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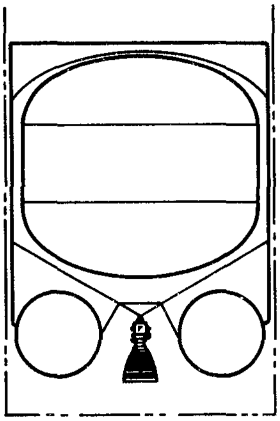

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# LOW-THRUST CHEMICAL PROPULSION SYSTEM PROPELLANT EXPULSION AND THERMAL CONDITIONING STUDY

## EXECUTIVE SUMMARY

**GENERAL DYNAMICS**
*Convair Division*

NASA CR-165622
GDC-NAS-82-001

# LOW-THRUST CHEMICAL PROPULSION SYSTEM PROPELLANT EXPULSION AND THERMAL CONDITIONING STUDY EXECUTIVE SUMMARY

**APRIL 1982**

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for

National Aeronautics and Space Administration
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Under
Contract NAS3-22650

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16. Abstract

Thermal conditioning systems for satisfying engine net positive suction pressure (NPSP) requirements, and propellant expulsion systems for achieving propellant dump during a return-to-launch-site (RTLS) abort were studied for $LH_2/LO_2$ and $LCH_4/LO_2$ upper stage propellant combinations. A state-of-the-art thermal conditioning system employing helium injection beneath the liquid surface showed the lowest weight penalty for $LO_2$ and $LCH_4$. A new technology system incorporating a thermal subcooler (heat exchanger) for engine NPSP resulted in the lowest weight penalty for the $LH_2$ tank. A preliminary design of two state-of-the-art and two new technology systems indicated a weight penalty difference too small to warrant development of a $LH_2$ thermal subcooler. Analysis results showed that the $LH_2/LO_2$ propellant expulsion system is optimized for maximum dump line diameters, whereas the $LCH_4/LO_2$ system is optimized for minimum dump line diameter ($LCH_4$) and maximum dump line diameter ($LO_2$). The primary uncertainty is the accurate determination of two-phase flow rates through the dump system; experimentation was not recommended because this uncertainty is not considered significant.

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# FOREWORD

The following final report summarizes the technical effort conducted under Contract NAS3-22650 by the General Dynamics Convair Division from August 1980 to January 1982. The contract was administered by the National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio.

NASA/LeRC Program Manager - J. C. Aydelott

Convair Program Manager - F. Merino

Assisting - I. Wakabayashi, R. L. Pleasant, M. Hill

All data are presented with the International System of Units as the primary system and English Units as the secondary system. The English system was used for the basic calculations.

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# SUMMARY

This study determined preferred techniques for providing abort pressurization and engine feed system net positive suction pressure (NPSP) for low-thrust chemical orbit-to-orbit propulsion systems (LTPS). The relative benefits and weight penalties of each technique and any required technology advances were determined. There were two major study areas: propellant expulsion systems for achieving propellant dump during a return-to-launch-site (RTLS) abort, and thermal conditioning systems for satisfying engine NPSP requirements.

Thermal conditioning techniques considered for providing main engine NPSP during engine start and steady-state operation included a) helium pressurization, b) thermal subcoolers (heat exchangers), and c) autogenous pressurization for steady-state engine burn with helium pressurization or thermal subcoolers for start-up. Parametric analyses were performed to obtain pressurant mass, hardware weights, ventage, and vapor residuals as a function of engine NPSP. Total system weight penalties were obtained for two $LH_2/LO_2$ stages with multi-layer insulation (MLI) and two $LCH_4/LO_2$ stages, one with MLI and the other with spray-on foam insulation (SOFI).

Major results include the following:

1. A state-of-the-art system, incorporating bubbler (helium injection beneath liquid surface) pressurization, was found to be the best for $LO_2$ and $LCH_4$, regardless of technology. It showed the lowest system weight penalty over the entire engine NPSP range.

2. A new technology system incorporating a subcooler for engine NPSP resulted in the lowest weight penalty for the liquid hydrogen tank.

3. Vent mass penalties due to the higher heating rates of a SOFI system were significantly greater than for the MLI system.

Following the parametric analysis, four systems, listed below, were selected for a preliminary design effort. Weight penalties were determined for NPSP levels up to 6.9 kpa (1.0 psid) and 13.8 kpa (2.0 psid), respectively, for the $LH_2$ and $LO_2$ sides. A weight penalty difference of 18 to 32 kg (40 to 70 lb) was found between state-of-the-art (1 and 2) and new technology (3 and 4) systems.

Thermal Conditioning Systems Selected for Preliminary Design

| System | $LO_2$ Tank<br>Engine Start/Engine Burn | $LH_2$ Tank<br>Engine Start/Engine Burn |
|---|---|---|
| 1 | Bubbler/Bubbler | Helium/Autogenous |
| 2 | Same as 1, except for cryogenic storage of helium | |
| 3 | Bubbler/Bubbler | Subcooler/Autogenous |
| 4 | Bubbler/Bubbler | Subcooler/Subcooler |

The only new technology identified for thermal conditioning systems was the heat exchanger portion of the $LH_2$ thermal subcooler. It was recommended that $LH_2$ thermal subcooler development not be pursued because the potential weight gain at low engine NPSPs is not significant. This recommendation is based on the premise that a low NPSP engine system is an achievable goal.

Propellant dump during Shuttle/LTPS abort modes was studied for purposes of identifying an LTPS propellant expulsion system, which consists of a helium pressurization system and an abort propellant dump system. Helium pressurization for propellant expulsion was the only technique considered for this analysis. Analysis results show that the $LH_2/LO_2$ system is optimized for minimum pressurization $\Delta P$ levels, which means increasing dump system line sizes to the maximum diameter possible. For the $LCH_4/LO_2$ system, the $LO_2$ side optimized at the minimum tank $\Delta P$ while the $LCH_4$ side optimized at the maximum tank $\Delta P$. It was determined that the $LCH_4/LO_2$ total system mass would be about 182 kg (400 lb) lighter than the $LH_2/LO_2$ system mass of 584 kg (1288 lb).

An assessment of the propellant expulsion system revealed that the primary uncertainty is whether "shifting" equilibrium or "frozen" equilibrium conditions will exist as propellant is dumped to a near-vacuum condition. An experimental program was not recommended because this uncertainty should not have a major impact upon LTPS performance.

# 1

## INTRODUCTION

Space missions planned for the mid-1980s and beyond will require increased Space Shuttle upperstage capability for placing Large Space Systems (LSS) in orbit. In concept, a lightweight structure will consist of a space platform on which would be mounted solar cells, antenna elements, computer systems and sensors appropriate to a specific mission. These LSS generate orbital transfer vehicle requirements considerably different from those for current vehicles. For example, transfer of an already assembled LSS from orbit-to-orbit requires a very low acceleration propulsion system, approximately 0.05 g, compared to the nearly 5 g maximum acceptable for current payloads. These low acceleration requirements can be met with low-thrust chemical propulsion systems (LTPS) having multiple-burn capability.

Recent studies (References 1-1 and 1-2) have been conducted to define and size LTPS configurations. Emphasis was placed on describing general vehicle requirements rather than on detailed evaluations of specific subsystems. The purpose of this study was to perform such a detailed evaluation of LTPS propellant expulsion and thermal conditioning subsystems. Specifically, the primary study objective was to determine preferred techniques for providing abort pressurization and engine feed system net positive suction pressure (NPSP) for LTPS. The relative benefits of each technique and any required technology advances would be identified during the 12-month study period. A representative LTPS vehicle configuration (identified by the Reference 1-1 study) is given in Figure 1-1.

### 1.1 SCOPE

This study was conducted in two phases consisting of six major tasks. During phase one, parametric analyses were performed to obtain pressurant mass, hardware weights, residuals and other payload penalties associated with each propellant expulsion and thermal conditioning system. The three major analysis tasks of this first study phase included:

- Task I - Propellant heating analysis.
- Task II - Pressurant requirements for abort propellant dump.
- Task III - Comparative analysis of pressurization techniques and thermal subcoolers.

At the completion of this phase, the NASA-LeRC selected four thermal conditioning systems for preliminary design.

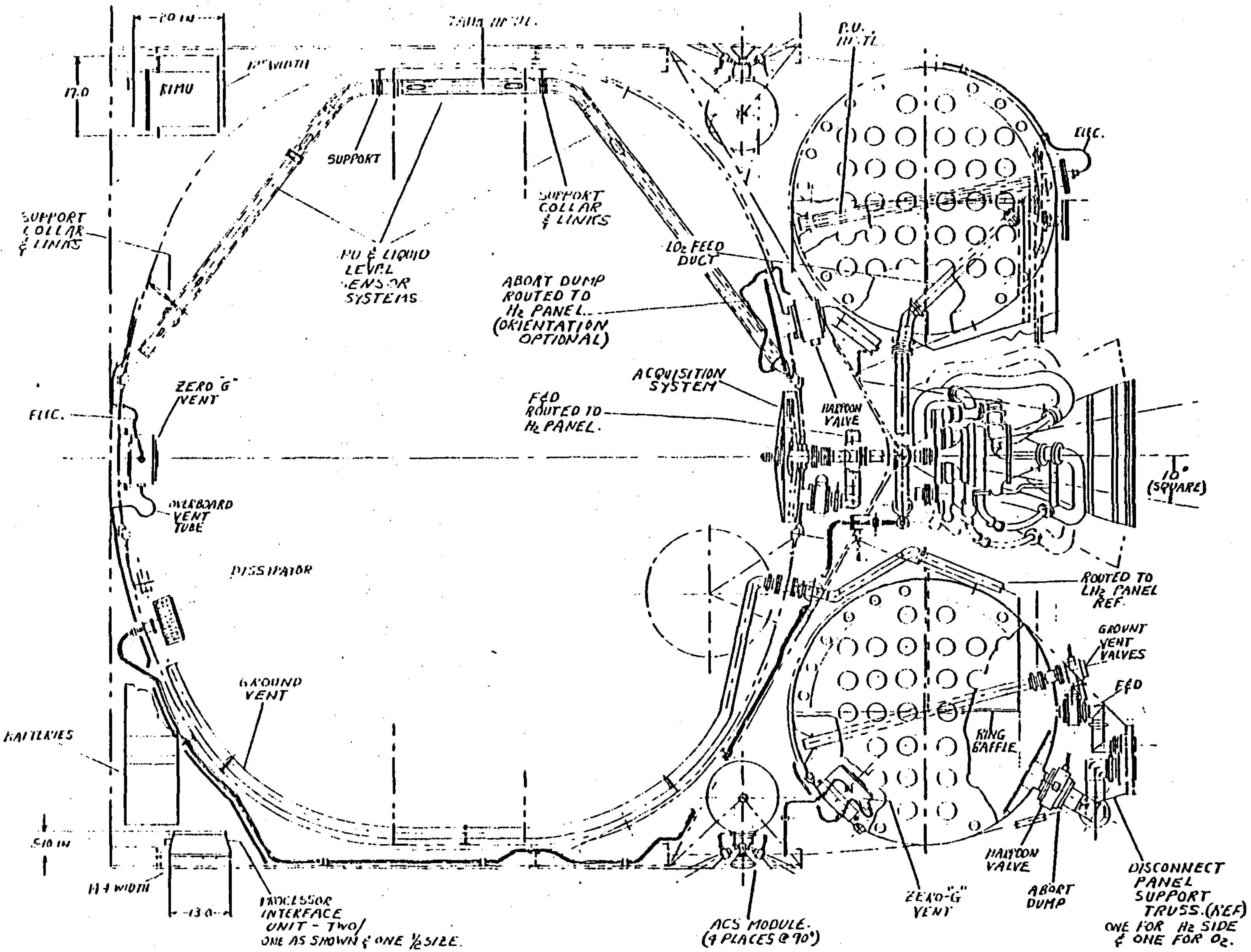


Figure 1-1. Representative LTPS Vehicle Configuration.

