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STS Propellant Densification Feasibility Study Data Book

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I. INTRODUCTION

A. Need

The need for increased payload capability for launch vehicles is driven by ever changing requirements. The Space Transportation System (STS) or space shuttle, having the requirement to support the International Space Station, is examining options to increase its payload capability. Cryogenic propellant densification is a potential option for doing so.

Propellant densification is not a new approach. Slush hydrogen has been examined in the past for various programs. Operational considerations have prevented its use in the past. The use of subcooled propellant, above the slush point, may offer a solution. In order to assess the use of subcooled propellant on the shuttle or other vehicles, the system, technical, operational, requirements, and, most importantly, cost must be known. Propellant densification on the shuttle has been proposed by Rockwell International. This report is in response to that proposal, as well as the desire to maximize launch vehicle payload.

B. Objective

A product development team (PDT) has been formed to determine the feasibility of propellant densification in terms of technical, operational, and cost factors. The main objective of the PDT is to recommend a means of increasing the space shuttle payload by taking advantage of propellant densification, thus partially fulfilling the payload requirement for the International Space Station.

The reference vehicle that will be used as a baseline or bench mark is the current space shuttle. Various propellant densification concepts will be examined to determine their feasibility, as well as whether both liquid hydrogen (LH_2) and liquid oxygen (LO_2) should be densified or only one or the other. As the PDT product, a recommendation(s) will be made as to the most promising approach.

C. Goal

The goal of this report is to gain a thorough and in-depth understanding of propellant densification, to recommend a concept(s) for propellant densification, and to provide a performance, operational, and cost assessment for the concept(s). Figures 1 and 2 show the work breakdown schedule and the task logic diagram.

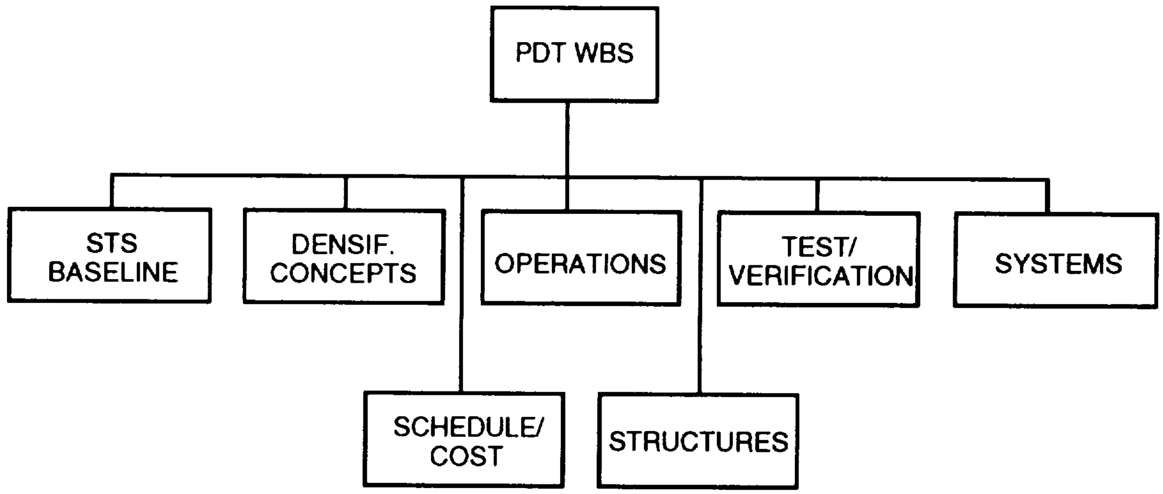


Figure 1. Work breakdown structure.

