LOW-THRUST CHEMICAL ORBIT TO ORBIT PROPULSION SYSTEM

PROPELLANT MANAGEMENT STUDY

Ralph H. Dergance
Martin Marietta Corporation

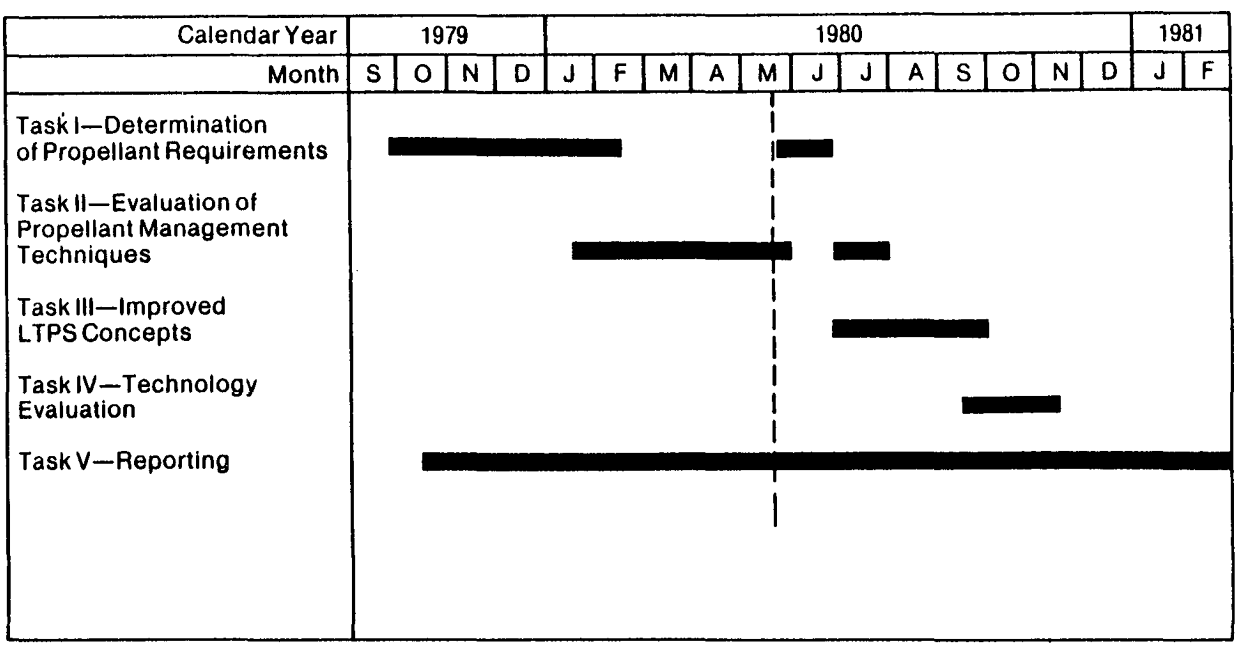
Contract Information

- Customer: NASA-Lewis Research Center
  Mr. John C. Aydelott

- Contract Number: NAS3-21954

- Period of Performance: 14 September 1979—14 November 1980

Program Schedule



LTPS Summary

The primary objective of the Low Thrust Chemical Orbit to Orbit Propulsion System Propellant Management Study Program is to determine propellant requirements, tankage configurations, preferred propellant management techniques, propulsion systems weights, and technology deficiencies for low-thrust expendable propulsion systems.

LTPS Task Objectives

Task I—Determination of Propellant Requirements—Determine propellant subsystem mass and volume for three propellant combinations and two insulation systems that minimize potential stage length.

Task II—Evaluation of Propellant Management Techniques—Determine feasibility of potential propellant management techniques and attendant weight penalties for tankage configurations determined in Task I.

Task III—Improved LTPS Concepts—Determine the maximum performance (minimum mass) LTPS for the three propellant combinations. Further refine Task I analyses.

Task IV—Technology Evaluation—Determine adequacy or deficiencies associated with the concepts defined in Task II and III.

Task V—Reporting—Monthly technical and financial reports, work plan, and final report.

Task I—Determination of Propellant Requirements

Ground Rules

Performance Specifications—MR, I_{SP}, total ΔV, and LEO to GEO transfer time supplied by NASA-LeRC; 60,000 lbm liftoff weight for propulsion system and payload.

Mission Timeline—Propellant topping is allowed to T-4 min; tanks locked up until T+90 sec; tank ΔP not to exceed 6 psid; 40-hr erection time; LEO to GEO transfer time specified by NASA-LeRC.

Design Criteria—Minimum length of propulsion system.

54 Study Candidates

3 Propellant Combinations	LO_2/LH_2, LO_2/LCH_4, LO_2/RP-1	All Combinations
3 Thrust Levels	100, 500, 1000 lbf	
3 Burn Strategies	1, 4, 8 Perigee Burns	
2 Insulation Concepts	MLI and SOFI	

Selected LTPS Point Design Parameters Supplied by NASA LeRC

Propellant Combination	Thrust (Lbs)	No. of Burns	ISP (Sec) 400:1	Total ΔV Required (ft/sec)	LEO to GEO Transfer Time (Hours)
LOX/LH_2 MR=6:1	100	1 4 8	422.5	18,166.3 17,294.8 16,349.9	59.21 61.38 72.37
	500	1 4 8	440.0	17,352.4 15,931.2 14,593.9	16.89 19.83 31.76
	1000	1 4 8	449.0	16,892.4 15,526.1 14,479.7	11.74 14.91 27.11
LOX/CH_4 MR=3.7:1	100	1 4 8	337.5	18,126.3 17,262.8 16.326.6	52.85 55.37 66.74
	500	1 4 8	356.5	17,258.6 15,874.2 14,571.4	15.77 18.83 30.87
	1000	1 4 8	364.5	16,759.0 15,450.4 14,448.1	11.19 14.41 26.67
LOX/RP-1 MR=3:1	100	1 4 8	317.5	18,115.5 17,254.1 16,320.3	51.08 53.69 65.16
	500	1 4 8	333.5	17,228.5 15,855.8 14,564.2	15.40 18.50 30.79
	1000	1 4 8	343.0	16.720.9 15,428.8 14,438.9	11.03 14.27 26.53.

Initial Screening of Tank Configurations

Objective—Find Minimum Length Tanking System

Method

- Compute Required Volume
  - —Compute Usable ΔV Propellant
  - —Assume 14-ft Diameter - 2% Ullage
  - —Assume Boiloff Is 5% of ΔV Propellant
- Compute Tank Sizes

Configurations

- Maximum and Minimum Propellant Requirements (1000 lbf, 100 lbf) Were Computed for Three Propellant Combinations:
  - —LO_2/LH_2
  - —LO_2/LCH_4
  - —LO_2/RP-1
- Three Tanking Configurations Were Sized for Each Propellant Combination

Results

- Minimum Length Systems Were Elliptical Domed/Toroidal for All Propellant Combinations
- Maximum Length Systems Were for LO_2/LH_2 Parallel Tanks; LO_2/LCH_4, LO_2/RP-1 Elliptical Tanks.