The second phase of this study required that a preliminary design be performed on each of the selected thermal conditioning systems. Hardware size and weight was estimated from these designs for a final subsystem comparison. Additionally, a technology evaluation was performed for each system.

## 1.2 PROPELLANT THERMAL CONDITIONING SYSTEMS ANALYSES

The interaction between Tasks I and III necessitated concurrent scheduling, Figure 1-2. In contrast, Task II was performed independently, with only minimal influence from the vehicle-mounted thermal conditioning system.

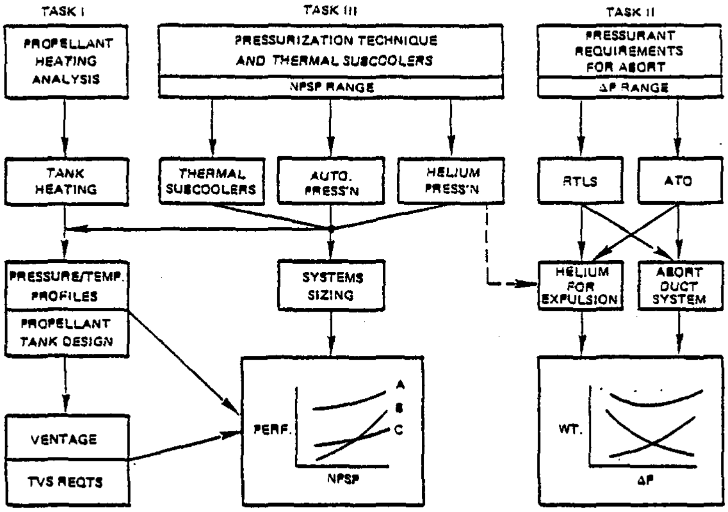


Figure 1-2. Tasks I and III Interaction Required Concurrent Scheduling.

1.2.1 <u>TASKS I AND III</u>. In Task I, we performed propellant tank thermodynamic analyses to establish tank pressure and propellant temperature histories as a function of time during a typical mission. Tankage configurations, heating rates and mission profiles were provided by NASA (Section 1.5). The LTPS mission conditions of low accelerations during engine burns, low propellant flow rates and long engine burn durations were analyzed to assess the influence of each upon vapor residuals and vapor vent masses.

Because it was known that the method of thermal conditioning could have an even greater influence on the propellant thermodynamic state than tank heating, Tasks I and III were conducted concurrently. The thermal conditioning techniques considered for providing main engine NPSP during engine start and steady-state operation included:

a. Helium pressurization (ambient and cryogenic temperature).

b. Thermal subcoolers (heat exchangers).

c. Autogenous pressurization for steady-state engine burn with helium pressurization for start-up.

d. Autogenous pressurization for steady-state engine burn with thermal subcoolers for start-up.

## 1.3 SHUTTLE ABORT PROPELLANT DUMP - TASK II

In this task, we determined helium pressurant mass required to expel LTPS propellants and perform tank inerting during return-to-launch-site (RTLS) emergency operating conditions for Shuttle. We weight-optimized the abort dump system, which consisted of propellant dump lines and a shuttle-mounted helium supply system. Helium pressurization for propellant expulsion was the only technique considered in this task.

## 1.4 PRELIMINARY DESIGN/TECHNOLOGY REQUIREMENTS

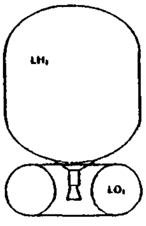
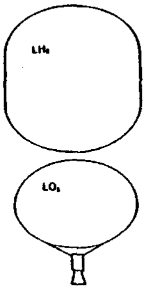
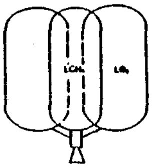
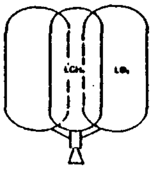
Following NASA Project Manager approval of the four pressurization/thermal conditioning systems, General Dynamics performed a preliminary design of each complete system (Task IV). System design was patterned after the criteria established for the Shuttle/Centaur program. From these designs, size and weight estimates were made of the required components. These weights were combined with propellant vent masses, vapor residuals and other penalties to derive the final LTPS weight penalty for each of the selected systems and are reported in Section 3.

## 1.5 GROUND RULES

The ground rules established for subsystem analysis included those imposed by the NASA Program Manager (vehicle configuration, mission profile, etc.) and a few imposed for convenience/simplicity. These latter ground rules did not significantly impact study results.

1.5.1 VEHICLE CONFIGURATIONS. The thermal conditioning and propellant expulsion subsystem analyses were performed for LTPS configurations and multiple-burn missions identified in a previous study, Reference 1-2. Details of the LTPS configurations are given in Table 1-1. Two $LO_2/LH_2$ stages and two $LO_2/LCH_4$ stages were selected. Note that the stages for each propellant combination are similarly sized. The major exception for the $LO_2/LH_2$ stages is a toroidal $LO_2$ tank (Configuration 1) versus an elliptical $LO_2$ tank (Configuration 2). Despite this difference, the configurations were virtually identical from a thermodynamic standpoint, which made the results of one configuration directly applicable to the other configuration. In contrast, although the $LO_2/LCH_4$ tank configurations

Table 1-1. Low-Thrust Propulsion System (LTPS) Configurations

| | | CONF.1 ($LO_2/LH_2$) | CONF.2 ($LO_2/LH_2$) | CONF.3 ($LO_2/LCH_4$) | CONF.4 ($LO_2/LCH_4$) |
|---|---|---|---|---|---|
| | |  |  |  |  |
| TANK VOLUME, $M^3$ ($ft^3$) | OXID. | 14.4 (507.4) | 14.2 (501.8) | 7.3 (259.1) | 7.8 (275.3) |
| | FUEL | 39.9 (1407.8) | 41.2 (1453.6) | 5.4 (191.2) | 5.7 (202.7) |
| TANK MASS, kg (lb) | OXID. | 92.0 (202.9) | 58.8 (129.7) | 36.5 (80.4) | 38.6 (85.1) |
| | FUEL | 165.4 (364.7) | 163.6 (360.6) | 30.7 (67.7) | 32.5 (71.6) |
| NO. OF TANKS | | ONE EACH | ONE EACH | TWO EACH | TWO EACH |
| INSULATION | | MLI | MLI | MLI | SOFI |
| SPACE HEATING RATES,WATTS (Btu/hr) | OXID. | 142.7 (487) | 142.3 (486) | 131.6 (449) | 819.5 (2797) |
| | FUEL | 216.8 (740) | 218.0 (744) | 119.8 (409) | 564.9 (1928) |

were virtually identical, the different insulation systems (MLI for Configuration 3 and SOFI for Configuration 4) resulted in a substantial thermodynamic dissimilarity. It was necessary, therefore, to analyze both LTPS configurations during the course of this study.

1.5.2 VEHICLE MISSIONS. Nine burn mission profiles were selected for each vehicle configuration. These mission profiles reflect a vehicle thrust level of 2.24 kN (500 lb), which accounts for burn durations totaling 28,200 seconds to 33,482 seconds. The same set of coast durations (which totaled 29 hours) was imposed upon each mission profile.

1.5.3 MAIN ENGINE REQUIREMENTS. The main engine requirements given below include flow rates, thrust level and engine NPSP:

NPSP Levels - 0.0 to 82.7 kpa (0.0 to 12 psid)

Thrust Level - 2.24 kN (500 lb)

Propellant Flow Rates

$LH_2$ = 0.074 kg/sec (0.162 lb/sec) } Isp = 440
$LO_2$ = 0.442 kg/sec (0.974 lb/sec) } Mixture ratio = 6 to 1

$LCH_4$ = 0.135 kg/sec (0.298 lb/sec) } Isp = 356.5
$LO_2$ = 0.501 kg/sec (1.104 lb/sec) } Mixture ratio = 3.7 to 1

1.5.4 THERMAL CONDITIONING SYSTEMS ASSUMPTIONS. The following assumptions were applicable to the thermal conditioning systems analyses:

1.5.4.1 Propellant Settling. An attitude control system will provide thrust for collecting propellants following each zero-g coast period. Thus, a surface tension screen acquisition system is not included as an element of the LTPS.

1.5.4.2 Tank Pressure Control. An initial propellant vapor pressure of 124 kpa (18 psia) was selected for all propellant combinations. It was also assumed that propellant tank venting would reduce tank pressure to 124 kpa (18 psia) at the end of each coast. A thermodynamic vent system (TVS) was used for zero-g venting.

1.5.5 ABORT DUMP SYSTEMS ASSUMPTIONS. It was found convenient to adopt a number of configurations, conditions and procedures developed during the Shuttle/Centaur study (Reference 1-3). These include the same helium supply system and propellant dump line configurations, and the same vehicle insulation system and engine system purge data.

# 2

# COMPARATIVE ANALYSIS OF PROPELLANT THERMAL CONDITIONING SYSTEMS

During this phase of the study, we conducted a comparative analysis of pressurization and thermal subcooler systems (categorized as thermal conditioning systems) over the entire NPSP range in order to recommend thermal conditioning systems for further study. A general description of each system is given in Section 2.1, with weight penalties described in Sections 2.2, 2.3 and 2.4. Comparisons were made on the basis of total weight penalty. Recommended systems are presented in Section 2.5.

## 2.1 THERMAL CONDITIONING SYSTEMS

Analyses were performed on the four vehicle configurations identified in Table 1-1 for the following thermal conditioning systems:

a. Helium pressurization (ambient and cryogenic temperature).

b. Thermal subcoolers (heat exchangers).

c. Autogenous pressurization (cryogenic temperature, 277.8K (500R) and 555.6K (1000R) for steady-state engine burn with helium pressurization (ambient and cryogenic temperature) for start-up.

d. Autogenous pressurization for steady-state engine burn with thermal subcoolers for start-up.

Pressurant mass, hardware weights, ventage, vapor residuals and other weight penalties associated with each system were determined as a function of engine NPSP.

2.1.1 <u>HELIUM PRESSURIZATION</u>. Helium pressurization systems that provide main engine NPSP requirements for engine start and steady-state conditions have been operational for many years. These systems have been thoroughly tested for both cryogens and earth storable propellants and are considered to be highly reliable. As such, a helium pressurization system can be treated as a baseline configuration to which all other configurations are compared on the basis of weight, performance and reliability.

2.1.1.1 <u>System Description</u>. A schematic of an ambient helium pressurization system is given in Figure 2-1. This system meters helium to the propellant tanks through orifices to satisfy main engine NPSP requirements. Tank pressure control is maintained through on-off commands of the pressurization solenoid valves that can either maintain tank pressure at an absolute level, at a fixed differential pressure, or at a given differential pressure relative to a continuously changing liquid vapor pressure.

