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Cryogenic Propellant Management Device Conceptual Design Study

*Mark Wollen, Fred Merino, John Schuster, Christopher Newton
Innovative Engineering Solutions, Murrieta, California*

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*Mark Wollen, Fred Merino, John Schuster, Christopher Newton
Innovative Engineering Solutions, Murrieta, California*

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National Aeronautics and
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Glenn Research Center
Cleveland, Ohio 44135

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Abstract

Concepts of Propellant Management Devices (PMDs) were designed for lunar descent stage reaction control system (RCS) and lunar ascent stage (main and RCS propulsion) missions using liquid oxygen (LO₂) and liquid methane (LCH₄). Study ground rules set a maximum of 19 days from launch to lunar touchdown, and an additional 210 days on the lunar surface before liftoff. Two PMDs were conceptually designed for each of the descent stage RCS propellant tanks, and two designs for each of the ascent stage main propellant tanks. One of the two PMD types is a traditional partial four-screen channel device. The other type is a novel, expanding volume device which uses a stretched, flexing screen. It was found that several unique design features simplified the PMD designs. These features are (1) high propellant tank operating pressures, (2) aluminum tanks for propellant storage, and (3) stringent insulation requirements. Consequently, it was possible to treat LO₂ and LCH₄ as if they were equivalent to Earth-storable propellants because they would remain substantially subcooled during the lunar mission. *In fact, pre-launch procedures are simplified with cryogenics, because any trapped vapor will condense once the propellant tanks are pressurized in space.*

Executive Summary

Overview

This report documents work conducted under contract with NASA Glenn Research Center (GRC) to evaluate design options for Propellant Management Devices (PMDs) suitable for lunar ascent and descent stages using liquid methane (LCH₄) and liquid oxygen (LO₂). Results indicate that PMD designs for this application can be simplified because of design requirements imposed upon the descent and ascent stages unrelated to the PMD itself. The major factors that serve to simplify PMD design are (1) high propellant tank operating pressures, (2) the selection of aluminum tanks for propellant storage, and (3) stringent insulation requirements. The high propellant tank pressures assure significant propellant sub cooling, even with propellant temperatures rising throughout the mission. The high aluminum tank thermal conductivity mitigates concerns related to tank heat penetrations by providing a near-uniform propellant tank wall temperature. Finally, the descent stage must be insulated to support cryogenic storage for 19 days, and the ascent stage must be insulated to support cryogenic storage for periods in excess of 200 days with, ideally, no venting. Study results show that venting will not be required prior to lunar touchdown. In fact, it is likely that venting of the ascent stage main propellant tanks will not be required during its 210 day lunar stay without the additional requirement of a Thermodynamic Vent System (TVS) or mixer.

The combination of low tank heat loads and high operating tank pressure create a propellant tank thermal environment where boiling and evaporation will not occur. Thus, designs were considered where PMDs could be integrated with the tank wall (instead of being stood off and cooled with a TVS). Consequently, PMD designs for these applications can more closely resemble designs suitable for Earth-storable propellants.

Options were developed for a partial communication PMD that satisfies mission requirements. The descent stage Reaction Control System (RCS) tank PMDs will have an unusable residual of 1.9 percent and be sized to access the last 16.6 percent of tank propellant. The ascent stage main tank PMDs will have an unusable residual of 0.3 percent and be sized to access the last 4 percent of tank propellant. A novel, expanding volume device that makes use of a stretched, flexing screen was also conceptually developed and considered for the lunar mission. This design meets the 2 percent residual requirement for the descent stage; 1 percent residual is predicted for ascent stage.

The currently defined operating requirements and conditions allow PMD designs that are easy to build and test.

PMD Design Concepts

The primary requirements that drive PMD design concepts are 1) vapor-free propellant must be provided throughout each mission, and 2) propellant residual must not exceed 2 percent of propellant by tank volume. Mission durations will range up to 19 days from launch to lunar touchdown for the descent stage mission, and up to 229 days from Earth launch to lunar launch for the ascent stage mission.

Design concepts were analyzed and developed as if for storable propellant application. That is, the PMD concepts are designed to satisfy the minimum liquid residual requirement before screen breakdown occurs. Any issue related to boiling (that may impact vapor-free delivery) or temperatures (that may exceed the maximum allowable levels) are deferred to the discussion which treats descent stage and ascent stage thermodynamic and thermal protection issues.

Partial Four-Screen Channel PMD

One of the two PMD types selected for design is a traditional partial f-screen channel device (Concept No. 1 for the RCS propellant tanks and Concept No. 3 for the ascent stage main tanks). Concept No. 1 designs selected for the descent stage RCS propellant tanks are identical except for the scale difference to accommodate the tank diameter. Four channels are equally spaced circumferentially and connected to a sump located over the tank outlet. Channel cross-section is the same for both tanks and for both concepts.

An analysis indicated that slightly less than 2 percent residual by tank volume remains within and outside the PMD, for both RCS tanks, when screen breakdown occurs. Screen breakdown occurs when the sum of pressure drops and losses exceeds screen bubble point ΔP .

The same approach as above was taken to determine Concept No. 3 residuals in the ascent stage main tanks. Analysis indicates that less than 0.3 percent residual will remain when the PMDs experience screen breakdown. The primary reason that Concept No. 3 shows lower residuals than does Concept No. 1 is that the PMDs are sized to retain a significantly lower quantity of tank propellants (4 percent rather than 16.6 percent).

Flexible Screen PMD Design

The flexible screen PMD is a new concept identified during the early part of this study. This PMD is a partial acquisition device because it contains a limited amount of propellant and is not in communication with the propellant bulk under all flight conditions. Its function is to contain the last few percent of propellant remaining in a tank so that it is provided vapor-free to the RCS thrusters upon demand. In its simplest form, the PMD is a single flexible screen designed with springs (or other loading mechanism) that allow it to expand to a predetermined level during propellant tanking and remain expanded during main engine burn. The screen will begin to contract only after all tank propellant in contact with the screen has been drawn into the PMD. Screen contraction will increase as continued flow demand drains propellant from within the PMD, and once fully contracted, any additional flow demand will result in vapor penetration of the screen. At this time, vapor-free flow will no longer occur, and the propellant remaining is considered unusable.

The ascent stage mission PMD (Concept No. 4) requirement is to provide the last 2 percent of usable propellant for rendezvous and docking. The PMD is sized to contain a maximum of 4 percent propellant (2 percent residual and 2 percent usable propellant). The flexible screen is located at the 2.5 percent liquid level (by tank volume), and is designed to expand to contain 4 percent propellant by volume, and contract to 1 percent propellant by volume as propellant is expelled. This residual quantity applies to the main LCH₄ tank as well.

Concept No. 2 PMD for the descent stage RCS tanks is sized to contain approximately 17 percent propellant (2 percent residual plus 15 percent usable propellant).

Flexible/Expandable Screen Evaluation

A novel feature of one of the proposed PMD designs is to use the flexibility of the screen to accommodate a significant volume change as liquid is extracted from the device. Pleating and stretching are two different approaches that have been considered to provide this capability. Pleating presents manufacturing challenges, but stretching may be a simpler method to provide the same functionality. A few simple bench tests were performed to evaluate the feasibility of making a flexible/expandable screen device with stretched screen material.

To assess the extent to which readily available screen material can be stretched, a device was fabricated to retain a circular disk of screen material around the edges, while the material was hydrostatically stretched. Results indicate that stainless steel screen can be “blown” into a spherical shape with the center deflected to a height of about 10 percent of the diameter of the disk. To assess the integrity of the screen following stretching, a simple water bubble point test was performed following the stretching process. Although water is not an ideal evaluation candidate, results indicate that the screen bubble point is not significantly degraded by the stretching process.

Finally, a device was fabricated which preloads the screen with a spring to maintain the screen in an expanded position, with liquid filling the chamber beneath the screen. Without liquid contact above the screen, extraction of liquid beneath the screen draws down on the screen and compresses the spring. When liquid is then brought into contact with the screen from above, the lower chamber spontaneously refills as the spring loaded screen returns to the fully expanded state. This simple testing convincingly

demonstrates the viability of a flexible/expandable screen device as a simplified and easy to build alternative to conventional PMD designs.

PMD Thermodynamics/Thermal Control Issues

The keys to treating descent and ascent stage designs as equivalent to an Earth storable vehicle design are the following:

1. High propellant tank operating pressures of 325 psia, to satisfy RCS and main engine requirements.
2. High thermal conductivity of the aluminum propellant tank designs.
3. Low propellant tank heat loads required for the long duration mission.

Three major issues addressed in this study were a) how to develop a methodology that conservatively predicts propellant tank pressures for the descent stage and ascent stage defined missions, b) how to adequately protect propellant contained within a PMD so that boiling does not occur internal to the device, and c) how to prevent boiling or evaporation from occurring at the screen surface so that screen breakdown is avoided.

Propellant Tank Pressures from Launch to Lunar Liftoff

A simplified heat conduction model, later validated by limited FLUENT CFD analyses, was used to identify peak tank wall temperature resulting from a combination of MLI and tank penetration heat rates. Saturation pressure-temperature relationships for LO₂ and LCH₄ were used to convert peak temperatures to peak mission pressures. This methodology showed that propellant tank venting will not be required for either the descent stage RCS propellant tanks or for the ascent stage main propellant tanks during the up to 18 or 19 day journey to the lunar surface. In fact, the main propellant tanks will not be required to vent during the 210 day residence on the lunar surface if the heating rates identified for this study are not exceeded.

Preventing Boiling Within PMD

The presence of vapor, or boiling, within the PMDs is of no concern as long as it can be removed hours in advance of first propellant use by the RCS engines or main engines. This can readily be achieved by pressurizing the RCS propellant tanks at any time after steady state low Earth orbit heating rates have been attained; any vapor within the PMD will condense and the released energy conducted into its surroundings within hours. This same approach applies to the ascent stage main tank PMDs. All vapor will be condensed if the tanks are pressurized hours (or days) prior to launch from the Moon's surface.

PMD Screen Breakdown

Screen breakdown will not occur during this lunar mission because bubbler pressurization (where helium is injected beneath the propellant surface) was ground ruled for this study. This pressurization technique creates a near-thermal equilibrium environment between propellant and ullage. Consequently, there will be little tendency for evaporation or boiling to occur when the PMD is exposed to ullage.

Conclusions

1. Propellant tank venting will not be required during the Earth- to-lunar phase of flight.
2. Propellant tank venting may not be required during the 210-day lunar stay. However, a 3.7 percent increase in LCH₄ tank heating rate will necessitate venting to maintain bulk liquid temperatures below the maximum allowable of 224 R. For the LO₂ tank, the heat rate increase must exceed 13 percent.

3. PMDs will remain vapor-free throughout the mission once propellant tanks are pressurized while in low Earth orbit.
4. Propellant contained within a PMD will reside at nearly the same temperature as that of the surrounding liquid. If the tank insulation requirements maintain bulk propellant temperatures within engine inlet requirements, propellant flow from a PMD will also satisfy engine inlet requirements. The exception to the above is that penetration heat rates may create “hot spots” in the range of 1 to 2 R above bulk propellant temperatures.
5. A TVS or propellant mixer is not required for the descent stage phase of flight.
6. A TVS or propellant mixer may not be required for the ascent stage long duration stay on the lunar surface.

Recommendations

The following recommendations are made:

1. Flexible screen PMD development program
2. A thermal study using CFD code to analyze the following:
 - a. Determine temperature gradients in propellants for long term storage on the lunar surface. Results would serve to quantify the need for TVS, mixer or improved insulation systems.
 - b. Determine temperature gradients and resulting heat rates and fluxes surrounding such heat penetrations as propellant tank support struts, vent lines feed lines. Such data would serve as a design guide for vehicle systems.
 - c. Compare the thermal environment of propellants contained within a PMD in direct thermal contact with a tank to that of a PMD thermally isolated from the tank wall.
3. Perform studies to include the influence of pressurization system type (including storage) upon a propellant tank insulation system design and PMD design to satisfy mission engine inlet temperature requirements.

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1.0 Introduction and Overview

This report documents work conducted under contract with NASA Glenn Research Center (GRC) to evaluate requirements and design options for Propellant Management Devices (PMDs) suitable for lunar ascent and descent stages using liquid methane (LCH₄) and liquid oxygen (LO₂). Results indicate that PMD designs for this application can be simplified because of design requirements imposed upon the Descent and Ascent stages unrelated to the PMD itself. The major factors that serve to simplify PMD design are (1) high propellant tank operating pressures, (2) the selection of aluminum tanks for propellant storage, and (3) stringent insulation requirements. The high propellant tank pressures assure significant propellant sub cooling, even with propellant temperatures rising throughout the mission. The high aluminum tank thermal conductivity mitigates concerns related to tank heat penetrations by providing a near-uniform propellant tank wall temperature. Finally, the descent stage must be insulated to support cryogenic storage for 19 days, and the ascent stage must be insulated to support cryogenic storage for periods in excess of 200 days with, ideally, no venting. It is likely that the above requirements will make it possible to accomplish the lunar mission without the additional requirement of a Thermodynamic Vent System (TVS) or mixer.

The combination of low tank heat loads and high tank pressure can lead to simplified PMD designs because boiling and evaporation becomes non-issues. Designs where PMDs are integrated with the tank wall (instead of being stood off and cooled) can be considered. Consequently, PMD designs for these applications can more closely resemble designs suitable for Earth-storable propellants.

Options have been developed for a partial communication PMD that satisfy mission requirements. The descent stage RCS tank PMDs will have an unusable residual of 1.9 percent and be sized to access the last 16.6 percent of tank propellant. The ascent stage main tank PMDs will have an unusable residual of 0.3 percent and be sized to access the last 4 percent of tank propellant. A novel, expanding volume device that makes use of a stretched, flexing screen is also developed and considered for these applications. This design meets the 2 percent residual requirement for the descent stage; 1 percent residual is predicted for ascent stage.

The currently defined operating requirements and conditions allow PMD designs that are relatively easy to build and test.

2.0 Literature Search and Background Information

A number of documents were reviewed to survey the use of surface tension-based propellant management devices for space applications, so as to identify the basic types, gauge their state of development and application, and their advantages and limitations. A bibliography of the documents reviewed can be found in the References section.

2.1 Discussion

A series of four AIAA papers (Refs. 1 to 4) provide an overview of most the basic types of propellant management devices; including vanes, sponges, traps and troughs, and galleries. Reference 5 also addressed a full pleated liner configuration which represents an additional basic approach. These propellant management devices can be grouped into two categories: total communication PMD types that are intended to enable liquid acquisition and delivery to the propellant tank outlet regardless of propellant orientation and distribution; and, control PMD types that retain a limited inventory of liquid, and are positioned over the tank outlet, thus making the liquid available. Figure 1 illustrates the total communication PMD types, which are the vane, the gallery and the pleated liner. To our knowledge, no total communication PMDs have been used yet in cryogenic propulsion applications.

The vane device has been used principally on monopropellant systems aboard satellites. It consists of multiple, contoured solid plates that provide interior corners where the plates meet the wall of the tank

and also in the interior of the tank where the plates intersect. The liquid propellant wets the surfaces, and surface tension causes the liquid to form a rounded fillet in the corners, thus enabling liquid to be transported along the fillet toward the tank outlet. This device is simple, light weight, and reliable. Because the capillary pumping force provided by the corner fillet is relatively small, use of the vane is limited to low flow, low acceleration applications.

The gallery device, often called a Liquid Acquisition Device (LAD), consists of multiple contoured tubes that incorporate windows of fine pore wicking screen. The liquid wets the screen and fills the tubes, which supply liquid to the tank outlet. The tube cross section is optional, but is often rectangular, triangular or round. The screen window is usually placed facing the tank wall, but an interior-facing window may also be an option. This device performs well for moderate flow, moderate acceleration applications, but it is relatively complex, and less reliable than the vane due to reliance on fine pore screen, which possibly might have imperfections that could result in screen early breakdown.

The pleated liner is fabricated of fine pore wicking screen that is contoured to cover the entire tank wall. Liquid wets the screen and fills the channels formed by the pleats, enabling liquid to be supplied to the tank outlet. This approach should perform well for high flow, high acceleration applications, but it is heavy and the least reliable due to the high amount of screen used.

Figure 2 illustrates the control PMD types, which are the sponge, the trough, and the trap. The sponge is an array of perforated plates, usually in a radial arrangement over the tank outlet. Liquid, contained by capillary forces between the plates, migrates radially inward toward the outlet. This device is light weight, reliable, and refills in zero-g, however it may drain under adverse acceleration.

The trough is an array of solid radial plates with circular end plates located over the tank outlet. The end plate adjacent to the outlet incorporates a fine mesh screen to prevent vapor ingestion. With lateral acceleration liquid is retained in the device by hydrostatic forces. This device is reliable, refills in zero-g, and can provide higher flow and tolerate more acceleration than the sponge. However, it is heavier and more sensitive to acceleration direction.

The trap, often called a start basket, is a closed structure located over the tank outlet, and having a fine mesh screen window. It holds and provides a specific amount of liquid to enable engine starting, and may contain pickup tubes or a small gallery to promote liquid acquisition under spinning conditions or lateral acceleration. It can incorporate a vent to make it refillable under settled conditions but the vent would make it susceptible to spilling under adverse acceleration.

AIAA paper (Ref. 6) describes the fluid management concept used in both the MMH and NTO tanks of the HS 601 communications satellite. This concept, which is illustrated in Figure 3, combines multiple simple devices to meet mission requirements, and has been used in over 200 tanks without a failure. It utilizes a vane assembly, a sponge assembly, and a trap with propellant pickup arms. Additionally, Reference 7 describes the more recent development of a small PMD for providing gas-free hydrazine in a spin-stabilized satellite. The PMD consists of a screen-covered pickup assembly and a radial-paneled sponge device mounted in the cylindrical side wall of the tank.

As previously stated, the devices that have been described here have their flight heritage in storable propellant applications. It has long been recognized that these devices might also be candidates for use with cryogenic propellants as long as proper attention is paid to the thermal issues associated cryogenics. References 8 and 9 provide NASA-funded design studies of free-flying and Shuttle-attached experiments for carrying out on-orbit, low-g cryo-fluid management experiments. Reference 10 describes a cryogenic propellant storage and supply system proposed as an upgrade to the Shuttle OMS/RCS. References 11, 12 and 13 address the application of capillary-based fluid management devices for space missions, including developing requirements and concepts, and characterizing cryogenic bubble points for candidate fine screen materials. References 14, 15 and 16 specifically address the effects of evaporation on the performance of wicking materials, both with regards to breakthrough and dry-out. G.R. Schmidt (Ref. 14) in his Ph.D dissertation provides a detailed theoretical analysis of the effects of evaporation and condensation on the performance of liquid acquisition devices. Reference 15 provides a comparison of analytical modeling of wicking with test data to illustrate the effects of evaporation.

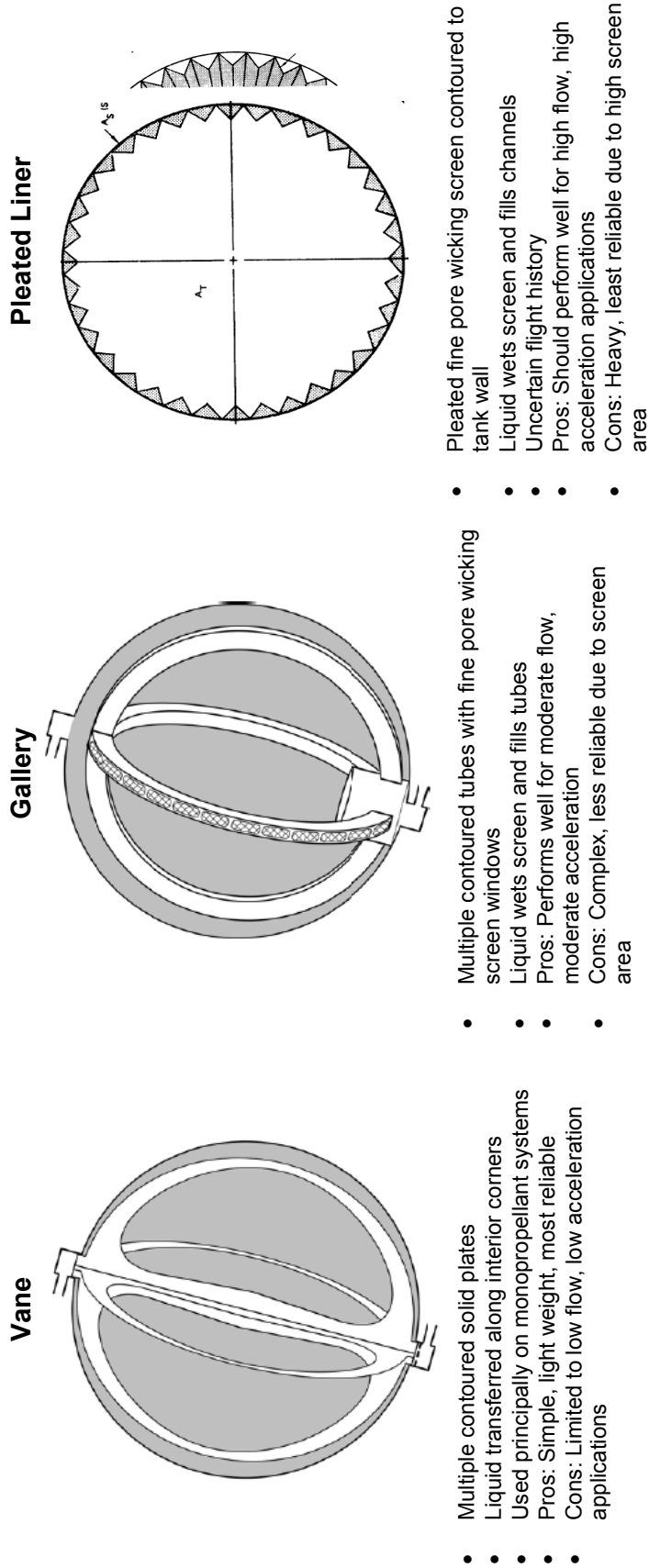
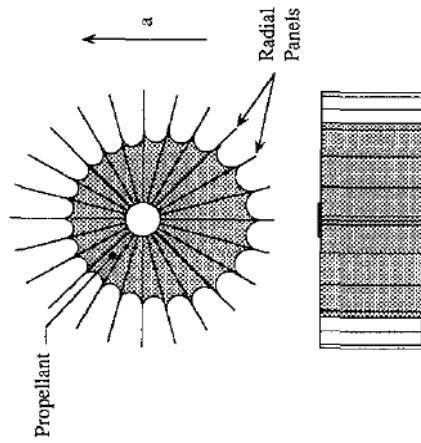


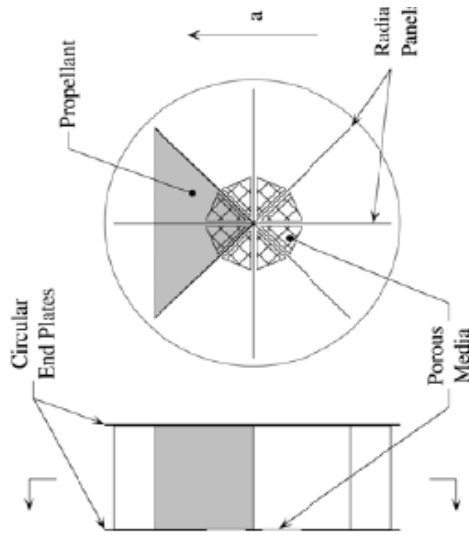
Figure 1.—Total communication PMD types.

Sponge



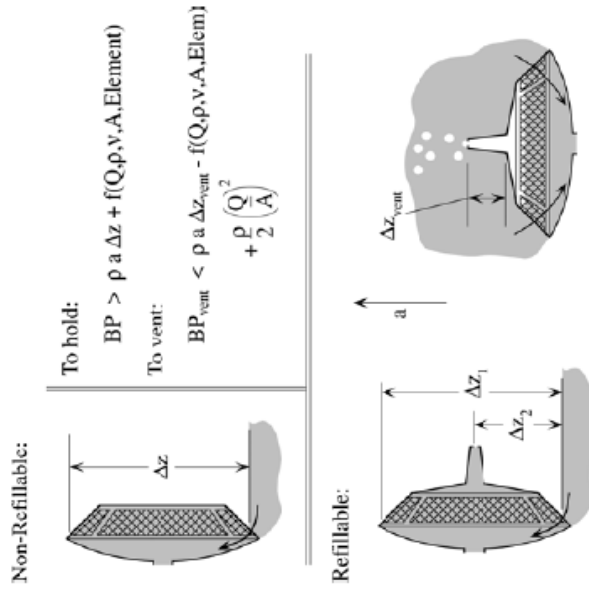
- An array of perforated radial plates mounted above an outlet screen
- Liquid migrates radially inward between the plates
- Pros: Light weight, reliable, refills in zero-G
- Cons: May drain under adverse acceleration

Trough



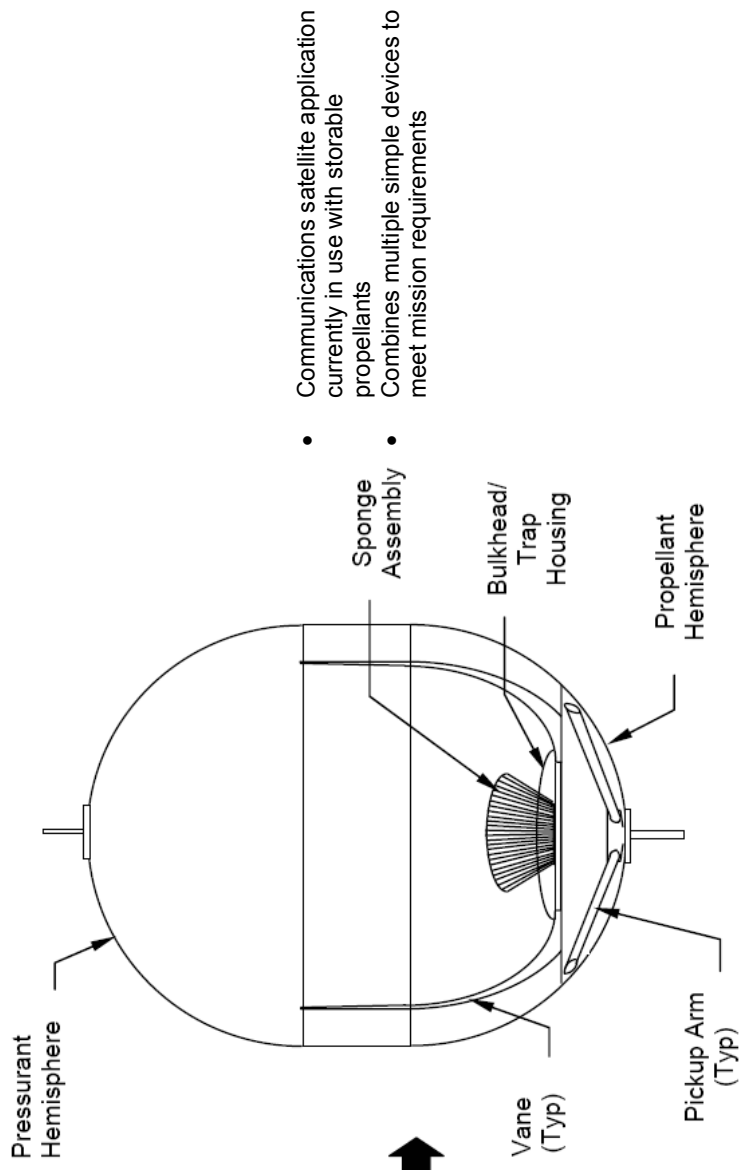
- An array of radial plates with circular end plates with an outlet screen
- Liquid is retained by hydrostatic forces
- Pros: Reliable, refills in zero-G, higher flow and acceleration than sponge
- Cons: Heavier and more sensitive to acceleration direction than sponge

Trap



- A closed structure over the tank outlet with a fine mesh screen window
- Holds and provides a specific amount of liquid
- May contain a small gallery
- Pros: If vented, can be refilled
- Cons: Not refillable in zero-G

Figure 2.—Control type PMDs.



- Communications satellite application currently in use with storable propellants
- Combines multiple simple devices to meet mission requirements

*1. MMH and NTO tanks are identical
 2. Source: AIAA 98-3199, "Design and Manufacture of the HS 601"

Block II Propellant Tank Assembly

Figure 3.—HS 601 propellant tank configuration.*

Reference 16 presents analyses and test data to demonstrate the effects of wicking and evaporation on dry-out, breakthrough, and conditions necessary for resealing of candidate fine screen materials, and demonstrate the use of a window screen device with the potential to improve the performance of LADs when dry-out or screen breakdown occurs. This work identifies a physical process (previously poorly understood) that explains difficulties with resealing a screen after breakdown. Most importantly, additional criteria are identified to achieve reliable re-wetting and resealing. These criteria may be difficult to meet, especially in a high gravity environment as would be the case during ground testing.

Finally, as an alternative to the use of capillary fluid management devices, Reference 17 describes the use of low-g settling in the range from 10^{-3} down to 10^{-5} g to provide propellant management for the Centaur during orbital coast. This is an available, effective method that could be used to support scavenging excess propellants from a cryogenic upper stage.

3.0 PMD Design Concepts

The purpose of this study was to develop PMD conceptual designs that would provide vapor-free liquid to lunar descent stage RCS engines and lunar ascent stage RCS engines and main engine as required throughout their respective operations of a lunar exploratory mission. The primary requirements that drive PMD design concepts are 1) vapor-free propellant must be provided throughout each mission, and 2) propellant residual must not exceed 2 percent of propellant by tank volume.

For the purposes of this study, NASA provided representative mission duration segments that will range up to 19 days from launch to lunar touchdown for the descent stage mission, and up to 229 days from Earth launch to lunar launch for the ascent stage mission. Mission timeline details are given in Table 1 and Table 2.

TABLE 1.—LUNAR DESCENT TIMELINE

Low Earth Orbit (LEO) Hold, RCS	<= 14 days
Lunar Transit Maneuvers, RCS	<= 4 days
Lunar Orbit Injection (LOI) Maneuver—Descent MPS	24 hr
Low Lunar Orbit (LLO) Plane Change—Descent RCS	During LOI
Lunar Descent	1.25 hr
Descent Orbit Insertion (DOI) – RCS	During descent
Final Descent Burns	During descent

TABLE 2.—LUNAR ASCENT TIMELINE

	Event Time	Elapsed Time
Low Earth Orbit (LEO) Hold, RCS	<= 14 days	<= 14 days
Lunar Transit Maneuvers, RCS	<= 4 days	<= 18 days
Lunar Orbit Injection (LOI) Maneuver- Descent MPS	24 hr	<= 19 days
Lunar Descent		<= 19 days
Lunar Liftoff to MECO	441 sec	<= 229 days
Terminal Phase Initiation	22 hr	
Terminal Phase final	8 hr	
Dock	-----	

3.1 Current State of PMD Development

The literature survey conducted and described in Section 2.0 identified a variety of screen channel PMDs, vanes, and sponges that have been developed and used for storable propellant applications. These devices have at least one characteristic in common: their operating propellant temperatures are readily maintained with proven thermal control techniques where boiling is not a factor because the propellant remains sub-cooled throughout its mission.

Design of a screen device can become complicated if boiling or evaporation becomes a factor because of the possibility that the screen will dry out and lose its ability to retain liquid or to be replenished by

liquid under adverse acceleration conditions. Once screen breakdown occurs, vapor-free liquid may no longer be available to a main engine or to RCS engines. The discussion of Section 5.0 will show that unique stage design characteristics (thick aluminum walls, high engine inlet pressure requirements and low tank design heating rates) combine to produce an environment equivalent to that of storable propellant PMD designs.

In this section, design concepts are analyzed and developed as if for storable propellant application. That is, the PMD concepts are designed to satisfy the minimum liquid residual requirement before screen breakdown occurs. Any issue related to boiling (that may impact vapor-free delivery) or temperatures (that may exceed the maximum allowable levels) are deferred to the discussion in Section 5.0, which treats descent stage and ascent stage thermodynamic and thermal protection issues.

3.2 Selected Concept Designs for the Descent Stage RCS Propellant Tanks and Ascent Stage Main Tanks

Two concepts were selected for detailed design and analysis following the study Interim Review in November 2008. These were the total communication PMD (Figure 4) and the flexible screen PMD (Figure 5). It was believed that both concepts would satisfy the study ground rules and assumptions summarized in Table 3 and Table 4. The PMD designs serve the same function in both stages. The only difference in requirements is that screen devices installed in the ascent stage main tanks must accommodate main engine and RCS engine flow rates, whereas, PMD designs for the descent stage RCS tanks will only experience RCS engine flow rates. Pressure losses at main engine flow rates will be less than 0.5 psi, and should have no significant impact upon any PMD design.

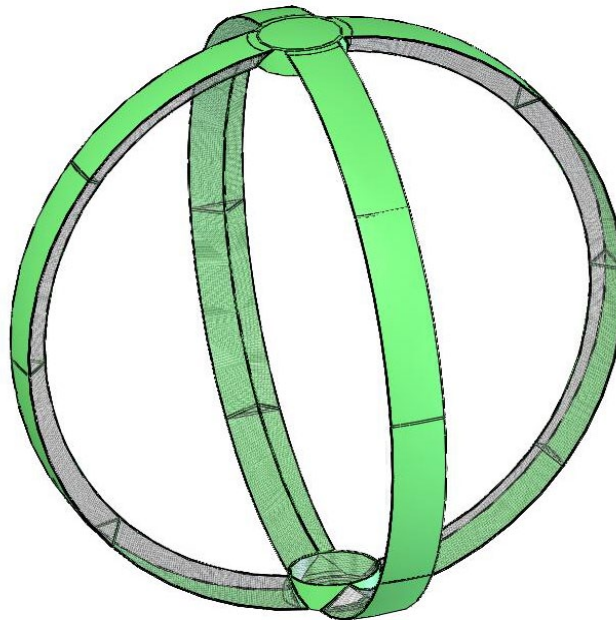


Figure 4.—Original Conceptual Design No. 2; four-channel triangular inward facing screen PMD.