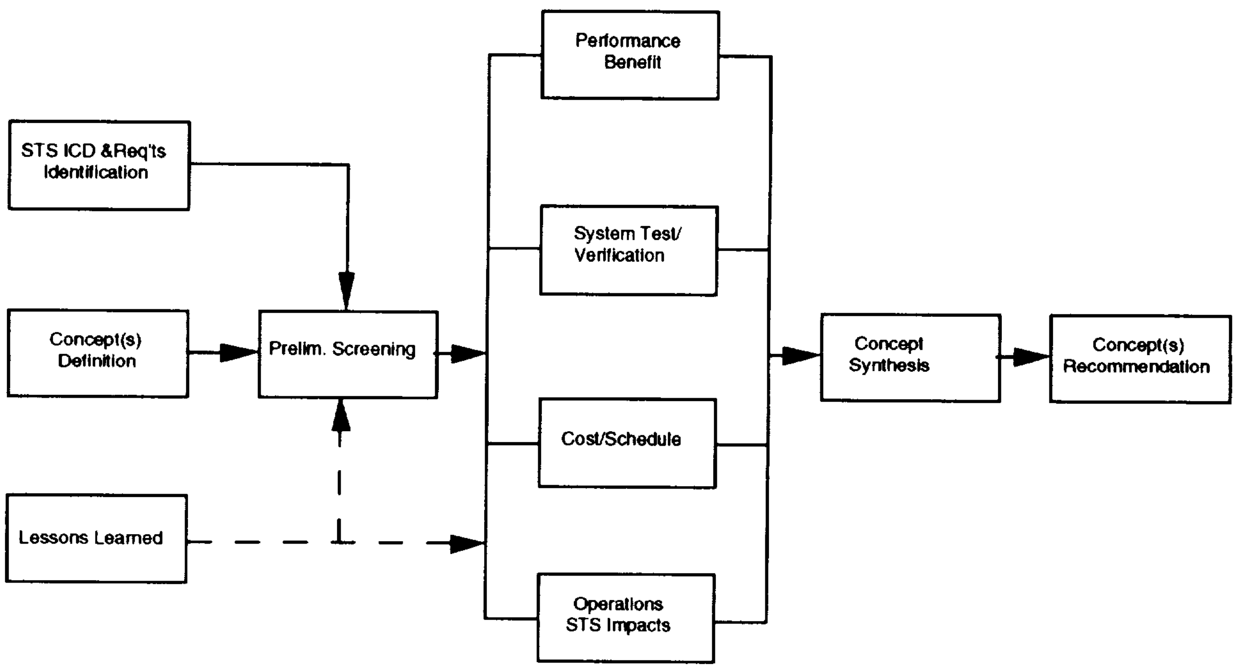


Figure 2. Task logic diagram.

II. ASSUMPTIONS/GROUND RULES

A. STS Enhancements

For the purposes of this study, the baseline vehicle will be the current STS, Johnson Space Center (JSC) Class 0, i.e., no enhancements.[1] Table 1 provides a summary of the ground rules. For further details, see reference 1.

Table 1. Reference trajectory.

Parameter	Value
Nominal Throttle Level	104 percent
Space Shuttle Main Engine (SSME) Rated Vacuum Thrust	470,259 lbf
SSME Rated Vacuum Isp	452.53 s
SSME Nominal Mixture Ratio	6.011:1
SRB PMBT	78 °F
Propellant Load at Startup	1,613,777 lbm
– LO_2	1,382,028 lbm
– LH_2	231,749 lbm
Main Engine Cut Off (MECO) Orbit Apogee	220 nm
MECO Orbit Perigee	31 nm
MECO Altitude	57 nm
Orbit Inclination	51.6°
Design Atmosphere	Summer
Design Winds	June
Maximum Dynamic Pressure (Q)	750 lb/ft^2
Minimum Q alpha	–3,000 lb/ft^2-°

III. STS BASELINE

A. External Tank (ET) Envelope

The densification subsystem shall operate within the existing dimensions of the ET as given in table 2.

Table 2. ET dimensions.

Description	LH_2	LO_2
Height (in)	1,160.75	588.4
Diameter (in)	330.0	330.0
Liq. Vol (ft^3) – Unpress	52,528	19,446
Liq. Vol (ft^3) – Press	53,152	19,672

B. ET Heat Flux

The nominal heat flux on the ET, for both the LH_2 and LO_2 tanks, are given in table 3.

Table 3. ET heat flux and vent rates.

Description	LH_2	LO_2
Q (Btu/s)	153.0	110.0
m,vent (lb/s)	0.77	1.2

C. Space Shuttle Main Engine (SSME) for Net Positive Static Pressure (NPSP)

The required NPSP for the low pressure LH_2 pump and the low pressure LO_2 pump are given in table 4.