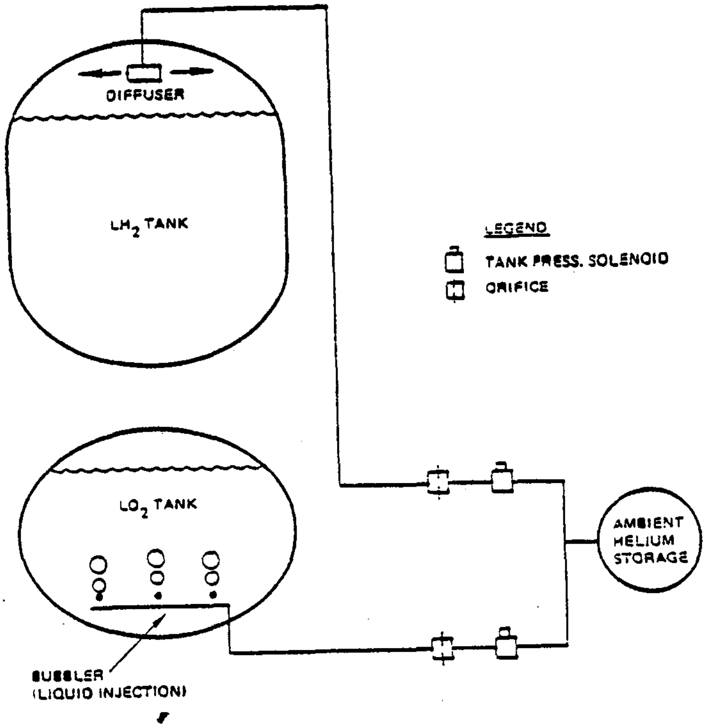


Figure 2-1. Helium Pressurization System.

Tank pressure control is maintained throughout a mission via a digital computer unit (DCU) that continuously monitors outputs from high-accuracy tank pressure transducers.

Pressurization Technique: $LH_2$ will be pressurized with helium flow into the ullage because the alternative of liquid injection will require considerably more helium. Helium will be introduced into $LO_2$ (or $LCH_4$) through a pressurization manifold beneath the liquid surface because substantially less helium is required than for ullage injection. This technique of "bubbler" pressurization has been successfully employed for pressurizing the Centaur $LO_2$ propellant tank. Tests have demonstrated that less helium is required for pressurization during engine start and steady-state engine operation when helium is "bubbled" through $LO_2$.

2.1.1.2 Ambient/Cryogenic Helium Storage. Helium storage at cryogen temperatures has the advantage of greater pressurant availability per pound of hardware weight. A weight benefit is derived for bubbler pressurization of $LO_2$ and $LCH_4$ because usage requirements will be the same, regardless of storage temperature conditions. Because ullage injection of helium is required for the $LH_2$ tank, any advantage due to helium storage at cryogen temperatures will be lost; the increased helium mass storage capability will be offset by increased helium mass requirements for pressurization. Furthermore, the additional helium in the propellant tank could raise its partial pressure enough to greatly increase vent mass requirements.

It is possible that cryogenically stored helium may be advantageous for $LH_2$ tank pressurization if a heat exchanger is used to increase helium temperature as it flows to the $LH_2$ tank. However, a heat exchanger would complicate this particular thermal conditioning system. It was decided, therefore, not to analyze this option as part of the parametric evaluation.

For the $LO_2$ and $LCH_4$ propellant tanks, cryogenic helium storage will afford a weight benefit over ambient storage. It was thought, however, that the benefit would not be significant for this parametric evaluation. The decision was made to analyze this cryogenic storage option in phase II of the study only if bubbler pressurization was found to be one of the preferred thermal conditioning techniques.

### 2.1.2 THERMAL SUBCOOLERS.

Thermal subcoolers (heat exchangers) can achieve engine NPSP conditions thermodynamically rather than through the traditional approach of propellant tank pressurization. With the traditional approach, engine inlet NPSP is satisfied when an ullage pressure increase subcools tank propellants. In contrast, thermal subcoolers will cool tank propellants as they flow to the main engine. Liquid vapor pressures decrease as propellants are cooled and, thus, engine inlet NPSP is achieved.

### 2.1.2.1 System Description.

Thermal subcoolers will provide NPSP by using throttled vent fluid to subcool the delivered propellant. This system is shown schematically in Figure 2-2. The cold-side fluid will experience a temperature drop as it is throttled to a low pressure. This fluid will boil as it absorbs heat from the hot-side fluid being delivered to the main engine. The hot-side fluid exits at the desired NPSP; the cold-side fluid, exiting at a high quality, can be either dumped overboard, returned to the liquid, or returned to the ullage.

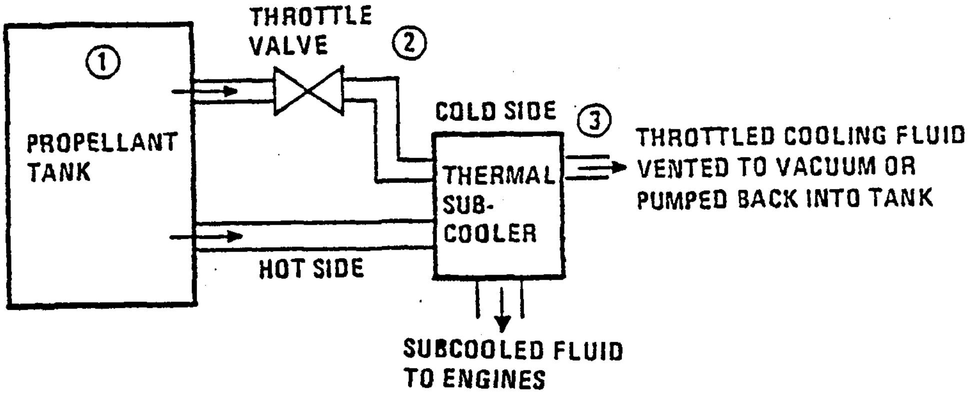


Figure 2-2. The Thermal Subcooler Supplies Subcooled Propellants to the Engines.

2.1.2.2 <u>Subcooler Configurations</u>. Two types of subcoolers were analyzed for the LTPS configurations: one for installation on the elliptical aft bulkheads of the $LH_2$, $LO_2$ and $LCH_4$ tanks, and the other for installation within a toroidal $LO_2$ tank. Each configuration was analyzed for each propellant.

The elliptical aft bulkhead subcooler configuration (Figure 2-3) is based upon a concept previously analyzed at General Dynamics for high thrust vehicles (References 2-1 and 2-2). The same analysis techniques have been applied for this study. The toroidal $LO_2$ tank subcooler configuration (Figure 2-4) had not been previously analyzed and, therefore, did not have an equivalent analysis data base.

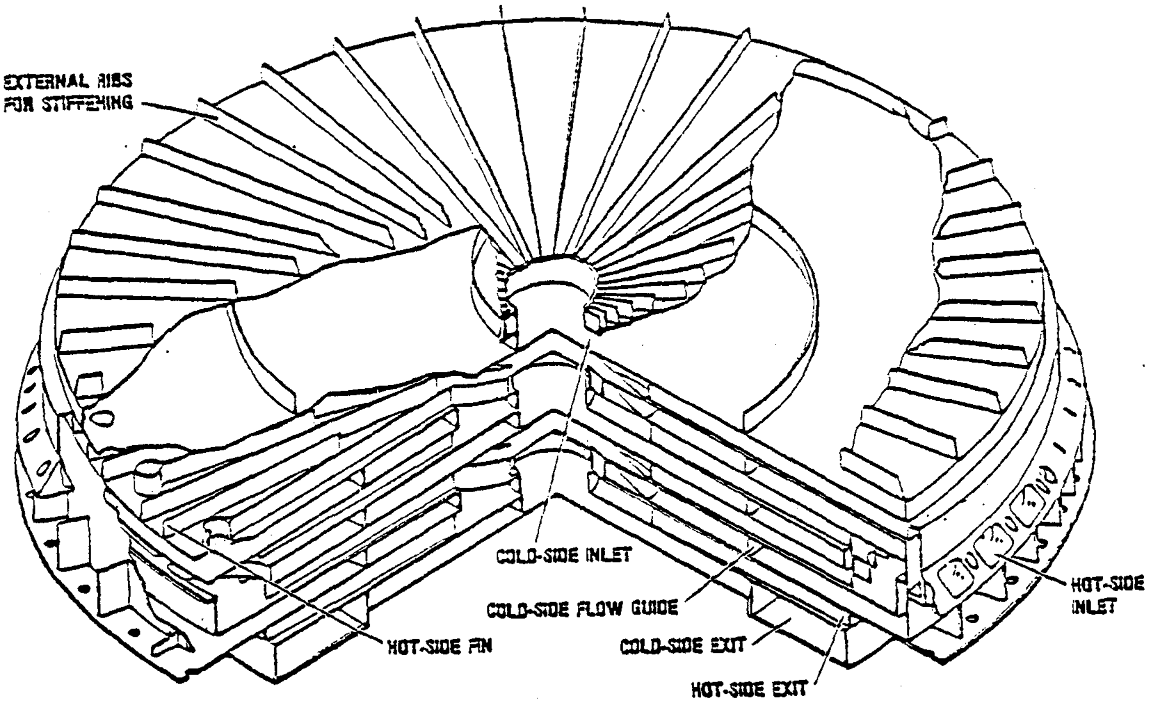


Figure 2-3. General Dynamics Subcooler Design Used as Basis for Elliptical Bulkhead Subcoolers of this Study.

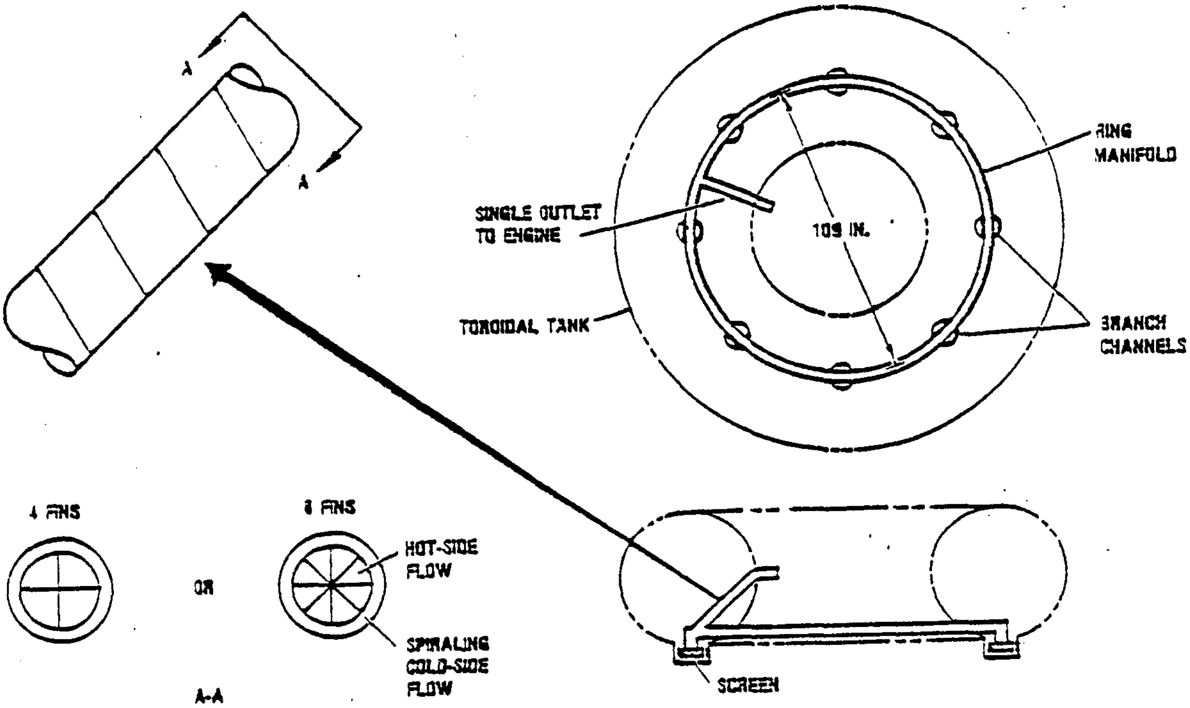


Figure 2-4. Toroidal Tank Subcooler Located in Outlet Tubing.