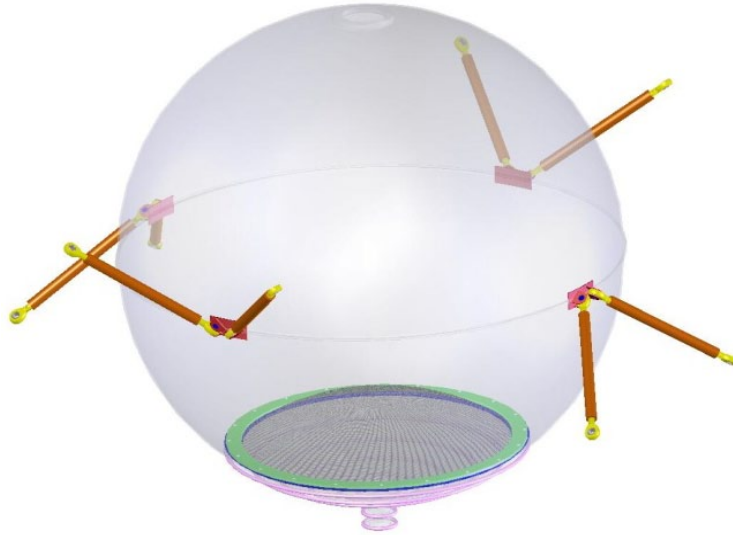


Figure 5.—Original Conceptual Design No. 3; flexible screen PMD.

TABLE 3.—STUDY ASSUMPTIONS AND REQUIREMENTS FOR LUNAR DESCENT STAGE

Descent Stage Study Assumptions/Requirements		
Propellant Tank Combination	LO2	LCH4
Nominal Mass Requirement for Propulsion	300 kg	100 kg
Spherical Propellant Tanks		
Tank Material	Aluminum (6061-T6 or equivalent assumed)	
MEOP	325 psia	
Operating Temperature Range	163 to 204 R	165 to 224 R
Acceleration Environment		
Main Engine Firing	0.8-g's aft	
RCS Engine Firing	0.02-g's any direction	
Nominal RCS Flow Rates	0.09 to 0.15 kg/sec	0.03 to 0.05 kg/sec
Provide vapor-free sub-cooled liquid to RCS engines		
Maintain expulsion efficiency > 98%		
RCS engine contingency operation requires continuous thrust duration to 300 sec (up to 15% total propellant consumption)		
Nominal thruster pulse duration is 0.07 to 0.09 sec		

TABLE 4.—STUDY ASSUMPTIONS AND REQUIREMENTS FOR LUNAR ASCENT STAGE

Ascent Stage Study Assumptions/Requirements		
Propellant Tank Combination	LO2	LCH4
Nominal Mass Requirement for Propulsion	2700 kg	900 kg
Spherical Propellant Tanks		
Tank Material	Aluminum (6061-T6 or equivalent assumed)	
MEOP	325 psia	
Operating Temperature Range	163 to 204 R	165 to 224 R
Acceleration Environment		
Main Engine Firing	0.8-g's aft	
RCS Engine Firing	0.02-g's any direction	
Nominal Main Engine Flow Rates	4.5 to 6.0 kg/sec	1.5 to 2.0 kg/sec
Nominal RCS Flow Rates	0.09 to 0.15 kg/sec	0.03 to 0.05 kg/sec
Provide vapor-free sub-cooled liquid to RCS engines		
Maintain expulsion efficiency > 98%		
RCS engine contingency operation requires continuous thrust duration to 300 sec (up to 15% total propellant consumption)		
2% propellant reserve required for RCS rendezvous and docking maneuvers		
Nominal thruster pulse duration is 0.07 to 0.09 sec		

Further evaluation of the four-channel total communication PMD revealed that propellant could not be maintained within the channels during descent stage main engine burn nor during an ascent stage main engine burn. Table 5 shows the maximum LO2 head that can be retained within the finest screen mesh available (325×2300 twilled dutch weave) is 1.34 ft at 0.8 g's. Since the RCS LO2 tank diameter is 2.68 ft, screen channel breakdown will occur once the RCS tank contains < 50 percent propellant during descent stage main engine burn.

TABLE 5.—LO2 RCS TANK PMD BUBBLE POINT ΔP DURING LOI AND LUNAR DESCENT

Screen Mesh	Nominal ΔP (1) psf	LO2 density lb/ft ³	g/g_c	Liquid Head Retention ft	LO2 Vapor Pressure (2) psia
200 x 1400	48.21	70.29	0.8	0.86	27
325 x 2300	75.17	70.29	0.8	1.34	27
200 x 1400	48.21	70.29	0.02	3.40	27
325 x 2300	75.17	70.29	0.02	53.60	27

Notes:

1. One standard deviation = 2.56 percent (Ref. 18)
2. LO2 vapor pressure at LOI

TABLE 6.—LCH4 RCS TANK PMD BUBBLE POINT ΔP DURING LOI AND LUNAR DESCENT

Screen Mesh	Nominal ΔP (1) psf	LCH4 density lb/ft ³	g/g_c	Liquid Head Retention ft	LCH4 Vapor Pressure (2) psia
200 x 1400	43.98	25.71	0.8	2.10	25.4
25 x 2300	66.33	25.71	0.8	3.22	25.4
200 x 1400	43.98	25.71	0.02	84.00	25.4
325 x 2300	66.33	25.71	0.02	128.80	25.4

Notes:

1. One standard deviation = 2.56 percent (Ref. 18)
2. LCH4 vapor pressure at LOI

Similarly, Table 7 shows that the maximum LO2 head that can be retained within the 325×2300 screen is 1.04 ft. during the ascent stage main engine burn. Screen channel breakdown will occur much earlier in flight for the ascent stage LO2 main propellant tank because its tank diameter is 5.75 ft. A decision was subsequently made to replace this design concept with a partial communication PMD, Figure 6.

A concern was also identified with the single screen flexible PMD design for the descent stage RCS tanks. PMD sizing for the descent mission requires that the device be sized to contain approximately 17 percent propellant (2 percent residual plus 15 percent usable propellant). Thus, a single flexible screen would have to be located at about the 9 percent level, expand to contain up to 17 percent propellant, and contract to contain 1 percent propellant. This is a deflection volume of about ±89 percent beyond the neutral position of 9 percent volume. However, limited tests conducted on a single screen prior to the Interim Review indicated a maximum deflection volume of about ±60 percent. Consequently, the decision was made to design a dual screen flexible PMD for the RCS tanks. A single screen flexible PMD will still be designed for the ascent stage main tanks.



Figure 6.—Descent stage RCS partial PMD/four-channel gallery.

TABLE 7.—LO2 RCS TANK PMD BUBBLE POINT ΔP DURING LUNAR ASCENT

Screen Mesh	Nominal ΔP (1) psf	LO2 density lb/ft ³	g/gc	Liquid Head Retention ft	LO2 Vapor Pressure (2) psia
200 x 1400	33.89	63.80	0.8	0.66	83.3
325 x 2300	52.83	63.80	0.8	1.04	83.3
200 x 1400	33.89	63.80	0.02	26.400	83.3
325 x 2300	52.83	63.80	0.02	41.600	83.3

Notes:

1. One standard deviation = 2.56 percent (Ref. 18)
2. LO2 vapor pressure at lunar liftoff

TABLE 8.—LCH4 RCS TANK PMD BUBBLE POINT ΔP DURING LUNAR ASCENT

Screen Mesh	Nominal ΔP (1) psf	LCH4 density lb/ft ³	g/gc	Liquid Head Retention ft	LCH4 Vapor Pressure (2) psia
200 x 1400	39.46	25.20	0.8	1.96	36.5
325 x 2300	59.52	25.20	0.8	2.95	36.5
200 x 1400	39.46	25.20	0.02	78.40	36.5
325 x 2300	59.52	25.20	0.02	118.00	36.5

Notes:

1. One standard deviation = 2.56 percent (Ref. 18)
2. LCH4 vapor pressure at lunar liftoff

3.2.1 Descent Stage and Ascent Stage Propellant Tanks Sizing Methodology

Descent stage RCS tank sizing was determined by identifying propellant requirements for expulsion, vapor residuals and unusable propellants, and identifying the initial ullage volume for launch. Expulsion propellants and unusable residuals were identified in the study assumptions and requirements of Table 3.

Vapor residuals had to be calculated. Generally, a 3 percent ullage volume at launch is selected in determining propellants tank volume. The unique aspect of descent stage tank sizing was that propellant tank sizing was based upon the assumption that a 3 percent ullage volume should exist at the beginning of RCS thrusting during lunar orbit insertion (LOI), 18 days into the mission. Consequently an iterative procedure was undertaken to determine propellant density at LOI, in order to specify the 3 percent ullage volume. The result is that a 5.5 percent ullage volume will exist at launch instead of the standard 3 percent volume.

The ascent tank sizing methodology was the same as for the descent stage, except that a 3 percent ullage volume was assumed at liftoff from the lunar surface, 229 days into the mission. An iterative procedure was undertaken to determine propellant density at lunar liftoff in order to identify the 3 percent ullage volume. The result is that a 7 percent (LCH₄) to 12 percent (LO₂) ullage volume will exist at launch. This is a significant departure for a standard vehicle launch from Earth, but the additional ullage volume is needed to accommodate propellant volume expansion during the 229 days before propellants are expelled for the first time.

The tank sizes of Table 9 reflect the sizing methodology used above. Tank wall thicknesses were calculated for a 325 psia operating pressure.

3.2.2 RCS Tank Partial PMD/Four-Channel Gallery Sizing Criteria

Concept No. 1 designs selected for the descent stage RCS propellant tanks are identical except for the scale difference to accommodate the tank diameter. Four channels are equally spaced circumferentially and connected to a sump located over the tank outlet. The channels will be mounted along the pitch and yaw vehicle axes to increase the likelihood that the liquid pool feeding the thrusters will reside over a channel when the pitch and yaw thrusters fire to maintain vehicle attitude control. Channel lengths are shown in Table 10 for the two propellant tanks. Channel cross-section is the same for both tanks. A triangular channel cross-section of 3.0-in. base by 1.0-in. height is selected for each tank. The triangular cross-section was selected for stability, ease of manufacture, assembly, and installation, as will be discussed in Section 3.3.

A rigid screen is placed just forward of the channels at a height of 8.2 in. above the tank bottom to contain 16.6 percent of the propellant. The screen placement assures that the remaining 15 percent of usable propellant (14.6 percent by tank volume) will be retained in close proximity to the screen channels and be available upon demand for RCS thruster consumption. At this time in descent stage flight the main engine is used in the throttle-mode to brake the vehicle as it descends to Moon's surface. Thus, main engine firing will tend to collect RCS propellants at the tank bottom, maintaining significant contact between liquid pool and screen channels to feed the RCS thrusters upon demand. The design challenge is to maintain sufficient contact between the liquid pool and screen channels as such that screen breakdown will not occur until less than 2 percent residual propellant by volume remains, even when thrusters are firing in a manner that may unsettle the propellants from the aft bulkhead. PMD design descriptions in Section 3.3 will satisfy all design requirements, as will be discussed in Section 3.4.

3.2.3 Ascent Stage Partial PMD/Four-Channel Gallery Sizing Criteria

Concept No. 3 designs selected for the ascent stage main propellant tanks are identical except for the scale difference to accommodate the tank diameter. Four channels are equally spaced circumferentially and connected to a sump located over the tank outlet. The channels will be mounted along the pitch and yaw vehicle axes to increase the likelihood that the liquid pool feeding the thrusters will reside over a channel when the pitch and yaw thrusters fire to maintain vehicle attitude control. Channel lengths are shown in Table 10 for the two propellant tanks. Channel cross-section design is identical to the RCS propellant tanks channel design.

A rigid screen is placed just forward of the channels at a height of 8.308 in. above the tank bottom to contain 4 percent of the tank propellants. The screen placement assures that the remaining 2 percent of usable propellant will be retained in close proximity to the screen channels and be available upon demand

for RCS thruster consumption. As with Concept No. 1, the design challenge is to maintain sufficient contact between the liquid pool and the screen channels such that screen breakdown will not occur until less than 2 percent residual propellant by volume remains, even when thrusters are firing in a manner that may unsettle the propellants from the aft bulkhead. The Concept No. 3 design description in Section 3.3 will satisfy all design requirements.

TABLE 9.—DESCENT AND ASCENT TANK SIZING

Tank Material	Aluminum (6061-T6 or equivalent assumed)	
Sigma	45-ksi	
Descent Stage	LO2	LCH4
Tank Volume	10.10-ft ³	9.08-ft ³
Tank Diameter	32.16-in.	31.08-in.
Tank Wall Thickness (S.F. of 2)	0.116-in.	0.112-in.
Ascent Stage	LO2	LCH4
Tank Volume	99.36-ft ³	83.60-ft ³
Tank Diameter	69-in.	65.04-in.
Tank Wall Thickness (S.F. of 2)	0.249-in.	0.235-in.

3.3 Partial PMD/Four-Channel Gallery—Descent and Ascent Stages

The design discussed in this section is a partial PMD/four-channel gallery type design, which is similar for both the descent and ascent stages.

3.3.1 Descent Stage Partial PMD/Four-Channel Gallery Concept No. 1

Descent stage tank sizing was accomplished by identifying propellant requirements for expulsion, vapor residuals and unusable propellants, and identifying the initial ullage volume for launch. Expulsion propellants and unusable residuals were identified in the study assumptions and requirements for Table 3, and vapor residuals had to be calculated. Generally, a 3 percent ullage volume at launch is selected in determining propellant tank volume. The unique aspect of descent stage tank sizing was that propellant tank sizing was based upon the assumption that a 3 percent ullage volume should exist at the beginning of RCS thrusting during lunar orbit insertion (LOI), 18 days into the mission. Consequently an iterative procedure was undertaken to determine propellant density at LOI, in order to specify the 3 percent ullage volume. The result is that a 5.5 percent ullage volume will exist at launch.

Figure 8 illustrates one of the possible propellant management devices, Concept No. 1, for the descent stage RCS tank. This design utilizes a partial PMD four-channel gallery in conjunction with a static screen PMD installed in the aft-dome of the descent stage RCS tank. In order to meet flow rate requirements, RCS engine contingency operation of a continuous thrust duration of 300 sec (up to 15 percent total propellant consumption), and a nominal thruster pulse duration of 0.07 to 0.09 sec. Approximately 16.6 percent of the propellant needs to be contained in the aft section of the tank to provide vapor-free propellant delivery. For Concept No. 1, LO2 tank, the static screen is positioned at a height of 8.32 in. from the bottom of the tank, shown in Figure 9, in order to retain 16.6 percent of the propellant in the aft-section.

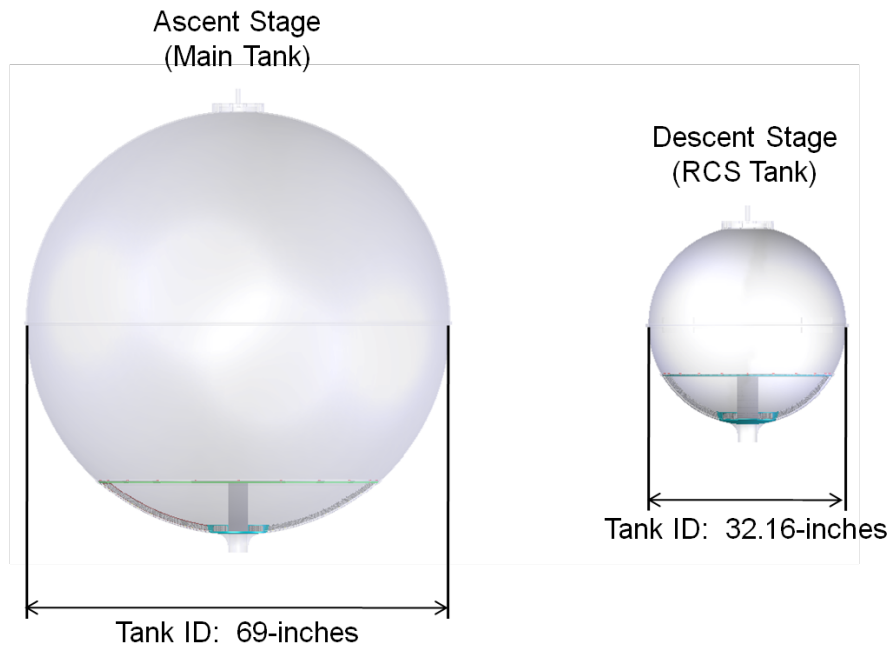


Figure 7.—Ascent stage RCS/ME and descent stage RCS tank size comparison.

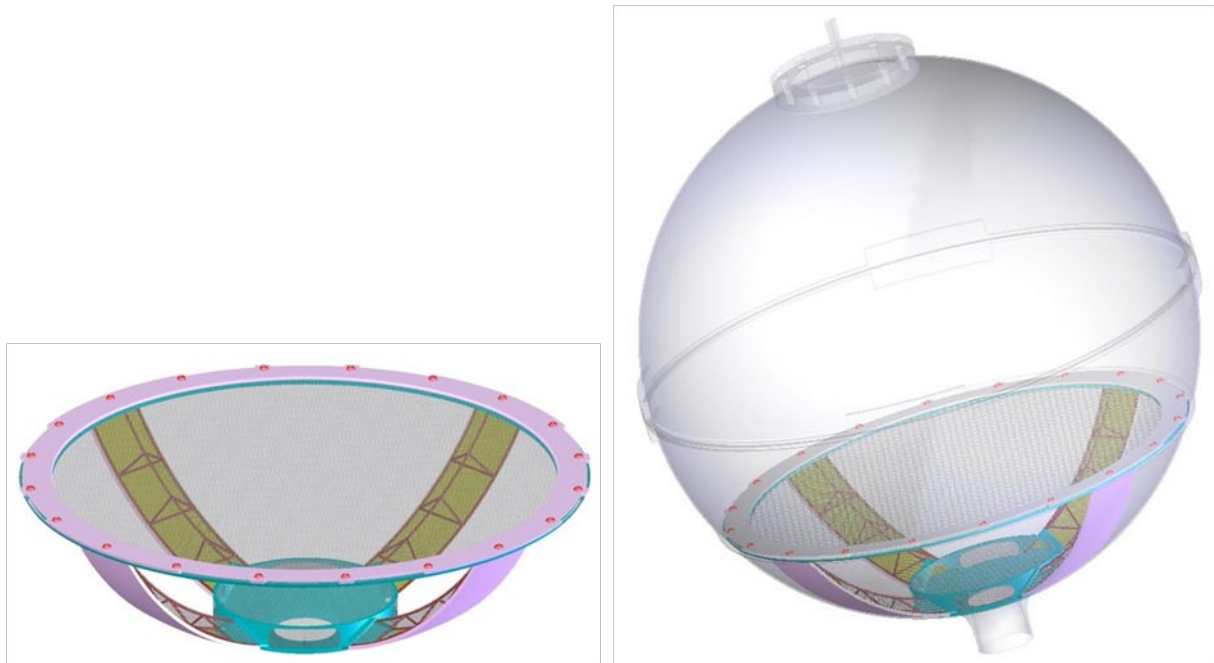


Figure 8.—Concept No. 1—Descent stage RCS partial PMD/four-channel gallery design (Left: PMD; Right: PMD installed in aft dome of tank).

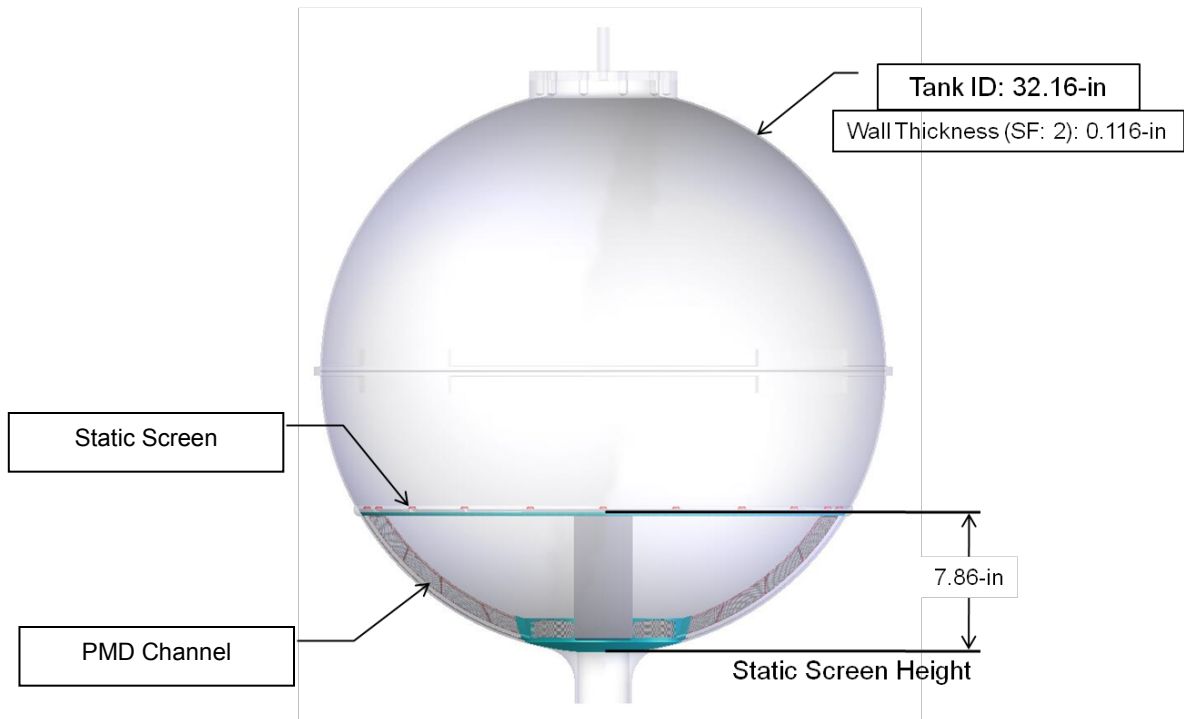


Figure 9.—Concept No. 1—Descent stage RCS LO2 tank partial PMD/four-channel gallery installed in aft dome at location to retain 16.6 percent of propellant.

The four-channel gallery component of Concept No. 1 consists of four screen covered channels and a common sump manifold. It is designed to meet the nominal RCS flow rate requirements of 0.09 to 0.15 kg/sec for the LO2 descent stage tank and 0.03 to 0.05 kg/sec for the LCH4 tank. Each channel is comprised of four separate components which can be welded or press-fit together, dependent upon a finalized design. Figure 10 shows the various components of the four-channel gallery. The gallery components consist of a triangular trussed ‘skeleton’ which is wrapped in a fine stainless steel mesh screen. The triangular cross-sectional area of the channels is 1.5 in.², as shown in Figure 11. The channels designed with the screen communication surface facing inward, toward the center of the tank, unlike conventional PMD gallery designs where the screen communication surface faces outward. The back of the channel ‘skeleton’ is fitted with a thin sheet-metal backing which is coated in Teflon to reduce the possibility of metal-on-metal rubbing due to vibration. The channels are then welded into the sump/manifold, as shown in

Figure 12, has communication windows covered by fine mesh stainless steel screen to aid in unusable residual reduction. The top of the sump is also covered with a fine mesh stainless steel screen. Figure 11 gives an outline of the channel and sump volumes and screen surface areas for the LO2 Descent stage RCS tank Concept No. 1.

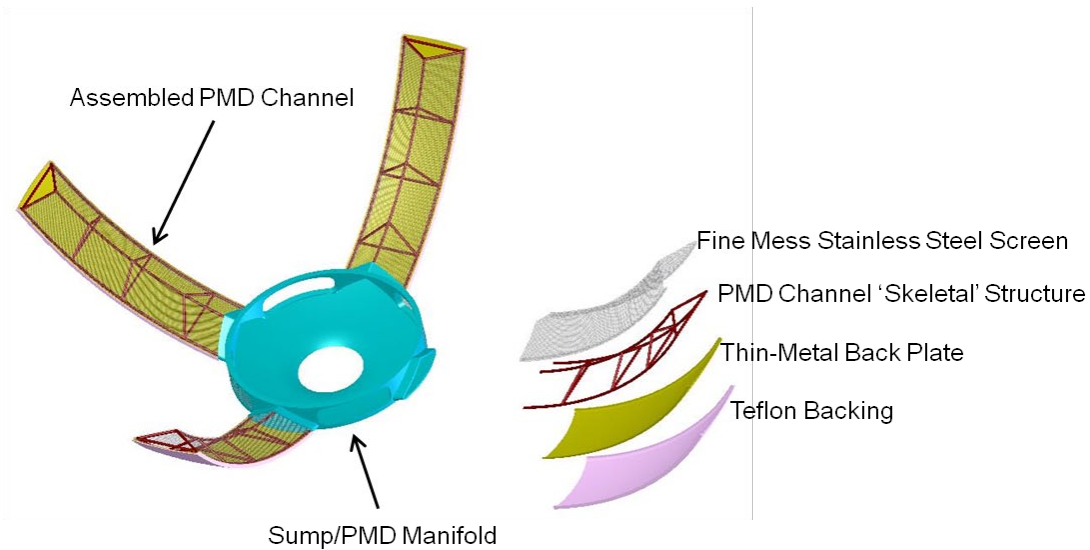
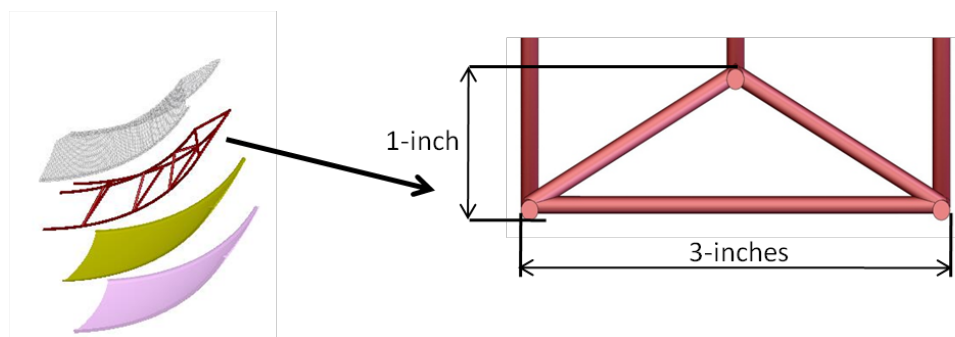


Figure 10.—Concept No. 1—Descent stage four-channel gallery and sump assembly.



- Channel Cross-sectional Area: 1.5-in.²
- Single Channel Screen Surface Area: 35.09-in.²
- Total Channel Screen Surface Area: 35.09-in.² x 4 = 140.36-in.²
- Single Channel Volume: 18.48-in.³
- Sump Volume: 88.02-in.³
- Total Partial PMD Channel Volume: 161.94-in.³

Figure 11.—Concept No. 1—Descent stage LO2 tank four-channel 'skeletal' structure cross-sectional area, channel screen surface area, and channel volume.

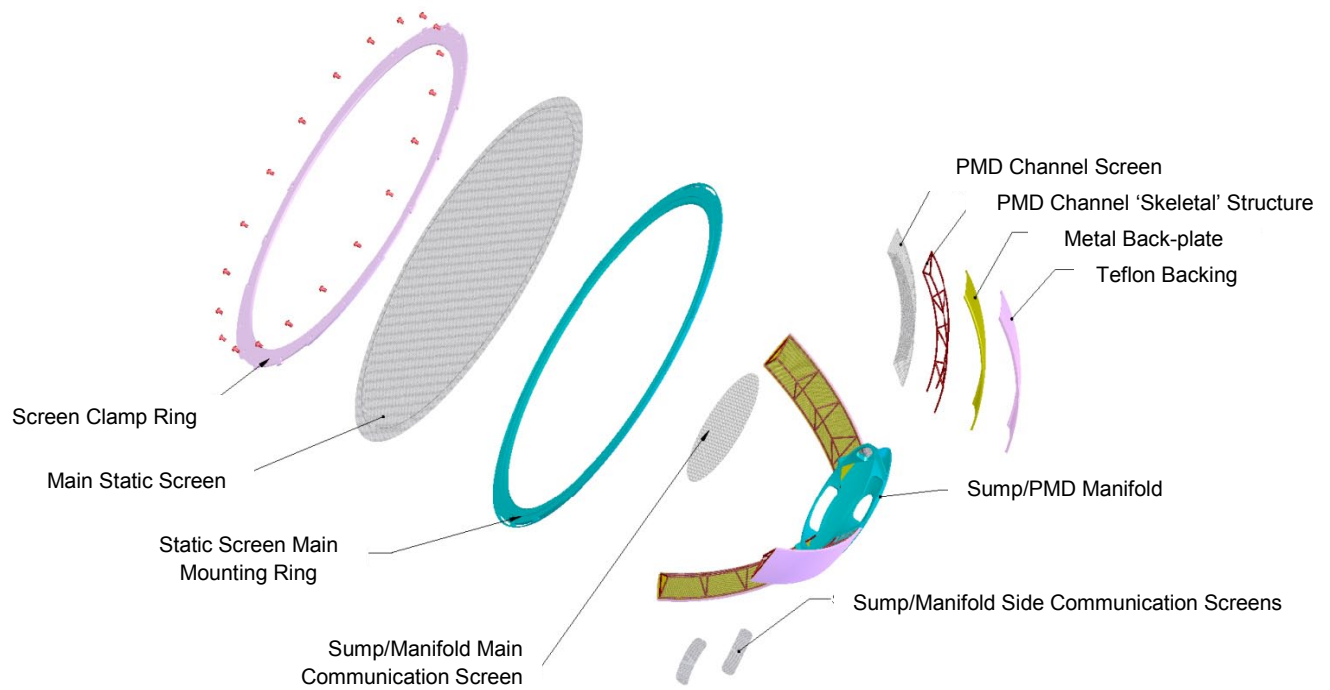


Figure 12.—Concept No. 1—Descent stage RCS partial PMD/four-channel gallery components and assembly.

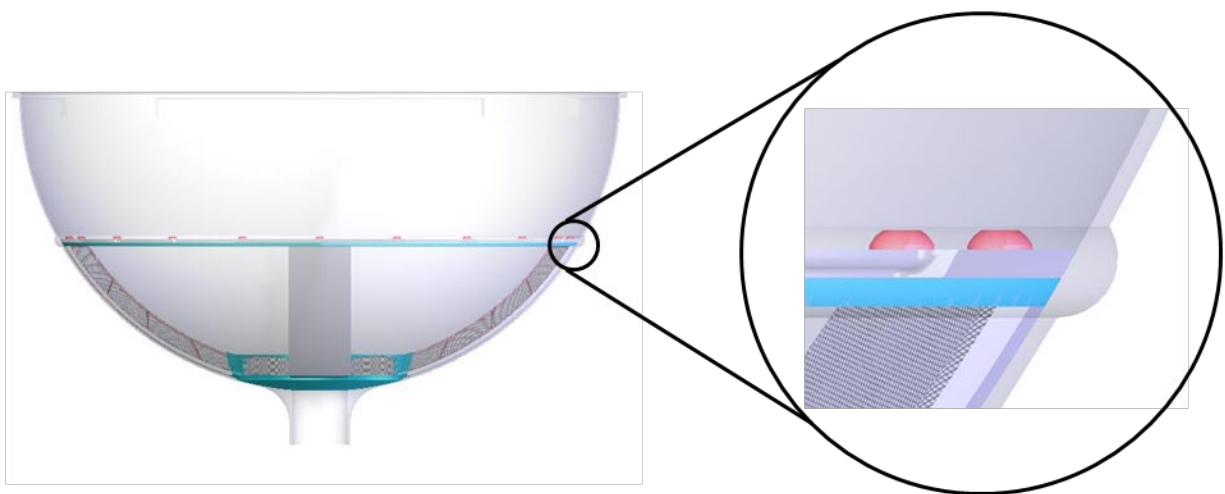


Figure 13.—Thicker tank material maintained locally to compensate for material deformation/degradation during welding process.

The static screen PMD component of Concept No. 1 consists of a main mounting ring, a fine mesh stainless steel screen, and a Teflon upper ring. The fine mesh stainless steel screen is clamped in place by the Teflon upper ring. The four-channel gallery component of the PMD is welded to the underside of the main mounting ring. Assembly of the PMD is illustrated in

Figure 12. The main mounting ring is welded to the inside of the aft-dome of the tank at the determined level before the tank halves are assembled. Excess material can be rolled into the particular region, shown in Figure 13, when the dome is spun to account for material deformation/degradation during the welding process. The driving parameters for this particular design, such as the inward facing gallery channels, are the simplicity of the design for assembly and the ease of installation.