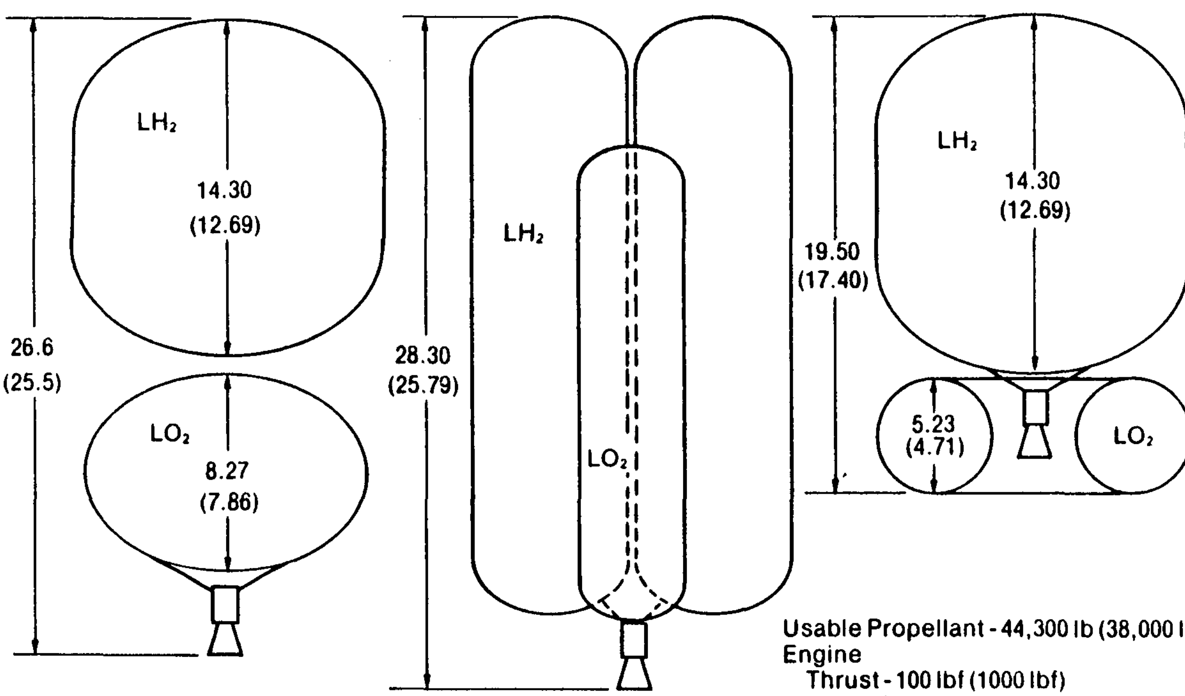
Preliminary Tanking Configurations

In preparation for the Propulsion System Characterization studies, some preliminary configuration sizing calculations were performed. Based on previous Tug Studies* several of the more promising configurations were considered for each of the LTPS propellant combinations and for both maximum and minimum propellant loads. The usable propellant quantities were calculated using the ideal velocity equation and the velocity increments and specific impulses for each propellant combination, burn strategy and thrust level. The minimum loads were derived from the maximum thrust, maximum I_{sp} and 8 perigee burn conditions; while the maximum loads were derived from the minimum thrust, minimum I_{sp} and 1 perigee burn conditions.

The series "conventional" tankage configuration utilizes either ellipsoidal ($\sqrt{2}$) or cylindrical/ellipsoidal ($\sqrt{2}$) tanks up to a maximum diameter of 14 feet. The parallel tank configuration utilizes four cylindrical/ellipsoidal ($\sqrt{2}$) tanks packaged within a 14-foot outer diameter. The specific oxidizer and fuel tank diameters were selected to minimize the overall stage length. A distance of 0.5 feet was used between adjoining tanks to allow for insulation and clearance. The series "non-conventional" tankage configuration utilizing a toroidal tank and either an ellipsoidal ($\sqrt{2}$) or a cylindrical/ellipsoidal ($\sqrt{2}$) tank was determined to be the minimum length configurations for all propellant combinations.

*"Space Tug Systems Study (Storable)", MCR-73-235, Final Report of Work Performed by Martin Marietta Corp. for Marshall Space Flight Center under Contract NAS8-29675, Sept. 1973.

Preliminary Tankage Configuration— LO_2/LH_2



Note:
Dimensions in feet.
Maximum diameter = 14 ft.
Engine length 3 ft (4 ft).

Usable Propellant - 44,300 lb (38,000 lb)
Engine
Thrust - 100 lbf (1000 lbf)
I_{sp} - 423 sec (449 sec)
MR - 6.0
Perigee Burns - 1 (8)
MLI Insulation

Embedded Engine Analysis

To imbed the engine in the center space of the parallel tank arrangement, the individual tank diameters must be reduced to create a space for at least the engine thrust chamber assembly. To determine the corresponding increase in length of the tank requires calculating the volume as a function of the length. By combining the volume relationships for $\sqrt{2}$ domes and right circular cylinders, the following expression was derived:

$$L_T = \frac{V_T}{\pi r^2} + \frac{2}{3\sqrt{2}} r = \frac{V}{\pi r^2} + 0.4714r$$

where:

L_T = tank length

V_T = tank volume

r = tank radius

or

$$\frac{dL_T}{dr} = -\frac{2V}{\pi r^3} + 0.4714$$

The value of dL_T/dr is large and increases rapidly as the diameter of the tank decreases.

The facing page presents the results of this analysis for the cases shown. In all instances, the stage length is increased by imbedding the engine.

Embedded Engine Analysis

Objective

Reduce parallel tank diameter (cylindrical with $\sqrt{2}$ domes) to accommodate embedded engines in an attempt to reduce length.

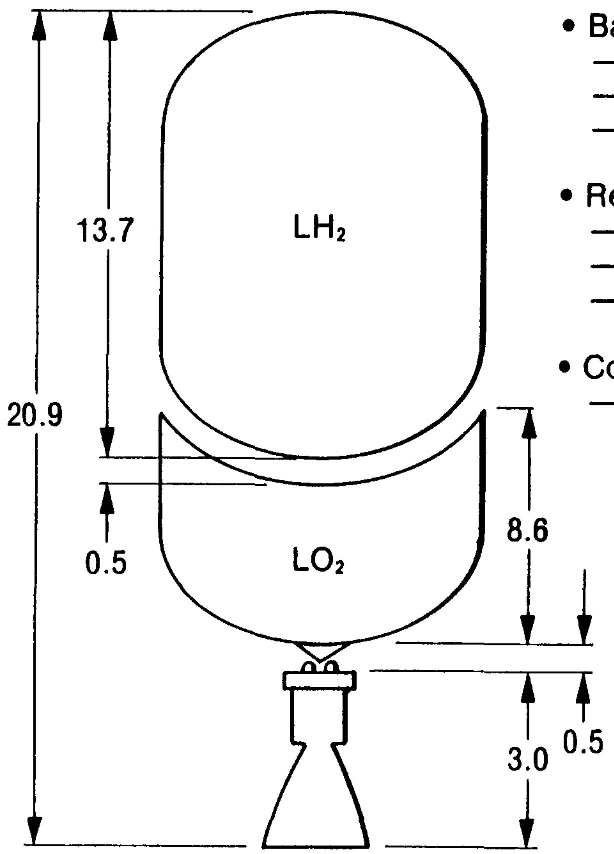
Propellant Combination	Thrust Level, lbf	Propellant Mass, lb	Δ Tank Length, ft	Engine Length, ft	Δ Stage Length, ft
LO_2/LCH_4	100	48,700	4.2	3.0	+1.2
LO_2/LCH_4	1000	42,500	4.7	4.0	+0.7
LO_2/RP-1	100	49,800	4.1	3.0	+0.9
LO_2/RP-1	1000	42,500	4.7	4.0	+0.7
LO_2/LH_2	100	46,100	6.6	3.0	+3.6
LO_2/LH_2	1000	38,000	7.1	4.0	+3.1

Conclusion—Elliptical/Toroid Tankage Scheme is Shorter

Concentric Bulkhead Configuration

For this analysis, one tank containing conventional $\sqrt{2}$ domes and the other with an inverted $\sqrt{2}$ dome were used. The overall stage length was calculated using (a) an inverted dome tank for the oxidizer tank with no change to the fuel tank, and (b) an inverted dome fuel tank with no change to the oxidizer tank. The shortest configuration was still 1.4 Ft. longer than the tandem/toroidal arrangement.