2.1.3 AUTOGENOUS PRESSURIZATION. A schematic of the autogenous pressurization system is given in Figure 2-5. This system will bleed high pressure gas from the main engine to pressurize propellant tanks. This system would represent the simplest hardware configuration for LTPS, except that autogenous pressurant becomes available only after steady-state engine firing conditions are attained. Consequently, another pressurant source is required for tank pressurization to satisfy engine start NPSP requirements. The schematic of Figure 2-5 includes an ambient storage helium supply system for pressurization through ullage injection ($LH_2$ tank). Bubbler pressurization would be employed for the $LO_2$ and $LCH_4$ tanks.

Aside from the option of selecting a supplementary pressurization system for main engine start, the only variables to consider with this system are autogenous gas temperature and engine NPSP. The influence of each variable upon propellant tank thermodynamic conditions was evaluated for the identified mission heating conditions and vehicle configurations. Neither variable will affect the weight of the autogenous bleed hardware. Only NPSP will influence the weight and selection of the supplementary pressurization system.

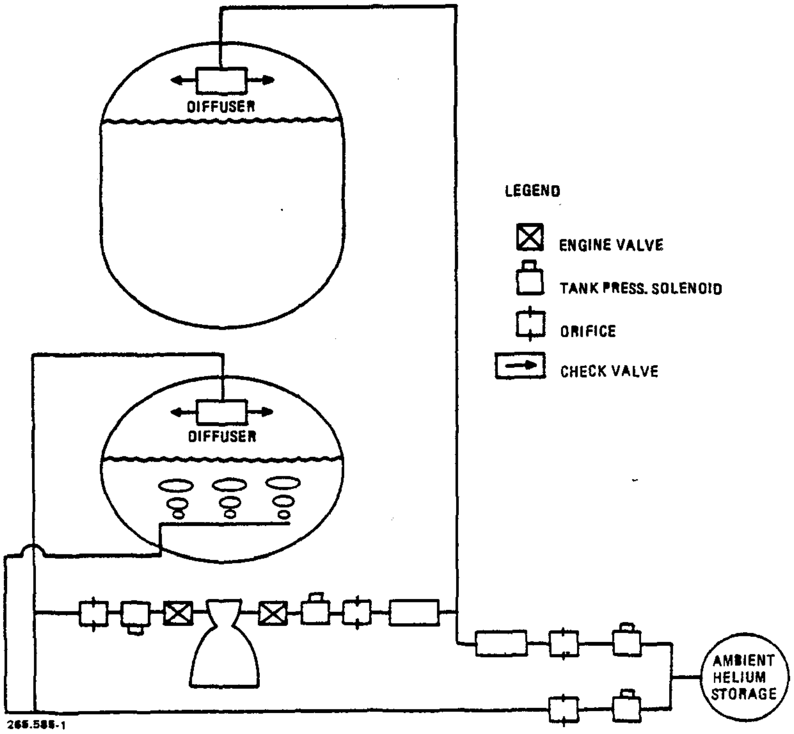


Figure 2-5. Autogenous Pressurization System (with Helium for Engine Start Pressurization).

2.1.3.1 Thermal Subcooler For Engine Start. A subcooler for engine start pressurization will eliminate helium pressurization hardware from LTPS. Not only will hardware weight be reduced, but the potentially adverse effects of helium partial pressure upon zero-g coast propellant tank venting will be eliminated.

## 2.2 $LH_2$ THERMAL CONDITIONING SYSTEMS WEIGHT PENALTIES

LTPS Configurations 1 and 2 are thermodynamically identical because initial propellant loads are nearly the same and MLI systems are similar. Consequently, the data presented for Configuration 1 applies in every respect to Configuration 2. Of the six systems evaluated, two were state-of-the-art (helium and autogenous pressurization) with substantial empirical data to support predictions. These two systems also show the maximum weight penalty. The four remaining systems include variations of a thermal subcooler which represents a totally new technology. These systems also show the lowest weight penalties. Consequently, comparisons must include a trade between state-of-the-art and performance gain.

2.2.1 STATE-OF-THE-ART SYSTEMS. Figure 2-6 gives a weight penalty comparison of the six thermal conditioning system options. Of the two state-of-the-art systems, helium pressurization (engine start)/autogenous (engine burn) is the lightest weight system, approximately 50 to 213 kg (110 to 470 lb) lighter over the NPSP range. Also, both systems are equivalent on a state-of-the-art basis since both are flight-proven. Consequently, the helium/autogenous system is selected for comparison to the new technology systems.

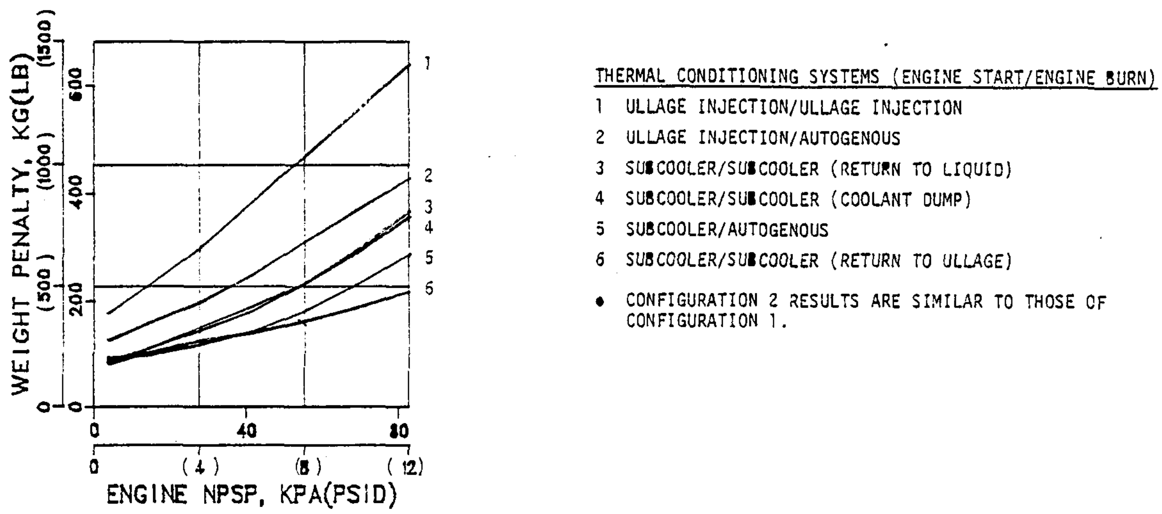


Figure 2-6. Comparison of $LH_2$ Tank Thermal Conditioning Systems (Configuration 1).

2.2.2 NEW TECHNOLOGY SYSTEMS. Figure 2-6 shows weight penalty differences of less than 13.6 kg (30 lb) for the four subcooler options at NPSP levels less than 13.8 kpa (2 psid). Weight differences will increase to 150 kg (330 lb) at the maximum NPSP of 82.7 kpa (12 psid). The return-to-ullage option exhibits the best performance, i.e., lowest weight penalty, over the entire NPSP range. However, it does require a pump for returning coolant vapor to the ullage. Furthermore, tank pressure controls during engine burn are more complicated than for other options because coolant flow rates must be decreased as autogenous pressurization $\Delta$Ps increase.

The least complicated subcooler options are coolant dump and subcooler/autogenous. Neither one requires a pump, nor is tank pressure control a concern. The advantage rests with the latter option because it exhibits the second best performance over the NPSP range.

The subcooler selection process can also be influenced by the design NPSP level. If, for example, an engine is developed for NPSP levels of 13.8 kpa (2.0 psid) or less, then the coolant dump option might represent the best compromise. Its weight penalty at low NPSPs is within about 6.8 kg (15 lb) of the return-to-ullage option penalty. It would also be slightly less complicated than the subcooler/autogenous option.

2.2.3 RECOMMENDED SYSTEMS. The systems recommended for preliminary design were the return-to-ullage and subcooler/autogenous options. The former was recommended because of lower weight penalties over the NPSP range. The latter recommendation was i) for the second lowest weight penalties over the NPSP range, and ii) because it is a less complicated system.

## 2.3 $LO_2$ THERMAL CONDITIONING SYSTEMS

$LO_2$ tank thermal conditioning system weight comparisons are shown in Figure 2-7 for vehicle Configurations 1, 2 and 3. The bubbler pressurization system is the obvious choice of all thermal conditioning systems studied. It has every advantage: state-of-the-art, simplicity and minimum weight penalty. Regarding the first benefit, bubbler pressurization has been flight demonstrated for low-g operation over a wide range of ullage volume conditions. It is the simplest of the thermal conditioning systems evaluated; no pump/motor unit, heat exchanger or autogenous pressurization are required. Finally, this system will experience the lowest weight penalty over the entire NPSP band. Although not shown, weight comparisons for vehicle Configuration 4 are identical to those of Figure 2.7, except that weight penalties are about 1130 kg (2500 lb) greater. This difference is due solely to the increased vent mass resulting from higher SOFI system heating rates.

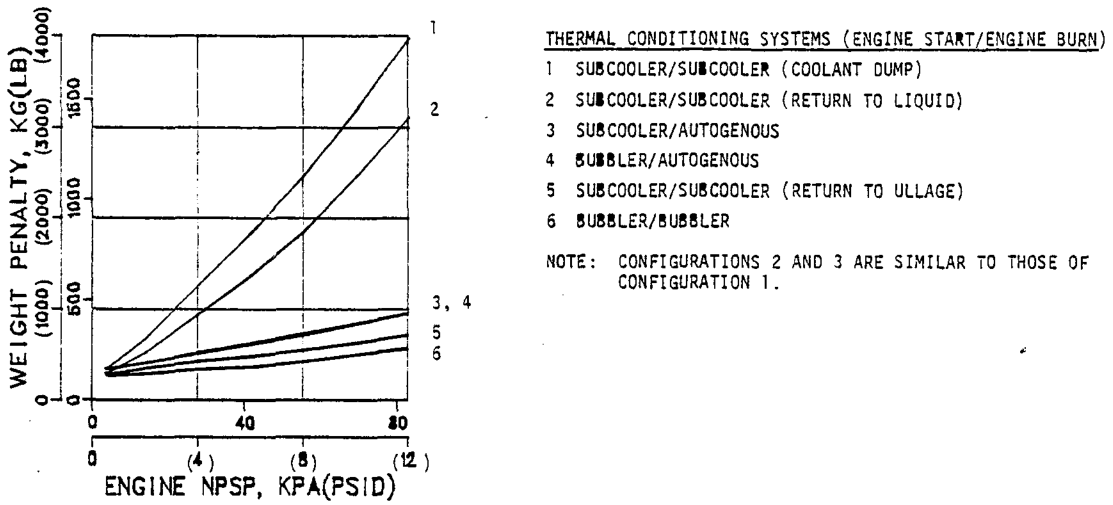


Figure 2-7. Comparison of $LO_2$ Tank Thermal Conditioning Systems (Configuration 1).