3.3.2 Ascent Stage Partial PMD/Four-Channel Gallery Design Concept No. 3

The ascent tank sizing methodology was the same as for the descent stage, except that a 3 percent ullage volume was assumed at liftoff from the lunar surface, 229 days into the mission. An iterative procedure was undertaken to determine propellant density at lunar liftoff in order to identify the 3 percent ullage volume. The result is that a 7 percent (LCH₄) to 12 percent (LO₂) ullage volume will exist at launch. This is a significant ullage volume for launch from Earth, but the additional ullage volume is needed for propellant volume expansion during the 229 days before propellants are expelled for the first time.

Concept No. 3, the partial PMD/four-channel gallery design for the ascent stage RCS/ME tank is similar to that discussed prior in Section 3.3.1. Figure 14 illustrates Concept No. 3, a partial PMD/four-channel gallery design for the ascent stage RCS/ME tank. The upper static screen for Concept No. 3, LO₂ tank, is located 8.31-in. from the bottom of the tank, with a local tank radius of 23.1-in. as depicted in Figure 15. At this position, the PMD retains approximately 4.0 percent of the propellant in the aft section of the tank. The main construction of Concept No. 3 is the same as that for Concept No. 1. The gallery channels retain the same cross-sectional area of 1.5-in.², as in Concept No. 1, but the gallery channel volume differs due to the difference in the tank sizes. These values are given in Figure 16.



Figure 14.—Concept No. 3—Ascent stage RCS/ME partial PMD/four-channel gallery design.

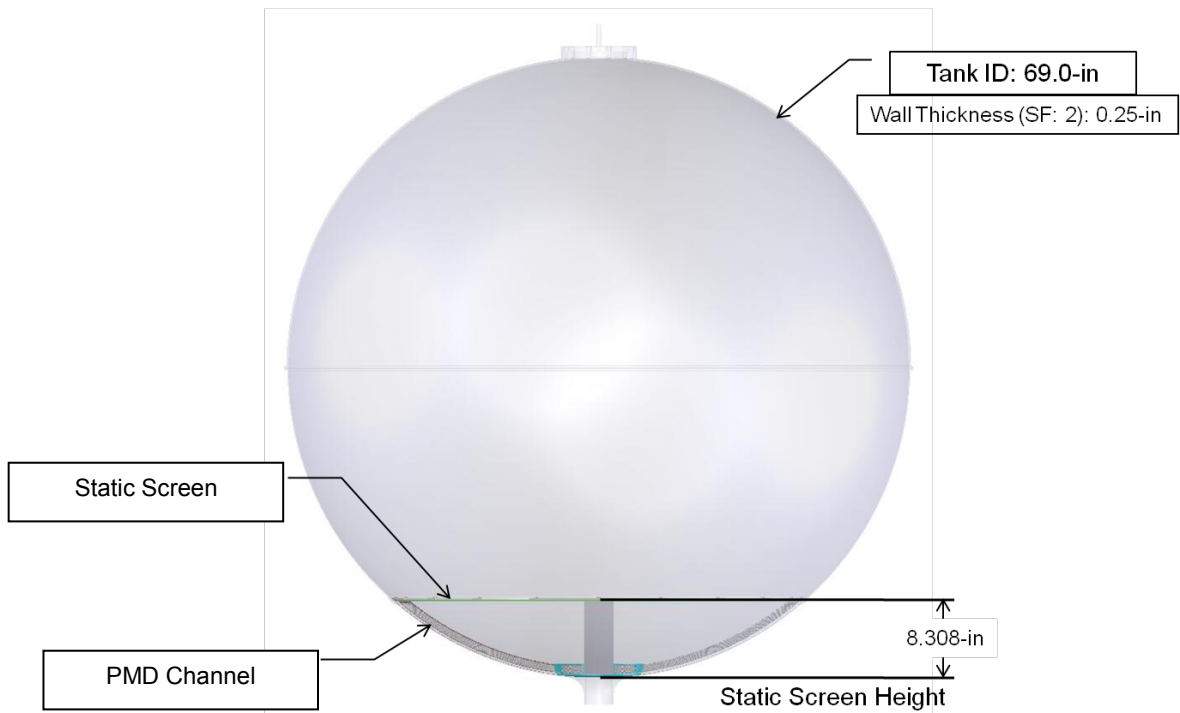
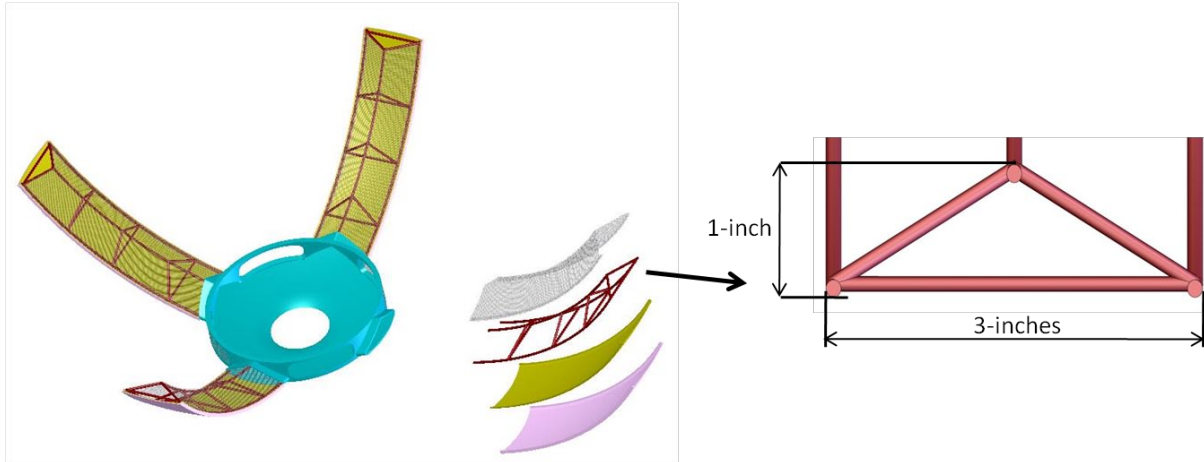


Figure 15.—Concept No. 3—Ascent stage RCS/ME Partial PMD/four-channel gallery installed in aft-dome at location to retain 4.0 percent of propellant.



- Channel Cross-sectional Area: 1.5-in.²
- Single Channel Screen Surface Area: 63.51-in.²
- Total Channel Screen Surface Area: 63.51-in.² x 4 = 254.04-in.²
- Single Channel Volume: 32.165-in.³
- Sump Volume: 75.35-in.³
- Total Partial PMD Channel Volume: 204.01-in.³

Figure 16.—Concept No. 3—Ascent stage four-channel 'skeletal' structure cross-sectional area, channel screen surface area, and channel volume.

3.4 PMD Screen Breakdown Criteria

PMD screen breakdown describes the condition where a PMD (filled with liquid) is surrounded by vapor and, as the differential pressure across the screen exceeds ΔP_{σ} , vapor flows into the PMD. Vapor-free flow of liquid can no longer be guaranteed once vapor begins to flow into the PMD. The unusable residual at screen breakdown represents the sum of liquid within the PMD plus the liquid pool outside the PMD.

Three orientation of liquid residual were evaluated in an effort to identify the maximum residual orientation; 1) liquid positioned forward against the rigid screen, 2) liquid positioned against the tank wall with an acceleration vector normal to the stage vertical axis, and 3) liquid positioned against the tank wall but with the acceleration vector at about 45° to the stage vertical axis. All orientations gave approximately the same residual as a function of channel screen wetted area. Item three was the liquid orientation selected for this study.

Screen breakdown will occur at the point of minimum internal pressure, which is likely to be at the top of the opposite channels (see Figure 17). Vapor-free flow of liquid will continue while ΔP_{σ} exceeds the sum of all pressure drops. This relationship is described in equation form as:

$$\Delta P_{\sigma} \geq \rho \frac{g}{g_c} H + \Delta P_{scr} + \Delta P_{flow} + q + \Delta P_{accel} \quad (1)$$

where

ΔP_{σ}	screen bubble point ΔP (psf)
$\rho \left(\frac{g}{g_c} \right) H$	liquid head (psf)
ρ	liquid density (lb/ft ³)
$\frac{g}{g_c}$	acceleration in g's
H	liquid head (ft)
ΔP_{scr}	flow pressure loss across screen (psf)
ΔP_{flow}	flow pressure loss across screen channel (psf)
q	velocity head pressure in screen channel (psf)
ΔP_{accel}	transient flow acceleration pressure drop (psf)

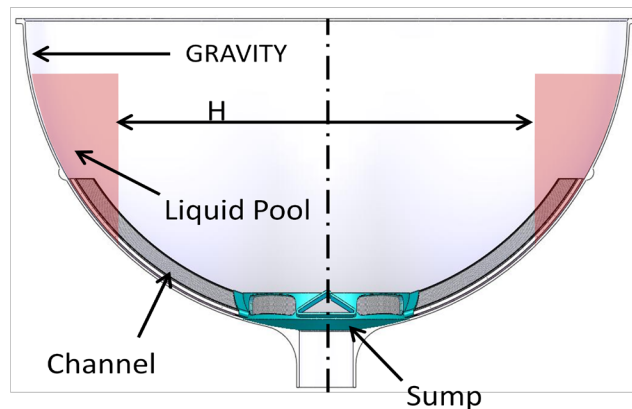


Figure 17.—Sketch depicting PMD pressure drops in correspondence to Equation (1).

ΔP_o is given in Table 5 and Table 6 for LO2 and LCH4, respectively, and for two twilled dutch metal screen meshes at liquid vapor pressures predicted for lunar orbit injection (LOI). Note also that liquid head retention capability of each screen mesh is given at 0.8 and 0.02 g's. Tabulated values of ΔP_o are measured nominal values from Reference 18 (LCH4) and 3.2 (LO2). The standard deviation applied to both propellants is the measured maximum value for LCH4 (Ref. 18). For conservatism, the ΔP_o values selected for use in Equation (1) are nominal values minus 3 standard deviations. Liquid densities are those included in Table 5 and Table 6.

Liquid head, H , is the radial distance from the top of any channel to the top of the opposite channel, and is approximately 2.34 ft (LO2 tank). Values of liquid head are given in Table 10 for all PMD designs (two for the Descent stage RCS tanks and two for the Ascent stage Main tanks)

The pressure loss due to flow through the woven screen, ΔP_{scr} , is calculated using screen properties, as shown in Reference 19, and propellant properties. The result is given in Figure 18 as pressure loss versus wetted screen flow area for the upper limit RCS engine flow rates of 0.33 lb/sec (LO2) and 0.11 lb/sec (LCH4).

The pressure loss due to flow through the screen channels is conservatively determined as follows:

$$\Delta P_{flow} = \left(\frac{fL}{D} \right) \times q \quad (2)$$

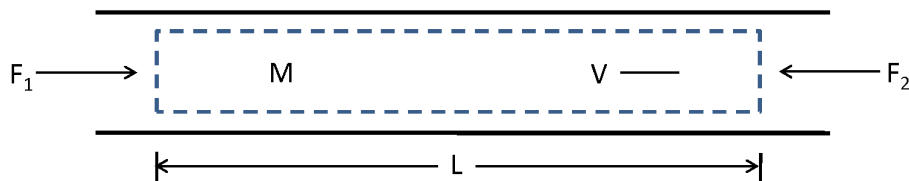
where

f	friction factor (function of Reynolds number and channel relative roughness) 0.1 (complete turbulence in a rough pipe)
L	channel length, 0.8 ft (LO2 tank)
D	equivalent channel diameter (based on 3.0 in. base by 1.0 in. high channel cross-section) $4 \times (A/P)$, 0.0757 ft (LO2 and LCH4 PMD)
A	cross-sectional channel flow area, 0.0104 ft ²
P	perimeter of channel cross-section, 0.55 ft

Values of L and A are given in Table 10 for all PMD designs.

During much of the Descent stage mission RCS engine flow will be nearly uniformly distributed through each of the four channels. However, it must be assumed that the residual liquid may pool over only one channel when RCS thrusters are fired. This means that all of the propellant may flow through a single channel when RCS engines are commanded on. The pressure loss for all RCS engine flow through a single channel is 0.59 psf (LO2). The corresponding velocity head pressures are 0.25 psf (LO2). These values are relatively insignificant in comparison to the other pressure drops and losses. Channel pressure losses and velocity head pressures are given in Table 10 for all PMD designs.

The pressure drop due to accelerating a propellant mass in a channel (sketch below) can be determined by applying Newton's second law as follows:



**LO2 and LCH4 Pressure Loss Through Dutch Twilled Woven Screen
(RCS Engine Flow Rates)**

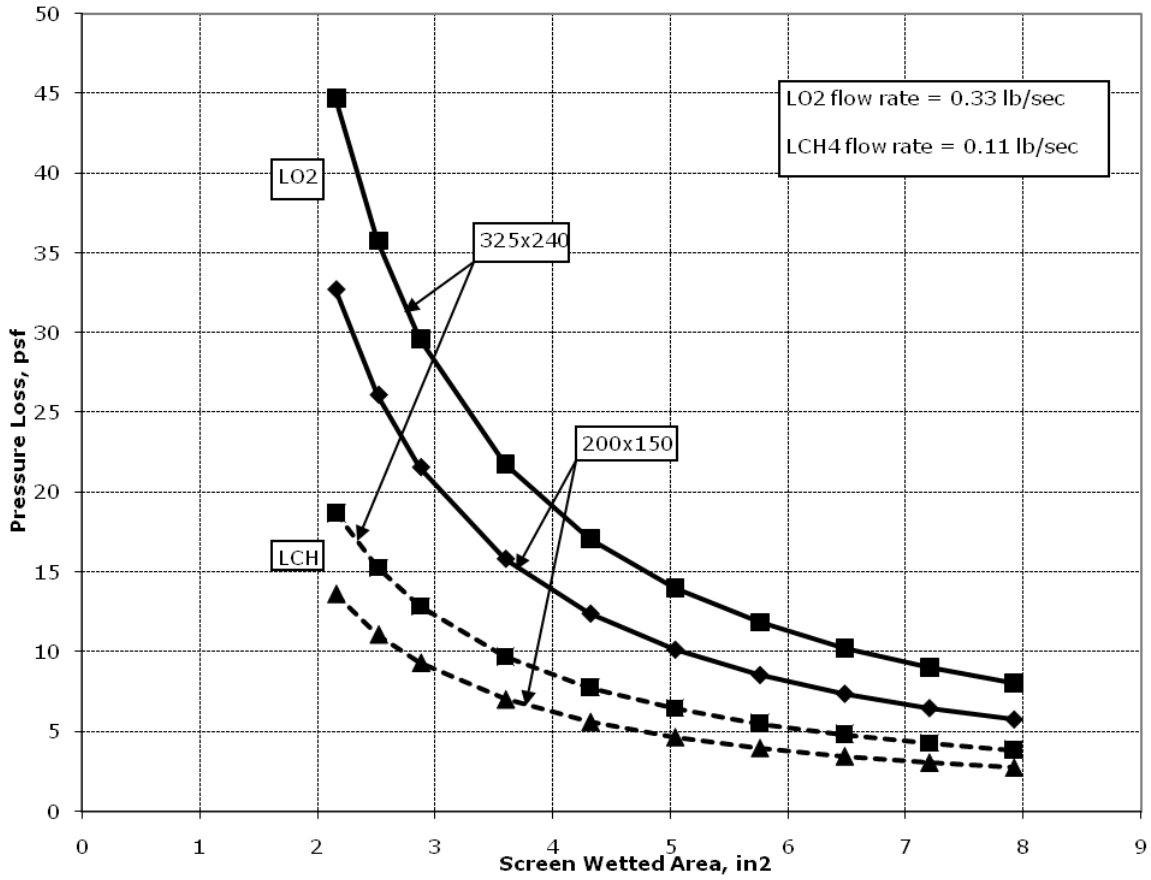


Figure 18.—Pressure loss through screen as function of wetted screen area.

$$F_1 - F_2 = \frac{M}{g_c} \cdot \frac{dV}{dt} \quad (3)$$

But,

$$F = PA \quad (4)$$

$$M = \rho AL \quad (5)$$

$$V = \frac{\dot{m}}{\rho A} \quad (6)$$

Therefore,

$$P_1 A_1 - P_2 A_2 = (P_1 - P_2)A = \frac{\rho L A}{g_c} \times \frac{dv}{dt} = \rho L A \times \frac{d\left(\frac{\dot{m}}{\rho A}\right)}{dt} = \frac{\rho L A}{\rho A} \times \frac{d\dot{m}}{dt} \quad (7)$$

For this study the assumption was made that RCS thruster flow rate would increase linearly from zero to steady state in a time, dt , which was varied from 0.01 to 0.08 sec. Thus Equation (7) becomes

$$\Delta P_{accel} = \left(\frac{L}{A}\right) \left(\frac{1}{g_c}\right) \left(\frac{d(\dot{m})}{dt}\right) [\text{psf}] \quad (8)$$

where

\dot{m}	propellant flow rate, $\frac{\text{lb}}{\text{sec}}$
$\frac{d(\dot{m})}{dt}$	rate of change of \dot{m} , $\frac{\text{lb}}{\text{sec}^2}$
g_c	$32.174 \frac{\text{lbf} \cdot \text{ft}}{\text{lbf} \cdot \text{sec}^2}$
L	channel length, ft
A	channel cross-section area, ft^2

Figure 19 gives ΔP_{accel} for transient flow through a single LO2 and LCH4 PMD channel. As stated above, it is possible that a pool of liquid may reside over a single channel toward the end of the descent stage mission, so the transient pressure drop should reflect this possibility for the RCS engines in a pulse-mode. Transient pressure drop is one of the two major factors in determining PMD screen breakdown. The other major factor, ΔP_{scr} , is discussed in Section 3.4.1.

Note that the large values of transient pressure drop predicted by Equation (8) are unlikely to occur because the equation is based upon transient flow in a rigid system, whereas the partial communication PMD is quite flexible. The more likely scenario is that the screen channels and screen covering the sump will collapse slightly as the RCS engines demand flow. For example, approximately 0.12 in.³ of LO2 will flow to the RCS engines from the PMD, assuming it takes 0.03 sec to achieve a steady state flow rate of 0.33 lb/sec. Because this volume change represents about a 0.05 percent of the PMD sump plus channel volumes the screen collapse will be imperceptible during the flow transient; recovery to the original volume will occur shortly after steady state flow is attained. If even 50 percent of the transient flow is provided by PMD volume collapse, the transient pressure drop could be 50 percent of that given for a rigid system. This assumption, which appears to be conservative, was made in predicting PMD performance, and the corresponding acceleration pressure drops are also shown in Figure 19.

**Pressure Drop in Screen Channel During RCS Engine Start Transient
(Flow Through single Channel)**

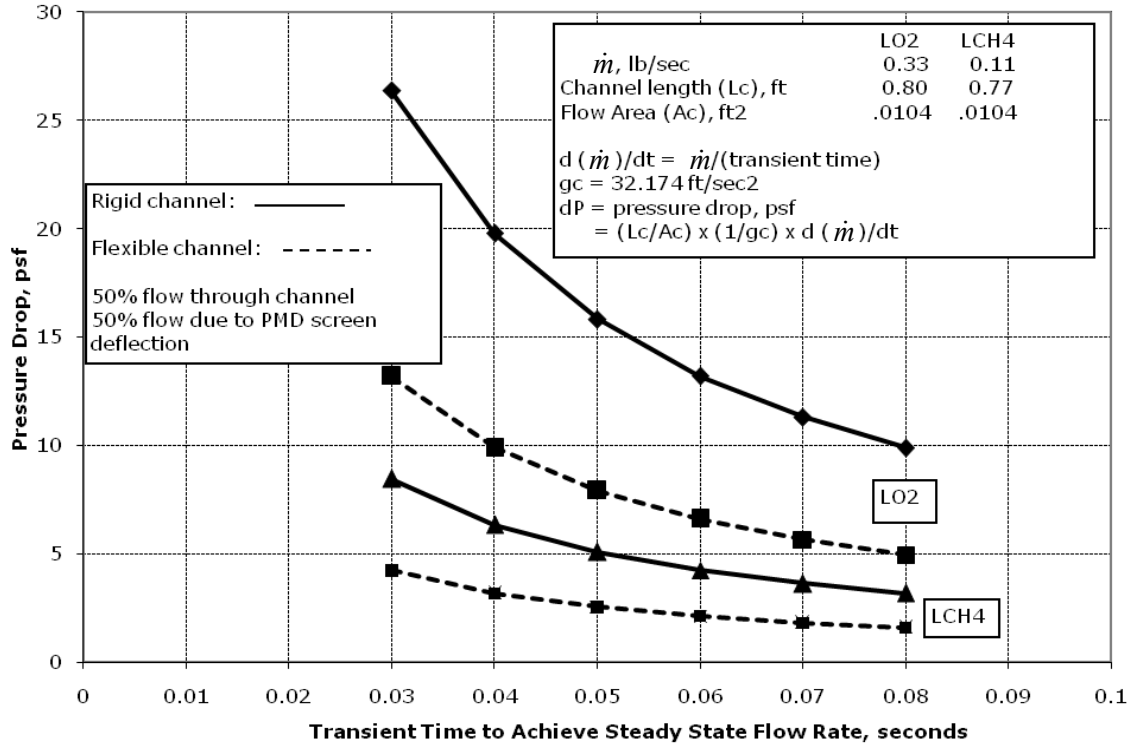


Figure 19.—Pressure drop in PMD screen during RCS engine start transient.

3.4.1 LO2 Residual for Descent Stage RCS Tank

Screen breakdown, which determines residuals, will occur when

$$\Delta P_{\sigma} - \left[\rho \left(\frac{g}{g_c} \right) H + \Delta P_{scr} + \Delta P_{flow} + q + \Delta P_{accel} \right] = 0 \tag{9}$$

Since, for this study, ΔP_{accel} can be known by selecting a representative transient time to achieve steady state propellant flow to the RCS engines, the solution of Equation (9) is a function of ΔP_{scr} alone. However, ΔP_{scr} is a function of screen area wetted by liquid residual residing outside the PMD. Consequently, a relationship between liquid residual outside of the PMD and the PMD screen area (wetted by the liquid residual) is needed. This relationship is given in Figure 20 and was obtained by assuming the following:

1. The liquid is symmetrically pooled between two channels and liquid surface is approximately at 45° to the main vehicle axis.
2. A flat liquid-vapor interface was assumed for simplicity and conservatism.

Two other orientations were considered; a pool of liquid at the tank wall with the interface parallel to the main vehicle axis, or a liquid pool in contact with the rigid screen forward of the four channels. The selected orientation yielded slightly more residual than the other two orientations. Screen channel plus sump residual quantities were added to the data from Figure 20 and the results plotted in Figure 21. Combining Figure 18 and Figure 21 yields a new relationship shown as PMD residuals versus ΔP_{scr} in Figure 22. Now, Equation (9) can be solved to give liquid residuals at the instant of screen breakdown.

However, Equation (9) can be arranged to provide additional useful information by defining a new variable, ΔP_{margin} as,

$$\Delta P_{margin} = \Delta P_{\sigma} - \left[\rho \left(\frac{g}{g_c} \right) H + \Delta P_{scr} + \Delta P_{flow} + q + \Delta P_{accel} \right] \quad (10)$$

Equation (10) was solved by assuming engine start transient times of 0.03 and 0.04 sec; a 325×2300 twilled dutch screen was also assumed. Results are given in Figure 23 and show that ΔP_{margin} will remain above values of 26 and 30 psf until the normalized residual has decreased to about 0.02 (or 2.0 percent by volume) at engine transient start times of 0.03 and 0.04 sec, respectively. This ΔP_{margin} is about 37 to 43 percent of ΔP_{σ} . Screen breakdown will occur at <1.94 percent residual for both engine start transient times.

No safety factor has been included in this analysis other than to select a value for ΔP_{σ} that is nominal value minus three standard deviations. It is expected that the PMD screen flexibility will diminish the magnitude of ΔP_{accel} , but testing will be necessary to determine the actual benefit of screen flexibility.

It is evident that RCS engine start transient time is an important factor in stage design. Clearly, there will be conflicting requirements between the desire for an instantaneous response from the stage RCS system, and the desire for an acceptably short response time from the designers in order not to overburden the PMD design.

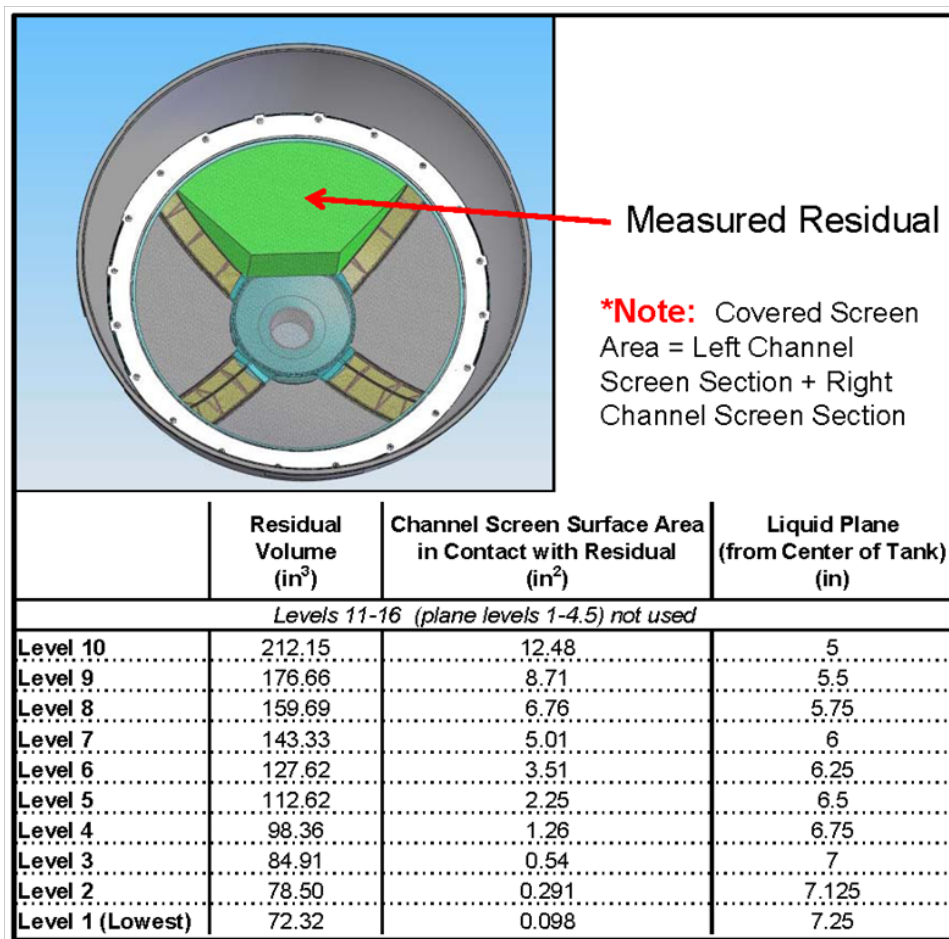


Figure 20.—Descent stage RCS partial PMD residual volume and screen surface area (covered by residual) between two channels.

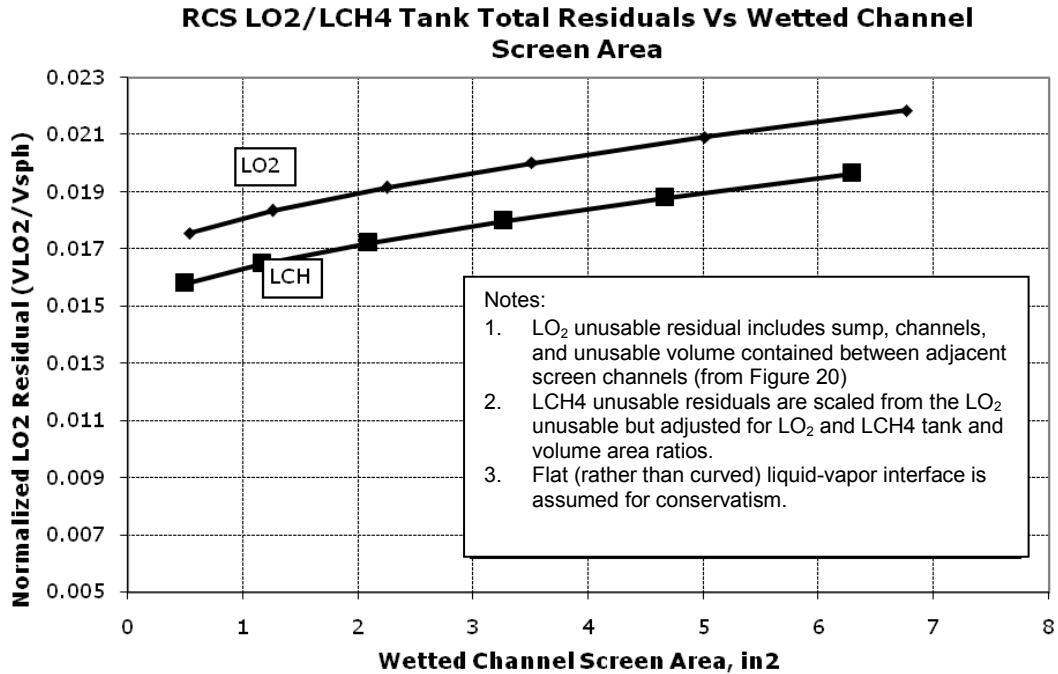


Figure 21.—LO₂ /LCH₄ tank residuals versus channel wetted screen area.

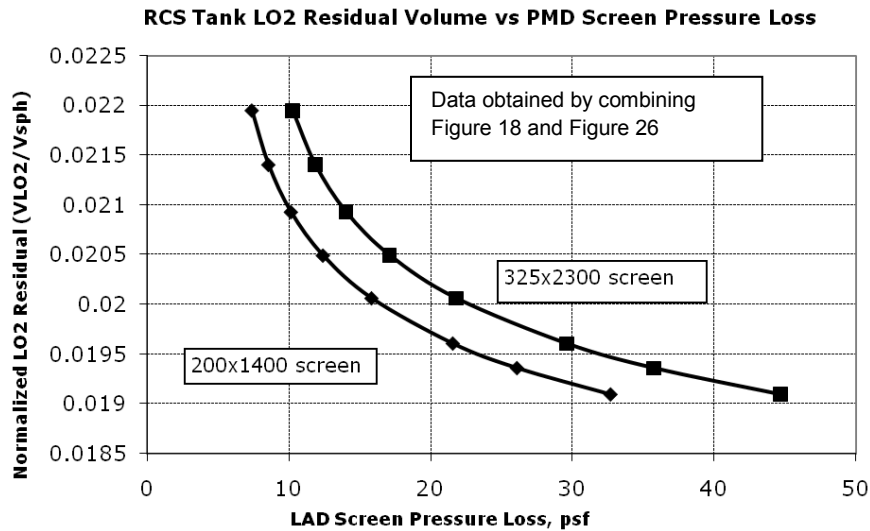


Figure 22.—LO₂ RCS tank residual volume versus PMD screen pressure loss.

3.4.2 LCH₄ Residuals For Descent Stage RCS Tank

An identical approach was taken to determine LCH₄ PMD residuals as described above for LO₂. For two primary reasons the LCH₄ design will have substantially more margin than will the LO₂ design: LCH₄ ΔP_{scr} is less than half that for LO₂ when flowing through the same wetted screen area (Figure 18), and ΔP_{accel} is about 30 percent that for LO₂ flow (Figure 19). At the same time, ΔP_o is only slightly less than for LO₂.

The LCH₄ normalized volume residuals versus screen area data shown in Figure 21 is scaled from Figure 20 based upon LO₂ and LCH₄ tank area and volume ratios. Consequently, combining Figure 18 (for LCH₄) with Figure 21 (for LCH₄) yields PMD residuals versus ΔP_{scr} (Figure 24). Now all

information is available (including Table 10 inputs) to solve Equation (11) for ΔP_{margin} versus the percentage of LCH4 residual volume (Figure 25).

The results of Figure 25 are shown for an engine start transient time of 0.03 sec and for two twilled dutch screen configurations, 325×2300 and 200×1400. The second screen configuration was included because a significant ΔP_{margin} can be shown for the coarser screen mesh at the low engine start transient time. Note that a 2.0 percent LCH4 residual by volume can be achieved at a ΔP_{margin} of about 28 and 46 psf for the two screen materials. This ΔP_{margin} is about 69 to 73 percent of ΔP_{σ} .

To summarize, the selected PMD design concepts for the Descent stage RCS tanks will satisfy study requirements of 2 percent unusable liquid residual by tank volume.

3.5 LO2 Residuals for Ascent Stage Main Tank

The same methodology was used to predict LO2 residuals for the ascent stage PMD design as for the descent stage LO2 RCS tank PMD design. ΔP_{scr} versus screen wetted area (Figure 18) is directly applicable to the main tank design. ΔP_{acc} data of Figure 19 is also applicable, but must be adjusted for channel length (see Table 10). ΔP_{acc} for this main tank design is 83 percent greater than shown in Figure 19. The relationship of liquid residual to screen wetted area was obtained for the liquid orientation shown in Figure 26, which data is plotted in Figure 27. Figure 27 was then combined with Figure 28 to generate residuals versus ΔP_{scr} , Figure 28. Finally, Equation (11) was solved using the data from Figure 28 and Table 10, and assuming engine start transient times of 0.03 and 0.04 sec for the adjusted data of Figure 19 using the 325×2300 screen. Results, given in Figure 29, show that liquid residual will be less than 0.50 percent by volume, even for a 0.03 sec engine start transient time. This corresponds to a ΔP_{margin} of about 33 percent of ΔP_{σ} . ΔP_{margin} will increase to about 45 percent if engine start transient time is 0.04 sec.