Table 4. Required NPSP for SSME liquid propellant (LP) pumps.

Power Level	LH_2 NPSP	LO_2 NPSP
65	4.8	6.0
100	5.3	7.8
109	5.6	20.0

D. Existing Requirements

These current STS baseline requirements must be either met or revised if propellant densification systems are incorporated.

1. Launch Commit Criteria (LCC).

- LCC MPS-11 MPS LH_2 17-Inch Manifold Disconnect Temperature/High-Point Bleed Temperature Anomaly
  – New maximum limits must be set for densified LH_2.

- LCC MPS-24 MPS LO_2 Engine Inlet Temperature Anomaly – High
  – LO_2 bleed flow temperature maximum limit will require change to reflect densified LO_2.

- LCC MPS-25 MPS LO_2 Engine Inlet Temperature Anomaly – Low
  – Lower temperature limit must be reestablished for densified LO_2.

- LCC MPS-33 Main Engine LH_2 Recirculation Anomaly
  – LH_2 recirculation interruptions (duration) will have to be reassessed for densified LH_2.

- LCC ET-04 ET LH_2 Prepress Cycle Anomaly
  – With colder LH_2, the number of prepress cycles required will likely increase.

2. Interface Control Document (ICD) Requirements.

- ICD-2-12001 Orbiter Vehicle/ET
  - Table 3.3.1-1 Orb/ET Fluid Separation Interface Conditions (Fluid Min, Nom, and Max Flowrate, Temperature and Pressure)
  - LH_2 Replenish
  - LH_2 Recirculation
  - LH_2 Drain (Detank)
  - LH_2 Engine Feed
  - GH_2 Pressurization
  - LO_2 Replenish
  - LO_2 Drainback
  - LO_2 Drain (Detank)
  - LO_2 Engine Feed
  - GO_2 Pressurization

  - Figure 3.3.2-1 Orb/ET Separation Interface LH_2 Prestart Requirements
  - Figure 3.3.2-2 Orb/ET Interface LH_2 Temperature Versus LH_2 Mass Remaining
  - Figure 3.3.2-4 Orb/ET I/F LH_2 Main Feed Line Propellant Requirements During Recirculation With LH_2 Tank Unpressurized
  - Figure 3.3.3-2 Orb/ET Interface LO_2 Main Engine Operation Requirements

- ICD-2-0A002 Space Shuttle Launch Pad and Platform
  - Table 4.3-1 ET Fluid Systems (Flowrate, Pressure and Temperature Limits)
    - GH_2 tank vent
    - GO_2 tank vent.

3. Operations and Maintenance Requirements and Specifications (OMRSD).

- LH_2 ullage pressure limits during various loading phases
- LO_2 ullage pressure limits during various loading phases.

E. New Requirements

Some new LCC, ICD, and OMRSD requirements would have to be established to incorporate densified propellants. Identifying new LCC and OMRSD requirements is beyond the scope of this study. However, it is likely that LCC's would be written to require a minimum amount of uninterrupted replenish time for each propellant to guarantee proper thermal conditioning.

- ICD-2-12001 Orbiter Vehicle/ET
  - Orb/ET interface conditions (fluid flowrate, temperature and pressure limits) for densified LH_2 recirculation line.

- ICD-2-0A002 Space Shuttle Launch Pad and Platform
  - Shuttle vehicle/pad interface conditions (fluid flowrate, temperature and pressure limits) for densified LH_2 recirculation line through LH_2 T-O umbilical and for LO_2 recirculation line through intertank.

IV. DENSIFICATION CONCEPT

A. Onboard Propellant Increase

STS payload gain can be achieved by increasing the effective density of cryogenic propellants, i.e., LH_2 and LO_2, by reducing the temperature of the liquid below that of the corresponding saturation temperature at ambient pressure. By densifying the propellant, i.e., increasing the effective density, more propellant mass can be loaded into the ET. This increase in propellant mass is translated into an increase in effective payload capability. Propellant densification can be accomplished on the LH_2 and LO_2 side either together or separately. Figures show the density versus temperature for LO_2 and LH_2.