A second, or backup, thermal conditioning system was not recommended for the $LO_2$ tank because the primary system is clearly superior. Its ranking remains unaffected by choice of insulation system.

## 2.4 $LCH_4$ THERMAL CONDITIONING SYSTEMS

Bubbler pressurization is also recommended for the $LCH_4$ tanks for the reasons given previously: state-of-the-art, simplicity and minimum weight penalty. Figure 2-8 shows that this thermal conditioning system will experience the lowest weight penalty of all systems considered for Configuration 3. Although this pressurization technique has not been attempted with $LCH_4$, it is expected that system performance will be, in every way, similar to what has been experienced with $LO_2$. Configuration 4 penalties are about 160 kg (350 lb) greater than for Configuration 3. This difference is due solely to the increased vent mass resulting from SOFI system heating rates.

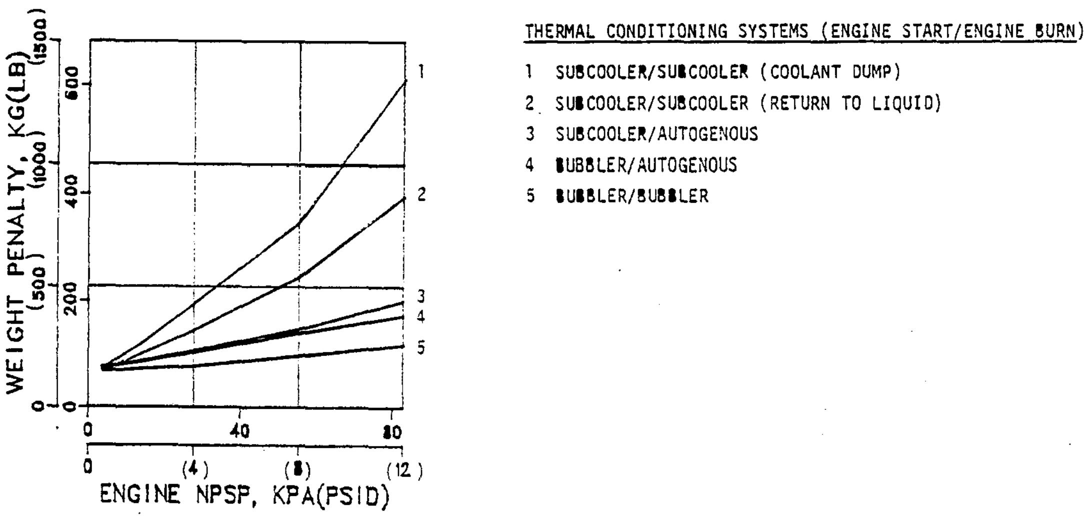
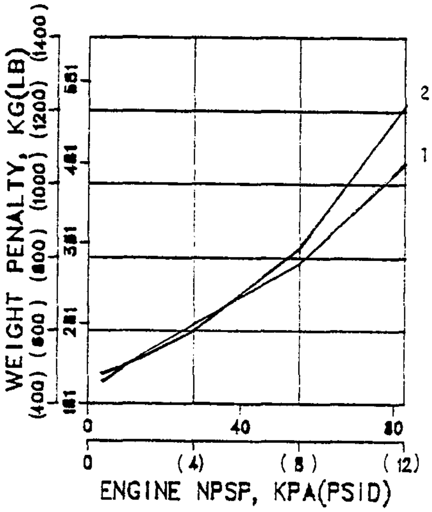


Figure 2-8. Comparison of $LCH_4$ Tank Thermal Conditioning Systems (Configuration 3).

## 2.5 LTPS RECOMMENDATIONS

A total of three thermal conditioning systems were recommended for the four LTPS configurations, two for the $LH_2/LO_2$ configurations and one for the $LCH_4/LO_2$ configurations. Weight penalties for the combined fuel/oxidizer systems that were recommended are given in Figures 2-9 and 2-10.



RECOMMENDED SYSTEMS

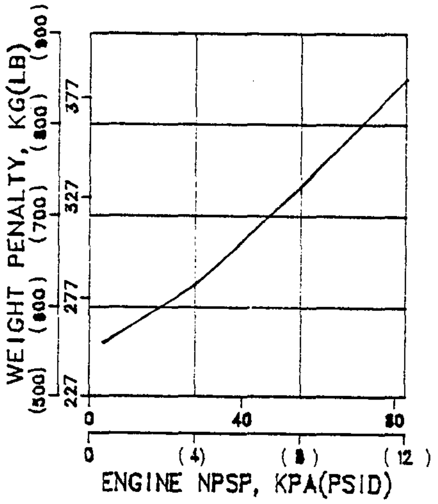
1 $LH_2$ SIDE - SUBCOOLER/SUBCOOLER (RETURN TO ULLAGE)
$LO_2$ SIDE - BUBBLER/BUBBLER

2 $LH_2$ SIDE - SUBCOOLER/AUTOGENOUS
$LO_2$ SIDE - BUBBLER/BUBBLER

NOTE: RECOMMENDATION APPLIES TO CONFIGURATION 2.

Figure 2-9. Weight Penalties for Recommended $LH_2/LO_2$ Thermal Conditioning Systems (Configuration 1).

Figure 2-9 shows that these systems are equivalent from 3.4 to 41.4 kpa (0.5 to 6.0 psid). A significant weight difference exists only at the upper end of the NPSP band. It is possible that System 2 could be preferred over System 1 at low NPSPs because of a less complex hydrogen system. Detailed analyses beyond the scope of this study would be required before such an assessment could be made.



RECOMMENDED SYSTEMS

$LCH_4$ SIDE - BUBBLER/BUBBLER
$LO_2$ SIDE - BUBBLER/BUBBLER

NOTE: RECOMMENDATION APPLIES TO CONFIGURATION 4.

Figure 2-10. Weight Penalties for Recommended $LCH_4/LO_2$ Thermal Conditioning Systems (Configuration 3).

# 3

# PRELIMINARY DESIGN OF SELECTED THERMAL CONDITIONING SYSTEMS

Following completion of Tasks I and III, General Dynamics recommended the three LTPS thermal conditioning systems identified in Section 2 for further study. The NASA project manager approved both $LH_2/LO_2$ LTPS systems and selected two additional $LH_2/LO_2$ systems for the Task IV preliminary design rather than the recommended $LCH_4/LO_2$ system. All preliminary designs were to be performed on vehicle Configuration 1. Hardware size and weights were estimated from the designs. These weights were added to propellant ventage and residuals and all other identifiable weight penalties. A final weight penalty comparison was made of the four thermal conditioning systems.

## 3.1 SYSTEMS SELECTION

System characteristics and operating conditions for Task IV were specified by the NASA project manager. Table 3-1 lists the four systems selected for preliminary design effort on vehicle Configuration 1.

Table 3-1. Selected Thermal Conditioning Systems

| System | $LO_2$ Tank Engine Start/Engine Burn | $LH_2$ Tank Engine Start/Engine Burn |
|---|---|---|
| 1 | Bubbler/Bubbler | Helium/Autogenous |
| 2 | Same as 1, except for cryogenic storage of helium | |
| 3 | Bubbler/Bubbler | Subcooler (coolant dump)/ Autogenous |
| 4 | Bubbler/Bubbler | Subcooler/Subcooler (coolant return to ullage) |

Three engine NPSP design points were considered for each system:

| Engine Design | $LO_2$ Side kpa (psid) | $LH_2$ Side kpa (psid) |
|---|---|---|
| Zero NPSP | 0 | 0 |
| Low NPSP | 6.9 (1.0) | 3.4 (0.5) |
| Moderate NPSP | 13.8 (2.0) | 6.9 (1.0) |

The low NPSP levels imposed upon the preliminary design activity are significant because, as shown in Section 2, weight penalty differences become small in this NPSP range. A comment should be made regarding the zero NPSP design point. It is generally accepted that development costs and, perhaps, engine weight and complexity will increase as engine NPSP levels approach zero. Furthermore, it is known that thermal conditioning system weight penalties will decrease as NPSP levels approach zero. Consequently, the weight penalties provided by this study can be used to show potential LTPS mission performance gains as engine complexity and cost are increased.

3.1.1 LO$_2$ TANK SYSTEM. Bubbler pressurization was selected for all four vehicle thermal conditioning systems. It is a simpler state-of-the-art technique than the other systems. Ambient storage of helium was selected for System 1 and cryogenic storage for the other systems. The thermodynamic effects of ambient versus cryogenically stored helium are trivial for bubbler pressurization, but there is a helium supply system weight benefit for cryogenic storage.

3.1.2 STATE-OF-THE-ART LH$_2$ TANK SYSTEMS. Systems 1 and 2 are helium/autogenous pressurization, one with ambient helium storage and the other with cryogenically stored helium. The comparisons of Section 2 (Figure 2-6) showed a significant weight penalty difference between the state-of-the-art and new technology options at the maximum NPSP level. This difference reduces to about 45 kg (110 lb) at the low NPSP range. Since Systems 1 and 2 represent state-of-the-art, they can serve as a basis for trading weight versus technology for thermal conditioning systems.

Thermal conditioning Systems 1 and 2 are identical, except for helium storage temperature. In Section 2, it was stated that cryogenic storage of helium would reduce weight penalties under certain conditions and that this option would be evaluated if bubbler pressurization was selected for further analysis. This evaluation was performed for System 2.

3.1.3 NEW TECHNOLOGY LH$_2$ TANK SYSTEMS. System 3 represents new technology since the hydrogen side will employ a thermal subcooler for engine start. However, autogenous pressurization for engine burn and bubbler pressurization for the LO$_2$ tank are current methods of propellant thermal conditioning. The weight penalties for this system will be lower than for either Systems 1 or 2. Penalties are not expected to be significantly lower than for System 2, however, because the only weight improvement will be in eliminating the LH$_2$ tank helium supply system, which is not significant.

System 4 is the most technologically advanced of the four thermal conditioning systems. The hydrogen subcooler will provide NPSP for both engine start and steady-state operation. Coolant vapor will be returned to the ullage (instead of being dumped overboard) where it will serve as pressurant to provide a portion of the total engine NPSP required. Weight penalties are expected to be the lowest of the four thermal conditioning systems.

3.1.4 SYSTEM DESIGN. Preliminary design drawings were prepared for all thermal conditioning systems. The Shuttle/Centaur design philosophy was adopted relative to component failures and safety considerations. In general, two-failure tolerancy is required for operations in the Shuttle, and single-failure tolerancy is required for post-deployment operations. Multiple pneumatic components are needed to satisfy these requirements. For example, four valves (two each in parallel) are needed to satisfy the requirement for single-failure tolerancy during the vehicle mission.