3.5.1 LCH4 Residuals for Ascent Stage Main Tank

An identical approach was taken to determine LCH4 PMD residuals as described above for LO2. As with the RCS tank PMD design, the LCH4 main tank PMD design will have substantially more margin than will the LO2 design for the same reasons as stated before: LCH4 ΔP_{scr} is less than half that for LO2 when flowing through the same wetted screen area (Figure 18), and ΔP_{accel} is about 30 percent that for LO2 flow (Figure 19). At the same time, ΔP_{σ} is only slightly less than for LO2.

The LCH4 normalized volume residuals versus screen area data shown in Figure 27 is scaled from Figure 26 using the LCH4-to-LO2 tank area and volume ratios of 0.8885 and 0.8375, respectively. Consequently, combining Figure 18 (for LCH4) with Figure 27 (for LCH4) yields residuals versus ΔP_{scr} (Figure 30). Now all information is available (including Table 10 inputs) to solve Equation (10) for ΔP_{margin} versus the percentage of LCH4 residual volume (Figure 31).

The results of Figure 31 are given for an engine start transient time of 0.03 sec and for two screen materials, 325×2300 and 200×1400. The second screen material was included because a significant ΔP_{margin} can be shown for this screen mesh at the selected engine start transient time. Note that a 0.3 percent LCH4 residual by volume can be achieved at a ΔP_{margin} of about 23 and 40 psf for the two screen materials, which is well below the study requirement. This ΔP_{margin} range is equivalent to 63 to 73 percent of ΔP_{σ} .

To summarize, the selected PMD design concepts for the ascent stage RCS tanks will be substantially lower than the study requirements of 2 percent unusable liquid residual by tank volume.

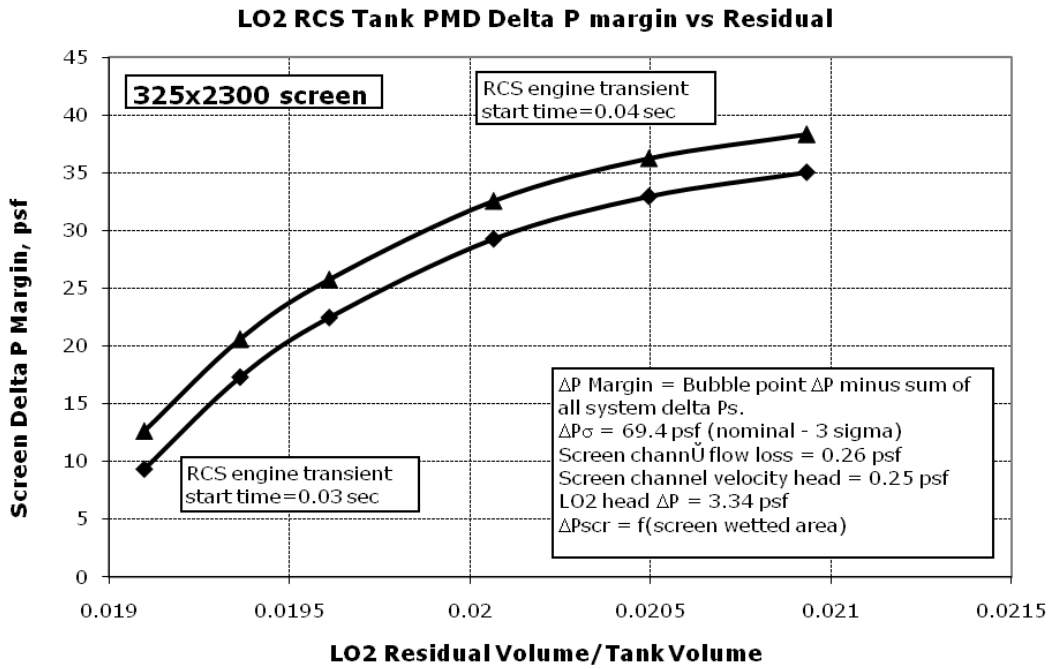


Figure 23.—LO2 RCS tank PMD screen ΔP margin versus LO2 residual.

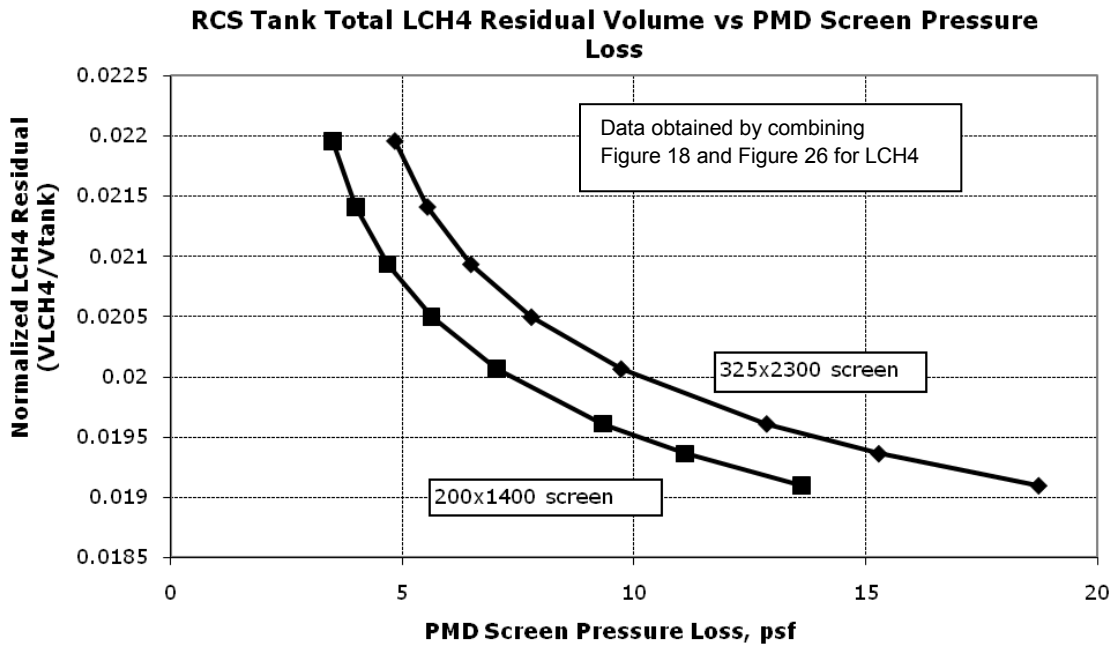


Figure 24.—LCH4 RCS tank residual volume versus PMD screen pressure loss.

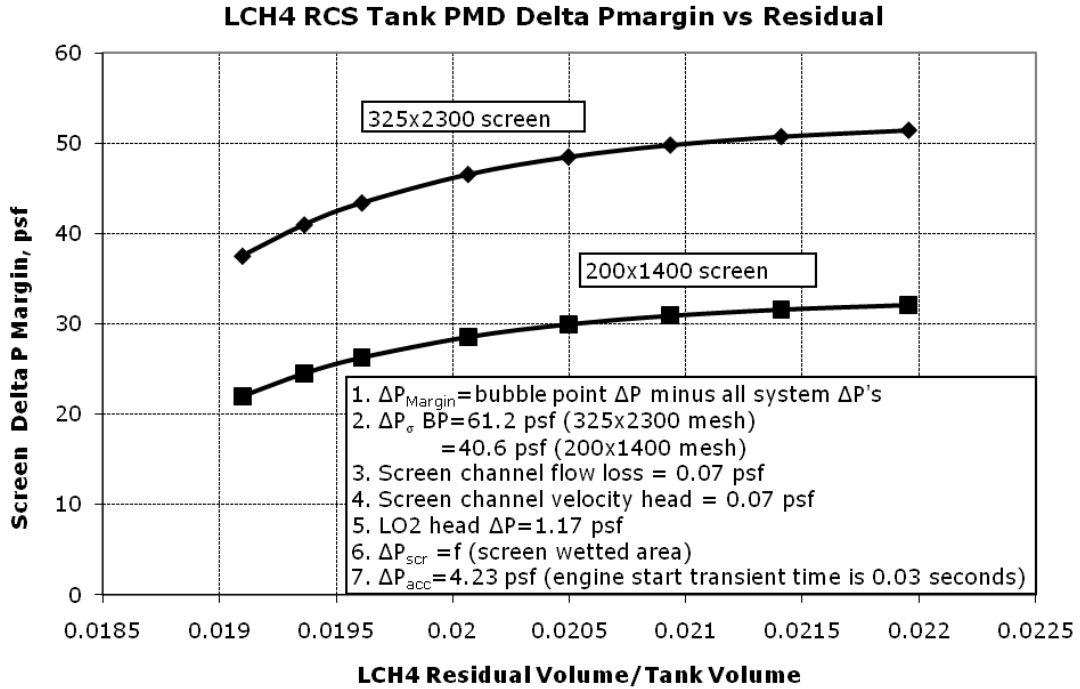


Figure 25.—LCH4 RCS tank PMD screen ΔP margin versus LCH4 residual.

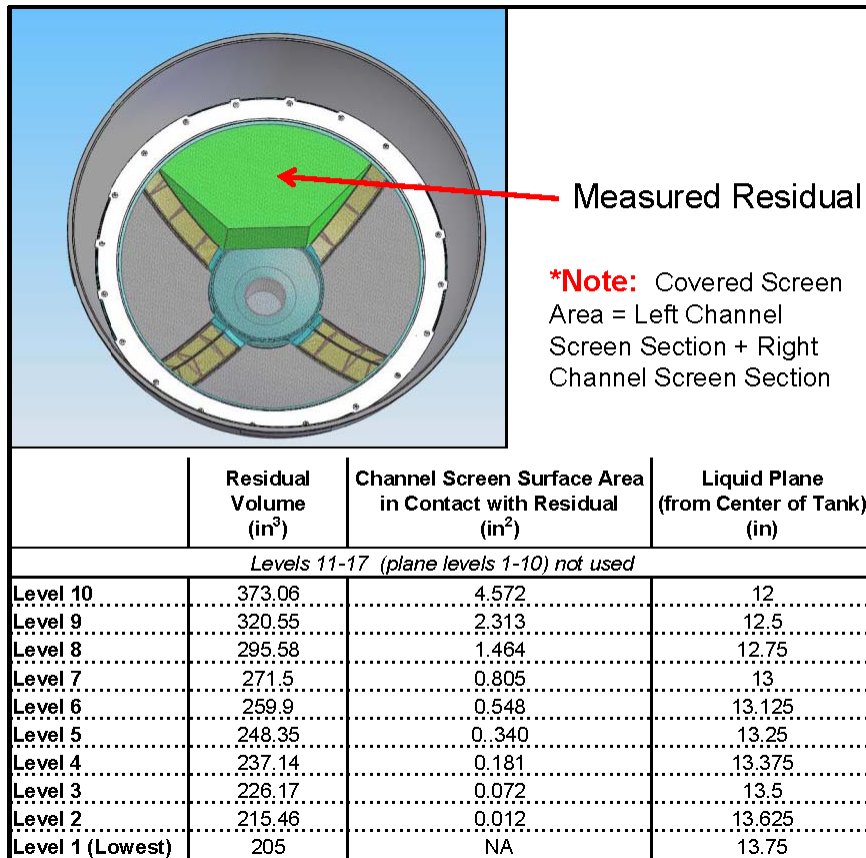


Figure 26.—Ascent stage RCS partial PMD residual volume and screen surface area (covered by residual) between two channels.

Main LO₂/LCH₄ Tank Total Residuals vs. Wetted Channel Screen Area

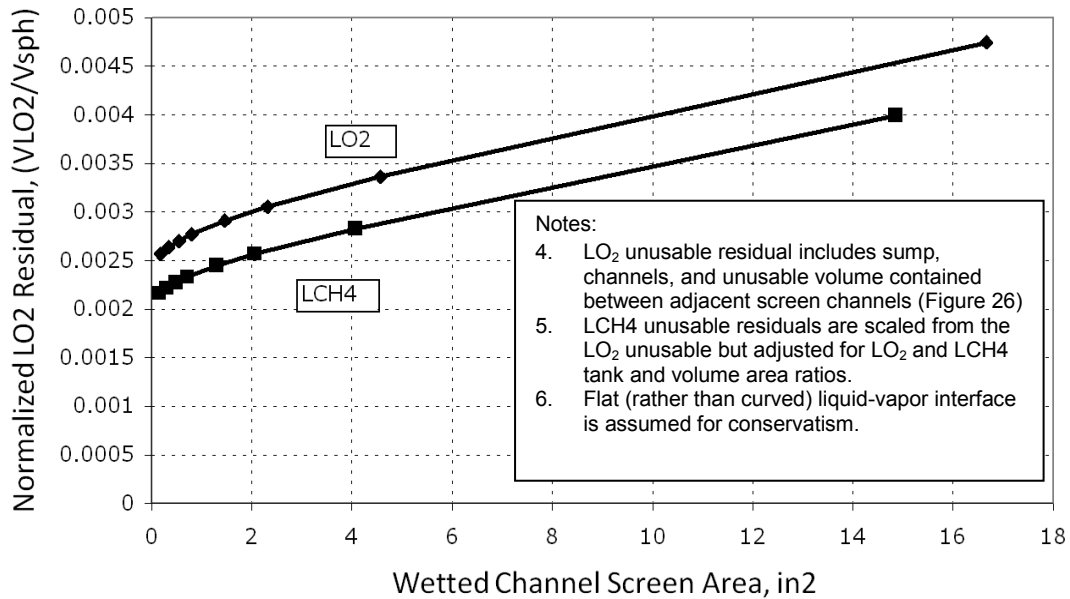


Figure 27.—Main LO₂ /LCH₄ tank residuals versus PMD channel wetted screen area.

Main Tank Total LO₂ Residual Volume vs PMD Screen Pressure Loss

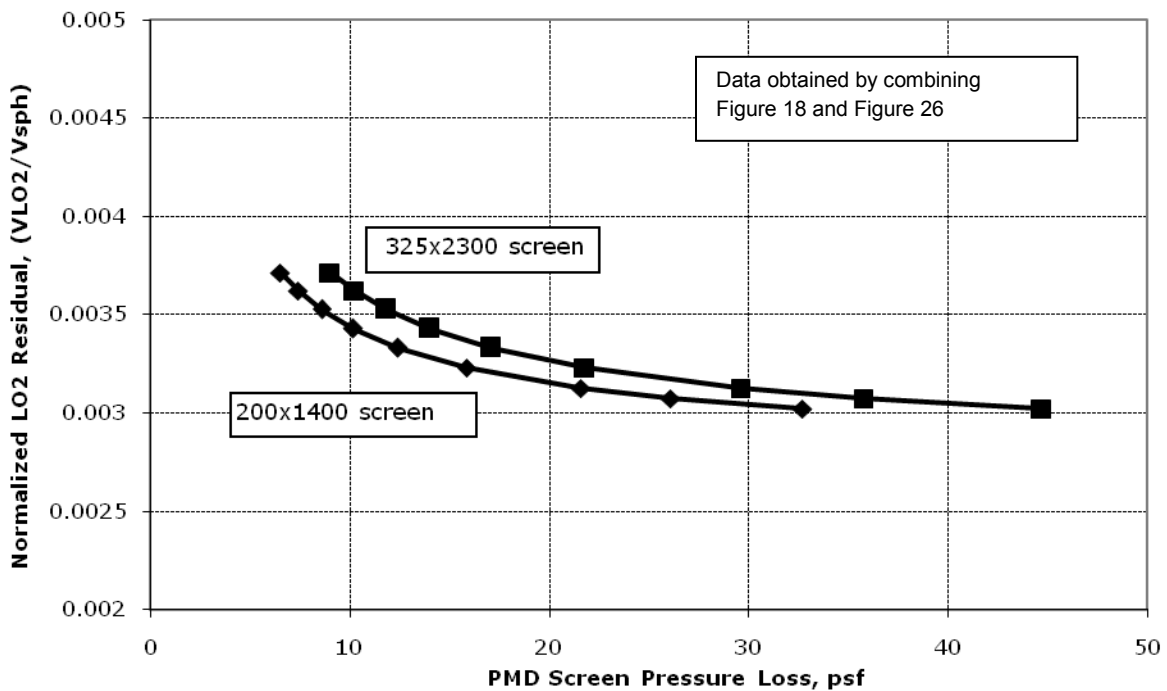


Figure 28.—Main tank LO₂ residual volume versus PMD screen pressure loss.

LO2 Main Tank Concept No. 3 ΔP Margin versus LO2 Residual

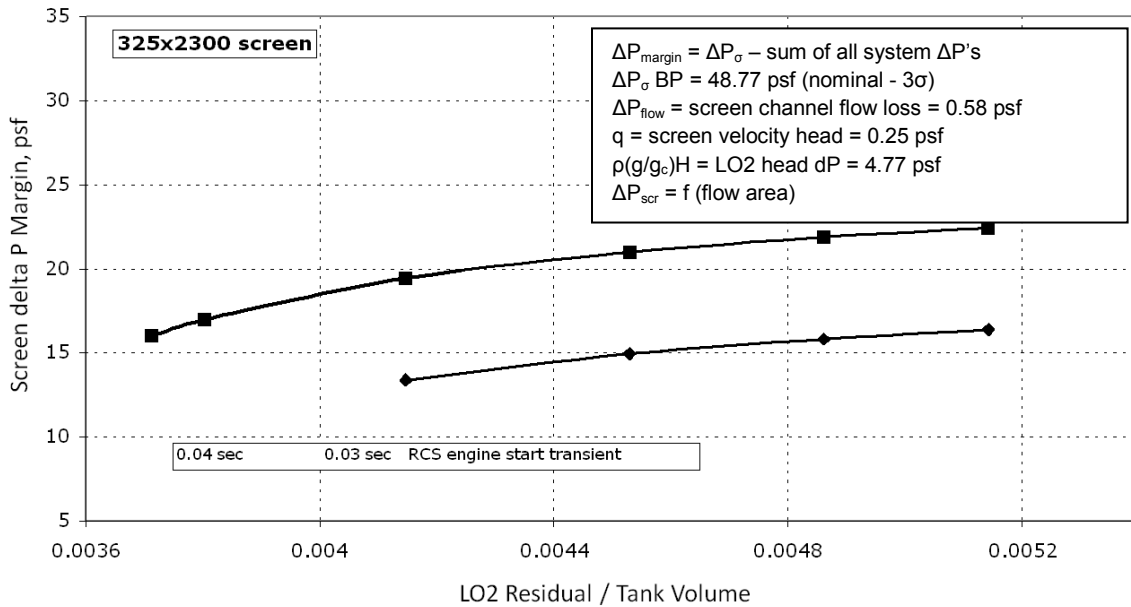


Figure 29.—LO2 main tank PMD screen ΔP versus LO2 residual.

Main Tank Total LCH4 Residual vs. PMD Screen Pressure Loss

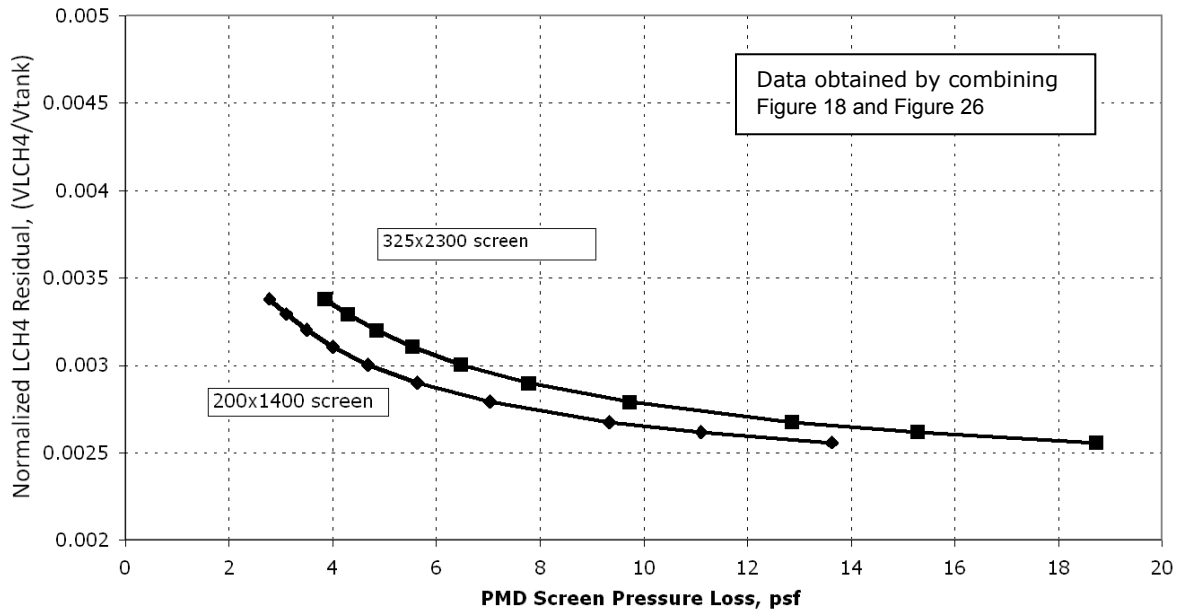


Figure 30.—Main tank LCH4 residual volume versus PMD screen pressure loss.

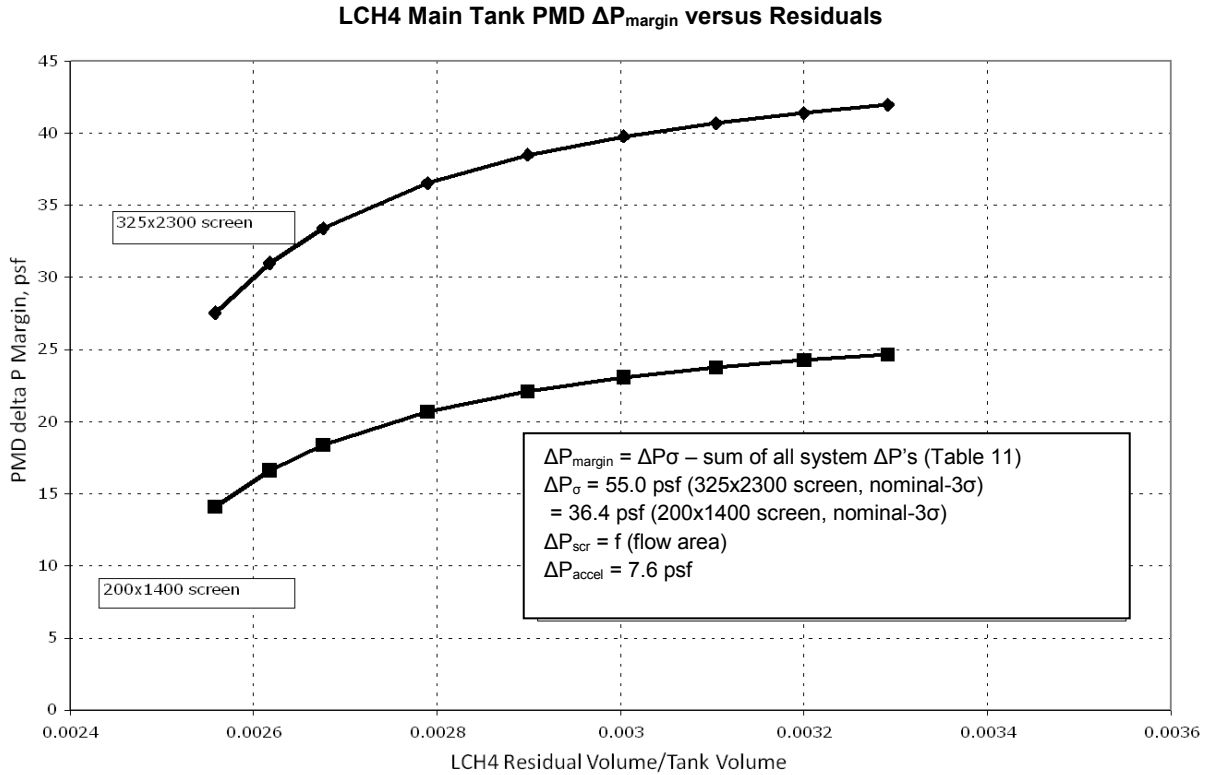


Figure 31.—LCH4 Main Tank PMD Screen ΔP versus LCH4 residual.

TABLE 10.—PMD PARAMETERS FOR DETERMINING ΔP_{margin}

	ρ lb/ft ³	H ft	Channel Length ft	Channel Flow Area ft ²	$\rho(g/g_c)H$ psf	q psf	ΔP_{flow} psf
Descent stage							
LO2 RCS Tank	70.29	2.34	1.81	0.0104	1.65	0.25	0.59
LCH4 RCS Tank	25.71	2.26	1.75	0.0104	0.58	0.07	0.16
Ascent stage							
LO2 Main Tank	63.8	3.66	1.47	0.0104	2.34	0.27	0.58
LCH4 main Tank	25.2	3.46	1.39	0.0104	0.87	0.07	0.13

Notes:

1. RCS flow rates are 0.33 lb/sec (LO2) and 0.11 lb/sec (LCH4)
2. Channel cross-section = 3.0 in. base by 1.0 in. height
3. H = radial distance from top of channel to top of opposite channel
4. q = velocity head pressure at RCS flow rates
5. ΔP_{flow} = pressure loss through a single channel at RCS flow rates

3.6 Flexible Screen PMD Design

The flexible screen PMD is a new concept identified during the early part of this study. This PMD is a partial acquisition device because it contains a limited amount of propellant and is not in communication with the propellant bulk under all flight conditions. Its function will be to contain the last few percent of propellant remaining in a tank so that it is provided vapor-free to the RCS thrusters. In its simplest form, the PMD is a single flexible screen designed with springs that allow it to expand to a pre-determined level during propellant tanking and remain expanded during main engine burn. The screen

will begin to contract only after all tank propellant has been expelled, except for that contained within the PMD. Screen contraction will increase as continued flow demand drains propellant from within the PMD; once fully contracted any additional flow demand will result in vapor penetration of the screen. At this time, vapor-free flow will no longer occur, and the propellant remaining is considered unusable.

It should be noted that PMD screen contraction is possible even when propellant remains outside the PMD, as long as there is no physical contact between the two pools of liquid. When contact re-occurs the outside pool will be drawn in and allow the flexible screen to re-expand.

3.6.1 Ascent Stage Flexible PMD

The ascent stage mission PMD requirement is to provide the last 2 percent of usable propellant for rendezvous and docking. This requirement can be satisfied by sizing the PMD to contain a maximum of 4 percent propellant (2 percent residual and 2 percent usable propellant). The flexible screen is located at the 2.5 percent liquid level (by tank volume), and is designed to expand to contain 4 percent propellant by volume, and contract to 1 percent propellant by volume as propellant is expelled. The range of screen contraction and expansion is shown in Figure 32 for the ascent stage main LO2 tank. This residual quantity applies to the main LCH4 tank as well.

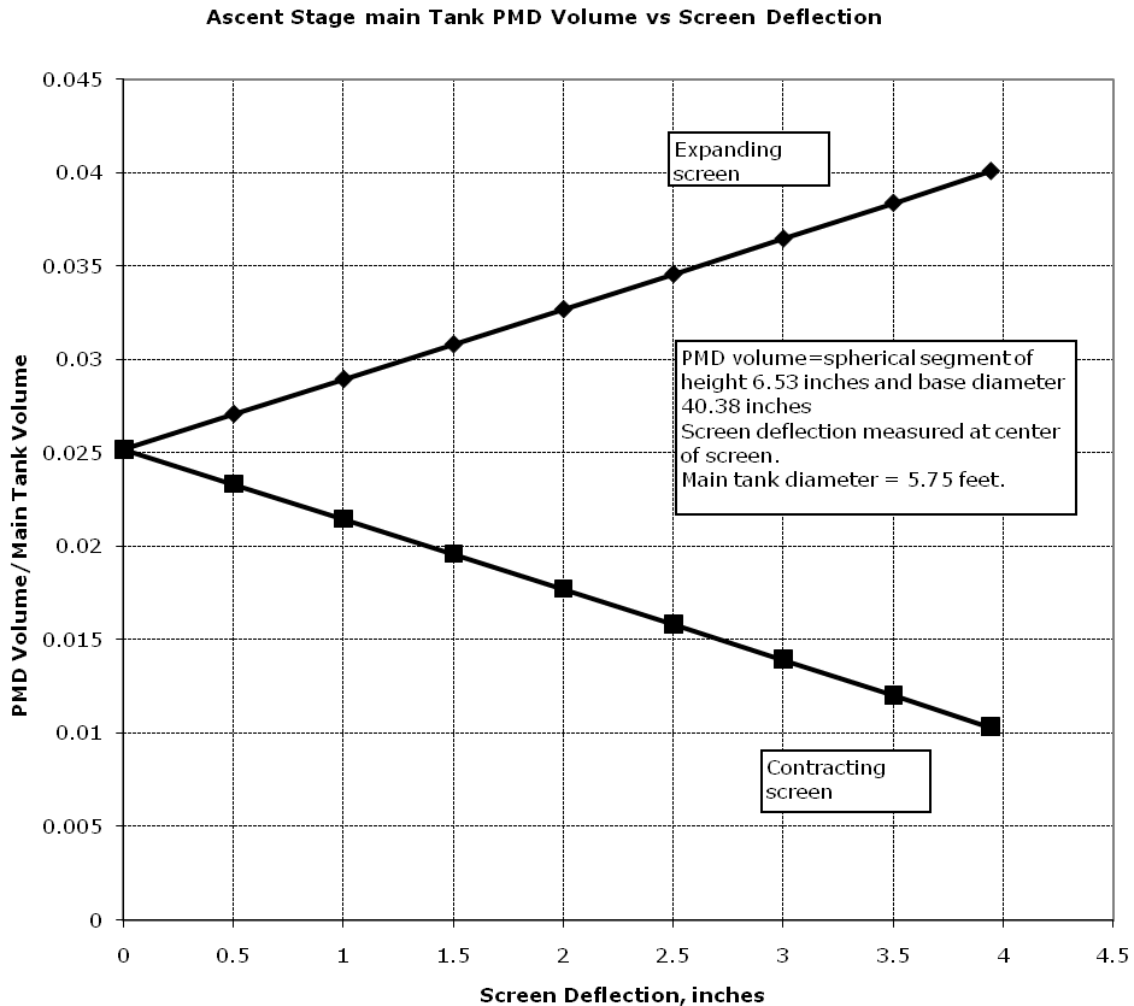
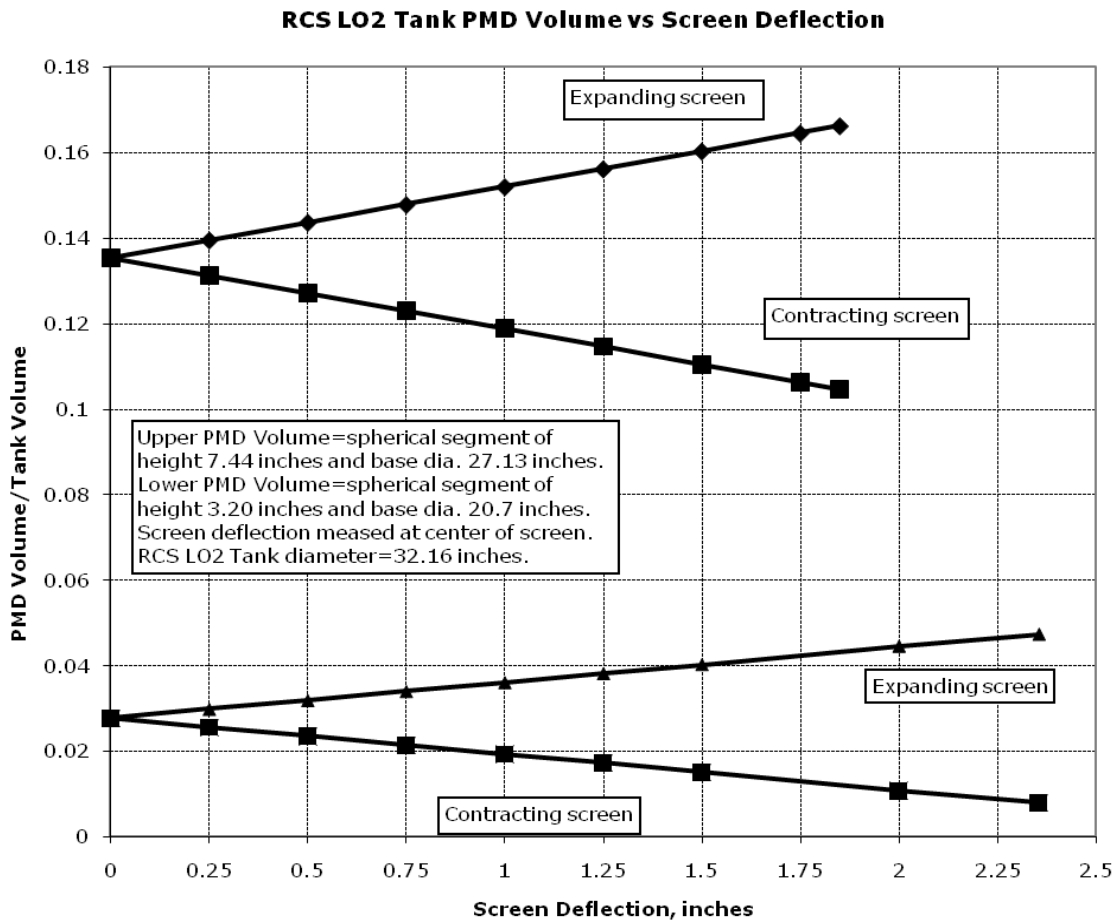


Figure 32.—Ascent stage main tank PMD volume versus screen deflection.