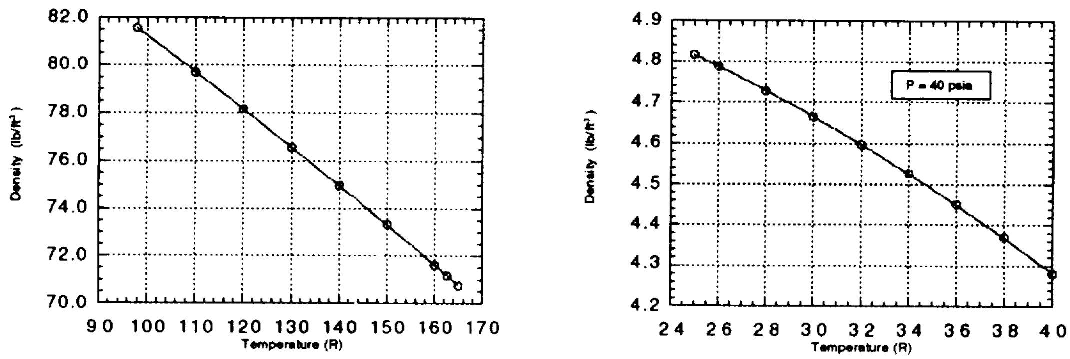


Figure 3. LO_2 and LH_2 density versus temperature.

Using the increased density propellant, an increase in the total propellant mass can obtained. Table 5 and figure 4 show the propellant mass gain for LO_2 and LH_2.

1. $\underline{LO_2/LH_2 \text{ Conditioning}}$. The following analysis shows the propellant mass increase in the ET by densifying both the LH_2 and the LO_2. The current overboard mixture ratio is approximately 6.011. The propellant load can be calculated by keeping the overboard mixture ratio at 6.011, therefore, limiting the engine impact or maximizing the propellant mass onboard by going to an off nominal mixture ratio.

The LH_2 side is the driver, since the triple point is close to the nominal LH_2 temperature as compared to the LO_2 side. In section V, various concepts are examined to determine which is the most feasible for the LH_2 and LO_2 side. A minimum LH_2 temperature of 29 °R will be used in this analysis. This value has been determined by heat exchanger analysis performed by Rockwell International and will be used as the LH_2 temperature in all cases. For the LO_2 side, temperatures are in the range of 130 to 145 °R.

Two LO_2 temperatures, 140 and 130 °R, will be examined to assess the possible payload benefit. For both cases, the LH_2 temperature will be 29 °R. As given in appendix A, propellant inventories were performed on these cases to determine unusable residuals and the overboard mixture ratio required. These are summarized in table 6.

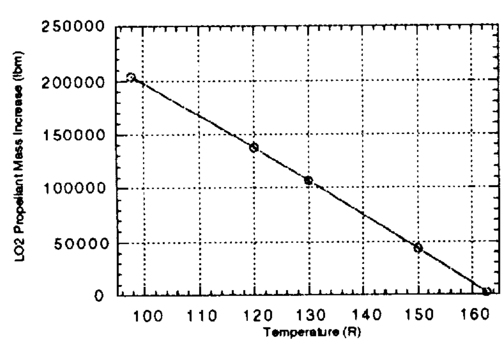
Table 5. LO_2 and LH_2 density versus temperature.

LH_2 Parametrics

Temp	Density	Mass Total	ΔMass
24.987	4.8154	255,952	21,337
25.00	4.8151	255,933	21,318
25.50	4.8014	255,207	20,592
26.00	4.7875	254,466	19,851
26.50	4.7732	253,709	19,095
27.00	4.7587	252,938	18,323
27.50	4.7439	252,151	17,536
28.00	4.7288	251,349	16,735
28.50	4.7135	250,533	15,918
29.00	4.6978	249,701	15,086
29.50	4.6819	248,853	14,239
30.00	4.6657	247,991	13,376
30.50	4.6492	247,114	12,499
31.00	4.6324	246,221	11,607
31.50	4.6153	245,314	10,699
32.00	4.5979	244,391	9,776
32.50	4.5803	243,453	8,839
33.00	4.5624	242,501	7,886
33.50	4.5441	241,532	6,918
34.00	4.5257	240,549	5,935
34.50	4.5069	239,551	4,936
35.00	4.4878	238,538	3,923
35.50	4.4685	237,509	2,894
36.00	4.4488	236,466	1,851