## 3.2 THERMAL CONDITIONING SYSTEMS COMPARISON

A weight penalty comparison of the four thermal conditioning systems is given in Figure 3-1. The new technology systems (3 and 4) show a lower weight penalty over the high-to-low NPSP range, as expected. What was not expected, however, was the small weight difference between the state-of-the-art systems and new technology systems. For example, the weight difference between Systems 2 and 4 is predicted to be 25.9 to 28.6 kg (57 to 63 lb) in the low-to-moderate NPSP range.

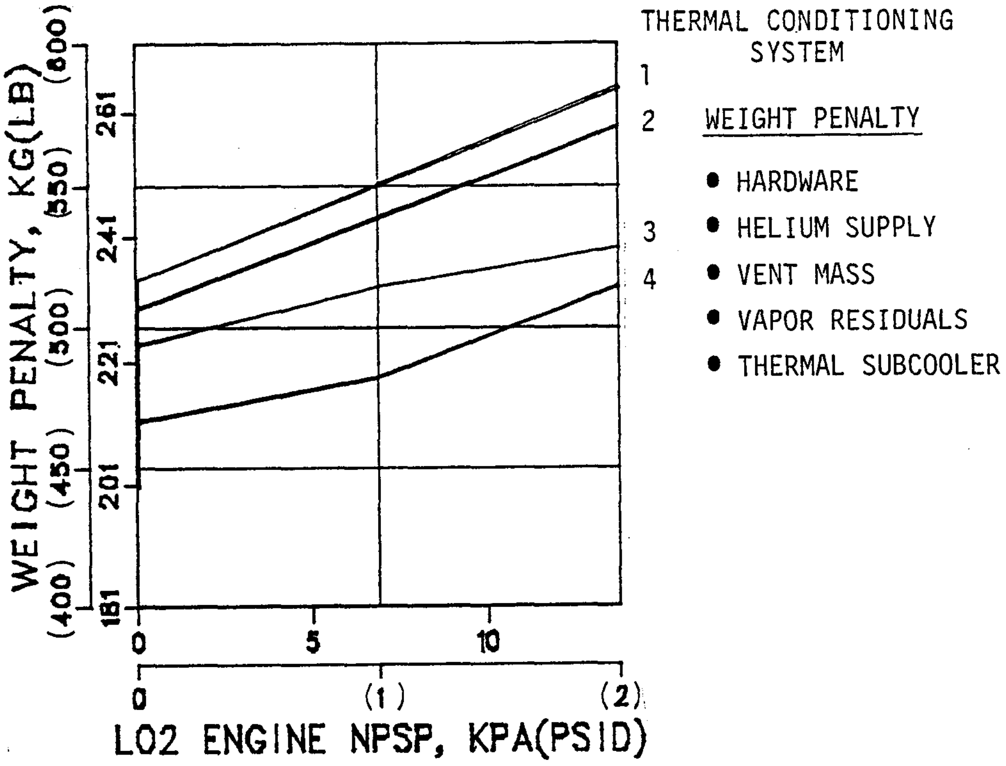


Figure 3-1. Thermal Conditioning Systems Weight Penalty Comparison.

Considering the development costs and risks that would be associated with the introduction of a thermal subcooler to replace $LH_2$ tank pressurization, the potential weight gain does not appear to be a big driver. It must be remembered, however, that the weight penalties of Figure 3-1 are not equivalent to vehicle performance penalties. Payload penalty can be determined by multiplying each weight penalty component of the total by a payload partial, which can be greater than 1.0. Only then can a proper assessment be made on the advantages of developing a new thermal conditioning system.

3.2.1 LTPS WEIGHT PENALTY AT ZERO NPSP. An alternative to thermal conditioning systems is to develop a low-thrust engine that requires zero NPSP. The benefit of a zero NPSP engine would be a reduced system weight penalty. The weight penalty would not, however, drop to zero because the combination of ventage and vapor residuals is non-zero. Furthermore, there is a minimum hardware weight required for RTLS pressurization during abort propellant dump that is common to all systems. The zero NPSP engine system weight improvement over System 2 would be 43 to 58 kg (96 to 128 lb), for low and moderate NPSP engine systems, respectively. The resulting performance gain would have to be traded against the costs and risks of a zero NPSP engine system.

# 4

# LTPS ABORT PRESSURIZATION REQUIREMENTS

In Task II we analytically determined helium pressurant mass requirements to expel LTPS propellants and perform tank inerting during Return-to-Launch-Site (RTLS) emergency operating conditions for Shuttle. Analyses were conducted for LTPS Configurations 1 and 3. Helium pressurization for propellant expulsion was the only technique considered for this analysis. Helium mass requirements were determined for tank pressure increases of 14, 28 and 55 kpa (2, 4 and 8 psid) during propellant expulsion and for tank inerting operations following propellant expulsion. Tank inerting consisted of two repressurization cycles following each of two tank vent cycles.

## 4.1 ABORT GUIDELINES AND REQUIREMENTS

During this task, we employed guidelines and ground rules established or identified from previous GDC studies. In particular, we relied upon the substantial data accumulated during the Shuttle/Centaur study (Reference 4-1) dealing with design, interface, operational and safety requirements imposed on the Centaur fluids systems while in the Orbiter cargo bay (Figure 4-1). Certain Centaur subsystems and support systems were selected for this study on the basis that they were representative of LTPS subsystems. Analysis techniques and computer programs developed or modified for the Shuttle/Centaur abort dump analysis were also used for this study.

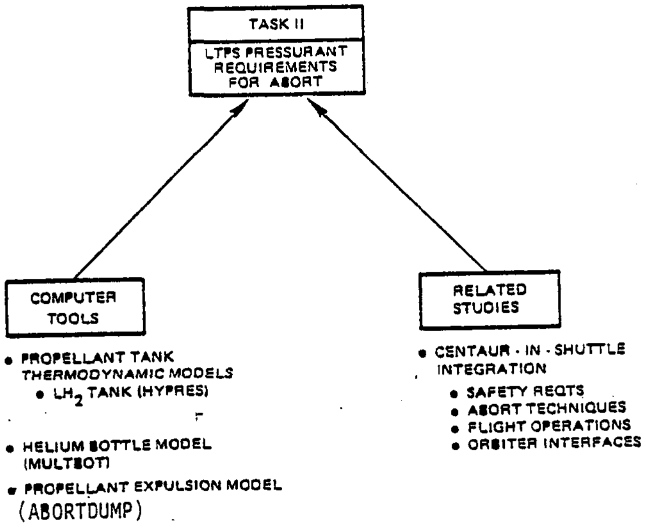


Figure 4-1. Our Centaur-in-Shuttle Study Resolved All Interface Problems Related to Centaur/Shuttle Abort.

4.1.1 LTPS/SHUTTLE ABORT MODES. The LTPS must be designed for compatibility with all Shuttle abort modes that occur before vehicle deployment. For these aborts, methods of safely operating the LTPS and subsequently disposing of propellants before landing must be devised. Shuttle aborts may be divided into two categories characterized by their impact on LTPS propellant dump design requirements: return-to-launch-site (RTLS) abort and orbital abort. Of the abort modes, RTLS was the only one considered because it would establish maximum helium requirements due to the limited time avaiable for dumping propellants. Our Centaur analysis reflected compliance with STS operational and safety requirements specified in NASA document NHB 1700.7 and interpreted by the JSC safety panel. Specifically, we used the latest JSC published abort trajectory having the lowest acceleration, which is based on an RTLS abort caused by one SSME out. A simultaneous dump of tank propellants will be accomplished in conjunction with the 250-second minimum propellant dump time. Dump can be safely accomplished while the Orbiter is above 100,000 feet altitude, which corresponds to an ambient pressure less than 0.7 kpa (0.1 psia).

4.1.2 LTPS ABORT DUMP FLUID SYSTEMS. The LTPS abort helium pressurization and propellant dump systems selected for Task II analyses are schematically shown in Figures 4-2 and 4-3, respectively. These fluid systems, selected for the Shuttle/Centaur configuration, are believed to be representative of the equivalent LTPS systems since they are compatible with all Shuttle abort modes.

4.1.2.1 Helium Pressurization System. The pressurization system of Figure 4-2 consists of vehicle-mounted and Shuttle-mounted hardware. The Shuttle-mounted hardware includes pneumatically-actuated solenoid valves, pressurization orifices and helium supply system. Helium will be stored in composite bottles (titanium liner, kevlar outer wrap), manifolded and mounted on an LTPS pallet. The vehicle-mounted hardware includes pressurization tubing, a $LH_2$ tank energy dissipator and a $LO_2$ tank bubbler manifold.

4.1.2.2 Abort Propellant Dump System. The dump line configurations used for this study were the same as those identified for Shuttle/Centaur. Dump line components include bellows, expansions/contractions, dividing/converging branches and numerous bends. The predicted component loss coefficients were used to determine tank pressurization $\Delta$Ps required to expel propellant within 250 seconds.

## 4.2 ABORT PROPELLANT EXPULSION

Pressurant helium for abort can be determined without considering dump line sizes. That is, helium usages can be calculated for each pressurization $\Delta P$ given the requirement that tank propellants will always be dumped in 250 seconds. Selection of an abort pressurization system, however, must consider size and weight of the abort dump line system in addition to pressurization system size and weight.

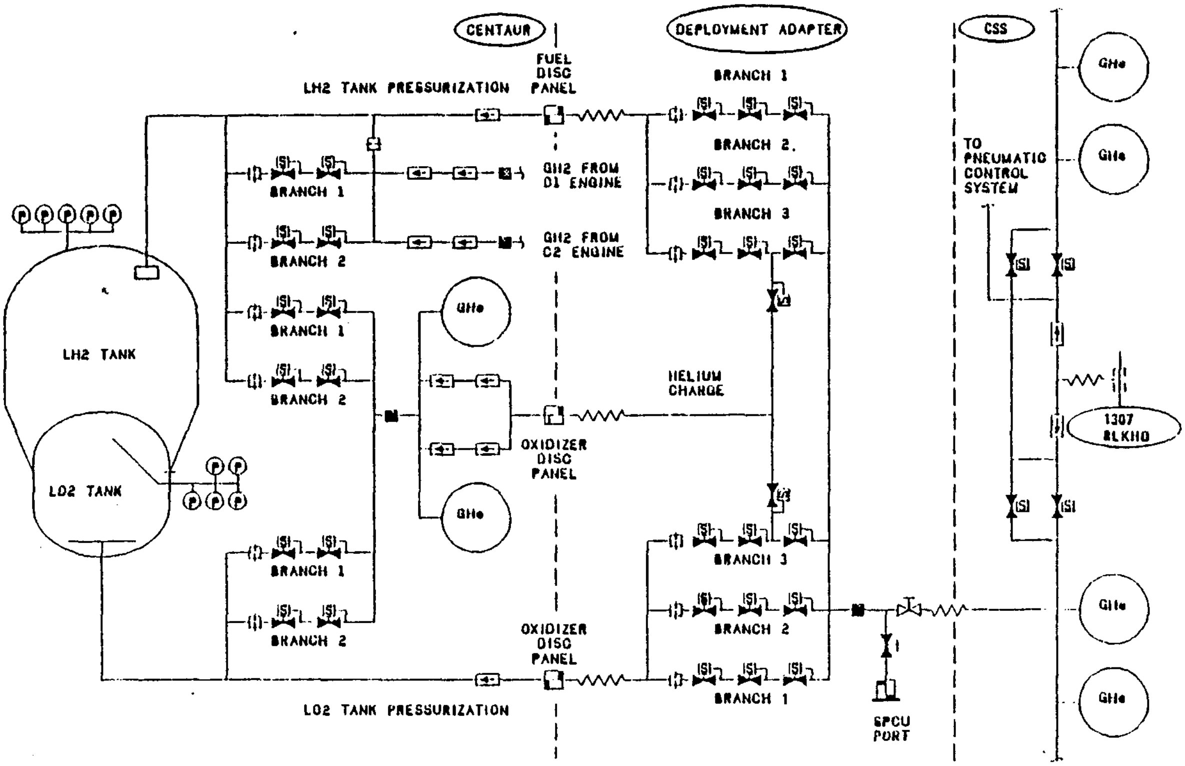


Figure 4-2. Abort Dump Helium Pressurization System for Shuttle/Centaur.