3.6.2 Descent Stage RCS Tanks Flexible Screen PMD

PMD sizing for the descent mission requires that the device be sized to contain approximately 17 percent propellant (2 percent residual plus 15 percent usable propellant). Thus, a single flexible screen would have to be located at about the 9 percent level, expand to contain up to 17 percent propellant, and contract to contain 1 percent propellant. This is a ± 89 percent volume deflection about the neutral position.

A decision was made to go with a dual screen concept design because the required deflection for a single screen exceeded the ± 60 percent volume deflection successfully tested prior to the Interim Review. The selected dual-screen design locates the forward screen neutral position at the 13.55 percent liquid level, with an expansion to contain 16.6 percent, and a contraction that contains 10.46 percent. The lower screen neutral position is at the 2.77 percent liquid level, with an expansion that contains 4.74 percent, and a contraction that contains 0.8 percent. The range of screen contraction and expansion is shown in Figure 33.



3.7 Flexible Screen PMD

A secondary conceptual design is that of a flexible screen PMD. The design specifications, tank size, screen locations, and propellant volumes, for the descent stage RCS tanks and ascent stage RCS/ME tanks is given below in Table 11. Figure 34 gives a comparison of the descent stage RCS tank (Concept No. 2) and that ascent stage RCS/ME tank (Concept No. 4).

TABLE 11.—DESCENT AND ASCENT STAGE FLEXIBLE SCREEN PMD SPECIFICATIONS

Flexible screen device for descent stage RCS tank—Dual screen				
	Screen height in.	Percent of tank volume at neutral	Percent of tank volume at expanded	Percent of tank volume at contracted
LO2 tank (upper)	7.56	13.55	16.60	10.46
LO2 tank (lower)	3.78	2.77	4.74	0.80
LCH4 tank (upper)	7.30	13.55	16.60	10.46
LCH4 tank (lower)	3.65	2.77	4.74	0.80
Flexible screen device for ascent stage RCS tank—Single screen				
	Screen height in.	Percent of tank volume at neutral	Percent of tank volume at expanded	Percent of tank volume at contracted
LO2 tank (upper)	6.521	2.50	4.00	1.00
LCH4 tank (lower)	6.146	2.50	4.00	1.00

3.7.1 Descent Stage RCS Tank Dual Flexible Screen PMD (Concept No. 2)

Figure 35 illustrates Concept No. 2, a dual flexible screen PMD designed for the descent stage RCS tank. The flexible screens are made by pre-stretching the fine mesh stainless steel screen to reflect the desired PMD volume range from fully expanded to fully contracted volumes. Small-scale test results, discussed further in Section 4.0, indicate that pre-stretching may have minimal impact screen bubble point ΔP . When installed, the screens will be preloaded with a spring-type mechanism, such as spring-steel ‘fingers’ (Figure 37). These ‘fingers’ will favor the expanded screen position, and be sized to allow for the screen to contract as the propellant is drawn out of the tank and the pressure differential across the screen increases. Properly designed, the screen will fully contract before the pressure differential exceeds screen bubble point ΔP , which is approximately 70 psf for this particular design and conditions. The upper and lower screen locations, for the LO2 descent stage tank, are shown in Figure 36.

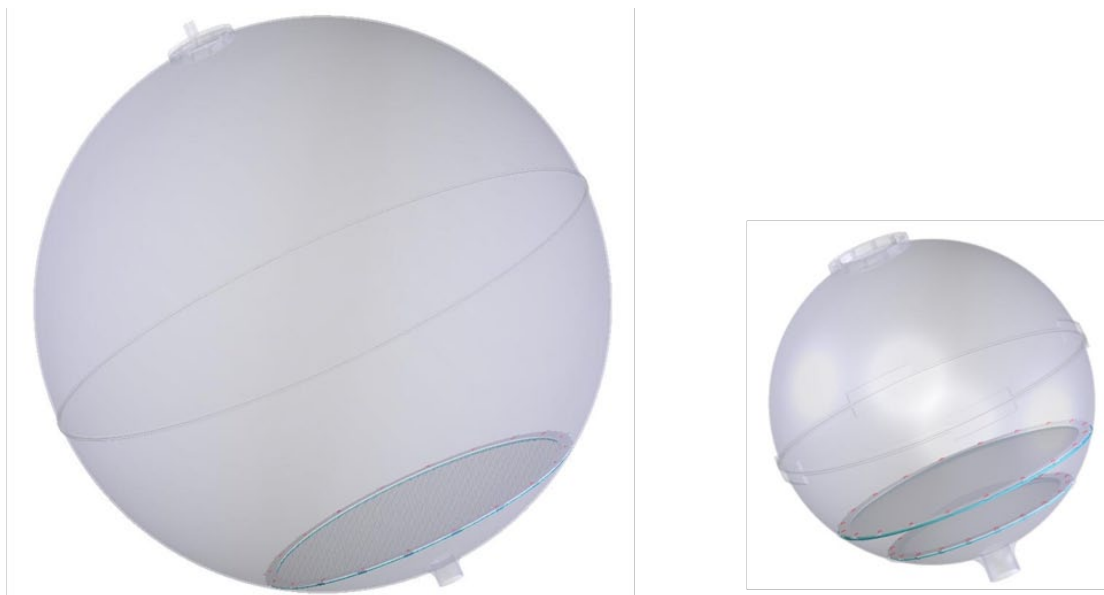


Figure 34.—Ascent and descent stage Concept No. 2: flexible screen PMD.



Figure 35.—Concept No. 2—Descent stage RCS tank dual flexible screen design.

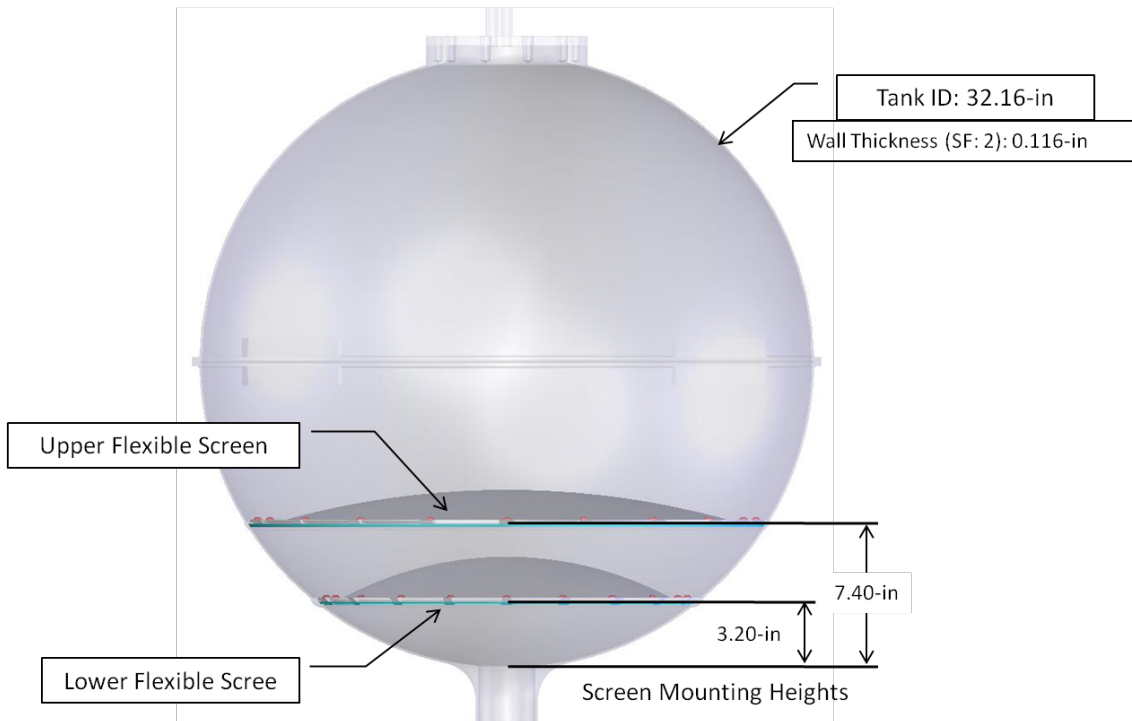


Figure 36.—Concept No. 2—Descent stage RCS LO2 tank dual flexible screeed design installed in aft dome at location to retain propellant.

The mounting ring and clamping system for both Concept No. 1 and Concept No. 2 are very similar in design. In order to reduce residuals and obtain as much usable propellant as possible, communication ports are added to the outer radius of the screen mounting rings. These communication ports are covered with a static stainless steel fine mesh screen to allow for propellant communication with minimal vapor pull-through, as seen in Figure 38. For the concepts discussed in this paper, the communication port areas differ between the two concepts and between the upper and lower screens of Concept No. 2. This is

because the communication port area is dependent upon the local radius of the screen mounting region, Figure 39. The mounting rings are welded in to the tank, as mentioned in Section 3.3.1, where additional material can be rolled in to the tank during manufacturing to reduce material degradation from the welding process. With the main mounting ring in place, the fine mesh screen and the spring-steel ‘fingers’ are positioned. The Teflon clamp is then positioned on top, holding the screen in place as it is tightened, holding the screen firm. The order of assembly and components are shown above in Figure 37.

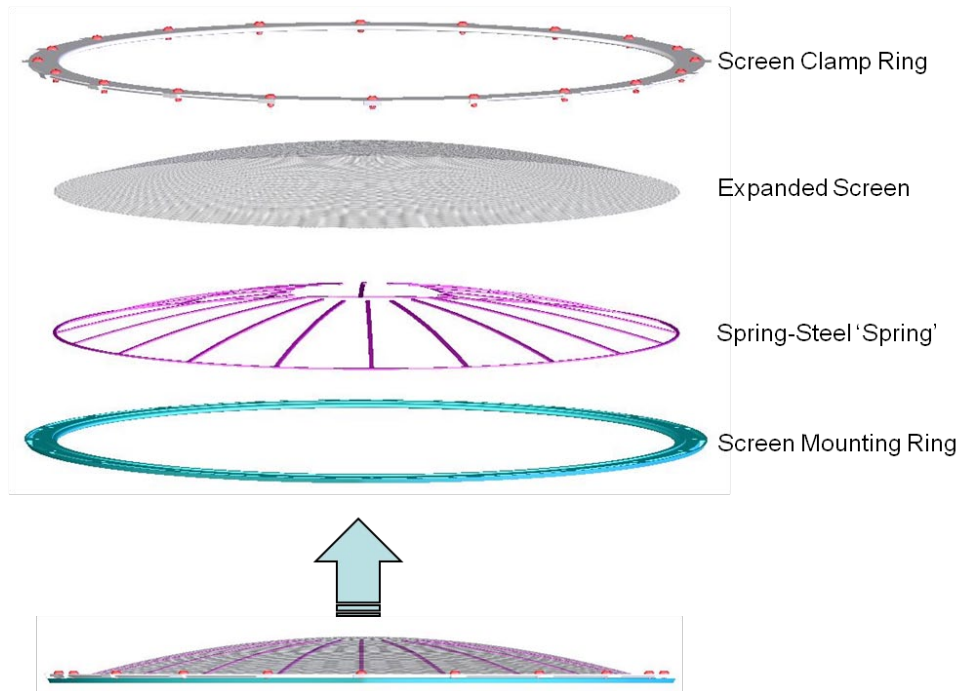


Figure 37.—Flexible screen PMD ‘steel spring’ retention concept.

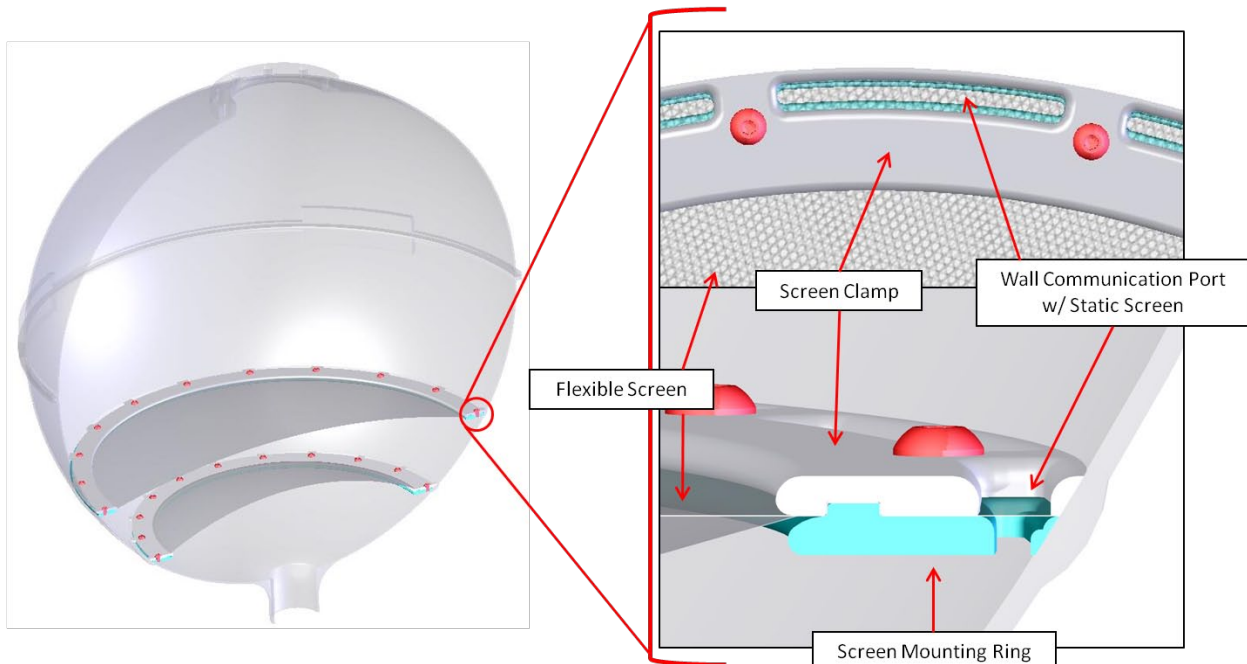


Figure 38.—Concept No. 2—Descent stage RCS tank dual flexible screen PMD close-up of screen mounting ring and wall communication port.

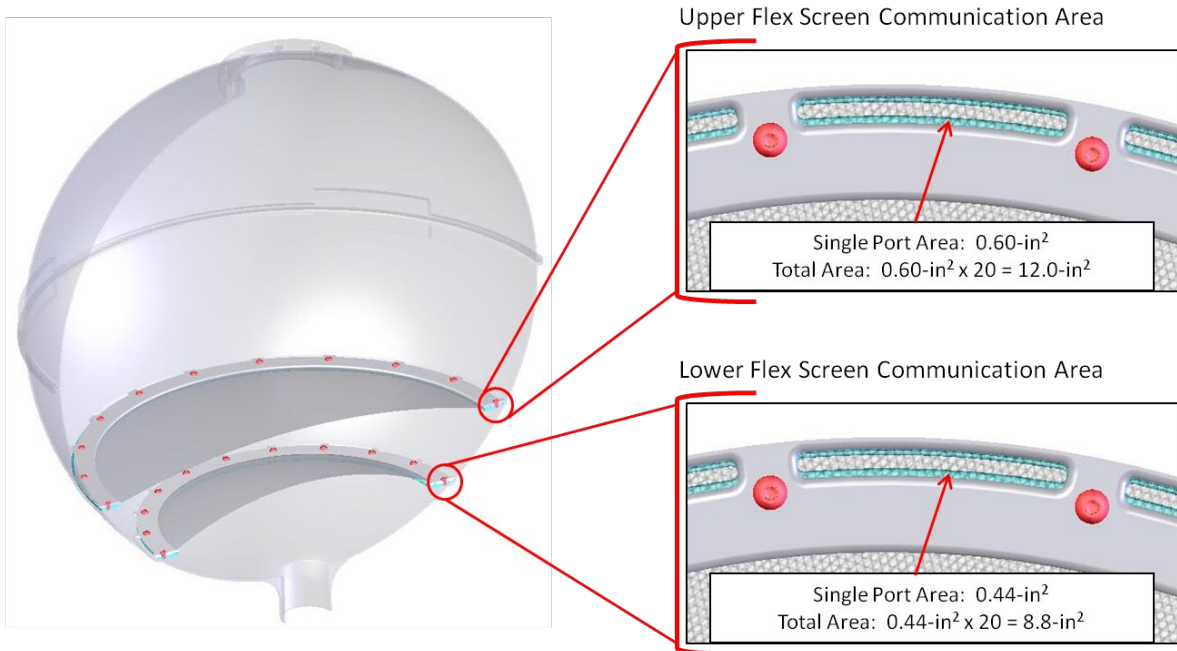


Figure 39.—Concept No. 2—Descent stage RCS LO2 tank dual flexible screen PMD wall communication port areas.

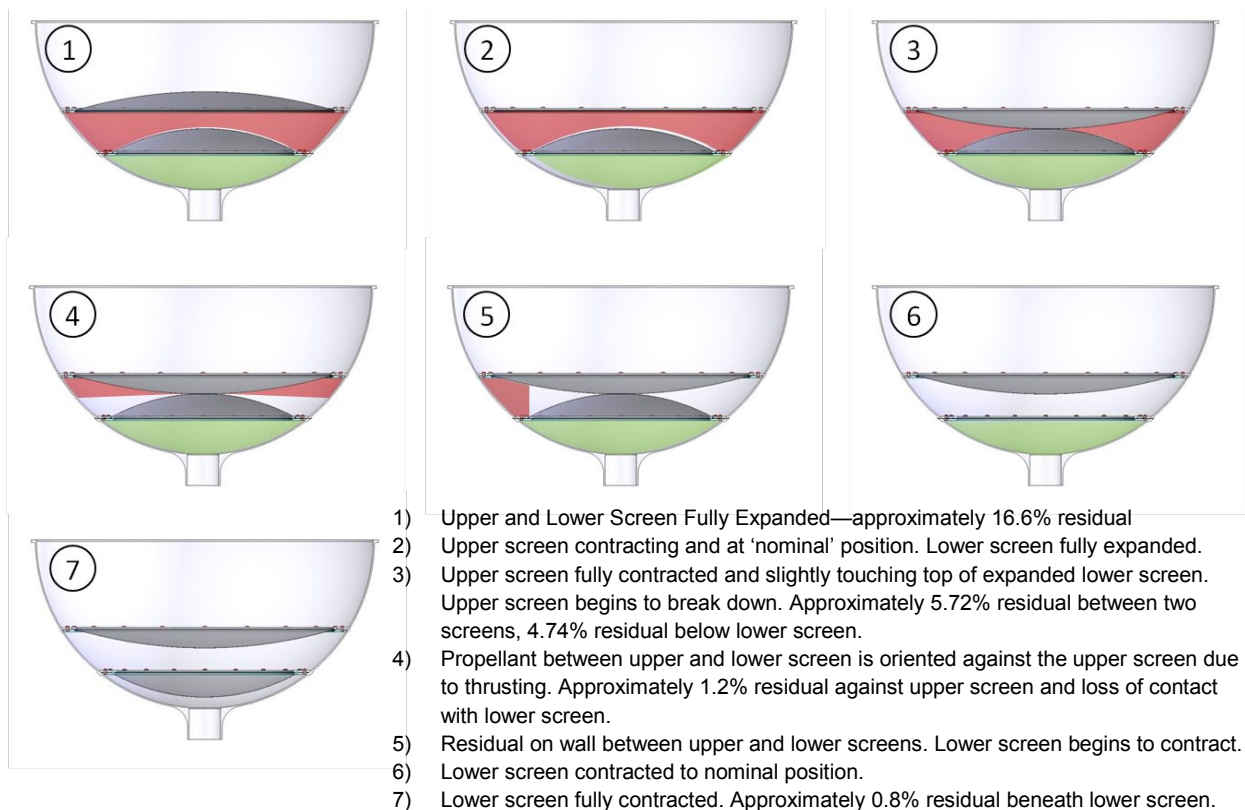


Figure 40.—Micro-g propellant orientation between the upper and lower flexible screens for Concept No. 2.

Figure 40 describes how the dual flexible screen concept is intended to operate. Figure 40.1 illustrates a propellant level at which both screens are fully expanded. In this position, both the upper and lower screens combined retain approximately 16.6 percent residual. As propellant is drawn from the tank, the upper screen begins to contract, Figure 40.2. Due to the pressure differential between the residual beneath the upper screen and the ullage in the tank, the upper screen continues to contract until it is in its fully depleted/contracted position, Figure 40.3. The residual contained between the upper and lower screen in Figure 40.3 configuration is calculated to be approximately 5.72 percent with about 4.74 percent residual contained beneath the lower, fully expanded, screen. Figure 40.4 and Figure 40.5 depict two possible worst case scenarios in which the propellant may be positioned between the screens in a micro-g environment. Figure 40.4 illustrates a case in which the propellant trapped between the upper and lower screens in transitioned forward, losing contact with the lower screen. Figure 40.5 depicts a second ‘worst-case’ scenario, in which the residual contained between the screens wets the tank wall and loses contact with the lower screen. The propellant is most likely to wet the Teflon upper ring and retain communication with residual beneath the lower screen through the wall communication ports along the outer radius of the screen mounting hardware. Around this point, the upper screen begins to break-down and vapor begins to be drawn through. The pressure differential between the upper screen and the ullage, due to screen break-down, is lower than the force required to keep the screen spring mechanism in its contracted state. The upper screen will then begin to return to its expanded position. As propellant communication between the lower screen and the propellant trapped between the upper and lower screens diminishes, the lower screen begins to collapse, as shown in Figure 40.6. The lower screen continues to contract until it begins to break-down and the usable propellant in the tank is depleted. The amount of unusable residual trapped beneath the lower screen is calculated to be approximately 0.8 percent. This unusable residual along with the possible 1.2 percent trapped, unusable residual between the two screens meets the allowable 2 percent of unusable propellant for the descent stage RCS tank. (Note that this is the worst case scenario; 0.8 percent residual below the lower screen and 1.2 percent residual between the two screens.) However, it is expected that the RCS thrusters and main engine in throttle mode, decelerating the vehicle, would ultimately orient the propellant towards the lower screen, where once the propellant regains communication with the lower screen, it would reseal and continue to be drawn in, ‘refilling’ the lower screen.

3.7.2 Ascent Stage RCS/ME Tank Flexible Screen PMD (Concept No. 4)

The ascent stage RCS/ME tank propellant management devices are similar to those as discussed for the descent stage RCS tanks.

A second concept design for the ascent stage RCS/ME tank, Concept No. 4, is illustrated in Figure 41. This design is similar to Concept No. 2 for the descent stage RCS tank design. Unlike Concept No. 2 which uses a dual flexible screen design, Concept No. 4 uses a single flexible stainless steel screen installed in the aft-section of the ascent stage RCS/ME tank. The screen is positioned and sized to meet the allowable 2 percent unusable residual and provision of 2 percent vapor-free propellant for rendezvous and docking RCS engine operations requirement. The screen works the same as described in Section 3.6.1 for the descent stage RCS tank Concept No. 2. The screen for Concept No. 4 is preloaded in the expanded position to retain about 4 percent residual, with approximately 1 percent retained beneath the screen when it is fully contracted. Concepts Nos. 3 and 4 for the ascent stage RCS/ME tanks also utilize the communication ports, as discussed for the descent stage RCS tanks in Section 3.6.1. The communication port area for Concept No. 4 is given in Figure 43.



Figure 41.—Concept No. 4—Ascent stage RCS/ME flexible screen PMD.

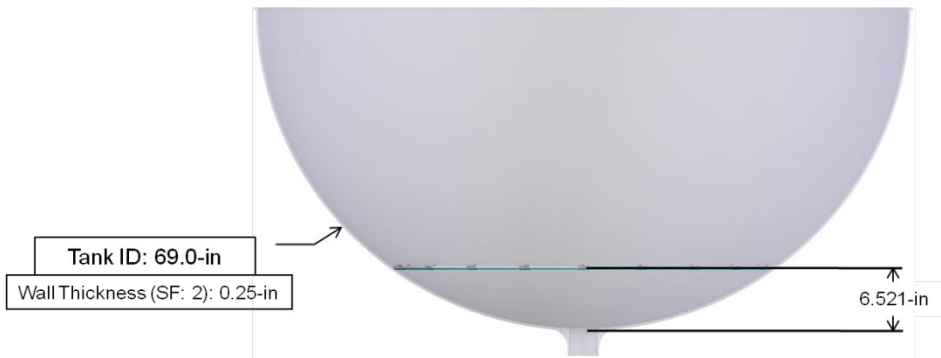


Figure 42.—Concept No. 4—Ascent stage RCS/ME flexible screen PMD installed in aft dome at location to retain and provide 2 percent of vapor-free propellant.

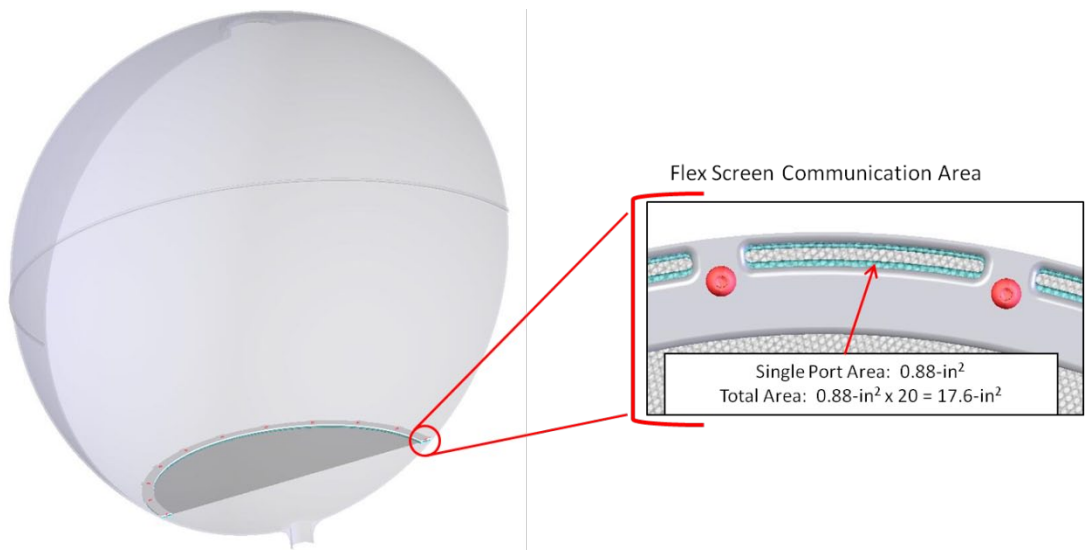


Figure 43.—Ascent stage RCS/ME flexible screen PMD wall communication port area.

4.0 Flexible/Expandable Screen Bench-Top Evaluation

Pleating and stretching are two basically different approaches that have been considered for producing a flexible PMD screen that could conform sufficiently to the tank contour to provide high propellant expulsion efficiency. It was decided to investigate the stretching approach since, if successful, this would prove to be the lightest, best-conforming screen. A stainless steel 200×1400 Dutch Twill screen material was chosen for the investigations. This material was not fully annealed, and thus had lower yield capability than is possible with annealing.

Figure 44 shows a fixture that was built to test the ability of a 6 in. diameter screen to sustain pressure loading and to undergo yielding so as to deform the flat screen into a rounded shape. Fronting the screen with a thin sheet of stretchable plastic enabled a pressure differential to be established across the screen so as to create a deformation. Figure 45 shows some initial results, where the screen was yielded to create a spherical contour, but due to over yielding it eventually failed due to a tear at the perimeter. Test results indicated that maximum screen deflection measured at the screen center was about 10 percent of the screen diameter. This corresponds to a 4 in. deflection of an ascent stage LO2 tank located at the 2.5 percent liquid level. Figure 46 shows, for a full-scale screen, the relationship between deflection and LO2 tank PMD volume. A 4 in. deflection capability should result in a 3 percent useable storage capacity for the PMD.

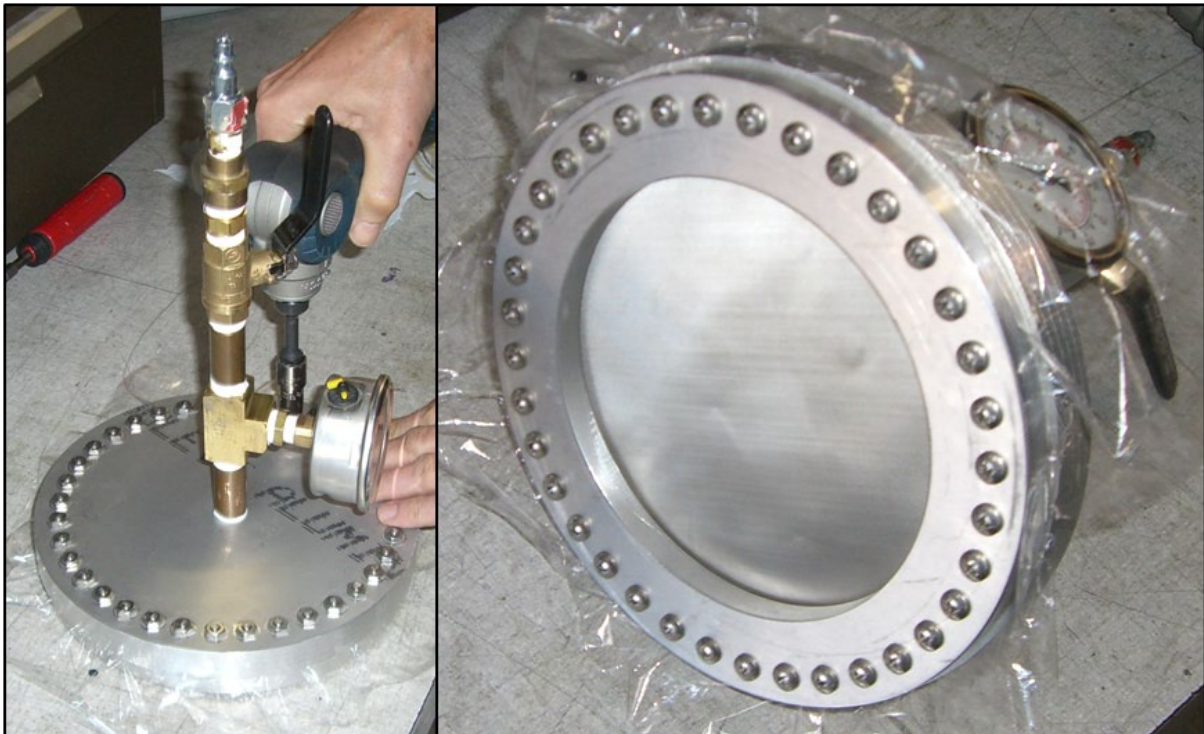


Figure 44.—Fixture built to test ability of 6-in. circular section of screen to sustain pressure loading.



Figure 45.—Images of yielded screen to retain spherical contour (top) and over yielding of screen (bottom-left) and yielding to tear (bottom-right).

Ascent Stage main Tank PMD Volume vs Screen Deflection

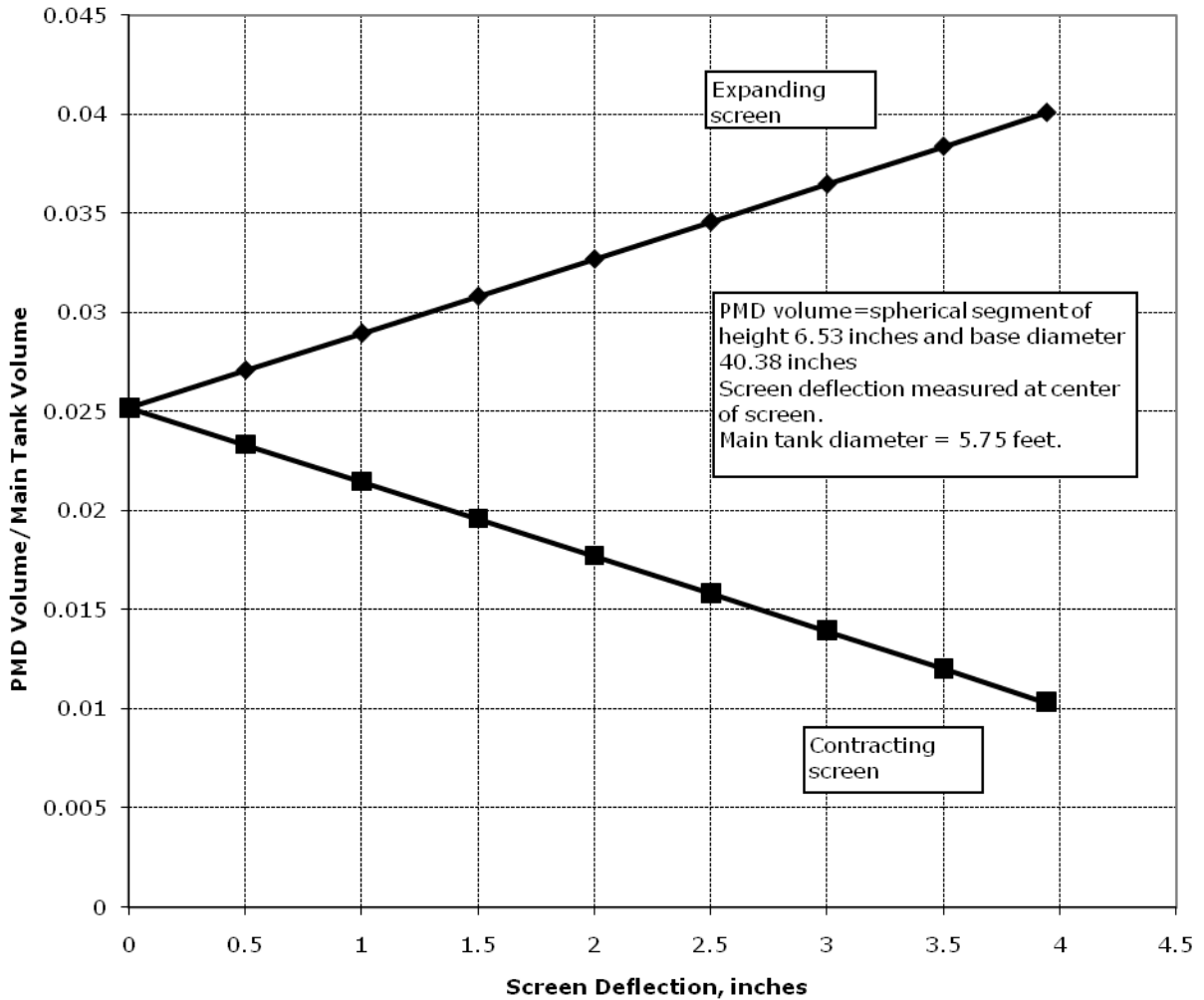


Figure 46.—Full-scale relationship between screen deflection and PMD volume.