LO_2 Parametrics

Temp	Density	Mass Total	ΔMass
97.853	81.5632	1,604,505	206,245
130.00	76.5819	1,506,514	108,253
131.50	76.3413	1,501,780	103,520
133.00	76.1000	1,497,032	98,772
134.50	75.8579	1,492,270	94,010
136.00	75.6150	1,487,493	89,233
137.50	75.3715	1,482,702	84,442
139.00	75.1272	1,477,897	79,636
140.50	74.8822	1,473,077	74,816
142.00	74.6365	1,468,243	69,982
143.50	74.3900	1,463,394	65,134
145.00	74.1428	1,458,531	60,271
146.50	73.8949	1,453,654	55,393
148.00	73.6462	1,448,762	50,502
149.50	73.3968	1,443,856	45,595
151.00	73.1467	1,438,935	40,675
152.50	72.8958	1,434,001	35,740
154.00	72.6442	1,429,051	30,791
155.50	72.3919	1,424,088	25,827
157.00	72.1389	1,419,110	20,849
158.50	71.8851	1,414,117	15,857
160.00	71.6306	1,409,111	10,850
161.50	71.3753	1,404,090	5,829
163.00	71.1193	1,399,054	794



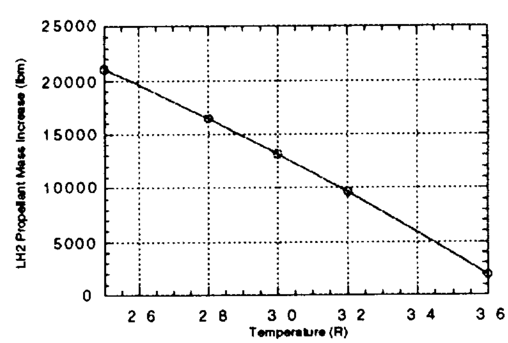


Figure 4. LO_2 and LH_2 propellant mass increase.

Table 6. Usable residuals and mixture ratios.

	LH_2 Temp	LO_2 Temp	LH_2 Resid.	LO_2 Resid.	M.R.
Option No. 1	28.5	141.5	2,050	4,887	5.93
Option No. 2	28.5	132.1	2,050	4,916	6.05

The delta propellant mass for these options are given in table 7.

Table 7. Delta propellant mass.

	LH_2 Temp	LO_2 Temp	ΔLH_2	ΔLO_2
Option No. 1	28.5	141.5	15,995	70,009
Option No. 2	28.5	132.1	16,002	100,004

2. <u>LH_2 Only Conditioning</u>. A LH_2 propellant mass gain can be accomplished by lowering the engine mixture ratio. As shown in section VII.A.2, the minimum mixture ratio that can be achieved is 5.61. Performing a propellant inventory for the LH_2 only case, for the minimum LH_2 temperature of 28.5 °R, the overboard mixture ratio is 5.64. This mixture ratio is within the minimum of 5.61.

Table 8 gives the delta propellant mass for the LH_2 only case.

Table 8. Delta propellant mass for LH_2 only case.

LH_2 Temp	LH_2 Resid.	ΔLH_2	M.R.
28.5	2,050	15,997	5.64

B. Concept Definition—Trade Tree

Various concepts providing propellant densification will be studied to identify the concept or concepts that are the most appealing in terms of cost, performance, and operations. The most appealing option will have the least impact to the current STS system, while still offering a substantial payload gain.

Propellant densification can be provided either internal or external to the ET as shown in figure 5.

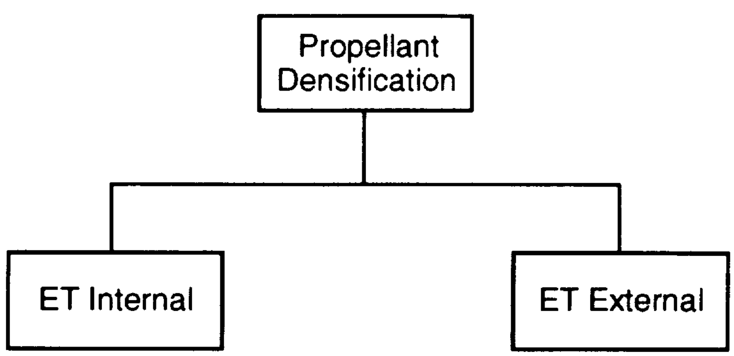


Figure 5. Propellant densification.