Concentric Bulkhead Configuration



Dimensions in Feet

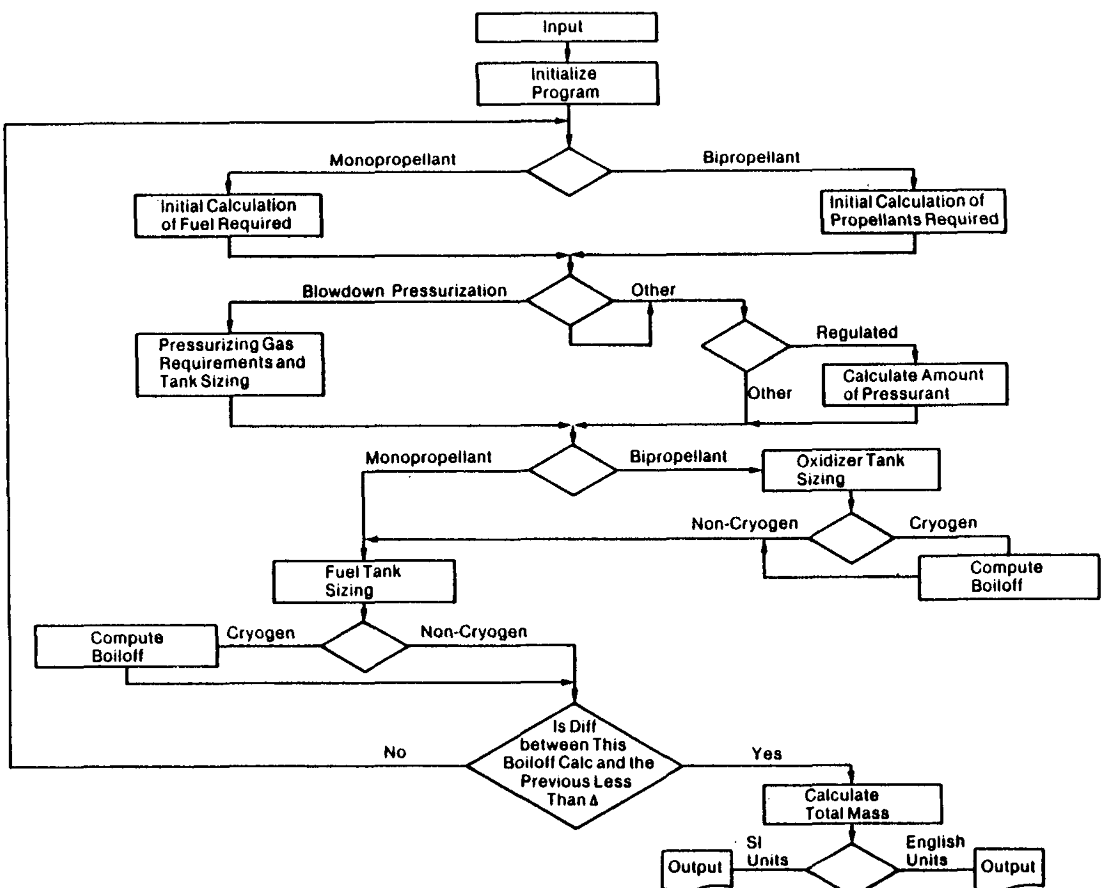
- Baseline
  - —LO_2/LH_2
  - —1000 lbf
  - —1 Perigee Burn
- Results
  - —Length = 20.9 ft
  - —Tandem/Toroidal Length = 19.5 ft
  - —Reversed Bulkhead Length = 22.6 ft
- Conclusion
  - —Tandem/Toroidal Configuration Is Shorter

This program (PROP) was written and checked out during the early Viking Program and has been used many times since as a design and analysis tool. The program has four major system options: first, the choice of a monopropellant or bipropellant propulsion system using cryogenic and/or earth storable propellants. Second, the pressurization system sizing includes either a blowdown or a regulated case; in addition a third option bypasses the pressurization sizing loop and substitutes a fixed input mass to accommodate other types of systems (autogenous, etc). Third, available propellant tank shapes are: 1) spherical, 2) cylindrical with hemispherical ends, 3) cylindrical with $\sqrt{2}$ ellipsoidal ends, 4) $\sqrt{2}$ ellipsoidal tank, and 5) toroidal. The fourth option allows the input/output units to be specified in one of four combinations, 1) English/English, 2) English/SI, 3) English/English and SI, and 4) SI/SI. Other options are chosen at input, such as the specific vehicle mass, delta-V, and ISP and allowing the computer to calculate the propellant mass; or specifying the mass of propellant burned. Also, the program will model a wide range of adiabatic or isothermal burns.

The program output includes a complete propellant inventory (including boil-off for cryogenic cases), pressurant and propellant tank dimensions for a given ullage, pressurant requirements, insulation requirements and miscellaneous masses. The output also includes the masses of all tanks; the mass of the insulation, engines and other components; total wet system and burnout mass; system mass fraction; total impulse and burn time.

In addition, a modification was programmed to provide the capability to calculate the remaining mass, volume, and ullage height at the beginning of all burns for each propellant. The ullage height is the length of the inside of the tank minus the height of the propellant if it were all settled in the bottom of the tank. Also calculated at the initiation of each burn is the total system mass and acceleration along with the burn duration. The same variables, except ullage height and burn duration, are also computed at the end of the circularization burn. The final outputs are propellant tank dimensions.

PROP Program Summary Flow Chart



Baseline Insulation Characteristics

A number of different insulation sytems were considered as LTPS candidates. The two most promising concepts appear to be a multilayer mylar system with a helium purge bag and the spray on foam insulation (SOFI) utilized on the Space Shuttle External Tank program. The SOFI (CPR-488) was compared with other foam insulations* and was selected because it had the best balance between low density and good thermal conductivity.

Multilayer insulation results in a relatively heavy system with adequate ground thermal conductivity but excellent on-orbit thermal conductivity. Thus, longer duration missions (i.e., multiple burn options which minimize ΔV but require longer transit times) stand to benefit the most from a multilayer system. The actual insulation system weight is a function of the required insulation thickness and average density; however, the optimum thickness is determined for some cases by a trade-off between boil-off/vent losses and insulation weight, and for other cases by the pressure rise during the ground hold and ascent period. The optimum insulation thickness for each of the 54 propulsion systems was determined using a analytical model programmed on a desk calculator.

Data for MLI was from; MCR-79-594 "Cryogenic Fluid Management Experiment, Thermal Analysis Report." June 1979. Martin Marietta Corp., Denver Division, Denver, Colo 80201.

SOFI Data was from; MMC Dwg. No. 82600200102 "Thermal Data Book, External Tank Project." October 1979. Michoud Operations, Martin Marietta Corp., Denver Division, Denver, Colo 80201.

*Sharpe, Ellsworth L., Helenbrook, Robert G.: "Cryogenic Foam Insulation for LH_2 Fueled Subsonic Transports", Delivered at International Cryogenic Materials Conference, July 10-11, 1978.