Bubble point testing was performed after screen stretching and results indicate that screen integrity was maintained. Additionally, moderate, repetitive deflections of the screen did not appear to cause screen failure. Figure 47 illustrates a revised bench test apparatus that has been built to enable bubble point testing and functional evaluations with a deformed screen sample. Figure 48 shows the actual components and testing apparatus.

Additional testing was conducted using the revised bench test apparatus to qualitatively evaluate pressure drop (using a water manometer) across the screen as it transitions from a fully expanded condition to a fully contracted condition when water is withdrawn from beneath the screen. The test setup and results are depicted in Figure 49 through Figure 52. An interpretation of results is given below:

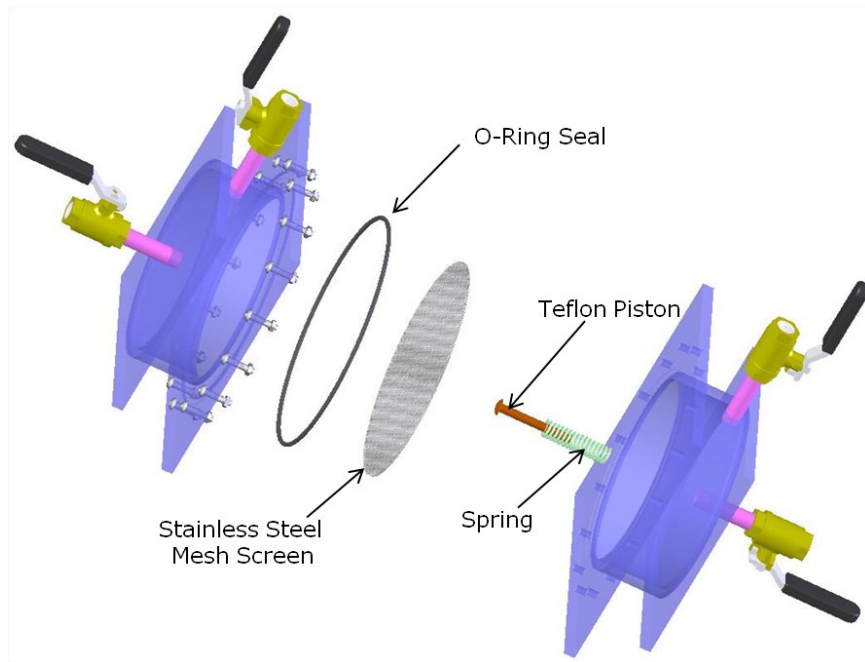


Figure 47.—CAD representation of the flexible screen testing device.

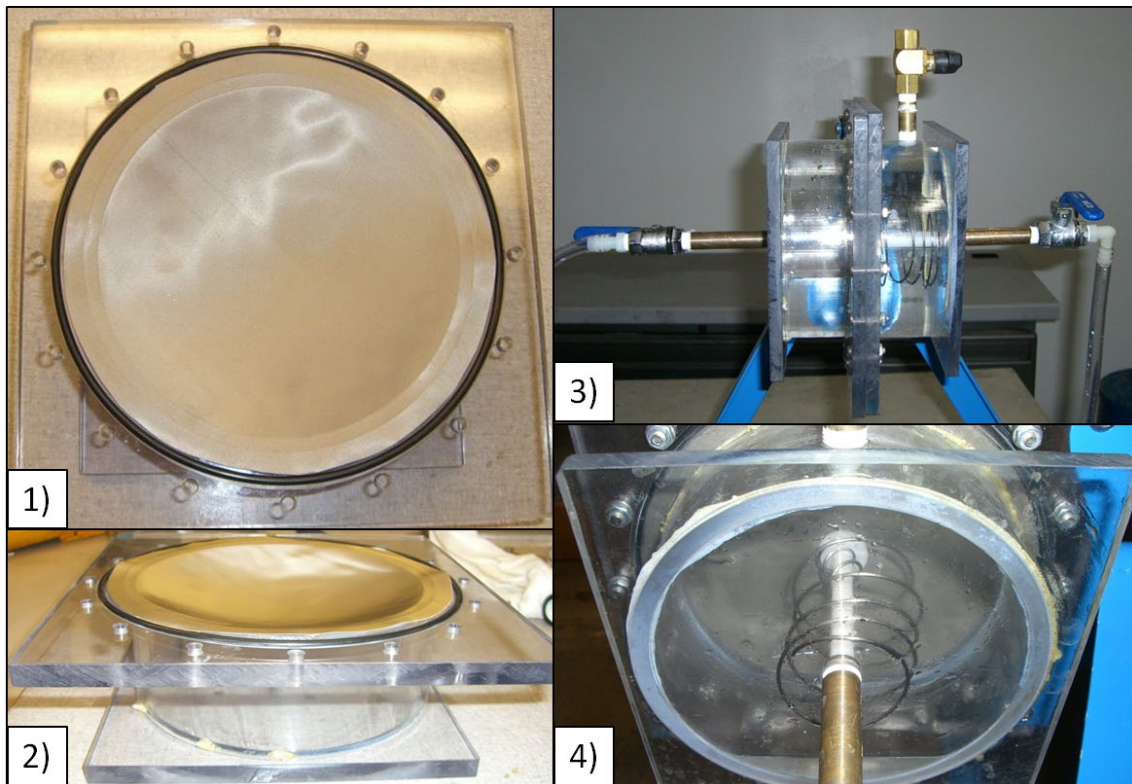


Figure 48.—Bench-top test apparatus for testing bubble point. 1) Stretched screen placed in apparatus, 2) Angled view of Screen installed to show hemispherical contour of screen, 3) Assembled bench-top test apparatus, 4) Close-up of Teflon 'plunger' and spring in bench-top apparatus.

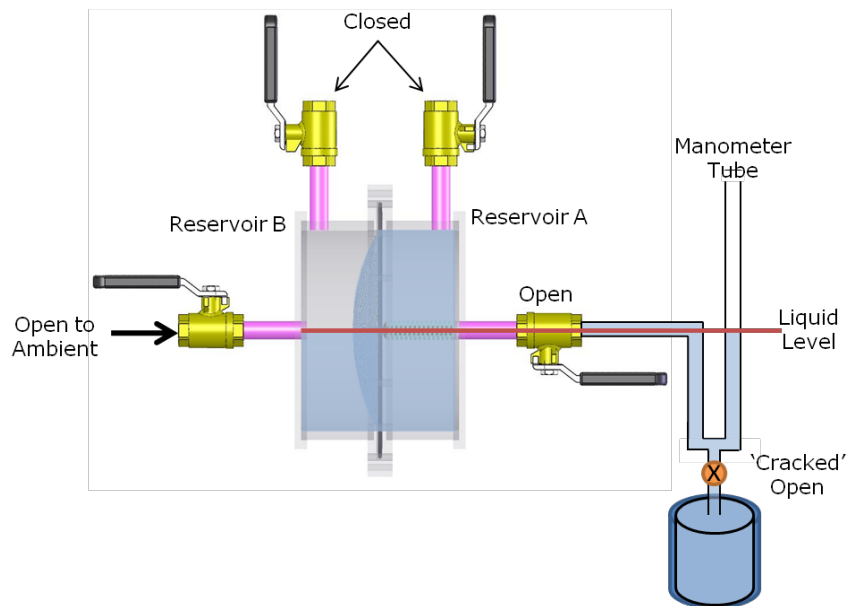


Figure 49.—Initial condition—Screen is fully expanded and completely immersed in water, reservoir A. Reservoir B, left of the screen, is open to atmosphere and contains water that is in contact with the screen. Water manometer is connected to volume of water below the screen.

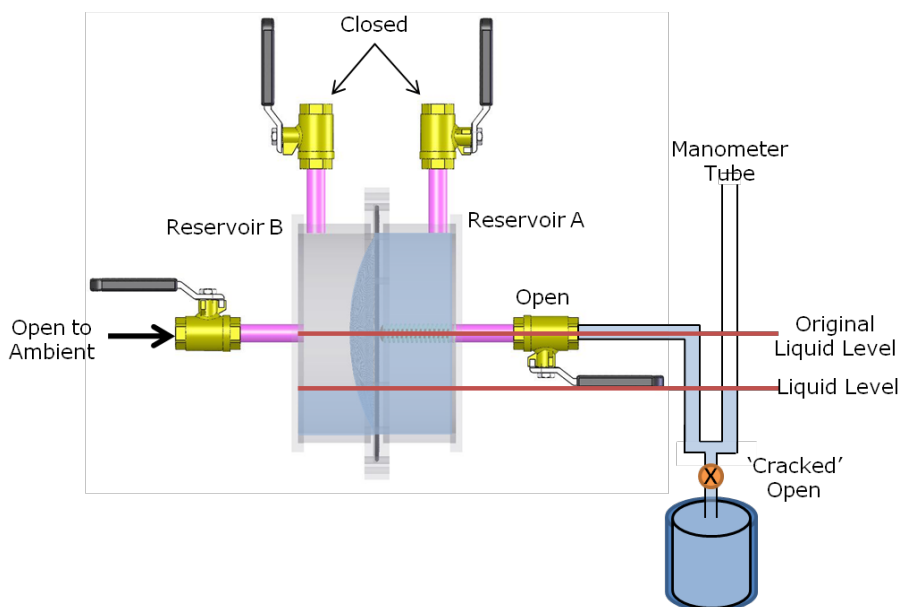


Figure 50.—Water level in reservoir B drops as water is slowly drained from reservoir A. Manometer level drops in unison with water level above screen. Screen remains fully expanded.

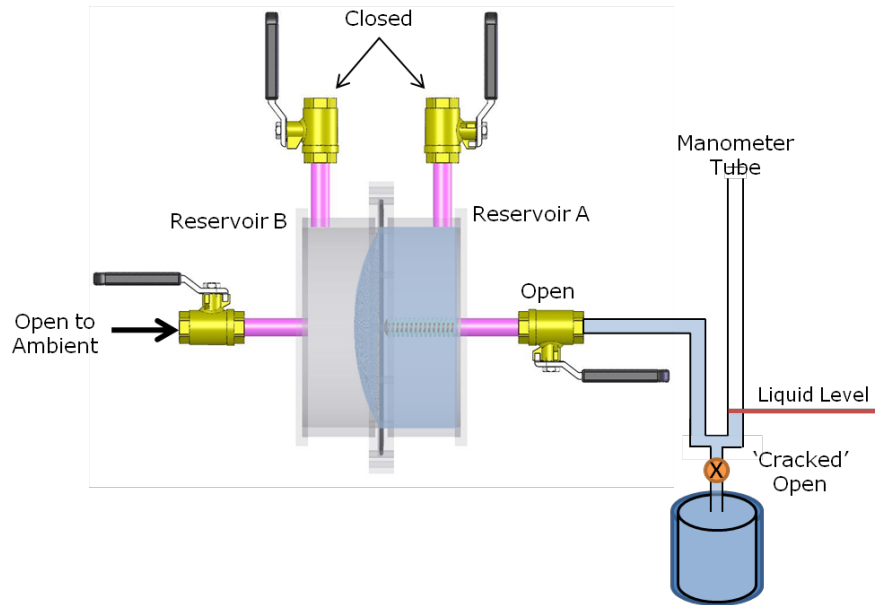


Figure 51.—Screen begins to contract as water is depleted from reservoir B. This replaces the drained water from reservoir A. Manometer level is now below the screen elevation, indicating a negative pressure across the screen.

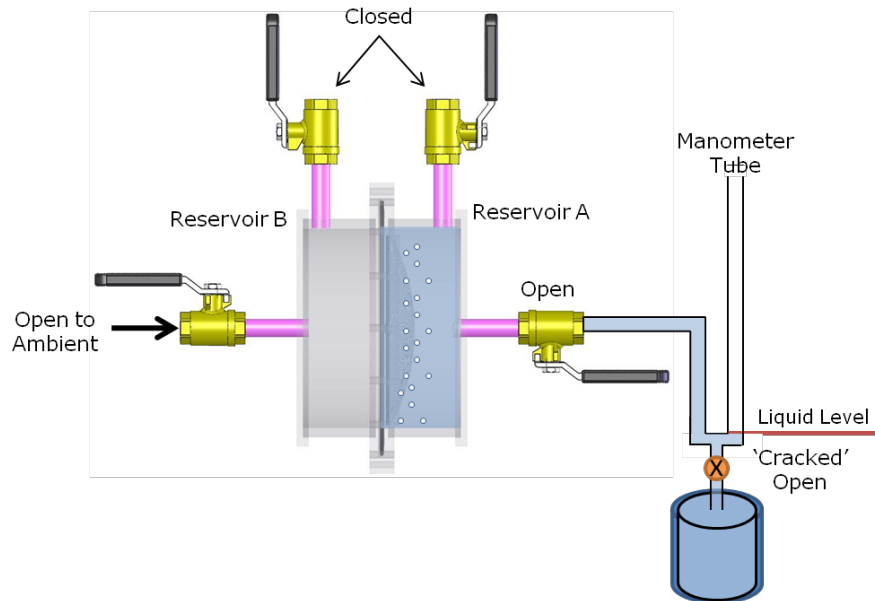


Figure 52.—Screen is fully contracted. Manometer level has bottomed and indicates bubble point differential pressure exists across the screen. Screen breakdown occurs at the low pressure point as more water is drained. Air is drawn into reservoir B as it flows through the screen into reservoir A. Air bubbles are seen rising through water in reservoir A.

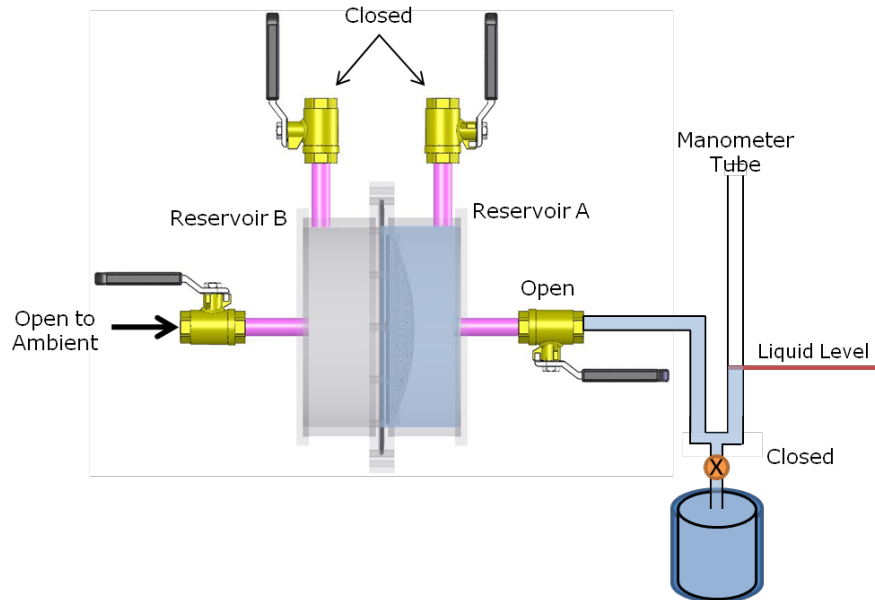


Figure 53.—The manometer level rises as air continues to flow into reservoir A, indicating an increasing pressure in the reservoir. Screen reseal occurs after manometer level has recovered approximately 40 to 45 percent of original drop to screen breakdown. At the moment of reseal, the manometer level has stabilized and air flowing into the reservoir A has stopped.

In summary, the flexible screen device performed as expected. The qualitative tests indicated that a twill dutch screen will re-seal, once breakdown has occurred, if there is a sufficient liquid residual pool to refill the screen ‘pores’. Complete resealing occurs when the screen differential has dropped approximately 40 to 45 percent from the maximum point at which breakdown is observed (in agreement with other studies of breakdown and resealing characteristics of screens). Following resealing and stabilization in this steady state condition, if liquid is added to reservoir B, or if residual liquid in reservoir B is brought into contact with the screen, this liquid is drawn across the screen into reservoir B allowing the screen to expand back towards its fully ‘inflated’ position.

5.0 PMD Thermodynamic/Thermal Control Issues

The fluid dynamics issues associated with the selected study design concepts were addressed in Section 2.0. In this section are addressed issues that impact the thermodynamics of the descent stage RCS tanks and ascent stage main propellant tanks, such as pressure control, boiling and engine inlet temperature requirements.

The devices described in Section 2.0 have their flight heritage in Earth storable propellant applications. Significant flight data exists to demonstrate that vapor free propellant can be provided to engines in a low or micro-gravity environment. It has long been recognized that these devices might also be candidates for use with cryogenic propellants as long as proper attention is paid to the thermal issues associated with cryogenics. Fully operational PMDs for cryogenic application remain unproven because achieving acceptably low heating rates generally requires multi-layer insulation (MLI) in combination with a thermodynamic vent system (TVS) for cooling penetration heat leaks, sophisticated strut designs to greatly reduce penetration heat rates, and a mixer to more uniformly distribute energy input such that “hot spots”, from which vapor can form, will be prevented. Thus excessively high tank pressure increases can be avoided in a low-g environment. Three major issues addressed in this study are a) how to adequately protect propellant contained within a PMD so that boiling does not occur internal to the device, b) how to prevent boiling or evaporation from occurring at the screen surface so that screen breakdown is avoided,

and c) how to develop a methodology that conservatively predicts propellant tank pressures for the descent stage and ascent stage defined missions.

The analysis approach described in this section shows that propellant tank venting will not be required for either the descent stage RCS propellant tanks nor for the ascent stage main propellant tanks during the up to 18 or 19 day journey to the lunar surface. Also, the main propellant tanks will not be required to vent during the 210 day residence on the lunar surface if the heating rates identified for this study are not exceeded. Furthermore, it appears likely that PMD designs described in Section 3.0 will be sufficiently protected that vapor-free propellant will be provided upon demand during the mission. Finally, propellant contained within the PMD designs will remain below the upper limit design temperatures, provided that propellant bulk temperatures remain below the upper limit temperature.

5.1 Key Descent and Ascent Stage Thermal Design Assumptions and Conditions

The keys to treating descent and ascent stage designs as equivalent to an Earth storable vehicle design are the following conditions (Table 3 and Table 4 contain the list of study assumptions and conditions):

1. High propellant tank operating pressures of 325 psia, to satisfy RCS and main engine requirements.
2. High thermal conductivity of the aluminum propellant tank designs.
3. Low propellant tank heat loads (Table 12 and Table 13) required for the long duration mission.

High propellant tank pressures simplify the task of avoiding tank venting during the period from low Earth orbit to lunar landing; LO₂ and LCH₄ saturation temperatures at 325 psia are 230 and 260 R, respectively. Consequently, propellant tank pressure increase, due to heat input, will not exceed 325 psia unless the above saturation temperatures are exceeded. The high aluminum tank thermal conductivity combined with thick tank walls (required to withstand 325 psia) should aid in preventing propellant hot spots from exceeding the above mentioned temperatures without the need for a TVS to cool hot spots.

Analyses will show that vapor can be readily removed from within a screen device by pressurizing the propellant tanks to 325 psia or lower after the descent stage is in low Earth orbit, and after the ascent stage is on the lunar surface. Once removed, vapor will not form within a PMD, when tank pressure is 325 psia, if the contained propellant temperature satisfies the maximum allowable engine inlet temperature of 204 R (LO₂) and 224 R (LCH₄). Thus, if analyses demonstrate that propellants contained within a PMD satisfy engine inlet temperature requirements during RCS and/or main engine operations, vapor will not be present until screen breakdown occurs.

5.2 Thermal Equilibrium Propellant Tank Pressures (Launch-to-Lunar Touchdown)

Descent stage and ascent stage propellants will be saturated at propellant tank pre-launch vent pressures, although they may be pressurized prior to launch to withstand vehicle loads during flight through the atmosphere. Prior to separation from the booster, the stages may also be vented so that pressures are returned to prelaunch levels. The details of flight from pre-launch tank lockup to the last vent period prior to being placed into low Earth orbit are not significant to this study. Such details are necessary, however, to a final stage design since they will impact the minimum allowable propellant tank heat rate that defines stage thermal insulation requirements.

Minimum expected propellant tank pressures are a very straightforward calculation. The First law of Thermodynamics is solved for the condition where liquid and vapor remain in thermal equilibrium throughout the 18 day period to LOI (descent stage) and 19 day period to lunar touchdown (ascent stage). Thermal equilibrium can be attained by periodically mixing propellants (perhaps using a pump). The resulting pressures are displayed in Figure 54 and Figure 55, respectively, for the descent stage RCS tanks and ascent stage main tanks, and using heat rates listed in Table 12 and Table 13. Thermal equilibrium pressures for both stages at lunar touchdown will not exceed 27 psia, which suggests that a substantial margin may exist before tank venting is required if high propellant temperature gradients can be avoided. A method of predicting conservatively high pressures is described in Section 5.3:

TABLE 12.—LUNAR DESCENT STAGE RCS TANKS HEAT LOAD

Descent stage (RCS tanks)	LOX Heat Load (W)	LCH4 Heat Load (W)
Q MLI	0.363	0.126
Q Struts	0.83	0.78
Q penetrations	0.74	0.74
Q helium bottle	0.00	0.00
Q per Tank Total	1.937 W	1.645 W
Q per Tank Total	6.61 B/hr	5.61 B/hr

TABLE 13.—LUNAR ASCENT STAGE MAIN TANKS HEAT LOAD

Ascent stage	LOX Heat Load (W)	%	LCH4 Heat Load (W)	%
Q MLI	1.67	33	0.56	27
Q Struts	0.83	17	0.78	38
Q penetrations	0.74	15	0.74	36
Q helium bottle	1.67	33	0.00	0
Q per Tank Total	5.00	100	2.04	100
Q per Tank Total	17.065	B/hr	6.952	B/hr

Thermal Equilibrium Descent Stage RCS Propellant Tank Pressures
(Launch to LOI)

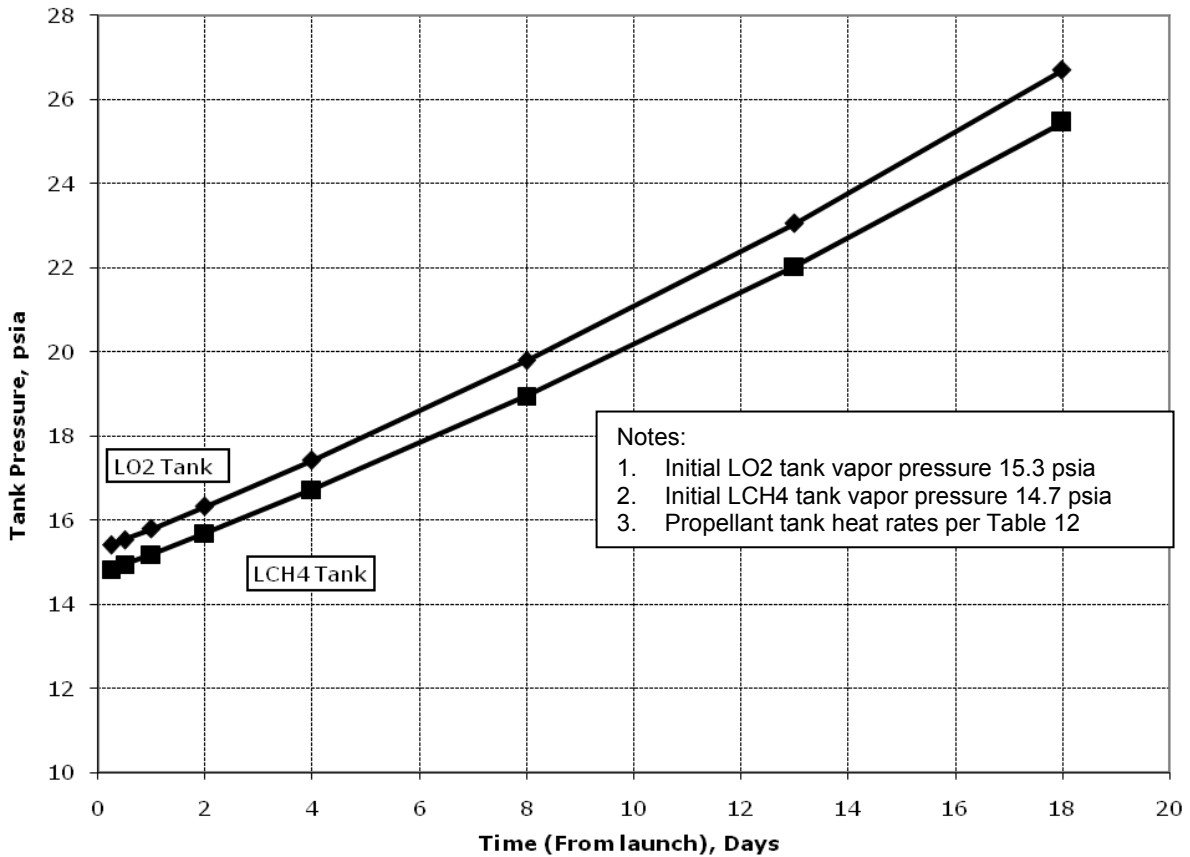


Figure 54.—Thermal equilibrium descent stage RCS propellant tank pressures (launch to LOI).

**Thermal Equilibrium Ascent Stage Main propellant Tank Pressures
(Launch to Lunar landing)**

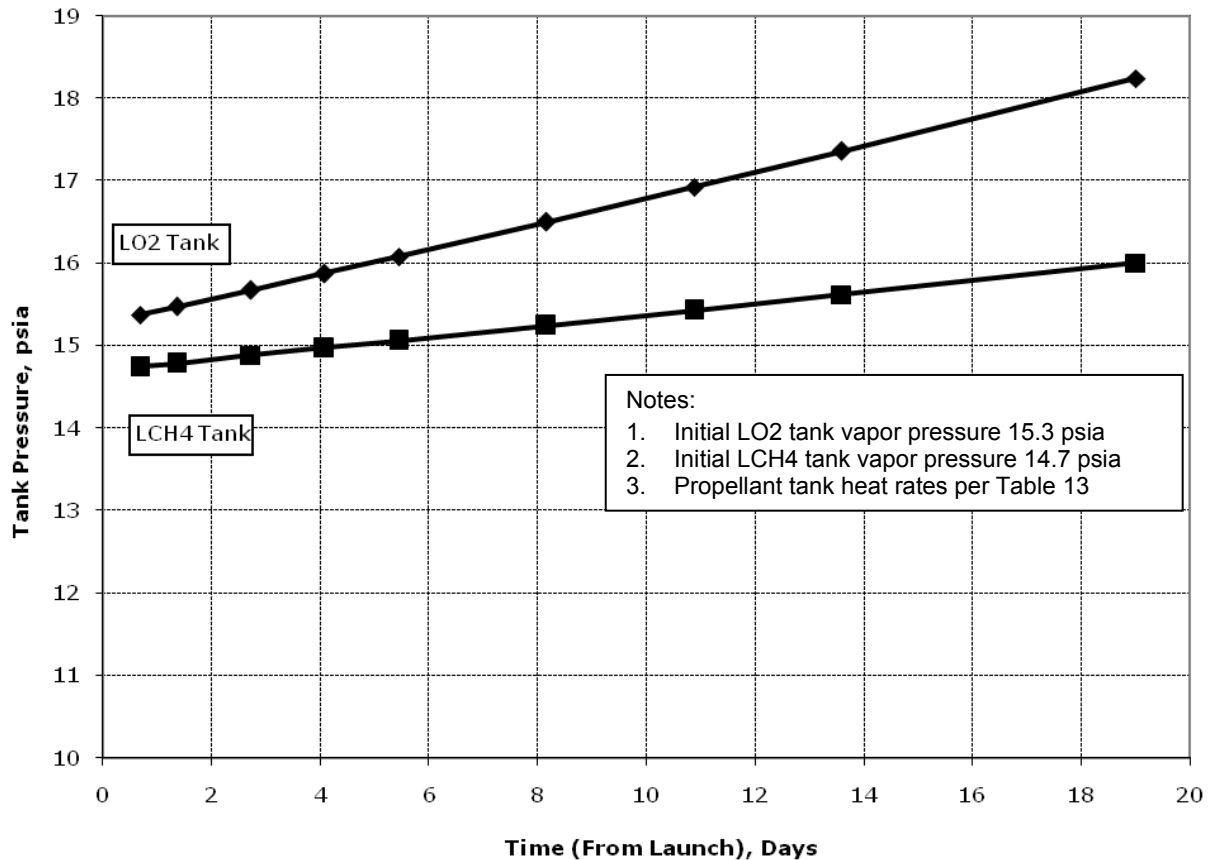


Figure 55.—Thermal equilibrium ascent stage main propellant tank pressures (launch to lunar landing).

5.3 A Model for Predicting Maximum Tank Pressures

The maximum possible tank pressure that can reasonably occur (for nearly full propellant tanks) in a low-g or micro-gravity environment is if the maximum liquid temperature that exists is converted to liquid vapor pressure. Figure 56 shows a series of liquid/vapor orientations and how the vapor bubble may be influenced by a “hot spot” at the tank wall. Early in flight a vapor bubble may be in close proximity to the hot spot, but a liquid film will likely be present. Over time, the bubble can attach to the wall, and allow heat to flow directly into the ullage, a worst case scenario. However, there are several factors to mitigate the worst-case: First, the high tank wall thermal conductivity will allow the “hot spot” to cool as heat is conducted away to a cooler tank region. Second, there will be substantially less energy conducted directly into a vapor bubble than to the surrounding liquid because the ratio of liquid-to-vapor thermal conductivities is more than a factor of 10. Finally, the small quantity of heat conducted directly into vapor will cause a more rapid pressure rise, sub cool the surrounding propellant which, in turn, will allow vapor to begin condensing at the interface. This process will reduce tank pressure, heat the interface and allow energy to be conducted into the liquid bulk from the interface. The combination of these three factors should tend to keep a vapor bubble in near-equilibrium with the surrounding propellant. This implies that the maximum bubble pressure is driven by maximum liquid temperature that, in turn, cannot exceed maximum wall temperature. Consequently, maximum tank pressure can be determined by calculating the maximum temperature that can occur anywhere on the tank wall, and that must be at a tank penetration.

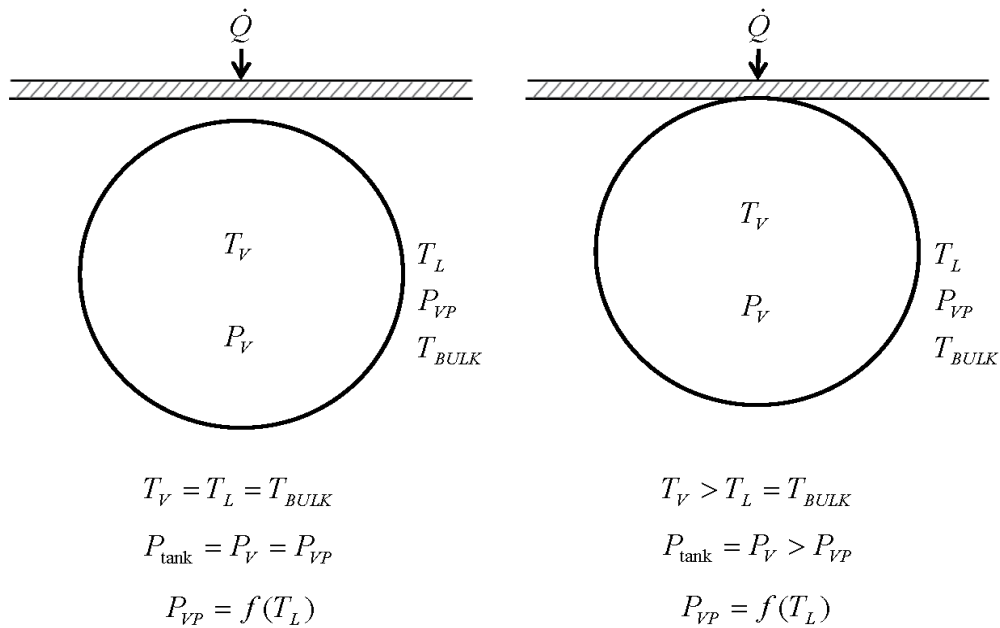


Figure 56.—Series of vapor bubbles at wall.