Depending on whether the densification is done internally or externally to the ET, various options are available. Also, densification may be performed on only the LH_2 or LO_2 side and may or may not be done on the propellant supply tanks.

1. ET Internal Densification. The trade tree given in figure 6 shows the various options for ET internal densification that will be considered in this study.

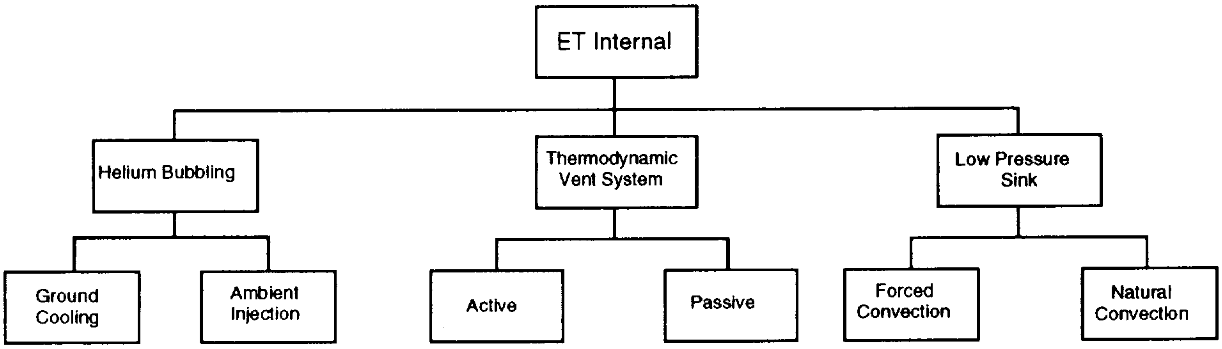


Figure 6. ET internal propellant densification.

(a) Helium (He) Bubbling. Propellant subcooling through He injection or He bubbling is obtained by evaporating LO_2 into the He bubbles and subsequently producing a cooling effect due to evaporation. This evaporation occurs due to the difference in LO_2 and He vapor pressure. As the LO_2 cools down and its vapor pressure decreases, the cooling effect becomes less, thus requiring large amounts of He to continue to cool the propellant. Due to LH_2's molecular weight being lower than He, using He injection to cool LH_2 is not practical.

An additional concern with using He injection to cool the propellants is the loss of loading control due to the presence of a large number of He bubbles. The He injection must, therefore, be terminated prior to launch to gain liquid level control and then replenish with ambient temperature liquid as required. Also, the added concern of the He going into solution with the propellant and subsequently coming out may be a problem. If He coolers are necessary to prechill the He prior to injection, the concept simplicity will be compromised.

(b) Thermodynamic Vent System (TVS). Propellant cooling through the use of a TVS is accomplished by expanding a small portion of the fluid to be cooled or a separate working fluid to a lower pressure, thus lowering its temperature. This cooler fluid is then used to cool the bulk propellant by circulating it through a heat exchanger.

If the TVS is carried onboard the STS, i.e. inside the ET, the weight and cost associated with the system would not be practical.

(c) Low Pressure Sink. Propellant cooling through the use of a low pressure sink is accomplished by exposing the propellant to a pressure lower then ambient, thus saturating the propellant at a lower temperature. The desired temperature of the propellant can be controlled by the system back pressure.

By lowering the propellant vapor pressure, without prepressing the system, the tank/system positive pressure will be compromised, thus introducing tank structural and propellant contamination issues.

2. ET External Densification. The following trade tree (fig. 7) shows the various options for ET external densification that will be considered in this study.