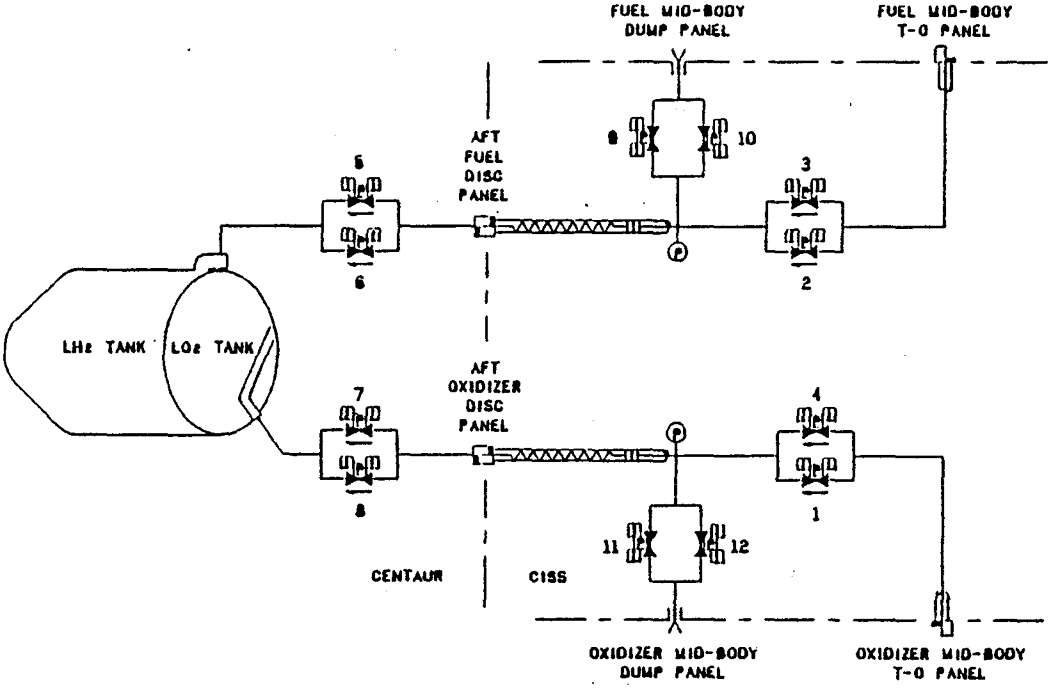


Figure 4-3. Abort Propellant Dump System for Shuttle/Centaur.

4.2.1 HELIUM SUPPLY SYSTEM. Helium supply system weights considered for optimization included only helium bottles, bottle supports and initial helium load. Other components, such as pressurization lines, solenoid valves and disconnects, were not included because these items are required for all systems and do not influence weight optimization.

4.2.1.1 Abort Pressurization Technique. The approach selected was to inject helium directly into the liquid hydrogen tank ullage and to inject helium beneath the liquid oxygen and liquid methane surfaces because each method minimized dump helium mass requirements. Note that these same helium pressurization techniques were also selected for LTPS mission pressurization (Section 2).

4.2.1.2 Helium Mass Requirements. Helium mass usages during propellant dump were determined for tank pressurization $\Delta$Ps of 14, 28 and 55 kpa (2, 4 and 8 psid). Tank pressures were maintained constant throughout the 250-second propellant dump period. Helium usages for bubbler injection to the $LO_2$ and $LCH_4$ tanks did not exceed 5 kg (11 lb) at the maximum pressurization $\Delta$P. $LH_2$ tank helium usages (for ullage injection) were found to exceed 17.4 kg (40 lb).

The Shuttle pallet-mounted helium supply bottles will provide helium for propellant tank inerting and specified purges, as well as for abort dump pressurization. The post-propellant dump helium requirements (discussed in Section 4.3) will influence helium supply temperatures during abort dump helium pressurization. $LO_2$ tank and $LCH_4$ tank helium usages during dump will not be affected by the post-dump helium demand because pressurant requirements will be the same whether helium enters the liquid at ambient or at liquid temperature. $LH_2$ tank helium mass requirements for propellant dump are a function of tank pressurization $\Delta$P and helium supply temperature. Helium supply temperature will be influenced by $LO_2$ tank abort pressurization requirements and by post-propellant dump helium requirements. Consequently, these effects must be specified before $LH_2$ tank helium usages and resulting supply system weights can be calculated.

4.2.2 DUMP LINE SYSTEM. The ABORTDUMP computer program was used to calculate mass flow rates for various line diameters and tank pressures. Flowrate calculations were based upon a thermodynamic equilibrium assumption as the propellant is dumped to space. The fluid model allowed the initially subcooled liquid to transition to a saturated and, finally, to a two-phase state as it continued downstream. Critical mass flow rate was determined by imposing sonic conditions at the dump line exit.

4.2.2.1 Dump System Selection. The dump system weights for each propellant were determined by combining abort propellant line weights with helium system weights. It was expected that an optimum system weight would exist within the pressure range under study because dump line and helium system weights are, respectively, decreasing and increasing functions of pressurization $\Delta$P. An optimum system weight was not found. For LTPS Configuration 3, Figure 4-4 shows that the $LCH_4$ system will optimize at a $\Delta$P greater than 55 kpa (8 psid), whereas the $LO_2$ system will optimize at a $\Delta$P less than 13.8 kpa (2 psid).

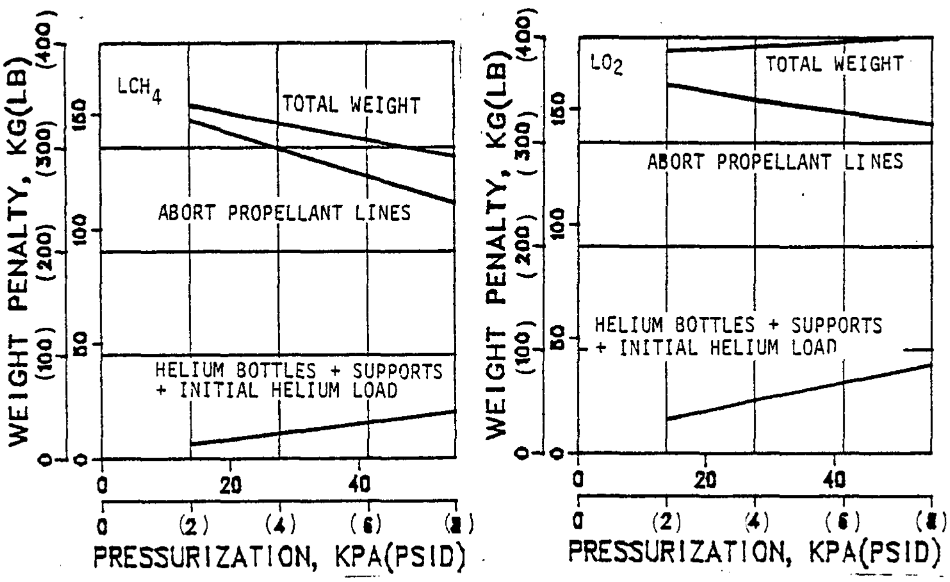


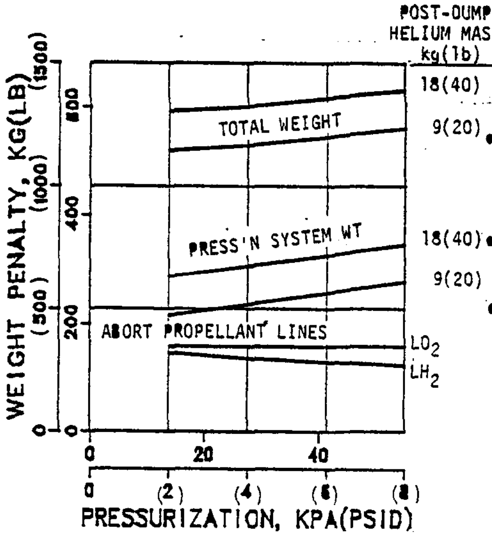
Figure 4-4. LCH$_4$ and LO$_2$ Tank Abort Dump System Weight Optimization (Configuration 3)

Thus, the selected abort dump system for this LTPS configuration was based upon the maximum LCH$_4$ tank ΔP and minimum LO$_2$ tank ΔP. Dump system weights do not include the additional helium mass and storage bottles required for post-propellant dump operations. These weights are treated in Section 4.3. The total abort system weights combining dump system and post-dump system weights are discussed in Section 4.4.

Figure 4-5 gives the individual and combined system weights versus tank ΔP for the Configuration 1 LH$_2$ and LO$_2$ dump systems. As with Configuration 3, an optimum weight system was not found for Configuration 1. The LO$_2$ system individual and combined weights were found to be similar to the LO$_2$ data of Figure 4-4. Thus, minimum weight for the LO$_2$ system will occur at a tank ΔP less than 14 kpa (2 psid). The LH$_2$ system data of Figure 4-5 exhibits the same trend as the LO$_2$ system data. Consequently, a minimum weight for this system will also occur at a pressurization ΔP less than 14 kpa (2 psid). The selected abort dump system for Configuration 1 incorporates the lowest analyzed tank pressurization ΔP of 14 kpa (2 psid).

## 4.3 POST-PROPELLANT DUMP HELIUM USAGES

Two vent and repressurization cycles will be performed at the completion of propellant dump. This procedure will dilute the propellant vapor concentration in the tank for vehicle "safing" prior to landing. LTPS helium purges were included as part of the abort helium pressurization system requirements. These purges were based upon Shuttle/Centaur estimates for the MLI blanket purge and engine purges. The MLI blanket purge and engine purge masses for Configuration 1 are given in Table 4-1.