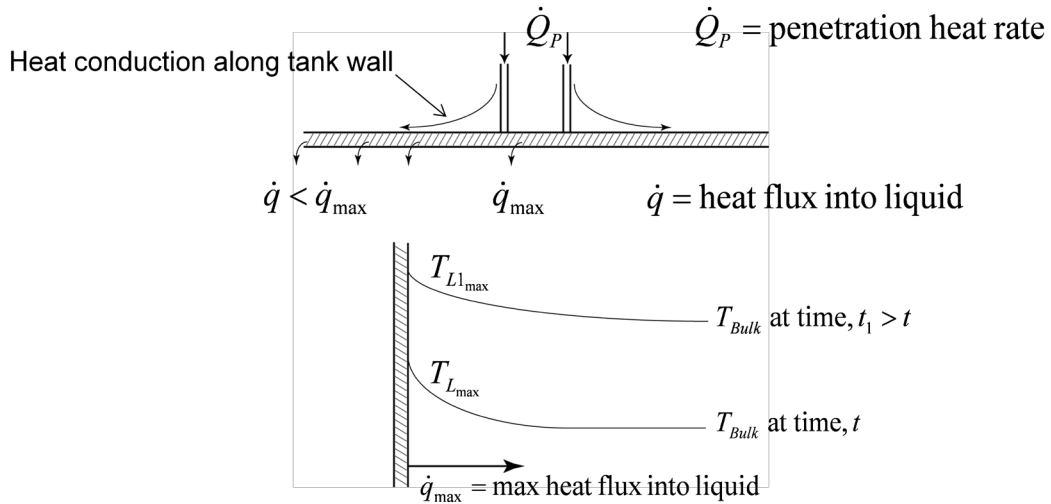
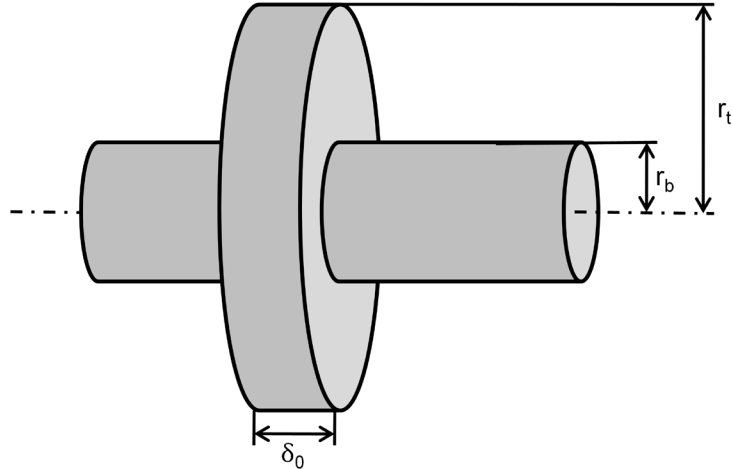


Figure 57.—Thermal conduction model.

Two heating models (depicted in Figure 57) were combined to predict a peak wall temperature. The first model, Reference 21, predicts the rate at which heat is conducted along the tank wall away from a tank penetration while, simultaneously, heat is conducted into the adjacent liquid. Heat flux into the liquid is determined as a function of radial distance along the tank wall from the penetration point. Total heat flux is assumed constant throughout the mission because penetration heat rates and heat rates through the MLI are assumed to be constant from liftoff. Thus, the heat flux condition that exists on the tank wall is constant with time but decreases in magnitude as distance increases from the penetration point. The heat conduction model is approximated by a radial fin, in the shape of a circular disk that has a constant cross-sectional area, shown below:



$$T_{fin}(R) = T_{\infty} + (T_b + T_{\infty}) \frac{K_1(M)I_0(MR) + I_1(M)K_0(MR)}{K_1(M)I_0(MR_b) + I_1(M)K_0(MR_b)} \quad (11)$$

where

$$R = \frac{r}{r_t}$$

$$R_b = \frac{r_b}{r_t}$$

$$M = \left(\frac{2h_{av}}{k\delta_0} \right)^{\frac{1}{2}} r_t$$

$T_b = T_{fin}(R_b)$ bulk temperature of the metal

T_{∞} bulk temperature of the surrounding fluid

K_0, I_0, K_1, I_1 Bessel functions

The second model, Reference 22, predicts temperature gradients from a spherical surface to the center of a sphere as a function of time for a constant heat flux applied at time zero. Pure conduction heat transfer is assumed through the liquid. There is no circumferential temperature gradient. Consequently, temperatures are everywhere the same at the tank wall although they vary with time. This model is mathematically described as:

$$v = \frac{2F_0 t}{\rho c a} + \frac{F_0(5r^2 - 3a^2)}{10Ka} - \frac{2F_0 a^2}{Kr} \sum_{n=1}^{\infty} \frac{\sin\left(\frac{r\alpha_n}{a}\right)}{\alpha_n^2 \sin(\alpha_n)} e^{-k\alpha_n^2 t/a^2} \quad (12)$$

where

v fluid temperature at time, t , minus fluid temperature at time, $t = 0$

F_0 constant heat flux

t time

ρ fluid density

c	fluid heat capacity
a	radius of sphere
r	radial distance from center of sphere
$K = \frac{k}{\rho c}$	fluid thermal diffusivity
k	thermal conductivity
α_n	where $n = 1, 2, \dots$ are the positive roots of $\tan(\alpha) = \alpha$

The approach is to select a maximum heat flux with the first model. This heat flux is then applied to the entire tank surface and wall temperature is predicted as a function of time. Peak temperatures, or “hot spots”, will exist at all penetration points. But only the maximum temperature is of interest for determining maximum tank pressure.

5.4 Descent Stage RCS Propellant Tank Pressures

Figure 58 predicts the maximum LO2 tank wall to-liquid bulk temperature difference caused by a range of penetration heat rates at LOI (a maximum of 18 days after launch). Maximum wall temperature is measured at the penetration point. As expected, maximum wall temperature increases with heat flux and decreases with radial distance along the tank wall from the penetration point. The influence of radial distance requires an explanation: Radial distance can be viewed as the midpoint between two penetration points. Temperature gradient (and peak wall temperature) is altered by distance between any two penetrations. Wall temperature will decrease as the distance between penetration points increases because there is more surface area for heat to be conducted into the liquid without interference from an adjacent heat penetration. This implies that heat penetrations should be judiciously located on a propellant tank.

The temperature difference of Figure 58 is converted to wall temperature by adding the initial bulk temperature at launch of 163 R. This temperature is then converted to vapor pressure as shown in Figure 59. Note that peak LO2 tank pressure at LOI can be significantly reduced if heat penetrations are spaced far apart.

Figure 60 predicts the maximum LCH4 tank wall to- liquid bulk temperature difference caused by a range of penetration heat rates at LOI (a maximum of 18 days after launch). Figure 61 shows those temperature differences converted to vapor pressure.

Finally, for the RCS tanks, Figure 62 shows maximum predicted pressure rise in each propellant tank versus time from launch to LOI. These pressures are approximately 77 psia (LO2 tank) and 69 psia (LCH4 tank). Maximum pressures are based upon the assumptions that a) Maximum penetration rate is 2.5 Btu/hr and b) adjacent heat penetrations are spaced no closer than 2 ft (or a 1 ft radius). The penetration heat rate appears to be a conservatively high value and well within thermal design capability. The separation distance of 2 ft between penetrations appears reasonable for the RCS tank sizes.

LOI was selected as the time in flight when tank pressure, resulting from heat input, would be a maximum because at this time the RCS tanks are pressurized to 325 psia in preparation for descent stage main engine and RCS engine firings required to achieve lunar orbit. From this point in the mission to touchdown, propellant tank pressures and propellant temperatures will be much more influenced by the sequence of engine firings required for the stage to descend to the Moon’s surface.

Because the maximum predicted tank pressures, due to heat input, are well below propellant tank operating pressure levels, it is clear that venting of the RCS tanks will not be required at any time during the descent stage mission. RCS tank thermal equilibrium pressures are also shown in Figure 62 as an illustration that the predicted RCS tank pressures appear to be conservatively high.

**MAXIMUM LO2 RCS TANK WALL-TO-LIQUID BULK TEMPERATURE DIFFERENCE
CAUSED BY PENETRATION HEAT RATE CONDUCTED INTO PROPELLANT**

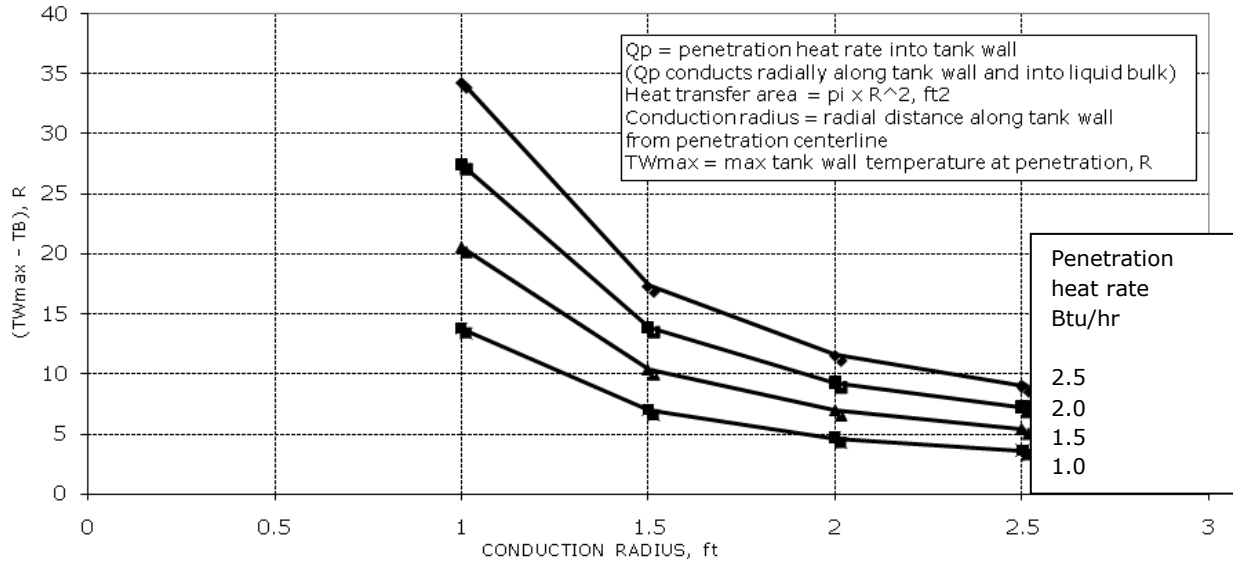


Figure 58.—Maximum RCS LO2 tank wall-to-liquid bulk temperature difference.

MAXIMUM RCS LO2 TANK VAPOR PRESSURE CAUSED BY PENETRATION HEAT RATE CONDUCTED INTO PROPELLANT

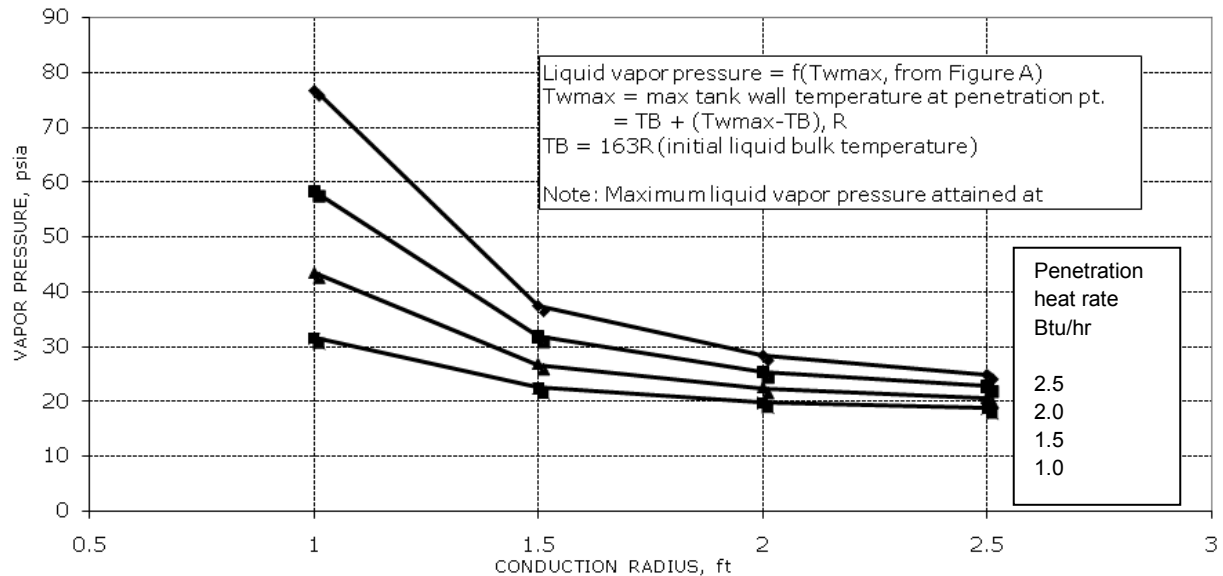


Figure 59.—Maximum RCS LO2 tank vapor pressure caused by penetration heat rate.

MAXIMUM LCH4 RCS TANK WALL TEMPERATURE CAUSED BY PENETRATION HEAT RATE CONDUCTED INTO LCH4 BULK

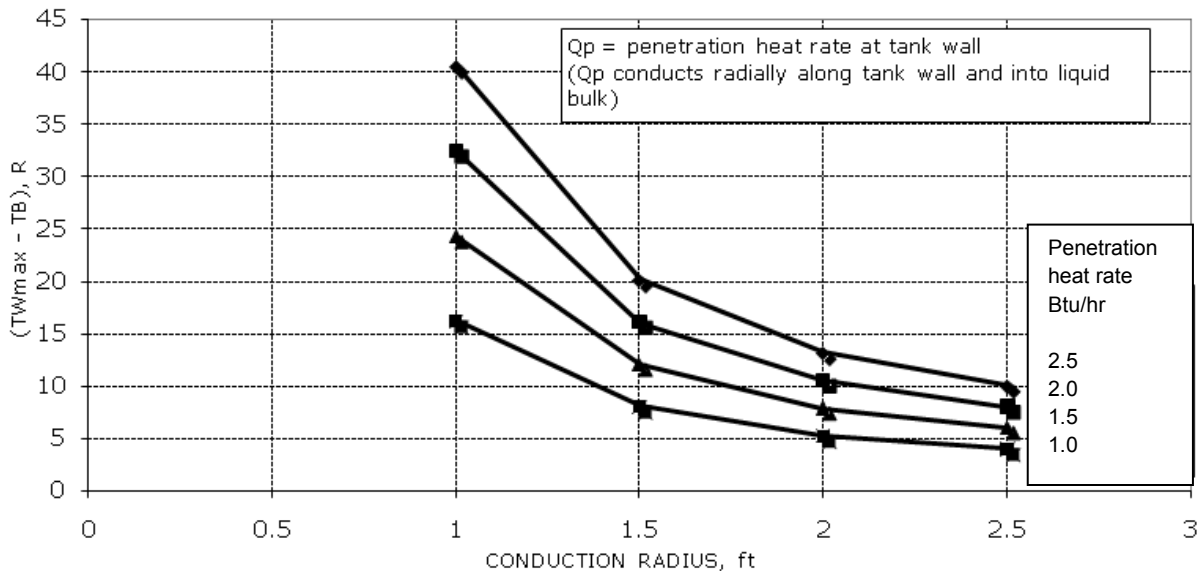


Figure 60.—Maximum RCS LCH4 tank wall to liquid bulk temperature difference.

RCS LCH4 TANK MAXIMUM VAPOR PRESSURE CAUSED BY PENETRATION HEAT RATE CONDUCTED INTO LCH4 BULK

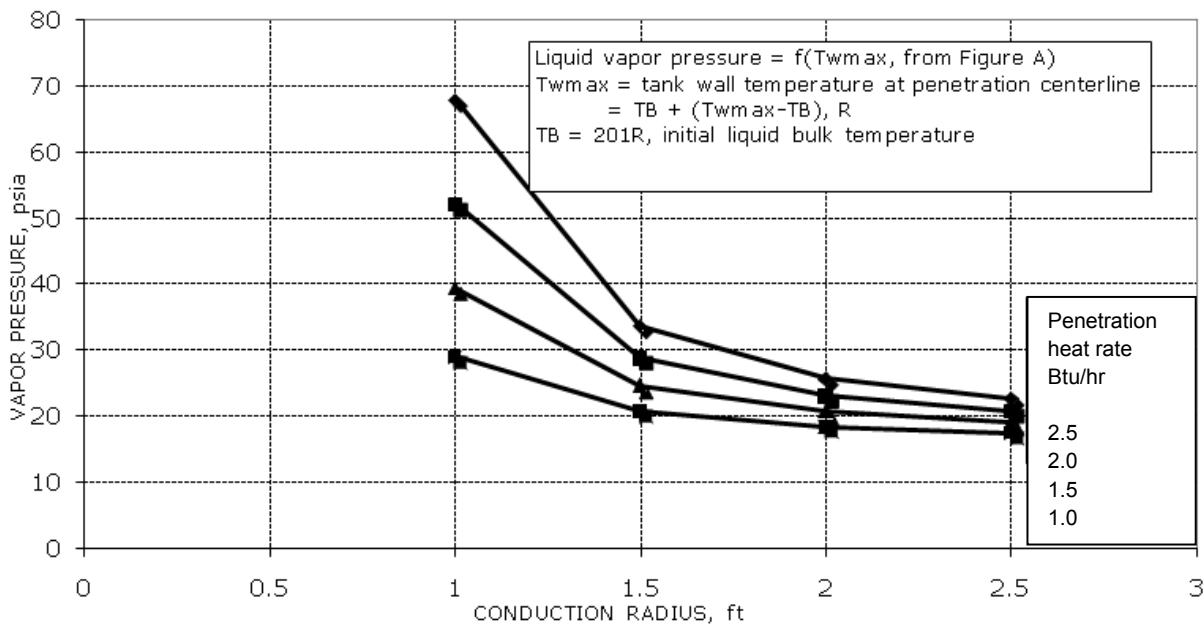


Figure 61.—Maximum RCS LCH4 tank vapor pressure caused by penetration heat rate.

MAXIMUM RCS PROPELLANT TANKS PRESSURES RESULTING FROM PENETRATION HEAT RATES

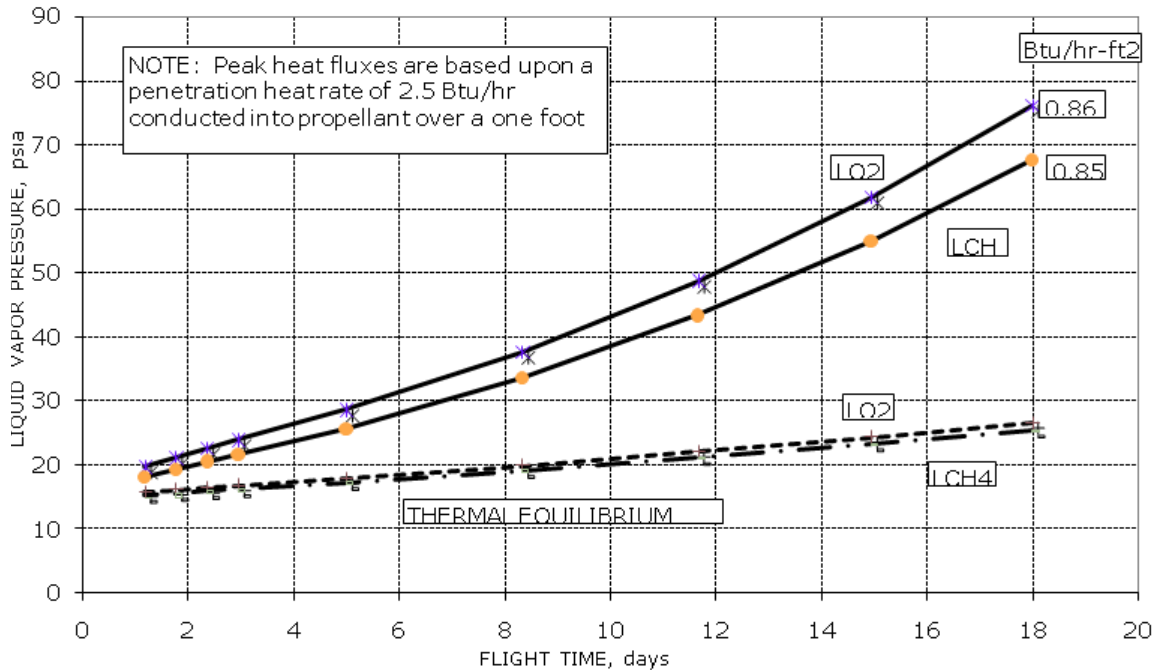


Figure 62.—Maximum RCS propellant tank pressures versus time (launch to LOI).

5.5 Ascent Stage Tank Pressures (Launch to Lunar Touchdown)

The same methodology was employed for the Ascent stage main propellant tanks as for the Descent stage RCS tanks. Propellant temperatures and pressures are lower than predicted for the RCS tanks because the heat input per pound of propellant is less than for the main tanks. Figure 63 and Figure 64 show the predicted LO₂ and LCH₄ tank maximum liquid vapor pressure rise from launch to lunar touchdown as a function of penetration heat rates and separation distance between penetrations. Figure 65 shows the maximum predicted pressure rise in each tank from launch to lunar touchdown. Pressures at touchdown will be approximately 46 psia (LO₂ tank) and 39 psia (LCH₄ tank). These maximum pressure are based upon the same assumptions as for the RCS tanks, i.e. a maximum penetration heat rate of 2.5 Btu/hr and adjacent penetrations spaced no closer than 2 ft (a 1-ft radius). It is concluded that venting of the main tanks will not be required from launch to lunar touchdown.

MAIN LO2 TANK MAXIMUM VAPOR PRESSURE CAUSED BY PENETRATION HEAT RATE CONDUCTED INTO LO2 BULK

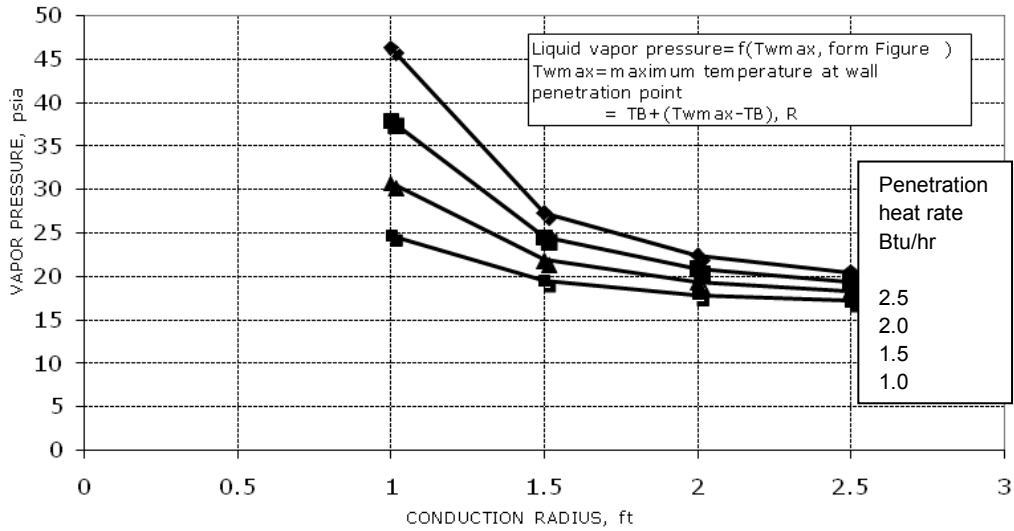


Figure 63.—Maximum main LO2 tank pressure caused by penetration heat rates.

MAIN LCH4 TANK MAXIMUM VAPOR PRESSURE CAUSED BY PENETRATION HEAT RATE CONDUCTED INTO LCH4 BULK

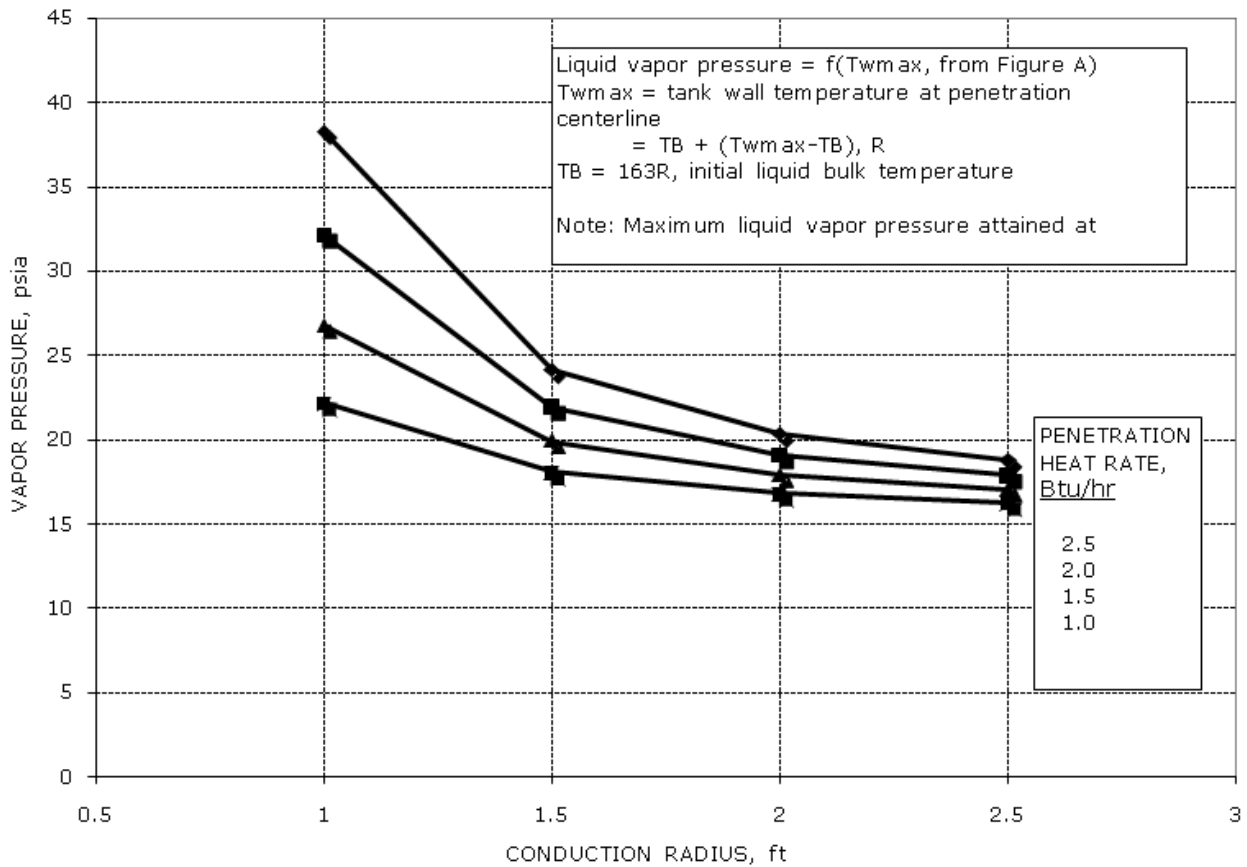


Figure 64.—Maximum main LCH4 tank pressure caused by penetration heat rates.

**MAXIMUM MAIN PROPELLANT TANKS PRESSURES RESULTING FROM
PENETRATION HEAT RATES**

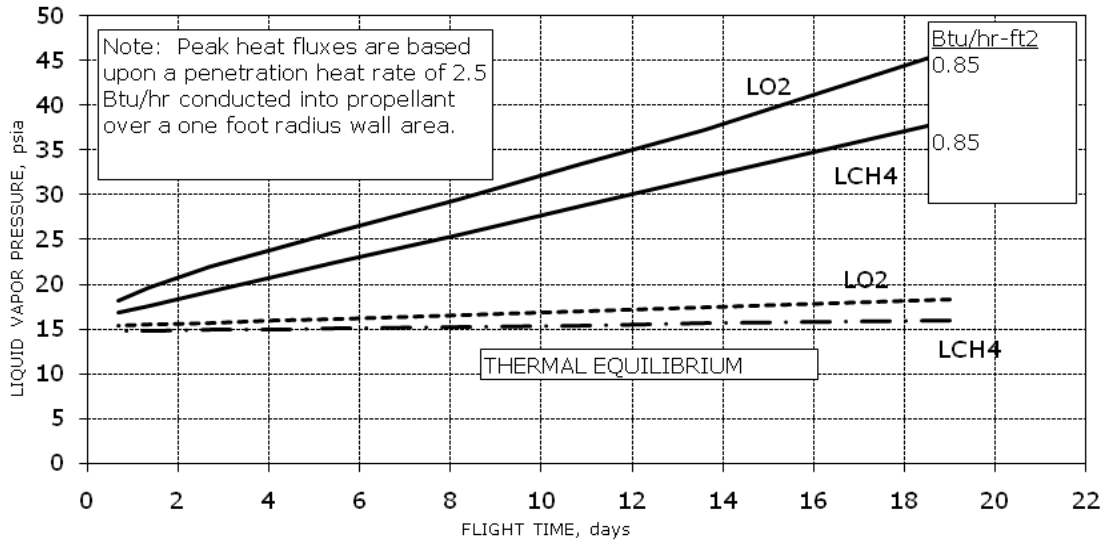


Figure 65.—Maximum main propellant tank pressures versus time (launch to lunar landing).

5.6 Propellant Tank Pressures (Lunar Touchdown to Lunar Liftoff)

The next step was to assess the lunar surface thermal environment to determine if propellant tank pressures will remain sufficiently low without the aid of a TVS or mixer. It was hoped that the lunar gravity (about one-sixth of Earth’s gravity) combined with low propellant tank heat rates would create a near-thermal equilibrium environment. Figure 66 gives wall-to-liquid temperature difference as a function of total tank heat rate for both propellants. The temperature difference was determined as follows:

$$\dot{Q} = hA(\Delta T) \tag{13}$$

Dividing both sides of (13) by A , yields

$$\frac{\dot{Q}}{A} = h(\Delta T) \tag{14}$$

where,

- \dot{Q} total heat rate into propellant tank, $\frac{\text{Btu}}{\text{hr}}$
- A propellant tank surface area, ft^2
- h average wall-to-fluid heat transfer coefficient, $\frac{\text{Btu}}{\text{ft}^2 \cdot \text{hr} \cdot \text{R}}$
- ΔT wall-to-fluid bulk temperature difference, R

Wall-to-fluid heat transfer coefficient was determined using the following Nusselt Number relationship (Ref. 23, Eqs. (7) to (23)) for free convection on a vertical wall under turbulent flow conditions ($Gr_L > 10^9$),

$$h \frac{L}{k} = 0.13 (Gr_L Pr)^{\frac{1}{3}} \tag{15}$$

where

L	height of vertical wall, ft
k	fluid thermal conductivity, $\frac{\text{Btu}}{\text{hr} \cdot \text{ft} \cdot \text{R}}$
Gr_L	$\frac{\rho^2 g \beta (\Delta T) L^3}{\mu^2}$, Grashof number
Pr	$c_p \frac{\mu}{k}$, Prandtl number
ρ	fluid density, lb/ft ³
g	acceleration, ft/sec ²
β	constant
μ	fluid viscosity, $\frac{\text{lb}}{\text{ft} \cdot \text{sec}}$
c_p	fluid heat capacity, $\frac{\text{Btu}}{\text{lb} \cdot \text{R}}$

Equation (15) was modified for propellant tank application by replacing L with tank diameter, D , and Equation (15) becomes,

$$h \frac{D}{k} = 0.13 (Gr_D Pr)^{\frac{1}{3}} \quad (16)$$

Equation (16) was used to approximate wall-to-liquid bulk heat transfer coefficient on the lunar surface where $g = 5.3 \text{ ft/sec}^2$. It was assumed that total propellant tank heat rate is distributed uniformly over the tank wall. ΔT for the LO2 tank was determined to be 0.024 R at 17.07 Btu/hr ($Gr_D > 10^{10}$). ΔT for the LCH4 tank was determined to be 0.012 R at 6.95 Btu/hr ($Gr_D > 10^9$). These low temperature differences offer compelling evidence that propellant tank pressures will not deviate substantially from thermal equilibrium conditions.

One final calculation was made to assess the likelihood of tank propellant conditions remaining in a near-thermal equilibrium state during the 210 lunar stay. Propellant tank pressure will be driven by penetration heat rates, so an attempt was made to determine wall temperature in the vicinity of a tank penetration. A 3-ft diameter surface area was assumed surrounding the heat penetration, and heat transfer coefficients were calculated using the Nusselt Number expression of Equation (16). Figure 67 shows that the wall-to-liquid temperature difference can be as much as 1.2 R, for both LO2 and LCH4, at a heat flux of 2.5 Btu/hr. Again, the implication is that propellant conditions will not deviate much from thermal equilibrium.

Predicted propellant tank pressures at the end of 210 days for thermal equilibrium conditions are given in Figure 68. LO2 tank pressure will be 83.4 psia, which is lower than the maximum allowable thermal equilibrium pressure level of 98.5 psia (based on 204 R max allowable engine inlet temperature). The predicted propellant bulk thermal equilibrium temperature is about 4.5 R below the maximum allowable LO2 temperature. A 13 percent increase in the predicted LO2 tank heating rate will bring this temperature margin to zero. Thus, it is likely that LO2 tank venting will not be required during the 210 days on the lunar surface.