Baseline Insulation Characteristics

Type / Parameter	Multilayer (MLI)		Spray-on Foam Insulation (CPR-488)
	Ground	On-Orbit	
Conductivity, Btu/hr-ft²-°R	0.35	$1.8824T^{0.6} \times 10^{-6}$	$(1.7 + 0.02452T) \times 10^{-3}$
Density, lb/ft³	3.51*	3.51*	2.2†

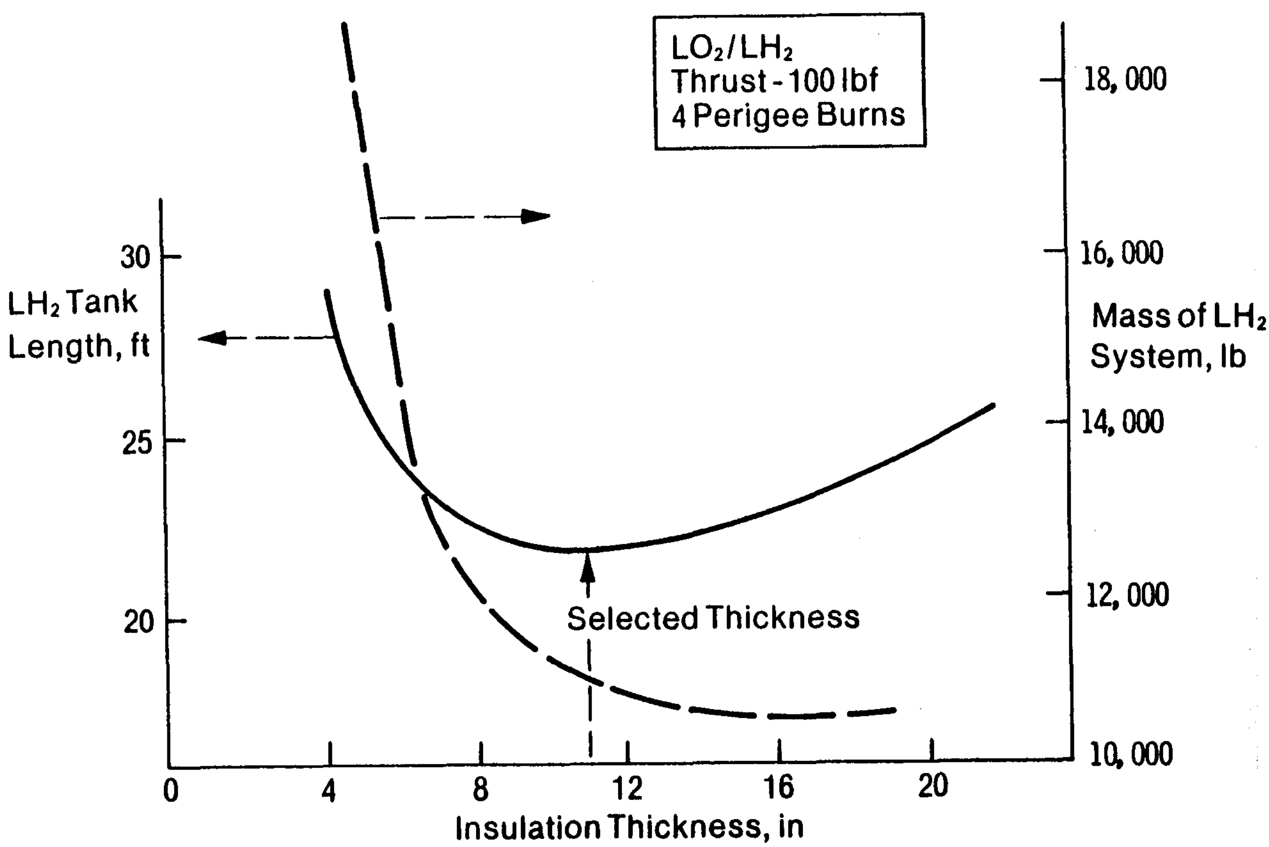
*Does not include protective cover sheet or fastening material.

†Values at 289°K (520°R).

Length - Optimized SOFI Insulation Thickness for LH_2 Tank

The two plots show Length vs Insulation Thickness (solid line) and Mass vs Thickness (broken line) for one particular mission. The mass-optimized thickness can be seen to occur at about 17 inches and the length optimized thickness is at about 11 inches. The large value of the slopes of the plots to the left of the optima are due to increasing boiloff. To the right of the optimum the slope is smaller and soon becomes constant due to additional insulation mass which is basically a linear function of thickness. As the insulation thickness decreases from 17 inches to 11 inches the length decreases about 20 inches and the mass increases approximately 500 lb_m. This means that for the LH_2 tank a substantial gain in length is accomplished without too large a weight penalty. Similar results were obtained for other SOFI-covered tanks, but where not as pronounced. Thus, when SOFI was used a length-optimized insulation thickness was also used. The selected thickness shown on the graph is the thickness predicted by the length-optimized analysis.

Length—Optimized SOFI Insulation Thickness for LH2 Tank



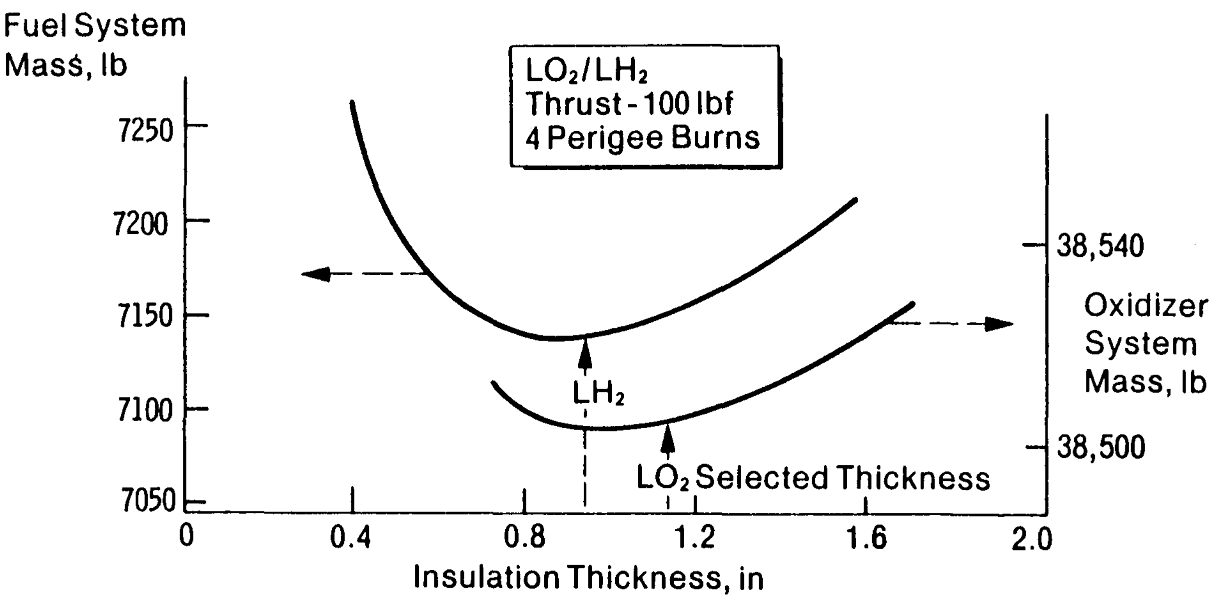
Liftoff Mass Optimized MLI Insulation Thickness

A mass optimized analytical model to predict optimum thermal insulation thickness was developed and programmed on a desk-top calculator. The final result is a single equation that calculates the insulation system thickness that results in the lowest propulsion system mass (including vent losses) for the given insulation system properties and ground and on-orbit conditions. Since a number of simplifying assumptions were required in the derivation of this equation, it was necessary to verify the relationship using the PROP computer program. The results of this checkout are shown in the following figure for MLI systems. These plots show the total mass of the system required to accommodate the propellants as a function of insulation thickness. The total mass includes insulation, tank, boil-off, trapped propellant, usable (ΔV) propellants, and start-shutdown losses. All heat transfer to the propellant is assumed to cause vaporization only with no sensible heating.