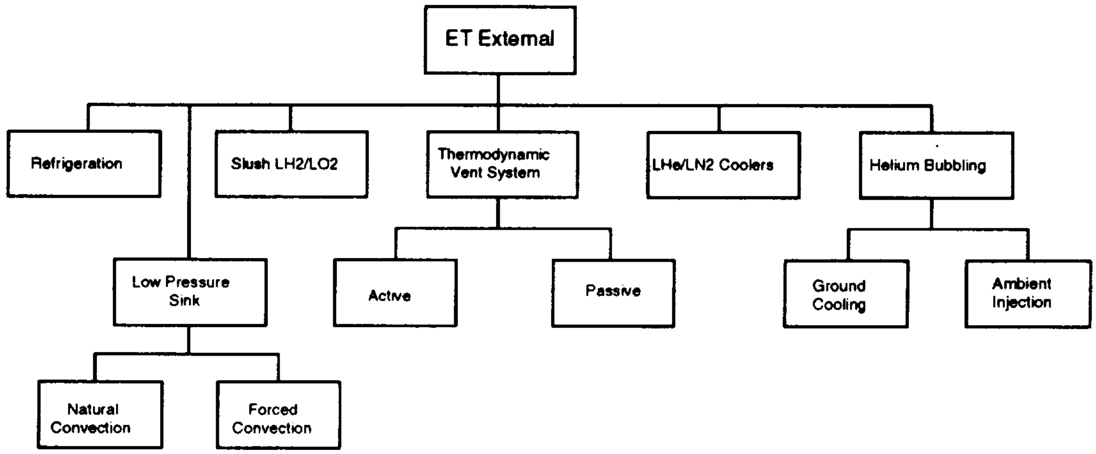


Figure 7. External propellant densification.

(a) Refrigeration. Propellant densification through refrigeration would require the use of complicated and expensive conditioning systems. An independent working fluid must be maintained to serve as the heat sink for the process. Components such as compressors, evaporators, and heat exchangers are required. Such a system becomes impractical for cryogenic systems.

(b) Low Pressure Sink. Propellant cooling through the use of a low-pressure sink is accomplished by exposing the propellant to a pressure lower then ambient, thus saturating the propellant at a lower temperature. The desired temperature of the propellant can be controlled by the system back pressure.

By lowering the propellant vapor pressure, without prepressing the system, the tank/system positive pressure will be compromised, thus introducing tank structural and propellant contamination issues.

(c) Slush LH_2/LO_2. Slush hydrogen or oxygen is the combination of the liquid and solid phases coexisting in solution. The temperature of the cryogen must be lowered to the triple point where solidification takes place. The advantage of slush is the large heat sink available due to latent heat from melting along with the latent heat from evaporation.

The disadvantages of slush hydrogen is that it must be mixed continually to prevent large solid hydrogen or oxygen particles from forming. Also, the cost of a slush production facility and the operational issues associated with its use have prevented slush hydrogen from being used in most vehicles under study in the past.

(d) Thermodynamic Vent System. Propellant cooling through the use of a TVS is accomplished by expanding a small portion of the fluid to be cooled or a separate working fluid to a lower pressure, thus lowering its temperature. This cooler fluid is then used to cool the bulk propellant by circulating it through a heat exchanger.

If the TVS is to be ground servicing equipment (GSE), the weight, operational impact, and recurring costs are significantly reduced.

(e) Liquid Helium (LHe)/Liquid Nitrogen (LN_2) Coolers. Propellant conditioning using coolers is accomplished by circulating the liquid propellant through a low-temperature bath, thus, ideally, exiting at the bath temperature. This concept is relatively simple, since the propellant is only circulated through a passive bath—no active TVS or refrigeration systems are required.

The use of coolers is limited by the saturation temperature of the working fluid and by its heat of vaporization.

(f) He Bubbling. Propellant subcooling through He injection or He bubbling is obtained by evaporating LO_2 into the He bubbles and subsequently producing a cooling effect due to evaporation. This evaporation occurs due to the difference in LO_2 and He vapor pressure. As the LO_2 cools down and its vapor pressure decreases, the cooling effect becomes less, thus requiring large amounts of He to continue to cool the propellant. Due to LH_2's lower molecular weight than He, using He injection to cool LH_2 is not practical.

An additional concern with using He injection to cool the propellants is the loss of loading control due to the presence of a large number of He bubbles. The He injection must, therefore, be terminated prior to launch to gain liquid level control and then replenish with ambient temperature liquid as required. Also, the added concern of the He going into solution with the propellant and subsequently coming out may be a problem. If He coolers are necessary to prechill the He prior to injection, the concept simplicity will be compromised.