NOTES

- PRESSURIZATION SYSTEM WEIGHT INCLUDES HELIUM BOTTLES + SUPPORTS + INITIAL HELIUM LOAD FOR BOTH $LO_2$ AND $LH_2$ TANKS.
- $LO_2$ TANK PRESSURIZATION $\Delta P = 6.9$(2 psid); HELIUM USAGE = 1.8 kg(3.9 lb)
- POST-DUMP HELIUM MASS INCLUDES:
  - $LH_2$ INSULATION PURGE
  - ENGINE SYSTEM PURGE
  - TANK INERTING

Figure 4-5. $LH_2/LO_2$ Abort Dump System Optimization (Configuration 1)

Table 4-1. RTLS Abort Helium Mass Usage Requirements

| Requirement | $LH_2/LO_2$, Config. 1 | $LCH_4/LO_2$, Config. 3 |
|---|---|---|
| Propellant Dump, kg(lb) | | |
| Fuel Tank | 13.8 (30.5) | 2.4 (5.3) |
| Oxygen tank | 1.8 ( 3.9) | 1.8 (4.0) |
| 1st Repressn,(1) kg(lb) | | |
| Fuel Tank | 3.3 (7.2) | 1.4 (3.0) |
| Oxygen Tank | 1.9 (4.2) | 1.8 (4.0) |
| 2nd Repressn,(1) kg(lb) | | |
| Fuel Tank | 3.4 (7.5) | 1.5 (3.2) |
| Oxygen Tank | 2.0 (4.4) | 2.0 (4.4) |
| MLI Blanket Purge,(2) kg(lb) | 3.1 (6.9) | NA |
| Engine Purge,(2) kg(lb) | 1.0 (2.1) | NA |
| 10% Margin, kg(lb) | 3.0 (6.7) | 1.1 (2.4) |
| TOTALS, kg(lb) | 33.3 (73.4) | 11.9 (26.3) |

(1) Repressurization mass usages increase tank pressures from 5 psia to 15 psia.

(2) Purges are based upon Shuttle/Centaur estimates for a 30-minute purge (15 minutes prior to and after landing) of the $LH_2$ side only. Purges are not required for $LO_2$ and $LCH_4$.

## 4.4 TOTAL ABORT DUMP SYSTEM WEIGHT

The total abort dump system weight includes propellant dump lines and a helium system that provides helium throughout the RTLS abort period, including MLI blanket and engine purges until landing plus 15 minutes. A total system weight was determined for vehicle Configurations 1 and 3 using the selected dump systems and post-propellant dump helium requirements given in Table 4-1. These abort dump system weights are given in Table 4-2. Note that the total system mass for Configuration 1 is about 50 percent greater than for Configuration 3. This difference is due solely to the liquid hydrogen system that requires considerably more helium for tank pressurization and purges than does the $LCH_4$ tank.

It should be mentioned that Table 4-2 does not represent the minimum weight abort dump system for either vehicle configuration. The optimum point is represented by lower tank pressurization ΔPs for $LO2$ and $LH_2$, and by a higher ΔP for $LCH_4$. It is probable, however, that space limitations within the Shuttle/Orbiter will preclude incorporating the larger lines sizes required to dump propellants at the lower tank ΔPs.

It is also noted that the available LTPS helium supply was not included when abort system helium mass usages were determined. This source of helium is not significant but it would decrease the usages identified in Table 4-2. Changes to the LTPS-mounted and Shuttle-mounted hardware would be required to make this helium available.

Table 4-2. LTPS Abort Dump System Total Weights

| Vehicle Configuration | Tank Press'n ΔP kpa (psid) | Total Helium Mass Usage kg (lb) | Helium Bottle Vol. Regments. $m^3(ft^3)$ | Initial Helium Load kg (lb) | Mass of Bottles + Supports kg (lb) | Dump Line Weights kg (lb) | Total System Mass kg (lb) |
|---|---|---|---|---|---|---|---|
| 1 | $LH_2^{(1)}$= 13.8(2.0)<br>$LO_2^{(1)}$= 13.8(2.0) | 33.3(73.4) | 0.87(30.9) | 34.3(75.7) | 245.9(542) | 303.9(670) | 584.1(1288) |
| 3 | $LCH_4$ = 55.2(8.0)<br>$LO_2^{(1)}$= 13.8(2.0) | 11.9(26.3) | 0.67(23.6) | 14.0(30.9) | 100.2(221) | 270.3(596) | 384.5( 848) |

(1) The lightest system weight may occur at a lower tank pressurization ΔP. However, space limitations may preclude incorporating a larger line size.

# 5

# TECHNOLOGY EVALUATION

In this section, technology requirements were evaluated for each propellant expulsion and thermal conditioning system identified in Sections 3 and 4. A discussion for the analysis, design, test and demonstration required to develop this technology is presented.

## 5.1 TECHNOLOGY REQUIREMENTS

The technology required for detailed design and development of selected propellant expulsion and thermal conditioning systems was identified. Two of the four selected thermal conditioning systems were state-of-the-art configurations and require no technology plan. Hydrogen thermal subcoolers for the two remaining thermal conditioning systems represent new technology. Regarding propellant expulsion during Shuttle abort modes, new technology is not required. Rather, deficiencies may exist in the ability to accurately predict/model certain fluid flow phenomena. Specific technology deficiencies, or unresolved problems, are described below.

5.1.1 THERMAL CONDITIONING SYSTEMS. A total of five propellant thermal conditioning systems are contained within the four vehicle systems; bubbler pressurization for the $LO_2$ tank and four (two pressurization and two subcooler) systems for the liquid hydrogen tank. Systems 1 and 2 require no discussion since they represent current technology.

5.1.1.1 Systems 3 and 4. $LO_2$ tank bubbler pressurization has no technology requirements. The $LH_2$ tank thermal conditioning systems are:

a. System 3: Engine start - Thermal Subcooler (coolant dump)
Engine burn - Autogenous pressurization

b. System 4: Engine start/engine burn - Thermal Subcooler (return to ullage)

Both subcooler concepts are the same, except that one dumps coolant overboard and the other uses a pump to return coolant to the ullage. This is considered to be a minimal technology difference. Since the subcooler concept is new, performance should be demonstrated through analytical and empirical efforts. The areas of interest relating to subcooler design and performance are:

a. Pressure regulator: Cold-side fluid pressure and temperature must be controlled during operation.

b. Heat exchanger: Heat transfer and fluid flow parameters must be established for subcooler sizing.

c. $GH_2$ pump: Pump requirements (where applicable) for returning cold-side fluid to the $LH_2$ tank ullage must be identified.

d. Engine start transient: Establish procedures through testing to determine NPSP histories of engine flow exiting the subcooler.

e. Engine inlet NPSP controls: Demonstrate through testing that engine NPSP requirements will be satisfied during engine burn.

Because of uncertainties associated with the low-g boiling heat transfer process, the heat exchanger is the only component that can be considered new technology. Specifically, vapor-blanketing could occur at the cold-side heat transfer surface since there are no phase-separating buoyancy forces to drive the vapor away. An acceptable solution would be to utilize the momentum of the flowing fluids to provide phase distribution control that would actively distribute the fluid so that vapor-blanketing of a surface is minimized.

5.1.2 ABORT EXPULSION SYSTEMS. The greatest uncertainty in designing an abort expulsion system is accurate determination of cryogen flow rate through the ducting. Ambient pressures will be less than 0.7 kpa (0.1 psia) during the expulsion period; consequently, sonic flow conditions will occur at the exit. It is also likely that the transition from pure liquid flow to two-phase flow will occur upstream of the abort dump line exit. An unknown is whether "shifting" equilibrium or "frozen" equilibrium conditions will exist during the two-phase flow process.

The impact of this two-phase flow uncertainty will be felt in design of the abort pressurization and dump systems. Propellant tank pressure levels or dump line diameters may be increased to compensate for this uncertainty. Either approach will increase abort expulsion system weights. For Shuttle/Centaur, this increase translates to two additional helium bottles for propellant dump, resulting in a weight increase of 41 kg (90 lb). This potential weight penalty is not a major driver for experimentation. Furthermore, it would be preferable to perform tests on a dump line configuration similar to the flight article. Such details for LTPS may be years from being developed. Consequently, a technology plan for two-phase flow experimentation is not recommended.

## 5.2 TECHNOLOGY PLAN

A technology plan for subcooler development should include two major areas: heat exchanger development and systems tests. A brief description of each is given in Sections 5.2.1 and 5.2.2. However, there may not be sufficient reason to pursue subcooler development, if thermal conditioning system weight reduction is the primary motive. The systems comparisons of Figure 3-1 indicates weight savings of less than 27 kg (60 lb) between state-of-the-art (System 2) and new technology (System 4).

5.2.1 HEAT EXCHANGER DEVELOPMENT. The key to developing a heat exchanger for low-g subcooler application is in designing heat exchanger surfaces that create fluid force fields to accomplish phase separation in zero gravity. Phase separation will assure that high boiling heat transfer coefficients will be present. Such heat exchangers have been built and limited testing has been performed with $LH_2$ and $LO_2$, References 5-1 and 5-2. Considerably more testing would be required to verify the heat exchanger concept for zero gravity application.

There is the possibility that zero gravity testing of this heat exchanger configuration may not be required. Hydrogen cold-side heat transfer coefficients have been estimated to be an order of magnitude greater than hot-side liquid phase coefficients. It is clear that heat exchanger surface area will be controlled by the hot-side overall conductance so that precise evaluation of the cold-side overall conductance is not required. Consequently, judicious design of heat exchanger curved channels could eliminate the need for zero-g testing.

5.2.2 SYSTEMS TESTS. Systems tests as a minimum should investigate engine start transients and engine inlet NPSP controls. Tests of this nature are normally not performed until substantial design data is available on the engine feed system and main engine.

5.2.2.1 Engine Start Transient. To establish an engine start sequence of events, it will be necessary to integrate feedline and main engine chilldown requirements with knowledge of the main engine NPSP requirements during the start transient. It is possible that feedline and engine chilldown requirements may be such that the subcooler will be operating at steady-state by main engine start. Otherwise, subcooler flow initiation must be planned to assure steady-state operation by main engine start. Transient tests would have to be performed during actual LTPS engine hot firings.

5.2.2.2 Engine Inlet NPSP Controls. With the coolant dump option, engine NPSP is satisfied by cooling propellant flowing to the engine system. The amount of propellant dumped overboard during engine start will be quite small, so it would be possible to over-size the heat exchanger with little impact on payload capability. For the coolant return-to-ullage option, however, the subcooler must be capable of cold-side flow control. This flow control is needed because main engine propellant NPSP will be a combination of propellant subcooling and tank pressurization (provided by coolant flow to the ullage). At main engine start, coolant flow demand will be a maximum. However, as ullage pressure is increased, due to coolant return to the ullage, coolant flow demand will diminish. A means must be developed for controlling coolant flow rates by continuously monitoring ullage pressures and liquid temperatures so that engine NPSP will be satisfied.

## 5.3 CONCLUSIONS AND RECOMMENDATIONS

Continued work with thermal subcoolers is not recommended. The potential weight gain for a thermal conditioning system that includes a thermal subcooler seems too small to warrant development of a $LH_2$ thermal subcooler. This recommendation is based on the premise that a low NPSP engine system is an achievable goal. It was also felt that considerable detail must be developed on LTPS propellant feed systems, engine system chilldown requirements and start transients before meaningful systems tests can be conducted.

For design of a propellant expulsion system, the unknown is in an accurate determination of two-phase flow rates through ducting. The unknown is whether "shifting" equilibrium or "frozen" equilibrium conditions will exist as propellant is dumped to ambient pressures less than 0.7 kpa (0.1 psia). An experimental program was not recommended because this uncertainty should not have a major impact upon LTPS performance.

# 6

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