The baseline propellant combination of LO_2/LH_2 at a mixture ratio of 6:1 was used for all cases. The total payload mass was approximately 60,000 lbm. The fuel tank was a 14 foot diameter cylinder with $\sqrt{2}$ ellipsoidal domes. The oxidizer was contained in a $\sqrt{2}$ ellipsoidal tank with a major axis of 11.4 feet. The tank material was 2219-T87 aluminum. On-orbit time was assumed to be 101 hours. An equivalent on-orbit time of (ground plus ascent) of 5.4 minutes, based upon average insulation performance values for a typical STS ascent profile, was used for the representative mission.

The predicted optimum insulation thickness for each propellant tank (using the calculator program) is noted by the arrows on the Figure while the curves shown the actual total propellant system masses (calculated by PROP) plotted as a function of insulation thickness. Note that the calculator model predicts a consistently conservative value for the optimum thickness compared to the PROP predicted value. However, the maximum difference in mass from the optimum is 4 lb_m which amounts to .01% difference in total net system mass. This difference is far less than the mass differences for the various propellant systems considered in this study and did not influence the comparative results.

Liftoff Mass Optimized MLI Insulation Thickness



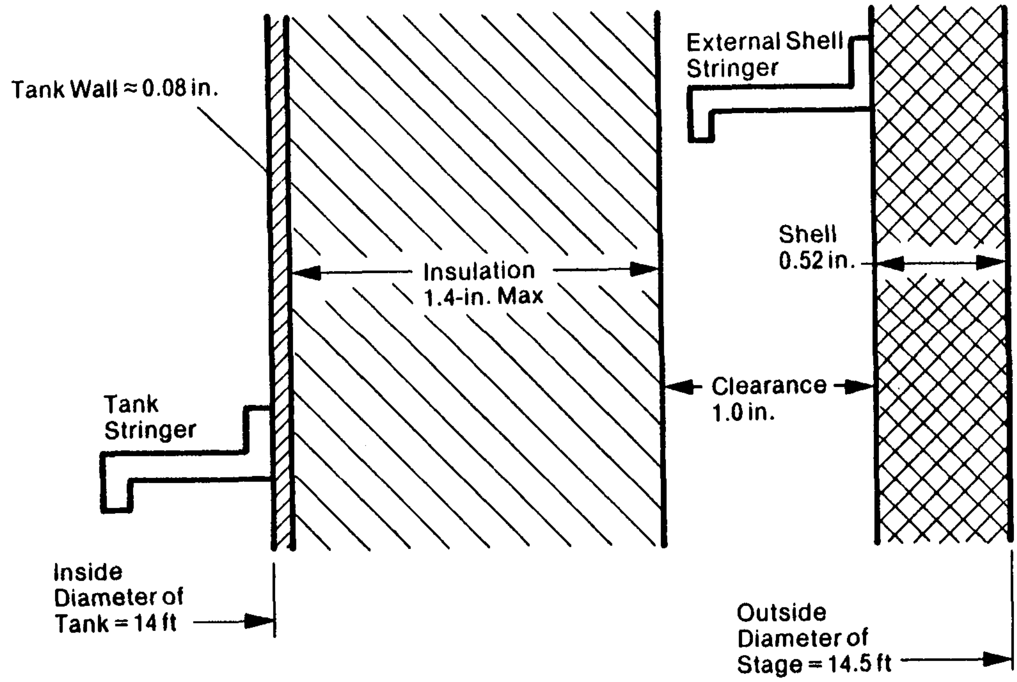
Length-optimized MLI represents significant weight penalty (≈350 lb) with a small length gain (≈0.8 in).

Baseline Tank Diameter (MLI)

This chart substantiates the 14 foot tank diameter assumed for the preliminary tank screening analyses.

Starting with the maximum cargo bay diameter of 15 feet, an allowable stage diameter of 14.5 feet was determined from inputs from Martin Marietta's Payload Integration Contract. The external skin arrangement, constructed of graphite expoxy composite material, was determined from Space Tug Study results. The 1.4 inch MLI thickness resulted from the insulation studies previously discussed. By considering a typical tank wall thickness of 0.08 inches, an inside diameter of 14 feet is derived for tank sizing.

Baseline Tank Diameter (MLI)



Note:
For the SOFI-covered tanks, the outside diameter of the insulation is constrained to 170 in., and the inside diameter of the tank will vary depending on the insulation thickness.

Propellant Inventory

The elements of a typical propellant inventory are shown. All items are self-explanatory with the exception of expulsion efficiency and loading accuracy.

Expulsion efficiency was based upon Martin Marietta's assessment of the performance of a typical surface tension propellant management device for this application. The 98% value, although representative, will be updated based on results of analyses conducted later in the contract.

Loading accuracy was based on values that have been achieved with demonstrated loading techniques.

Propellant Inventory

- ΔV—Calculated Using the Ideal Velocity Equation
- Performance Reserve—2% of ΔV Requirement
- Start/Shutdown Losses—Scaled Down from Centaur Data
- Boiloff—Calculated as a Function of Mission Profile, Tank Structure, and Insulation
- Trapped—Estimated from Stage and Tanking Geometry
- Expulsion Efficiency—98%
- Loading Accuracy—0.5%

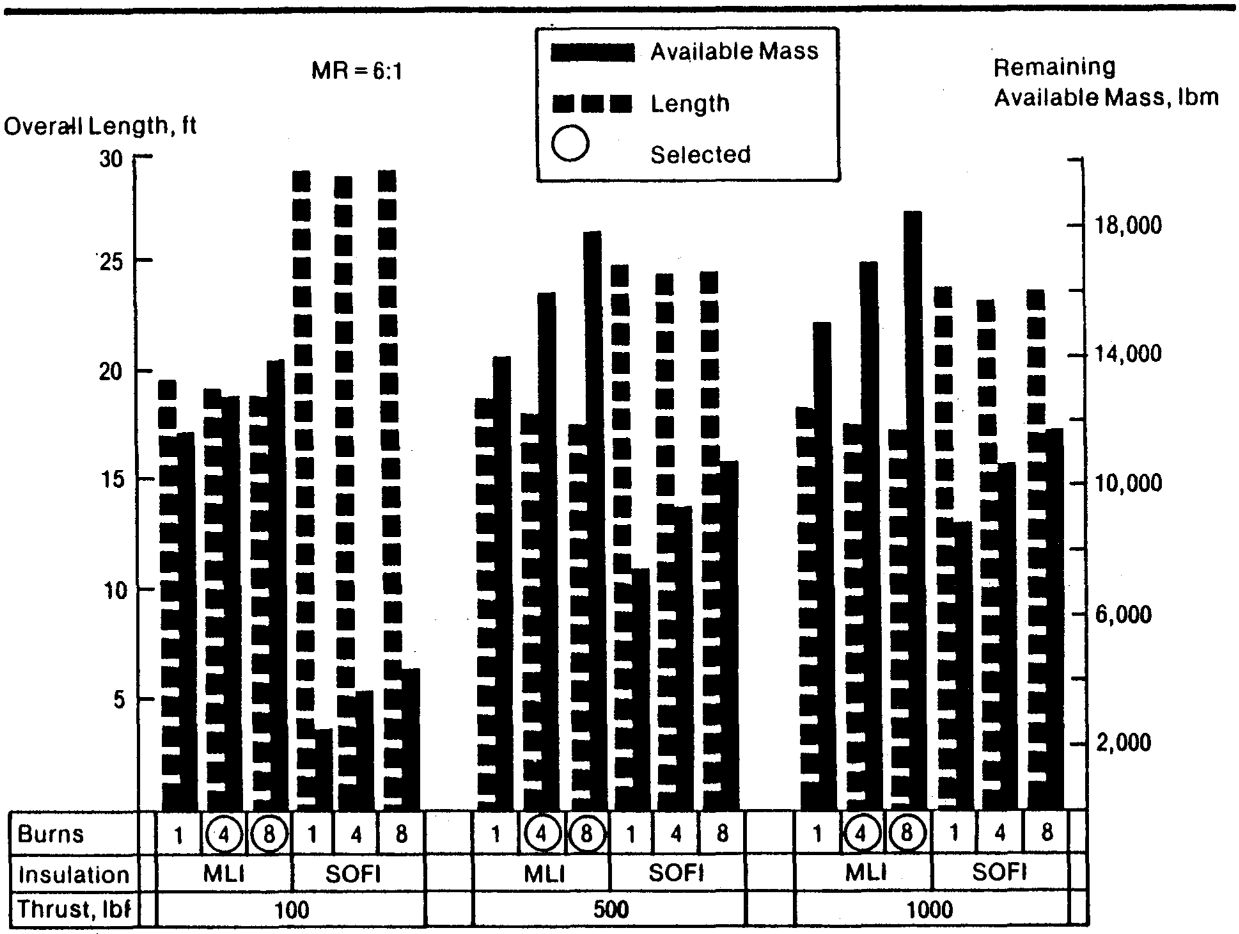
Propellant System Length & Available Mass