LCH4 tank predictions (Figure 68) show a thermal equilibrium pressure of 36.5 psia after 210 days on the Moon's surface. The bulk liquid temperature will be about 0.8 R below the maximum allowable temperature of 224 R. A 3.7 percent increase in the predicted tank heating rate will reduce this temperature margin to zero. In this case, it appears that LCH4 tank venting may be required in order to avoid violating the upper limit liquid temperature allowed at the engine inlet.

Ascent Stage Tank Wall-to-Liquid Bulk Temperature Difference vs
MLI Heat Rate on Lunar Surface

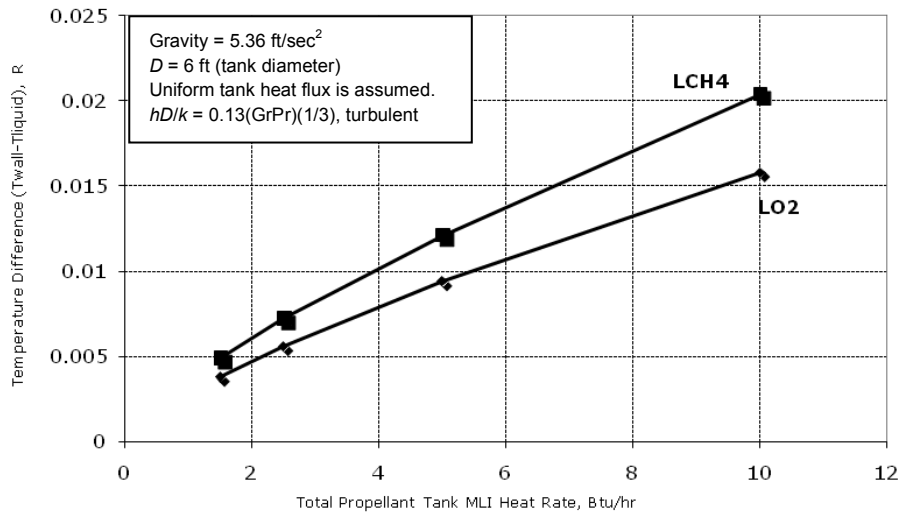


Figure 66.—Ascent stage tank wall-to liquid temperature difference on lunar surface.

Ascent Stage Tank Wall-To-Liquid Peak Temperature Difference Vs
Penetration Heat Rate On Lunar Surface

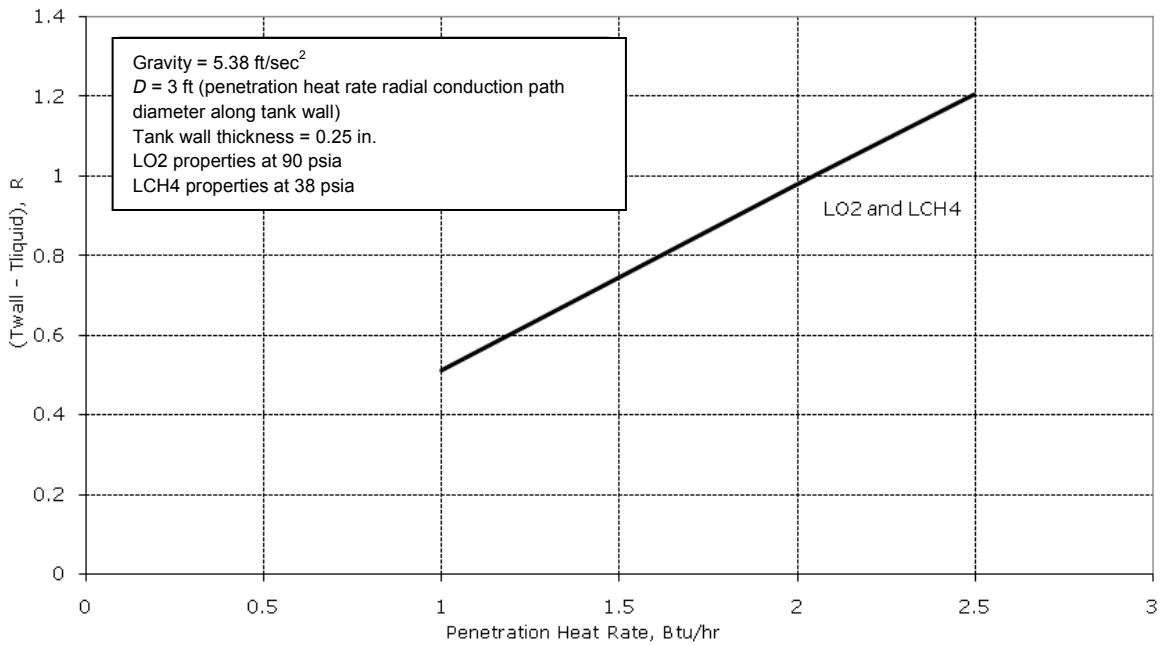


Figure 67.—Ascent stage wall-to-liquid temperature difference due to heat penetrations.

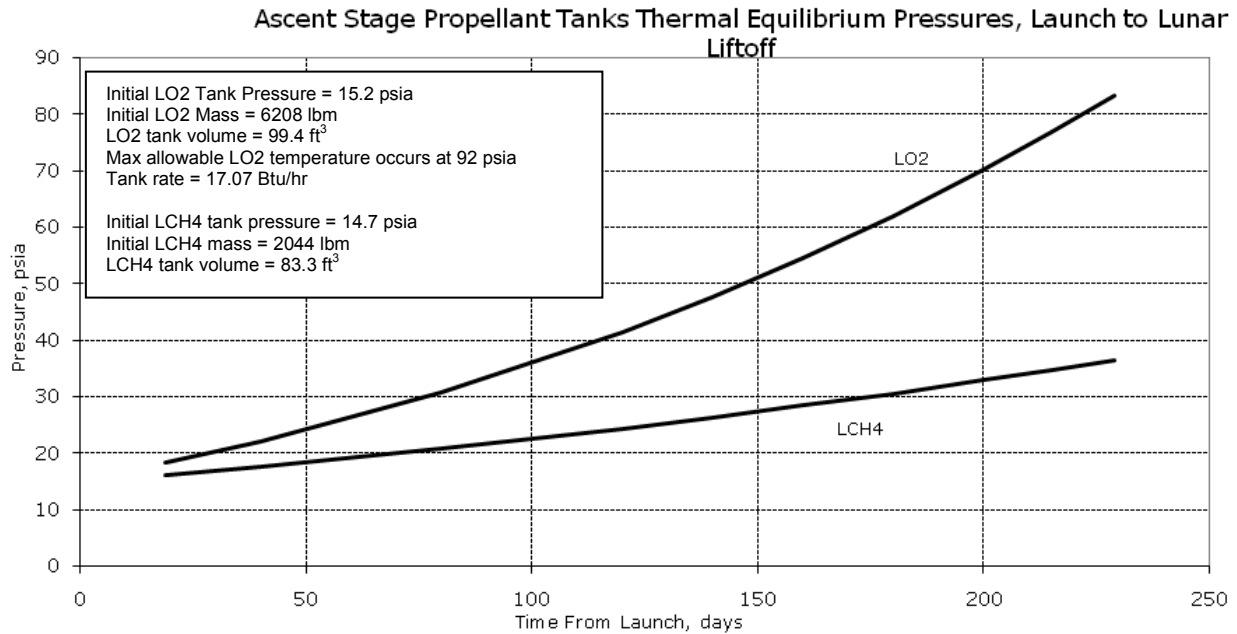


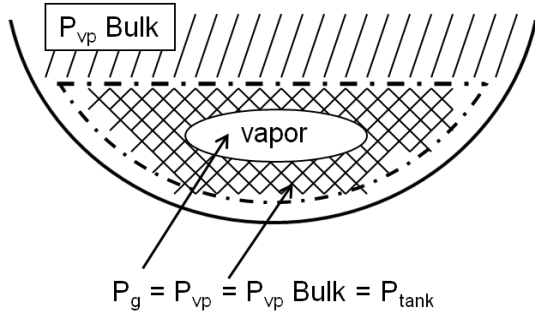
Figure 68.—Ascent stage thermal equilibrium tank pressures (launch to lunar launch).

5.7 Creating a PMD Vapor-Free Environment

One of two remaining issues to be discussed is how to maintain/assure a vapor-free environment of propellant within PMD designs during the long duration Descent stage and Ascent stage mission. It is almost assured that vapor will exist within the screen devices at the end of propellant tanking, and even during the ascent phase of flight. This condition is of no concern because there is a simple procedure for eliminating all entrapped vapor before vapor-free propellant flow is required by RCS thrusters or the Ascent stage main engine.

The first step in eliminating vapor from within PMD is to pressurize the propellant tanks to a level of 50 to 100 psia. But pressurization should be delayed until steady state space heating rates have been attained, which may take many hours. The process of pressurizing tanks will collapse the entrapped vapor to a volume that is 15 to 30 percent of the original volume. Propellant surrounding the entrapped vapor will become sub cooled and the vapor will subsequently begin to condense, heating up the surrounding liquid. Over time, the warm liquid will cool as heat is conducted into the propellant bulk. This thermodynamic scenario is illustrated in Figure 69, and quantified in Figure 70. There should be ample time for the energy released during the condensation process to be conducted away.

At the same time that the constrained liquid is conducting energy to the surrounding propellant, it is responding to the surrounding thermal environment, which will ultimately determine its final temperature.



Prior To Pressurization

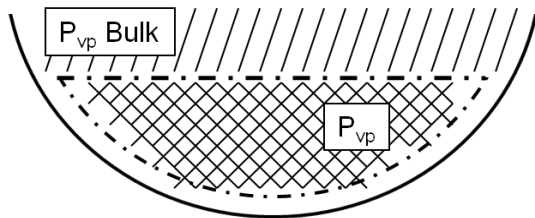
P_{tank} = tank pressure

P_g = pressure of vapor within PMD/LAD

P_{vp} = LO2 vapor pressure within PMD/LAD

$P_{\text{vp Bulk}}$ = vapor pressure of bulk liquid within PMD/LAD

$P_g = P_{\text{vp}} = P_{\text{vp Bulk}} = P_{\text{tank}}$



Following Pressurization

P_{tank} = 325 psia

$P_{\text{vp}} > P_{\text{vp Bulk}}$

Figure 69.—Vapor bubble collapse pictorial description.

Pressurization for Launch Will Collapse Vapor Bubbles (and increase Pvp) Within PMD/LAD

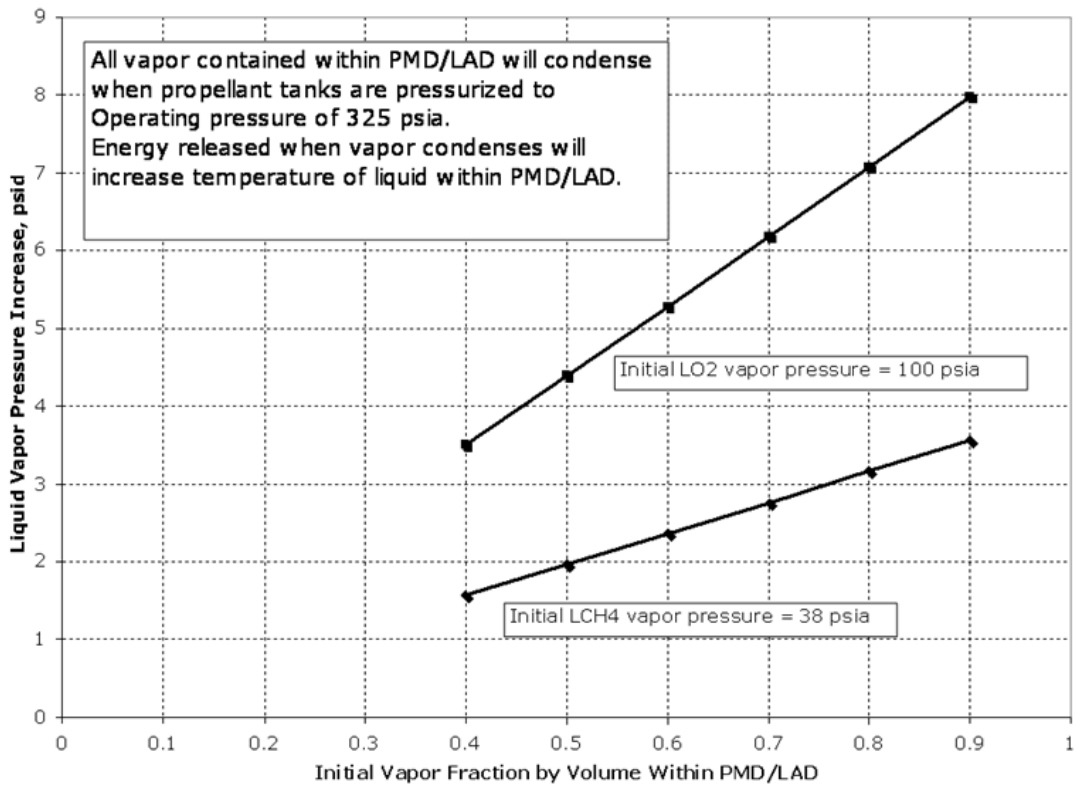


Figure 70.—Vapor bubble collapse.

5.8 Thermal Protection of PMD Propellants

The thermal protection goal is to maintain temperature of the contained propellants below that of the engine inlet requirement, which is 204 R (LO2) and 224 R (LCH4). In Section 5.6, it was reported that bulk propellant temperature in the LO2 and LCH4 main tanks prior to launch from the lunar surface will be about 4.5 R (LO2) and 0.8 R (LCH4) cooler than the maximum allowable. It is reasonable to surmise that propellant temperature, constrained within a PMD will be close to the temperature of the surrounding propellant. This is because the presence of a metal screen should be no impediment to achieving temperature equilibrium with the surrounding liquid because liquid thermal conductivity will be less than that of the metal.

Liquid bulk temperature gradients on the lunar surface were not determined for this study. However, as a first approximation, the maximum liquid temperature anywhere in the tank is the wall-to-liquid bulk ΔT added to the liquid bulk temperature from the thermal equilibrium analysis. As a worst case, the maximum ΔT from Figure 67 can be applied to liquid within the PMD to yield a “hot spot” of 1.2 R warmer than bulk temperature. Consequently, LO2 within a PMD may remain about 3.3 R cooler than the max allowable temperature, and LCH4 may slightly exceed the maximum allowable temperature at ascent stage launch from the lunar surface.

The above assessment applies to ascent stage main tank propellant conditions within a PMD. Descent stage RCS tank LO2 and LCH4 propellant bulk temperatures will be substantially below the maximum allowable for the RCS engines. Thus, engine inlet temperature requirements will be satisfied, and vapor-free propellant will be provided upon demand during the descent stage engine firing periods.

Substantially more effort should be devoted to mapping propellant temperature gradients within a propellant tank on the lunar surface, and constrained by a PMD, before a definitive answer is given regarding two questions; first, will propellant tank pressures rise rates on the lunar surface closely track thermal equilibrium pressure rise rates? Second, will the temperature of liquid contained within a PMD closely track that of propellant surrounding the devices? For this study, however, it is concluded that LO2 thermal conditions within the ascent stage main tank, and within the PMD, will satisfy all requirements without having to vent the tank while on the lunar surface. The LCH4 main tank thermal conditions are marginal, and it is likely that propellant temperatures will exceed engine inlet temperature unless tank venting occurs on the lunar surface.

As previously stated for the descent stage, propellant tank venting will not be required for its mission, and vapor-free propellants, within temperature requirements, will be provided throughout the RCS engine firing periods.

5.9 Verification of Simplified Tank Conduction Model

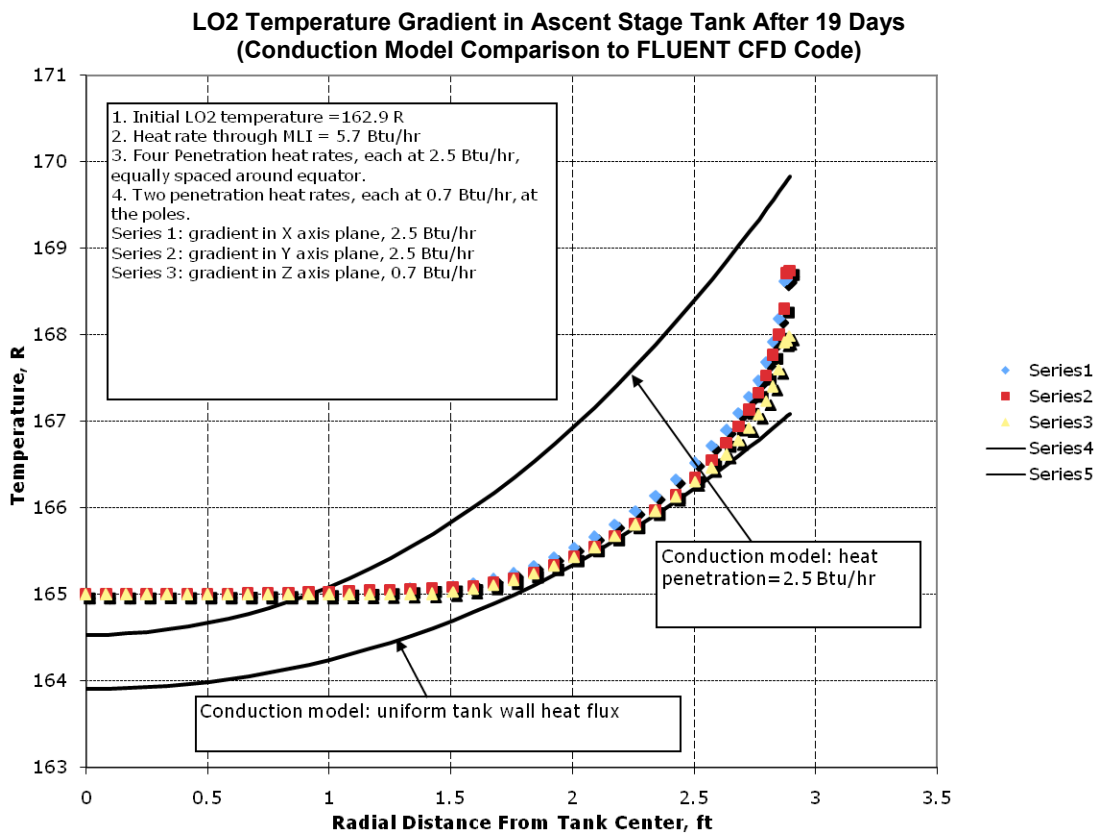
The tank heat conduction model described in Section 5.3 was necessarily simplified in order to obtain solutions that reasonably reflected the combined effects of MLI heating rates and penetration heat rates upon propellants during a long duration mission. Consequently, some limited FLUENT CFD analyses were conducted in order to validate using the heat conduction model as a conceptual design analysis tool. A case was set up to thermally model the Ascent stage LO2 tank for a 19 day duration for the following conditions:

1. Heat transfer into the tank is by conduction only.
2. MLI heat rate is 5.7 Btu/hr
3. Four heat penetrations at the tank equator, each at 2.5 Btu/hr
4. Two heat penetrations at the poles, each at 0.7 Btu/hr
5. Initial liquid temperature is 162.9 R
6. The ullage bubble is assumed to be at the tank center.
7. LO2 mass is 6207 lb.

Results shown in Figure 71 give LO2 temperature gradient, from the wall to tank centerline at the end of 19 days. The gradients are along the x, y and z axes of the tank sphere, with origin at the center. The x and y axes are coincident with a 2.5 Btu/hr penetration at the equator, and the z axis is coincident with a 0.7 Btu/hr penetration at one of the poles. The peak LO2 temperature at the wall is 168.7 R, at the point of a 2.5 Btu/hr heat penetration; the lower peak of 167.9 R occurs at a 0.7 Btu/hr penetration point.

Note that the three temperature gradients are nearly the same, which means that the high tank wall thermal conductivity distributes energy from the penetration points in a nearly uniform manner around the tank surface. This result then validates the simplified conduction model assumption of uniform heat flux into the propellant. Although not give in Figure 71, FLUENT output showed that the minimum wall temperature between any two major penetrations was about 1.8 R lower than the peak values. This again shows that energy is nearly uniformly distributed around the tank surface before being conducted into the propellant.

A comparison of the above results with the conduction model shows that model predictions yield slightly higher liquid temperatures at the wall and slightly lower liquid temperatures at the tank center, than predicted by the FLUENT CFD code. Since peak wall and liquid temperatures were used in this study to determine maximum propellant tank pressures during the descent stage and ascent stage missions, conservatively high pressure predictions resulted from using the conduction model in this study.



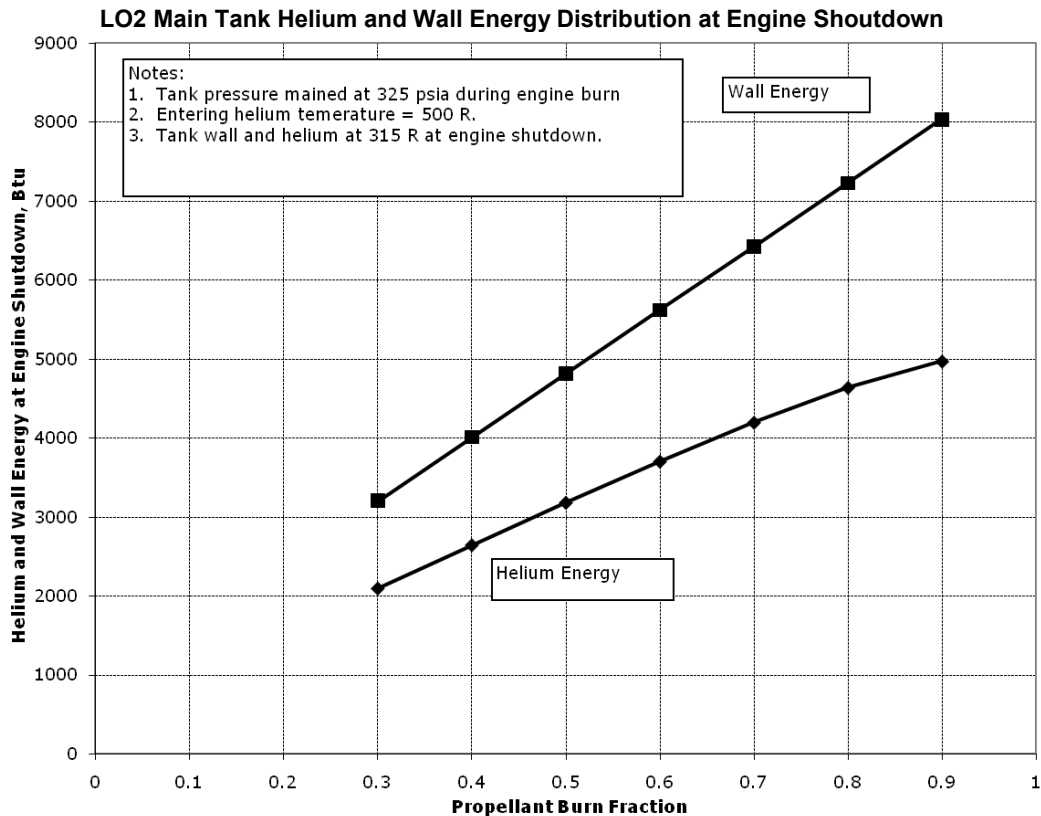


Figure 72.—LO2 main tank helium and wall energy distribution at engine shutdown.

6.0 Influence of Pressurization System Method on Stage and Propellant Management Device (PMD) Design

The study requirements did not include the type of pressurization system to assume for the descent and ascent stages. However, it became clear early in the study that the pressurization system would have to be defined since the PMD thermal environment could be significantly influenced by the pressurization system. A conversation with GRC led to the decision that an ambient storage helium pressurization system (with ullage injection of the pressurant) would also be ground ruled for this study. Thermodynamic analyses of the ascent stage LO2 tank using this pressurization system revealed serious shortcomings. First, the long first burn will consume approximately 90 percent of tank propellants to place the ascent stage into lunar orbit for rendezvous. The LO2 tank ullage temperature will be about 300 R at main engine shutdown; tank wall will also be at about 300 R. The stored energy in the walls and ullage will be about 8000 and 5000 Btu, respectively, at engine shutdown (Figure 72). The stage will then coast in zero-g for up to 24 hr before rendezvous and docking, ample time for liquid, vapor and walls to approach equilibrium conditions. Should thermal equilibrium conditions be attained (and 10 percent propellant residual remains at engine shutdown), tank pressure will decay from 325 to 263 psia, approximately 80 lb of LO2 will evaporate, and the residual liquid temperature will increase by about 13 R. Since LO2 temperature at liftoff from the lunar surface is expected to be approximately 4 R below the maximum allowable engine inlet temperature, the 13 R temperature rise will greatly exceed temperature requirements for the subsequent rendezvous and docking operations.

A second problem is that the high helium partial pressure may cause significant evaporation at the PMD screen-ullage interface should the PMD be directly exposed to the ullage. This could cause screen breakdown, or allow vapor flow into the PMD, thus jeopardizing the vapor-free propellant delivery requirement.

A third concern is that significant heat conduction along the tank wall from the hot ullage region to liquid contained within a PMD may cause boiling which can jeopardize the requirement for vapor-free propellant delivery.

All of the above concerns led to the recommendation that a more benign method of pressurization be selected for this study; method bubbler pressurization. This pressurization technique introduces helium beneath the liquid surface, allowing propellant to evaporate into the helium bubbles and contribute to tank pressurization. Properly designed, the helium-propellant vapor mixture will be in equilibrium as it enters the ullage and, thus, the ullage will be in near-equilibrium with the propellant throughout engine firings.

There are several advantages to a bubbler pressurization system. One is that the propellant and ullage will be in near-equilibrium throughout the mission which means that a) there will be little to no pressure collapse following an engine shutdown, b) there will be little to no energy exchange between propellant ullage and tank walls following an engine shutdown, c) bubbling helium beneath the liquid surface maintains the bulk at a near-uniform temperature during engine burn, and d) evaporation at the PMD screen-ullage interface should be negligible because the ullage and liquid will be at near-thermal equilibrium.

Another advantage is that bubbler pressurization will cool the tank propellants during engine burn because liquid evaporating into the helium bubbles cools the remaining propellant. The degree of cooling can be controlled, in part, by selecting the helium storage temperature. If helium is stored at propellant temperatures, maximum cooling will be realized. Less propellant cooling will result if helium is stored at higher temperatures, because some of the helium sensible energy will be released to the propellant, causing a temperature rise.

To minimize the impact of helium bubbler pressurization upon PMD design, the assumption was made that propellant temperature would be unaffected during engine burn.

A more detailed evaluation should be made of a bubbler pressurization system (or any pressurization system) to assure that all issues stage and PMD design have been adequately addressed.

7.0 Conclusions/Recommendations

Conceptual designs have been identified for Propellant Management Devices (PMDs) suitable for long duration missions of lunar ascent (main and RCS propulsion) and descent stages (RCS propulsion) using methane and liquid oxygen. Results indicate that simplified PMD designs will satisfy mission requirements as a result of key design factors imposed upon the descent and ascent stages, unrelated to the PMD itself. The major factors that serve to simplify PMD design are 1) stringent insulation requirements, 2) high propellant tank operating tank pressures and 3) the selection of aluminum tanks for propellant storage. Insulation requirements must support cryogenic storage for periods in excess of 200 days with, ideally, no boil-off losses. High propellant tank pressures assure significant propellant sub-cooling once propellant tanks are pressurized to 325 psia. The degree of sub cooling, at 325 psia, will be as much as 40 R (LO₂) and 80 R (LCH₄) at the maximum predicted ascent stage propellant temperatures. An even greater margin will exist for the shorter duration descent stage phase of the lunar mission. The high aluminum tank thermal conductivity will provide a near-uniform propellant tank wall temperature throughout the mission. Tank “hot spots” created by heat penetrations such as struts, feed lines or vent lines, will become only a few degrees warmer than the average wall temperature because the incoming heat rate will readily be conducted away from the “point source”. Consequently, heat flow into the tank propellant (and the resulting temperature gradients) will be nearly uniform.

Conclusions resulting from the above beneficial factors are:

- (1) Propellant tank venting will not be required during the Earth- to-lunar phase of flight.
- (2) Propellant tank venting may not be required during the 210-day lunar stay. However, a 3.7 percent increase in LCH₄ tank heating rate will necessitate venting to maintain bulk liquid temperatures below the maximum allowable of 224 R. For the LO₂ tank, the heat rate increase must exceed 13 percent.

(3) PMDs will remain vapor-free throughout the mission once propellant tanks are pressurized while in low Earth orbit.

(4) Propellant contained within a PMD will reside at nearly the same temperature as that of the surrounding liquid. If the tank insulation requirements maintain bulk propellant temperatures within engine inlet requirements, propellant flow from a PMD will also satisfy engine inlet requirements. The exception to the above is that penetration heat rates may create “hot spots” in the range of 1 to 2 R above bulk propellant temperatures.

(5) A TVS or propellant mixer is not required for the descent stage phase of flight.

(6) A TVS or propellant mixer may not be required for the ascent stage long duration stay on the lunar surface.

(7) Under the thermal and operational constraints of this study, LO₂ and LCH₄ PMDs can employ designs and operational procedures that are no more complex than those previously developed and used for Earth storable propellants.

The following recommendations are made:

(1) Flexible screen PMD development program should be implemented

(2) Further thermal study using CFD code should be performed to analyze the following:

a. Determine temperature gradients in propellants for long term storage on the lunar surface.

Results would serve to quantify the need for TVS, mixer or improved insulation systems.

b. Determine temperature gradients and resulting heat rates and fluxes surrounding such heat penetrations as propellant tank support struts, vent lines feed lines. Such data would serve as a design guide for vehicle systems.

c. Compare the thermal environment of propellants contained within a PMD in direct thermal contact with a tank to that of a PMD thermally isolated from the tank wall.

(3) Perform studies to include the influence of pressurization system type (including storage) upon a propellant tank insulation system design and PMD design to satisfy mission engine inlet temperature requirements.

Appendix A.—Nomenclature

\dot{m}	propellant flow rate
\dot{Q}	total heat rate into propellant tank, $\frac{\text{Btu}}{\text{hr}}$
ΔT	wall-to-fluid bulk temperature difference, R
A	channel cross-sectional area, ft ²
a	radius of sphere
c	fluid heat capacity
c_p	fluid heat capacity, $\frac{\text{Btu}}{\text{lb} \cdot \text{R}}$
D	equivalent channel diameter, ft
f	friction factor
F_0	constant heat flux
g	acceleration, ft/sec ²
g_c	gravitational constant, lb _f -ft/lb-sec ²
Gr_L	$\frac{\rho^2 g \beta (\Delta T) L^3}{\mu^2}$, Grashof number
h	average wall-to-fluid heat transfer coefficient, $\frac{\text{Btu}}{\text{ft}^2 \cdot \text{hr} \cdot \text{R}}$
H	liquid head, ft
$K = \frac{k}{\rho c}$	fluid thermal diffusivity
K_0, I_0, K_1, I_1	Bessel functions
k	fluid thermal conductivity, $\frac{\text{Btu}}{\text{hr} \cdot \text{ft} \cdot \text{R}}$
L	channel length, ft
L	height of vertical wall, ft
P	channel perimeter, ft
ΔP_{accel}	pressure drop in screen channel due to accelerating channel propellant mass
ΔP_{flow}	flow pressure loss in screen channel, psf

ΔP_{scr}	flow pressure loss across screen, psf
Pr	$c_p \frac{\mu}{k}$, Prandtl number
q	velocity pressure, psf
r	radial distance from center of sphere
t	time
ΔT	wall-to-fluid bulk temperature difference, R
T_∞	bulk temperature of the surrounding fluid
$T_b = T_{fm}(R_b)$	bulk temperature of the metal
v	fluid temperature at time, t , minus fluid temperature at time, $t = 0$
β	constant
μ	fluid viscosity, $\frac{\text{lb}}{\text{ft} \cdot \text{sec}}$
ρ	density, $\frac{\text{lb}}{\text{ft}^3}$
σ	liquid-gas surface-tension, $\frac{\text{lb}_f}{\text{ft}}$
Δ	difference, or change

A.1 Subscripts

c	constant
scr	screen
$flow$	flow
$accel$	acceleration

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14. ABSTRACT Concepts of Propellant Management Devices (PMDs) were designed for lunar descent stage reaction control system (RCS) and lunar ascent stage (main and RCS propulsion) missions using liquid oxygen (LO2) and liquid methane (LCH4). Study ground rules set a maximum of 19 days from launch to lunar touchdown, and an additional 210 days on the lunar surface before liftoff. Two PMDs were conceptually designed for each of the descent stage RCS propellant tanks, and two designs for each of the ascent stage main propellant tanks. One of the two PMD types is a traditional partial four-screen channel device. The other type is a novel, expanding volume device which uses a stretched, flexing screen. It was found that several unique design features simplified the PMD designs. These features are (1) high propellant tank operating pressures, (2) aluminum tanks for propellant storage, and (3) stringent insulation requirements. Consequently, it was possible to treat LO2 and LCH4 as if they were equivalent to Earth-storable propellants because they would remain substantially subcooled during the lunar mission. <i>In fact, pre-launch procedures are simplified with cryogenics, because any trapped vapor will condense once the propellant tanks are pressurized in space.</i>					
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