead of mounting between the bolt flanges of the test tank configuration.

Performance Verification

Testing verified the capability of the PPMS to provide gas-free liquid under a variety of acceleration and temperature environments. Three expulsion orientations of Fig. 7 and temperatures of 40° to 175°F were utilized. All testing was accomplished with hydrazine and a simulation fluid, isopropyl alcohol. The following discussion describes the tests.

Because of the inherent capability of the PPMS to operate in high-acceleration environments, it is capable of successful operation under earthbound 1-*g* test conditions. Figures 9 and 10 show that for side and top oriented propellant, expulsion efficiencies of 98% are attainable in the Earth environment (1-*g*). For bottom oriented propellant the 1-*g* environment is not severe enough to verify the high-*g* design requirement. That environment was simulated by outflow testing with isopropyl alcohol. This simulation fluid was selected on the basis of modeling the high-*g* hydrazine outflow in a 1-*g* environment with the same expulsion efficiency. The applicable modeling parameters are the Bond, Weber, Froude, and Reynolds numbers. Justification of this simulation approach can be found in Ref. 7. It is based on maintaining the same ratios of body to capillary forces (Bond number) and inertia to capillary forces (Weber number) in the simulation tests and operating environment. Using that rationale, the fluid properties of isopropyl alcohol in a 1-*g* environment simulate hydrazine in a 2.5-*g* environment. The test conditions and results are shown in Table 3. These tests verified the design expulsion efficiency with various tank attitudes, propellant temperatures, and flow rates.

Conclusions

The design and performance of a passive propellant acquisition device that has the capability to be used on advanced spacecraft has been verified. The system is fully reusable with no moving parts and can be checked out before reuse to verify capability. The system can be used with the Earth storable propellants: hydrazine, monomethyl hydrazine, and nitrogen tetroxide. The system performance has been verified by tests with hydrazine to exceed the design requirement of 98% expulsion efficiency in acceleration environments ranging from 2.5 *g* in a $+X$ axial direction to 1 *g* in lateral and $-X$ axial directions.

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