- Overall Length
  - All Elliptical/Toroidal Configurations
  - Tankage (Including Insulation) Only
  - Top of Toroid Coplanar with Bottom of Ellipsoid
- Remaining Available Mass
  - 65,000 lbm STS Capability
  - 5,000 lbm ASE
  - 60,000 lbm Liftoff
  - Available = 60,000 lbm—Stage Not Including Avionics, Propellant Management Device, ACPS, or Adapters.

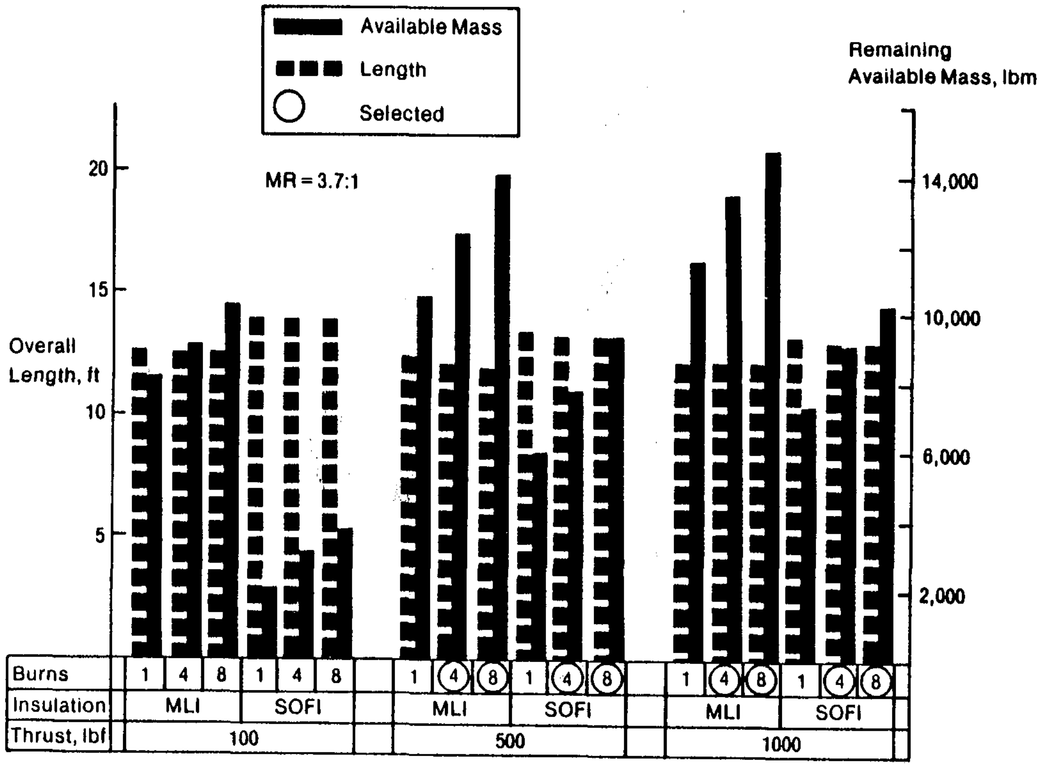
LO_2/LH_2 Propellant System Length and Available Mass

The definitions of length and available mass were presented on the previous page. The configurations circled on the next 3 charts are those selected for use in Task II - Evaluation of Propellant Management Techniques - of this program. They were selected to maximize available mass while minimizing length. However, some SOFI configurations were chosen even without satisfying the aforementioned criteria, to maintain this concept for technology evaluation.

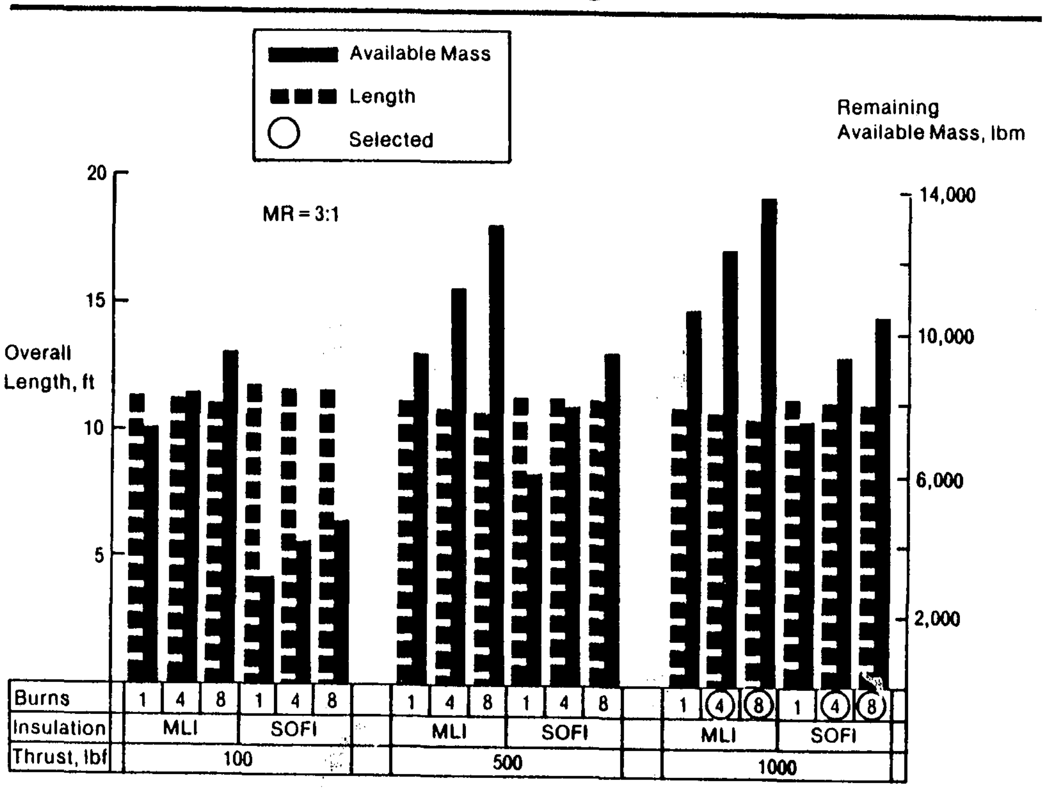
LO_2/LH_2 Propellant System Length and Available Mass



LO2/LCH4 Propellant System Length and Available Mass



LO2/RP-1 Propellant System Length and Available Mass



Task II - Evaluation of Propellant Management Techniques

Three types of propellant management methods; propulsive settling, partial acquisition devices and total acquisition devices, were applied to the selected propulsion systems. The propellant for the settling thrusters was either the primary propellants or N_2O_4 and MMH. NASA LeRC provided a computer model used to predict the propellant settling times.* The partial and total acquisition devices are fine mesh screen surface tension type propellant management devices.

For each propellant management method, its feasibility for this application was determined and the total weight penalty for each method was calculated.

*I.E. Sumner: "Liquid Propellant Reorientation in a Low-Gravity Environment", NASA TM-78969, NASA Lewis Research Center, Cleveland, Ohio, July 1978.

Task II—Evaluation of Propellant Management Techniques

Determine feasibility and weight penalty of propellant management concepts for the selected low-thrust propulsion systems.

Concepts:

- Propulsive settling—Utilizing LeRC-supplied model
  - —Using main engine propellants for settling thrusters
  - —Using N_2O_4 and MMH as propellants for settling thrusters
- Fine mesh screen partial acquisition system
- Fine mesh screen total acquisition system

Results - Propulsive Settling

It was found that by using very small thrusters, in the range of 0.1 to 1.0 lb_f, the amount of propellant required to perform settling prior to every burn is small (less than 10 lbm). However, the residuals left in the tank due to suction dip during terminal drain can be large (200 to 800 lbm), especially in the toroidal tank. Means of reducing the draining residuals will be investigated under a subsequent task of this program. Of the three propellant management methods, propulsive settling had the highest weight penalty.

Results—Propulsive Settling

- By using very small thrusters (0.1 to 1.0 lbf), propellant requirement for settling is very small (< 10 lbm).

- Residuals due to draining can be large (200 to 800 lbm), especially in toroidal tank.

- Highest weight penalty.

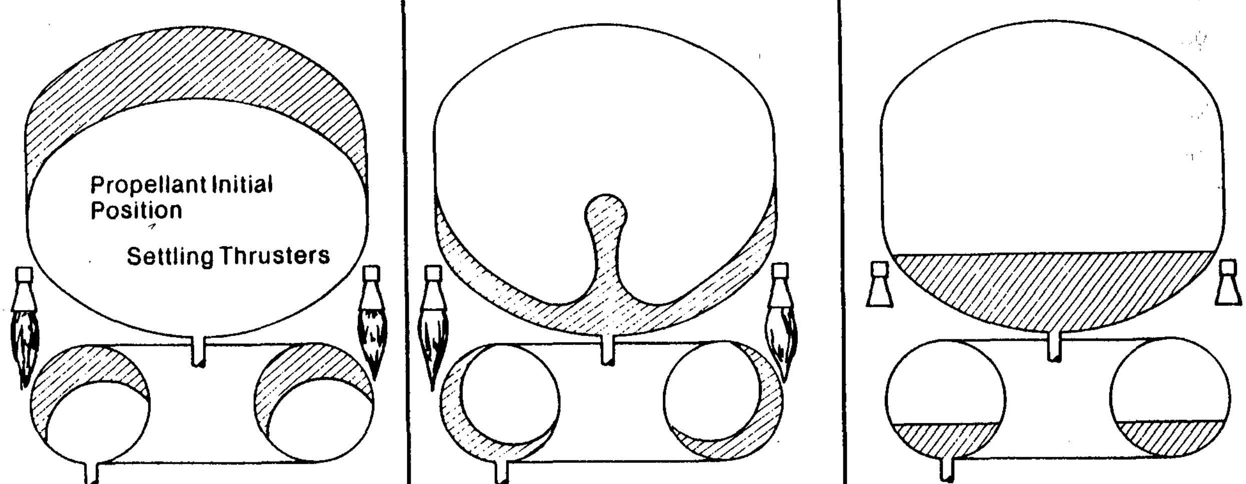
Propellant Settling Approach

Prior to each main engine burn the settling thrusters fire, producing an acceleration capable of causing reorientation of the propellant. This acceleration must be maintained for a period long enough to position the propellant at the tank outlet so that the main engines can start. To cause reorientation the acceleration must be greater than atmospheric drag, which is significant prior to the first burn in low earth orbit. In addition, the acceleration must be large enough to create interface instability in both tanks, with the smaller radius toroidal tank being the most stable. Too large an acceleration can cause liquid geysering, which will increase the time required to complete settling.

It was assumed that the settling thrusters were part of the attitude control system, and their thrust level and the number firing could be selected. Therefore, only the weight of the propellant used to perform the settling contributed to the weight penalty. The draining residuals also add to the weight penalty.

Propellant Settling Approach

Initial Conditions	Settling Underway	Settling Complete



Initial Conditions

Settling Thrusters Fire
- Overcome Atmospheric Drag
- Cause Interface Instability

Settling Underway

- Settling Thrusters Continue to Fire
- Thrust Selected to Minimize Liquid Geysering
- Thrusters Assumed To Be Part of Attitude Control System

Settling Complete

- Settling Thrusters Shut off when Settling Predicted To Be Complete
- Main Engine Immediately Started

Weight Penalty:
Propellant Required to Produce Settling Draining Residuals

Results - Partial Acquisition Systems

It was found that a reservoir of reasonable size (less than 15 ft^3) will meet the expulsion requirements. Methods of refilling the reservoir during an engine burn were not feasible due to the low acceleration produced by the main engines. A significant portion of the propellant in the reservoir is lost due to vaporization. Since the sizing of the reservoir is critical to the successful operation of the device, careful accounting of all such losses is required. The reservoir will have to be constructed of a sandwich of perforated plate and screen layers so that the screen will remain wetted and retain propellant within the reservoir.

With a few exceptions, the partial acquisition devices had the lowest weight penalty of the three propellant management methods.

Results—Partial Acquisition Systems

- Refillable traps not feasible for this application primarily due to low accelerations.

- Nonrefillable traps, with a relatively small volume (< 15 ft^3) will satisy requirements.

- Significant portion of propellant in trap is lost due to vaporization (typically 1/2 to 2/3).

- Sizing of trap to supply all requirements is critical.

- Dryout of reservoir screen is a concern.

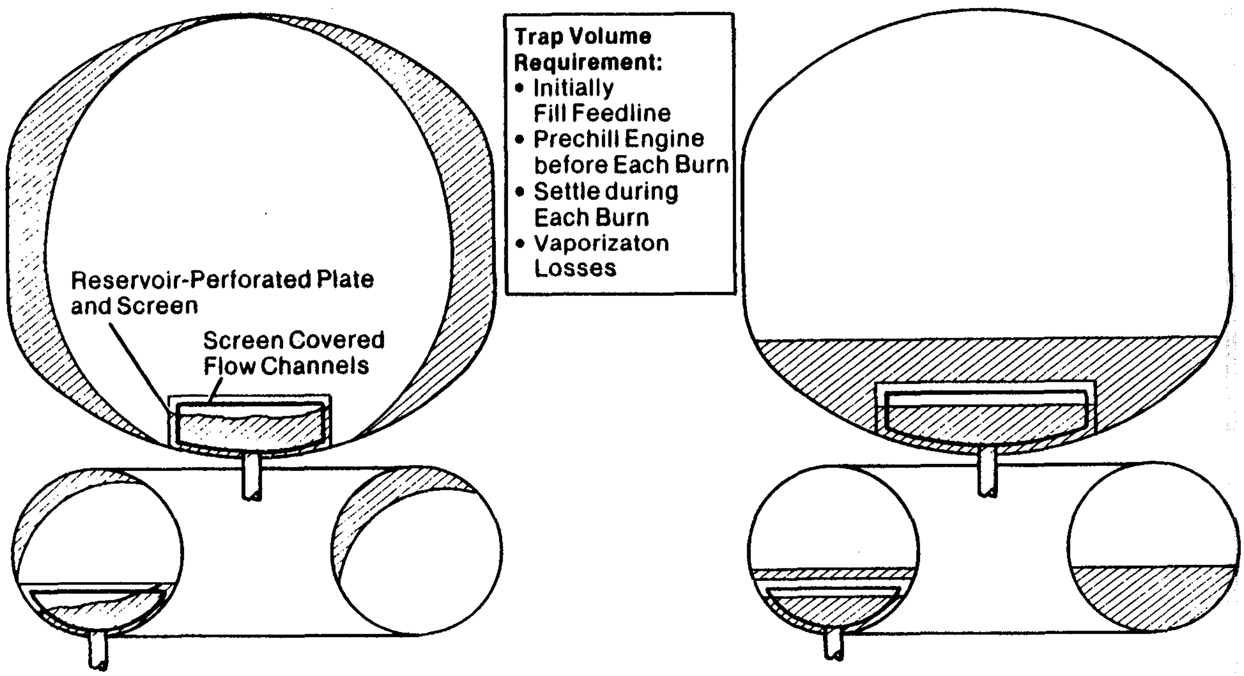
- Lowest weight penalty (with a few exceptions).

Partial Acquisition Device

A partial acquisition device consists of a reservoir that holds sufficient propellant to start the main engine for each burn and a channel network within the reservoir that guarantees gas-free flow of propellant to the tank outlet. The reservoir and channels are made of a frame covered with a fine-mesh screen, which provides the necessary liquid retention characteristics. In addition to supplying propellant to the engines until the bulk propellant settles, the reservoir must also contain sufficient propellant to fill the feedline, prechill the engine and provide for losses from the reservoir due to vaporization. The weight penalty is the weight of the device plus the weight of residual propellant that cannot be expelled.

Partial Acquisition Device

Propellant Settling | Continued Main Engine Firing



- Main Engine Starts
- Device Supplies Propellant as Bulk Propellant Settles
- Gas Enters Device When It Is Not in Contact with Bulk Liquid

- Propellant Feed Continues
- Gas Cannot Be Purged

Weight Penalty:
Propellant Residuals
Device Weight

Results - Total Acquisition Systems

A simple channel network, with a small channel flow area, will meet the expulsion requirements. At terminal drain, screen area becomes critical, so screen manifolds at the outlet are necessary. The largest manifolds are required for those systems with the greatest acceleration during terminal drain.

These frail channels must be supported from the tank wall so as to withstand launch loads. Heat transfer into the channels must be limited to prevent the boiling of propellant inside the channels.

Since this device operates independent of propellant settling, it can expel propellant whenever required and, therefore, makes it more flexible than the other methods. The weight penalty for total acquisition was close to that of partial acquisition, but slightly heavier.

Results—Total Acquisition Systems

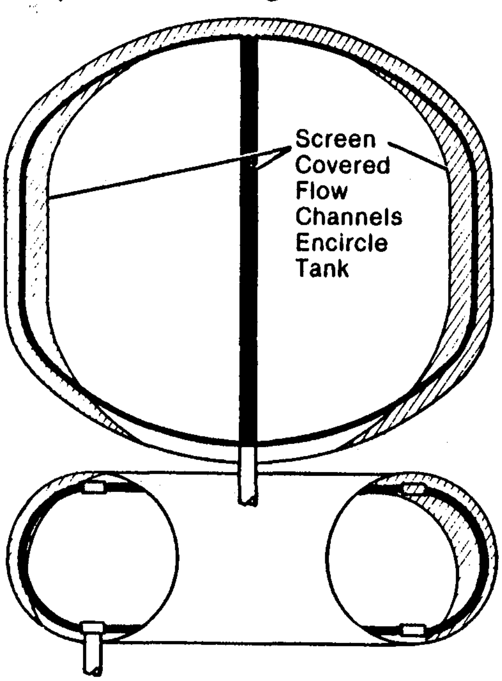
- Simple channel concept can meet requirements.
- Small channel cross-section, 4x½ in. maximum.
- Larger manifolds (10x10 in.) are required for systems with 1000 lbf thrust and SOFI, due to high accelerations during terminal drain.
- Structural support and thermal isolation of device is critical.
- Provide propellant management system flexibility.

Total Acquisition Device

A total acquisition system consists of screen covered flow channels that encircle the tank. These channels are always in contact with the bulk propellant regardless of its location so that gas-free propellant can be fed from the tank as required. The weight penalty is the weight of the device plus the weight of the propellant residuals.

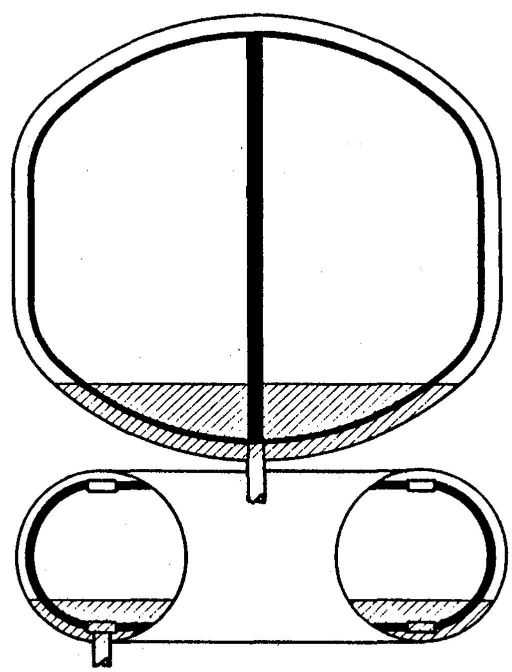
Total Acquisition Device

Propellant Settling



- Main Engine Starts
- Channels Maintain Liquid Outflow during Start and Settling

Continued Main Engine Firing



- Propellant Feed Continues
- Terminal Drain Is Worst-Case Design Condition

Weight Penalty:
Propellant Residual
Device Weight

Propellant Management Weight Penalties

The following two tables summarize the configuration of the 18 selected propulsion systems and the weight penalties of the three propellant management methods for each system.

Main engine thrust, with its resulting effect on flow rate and acceleration, had a significant effect on the draining residuals and the resulting weight penalty for propulsive settling. The weight of the total acquisition devices was also sensitive to the main engine thrust since the channel cross-section had to be increased to accommodate the greater flow rates. The variation of the weight penalty of the partial acquisition devices is rather small in comparison.

Selected Propellant System Configurations

Configuration	Propellant	Thrust, lbf	No. of Burns	Insulation System
1	LO_2/LH_2	100	4	MLI
2	↓	100	8	↓
3	↓	500	4	↓
4	↓	500	8	↓
5	↓	1000	4	↓
6	↓	1000	8	↓
7	LO_2/LCH_4	500	4	MLI
8	↓	500	8	MLI
9	↓	500	4	SOFI
10	↓	500	8	SOFI
11	↓	1000	4	MLI
12	↓	1000	8	MLI
13	↓	1000	4	SOFI
14	↓	1000	8	SOFI
15	LO_2/RP-1	1000	4	MLI
16	↓	1000	8	MLI
17	↓	1000	4	SOFI
18	↓	1000	8	SOFI

Propellant Management Weight Penalties

Config-uration	Settling N$_2$O$_4$/MMH	Settling Primary Propellant	Partial Acquisition	Total Acquisition
1	167	166	156	118
2	164	163	169	118
3	398	397	158	160
4	429	427	175	160
5	592	590	171	244
6	576	573	188	243
7	534	534	96	155
8	528	527	105	154
9	507	506	109	156
10	505	504	122	154
11	798	798	107	234
12	784	783	123	234
13	785	784	121	237
14	784	783	143	236
15	302	302	132	270
16	309	308	145	269
17	287	286	143	274
18	299	298	159	274

Weights in lbm.