V. PRELIMINARY CONCEPT SCREENING

The preliminary concept screening will entail weighting the concepts in four areas, conditioning performance, STS impacts, operational impacts and cost, in terms of high, medium or low merit; High being the most desirable and low being the least. The main goal of this section is to identify the concepts that are the most feasible for propellant densification. The top two concepts, on the LH_2 and LO_2 side, will be retained for more detailed analysis in subsequent sections.

A. Screening Criteria

The following categories will be used to screen the concepts identified in section IV.C.

- Densification Performance (Perform): A measure of the concepts ability to condition the propellant in 6 hours to some reference temperature based on its inherit thermodynamic and physical limitations.

- Current System Impact (STS Impact): A relative measure of the degree of impact required on the current system. This impact is measured in terms of physical changes and required testing. These are restricted to nonrecurring impacts.

- Operational Impacts (Ops): A relative measure of the degree of impact on the operations necessary to operate an STS configuration using this concept for propellant densification. These are restricted to recurring impacts.

- Implementation Costs (Cost): A relative measure of the cost associated with the specific concept. This includes all costs associated with the concept.

In tables 9 and 10, each concept is weighted High = 2, Medium = 1, and Low = 0 in each of the four areas. A score of 8 is the maximum and 0 is the minimum. For propellant conditioning inside the ET, He injection is the most viable in terms of the four areas described for the LO_2 side only. None of the options is viable for the LH_2 side.

Table 9. Internal propellant densification.

Concept	Perform.	STS Impact	Ops	Cost	Total Score
He Injection (LH_2)					
– Ambient	0	2	0	1	3
– Cooled	0	2	0	1	3
Heat Exchanger (LH_2)					
– Active	2	0	0	0	2
– Passive	1	0	0	0	1
Low Pressure Sink (LH_2)					
– Natural Convection	2	0	0	1	3
– Forced Convection	2	0	0	0	2
He Injection (LO_2)					
– Ambient	1	2	0	1	4
– Cooled	1	2	0	1	4
Heat Exchanger (LO_2)					
– Active	2	0	0	0	2
– Passive	1	0	0	0	1
Low Pressure Sink (LO_2)					
– Natural Convection	2	0	0	1	3
– Forced Convection	2	0	0	0	2

* High = 2, Medium = 1, Low = 0

Table 10. External propellant densification.

Concept	Perform.	STS Impact	Ops	Cost	Total Score
He Injection (LH_2)					
– Ambient	0	2	0	1	3
– Cooled	0	2	0	1	3
Heat Exchanger (LH_2)	2	2	1	1	6
Low Pressure Sink (LH_2)					
– Natural Convection	2	0	0	1	3
– Forced Convection	2	0	0	0	2
Refrigeration (LH_2)	2	2	1	1	6
Slush (LH_2)	2	0	0	0	2
LHe Cooler (LH_2)	2	2	1	1	6
He Injection (LO_2)					
– Ambient	1	2	0	1	4
– Cooled	1	2	0	1	4
Heat Exchanger (LO_2)	2	2	1	1	6
Low Pressure Sink (LO_2)					
– Natural Convection	2	0	0	1	3
– Forced Convection	2	0	0	0	2
Refrigeration (LO_2)	2	2	0	0	4
Slush (LO_2)	2	0	0	0	2
LN_2 Cooler (LO_2)	2	2	1	1	6

* High = 2, Medium = 1, Low = 0

For propellant conditioning external to the ET, the following concepts are the most appealing:

- LH_2
  - LH_2 Heat exchanger
  - LHe Cooler
  - LHe/LH_2 Refrigerator
- LO_2
  - LN_2 heat exchanger
  - LN_2 Cooler

VI. CONCEPT REFINEMENT

A. Heat Exchanger Design Parameters/Feasibility

As shown in section V, the most feasible densification technique is to perform the conditioning external to the ET. The simplest heat exchanger design, which will give the required performance, is a constant temperature bath heat exchanger. For the LO_2 conditioning, a LN_2 can be used, and, for the LH_2 side, a subcooled LH_2 bath can be used. Figure 8 shows a typical constant temperature bath heat exchanger. The bath can be subcooled through the use of the compressor if lower bath temperatures are required.

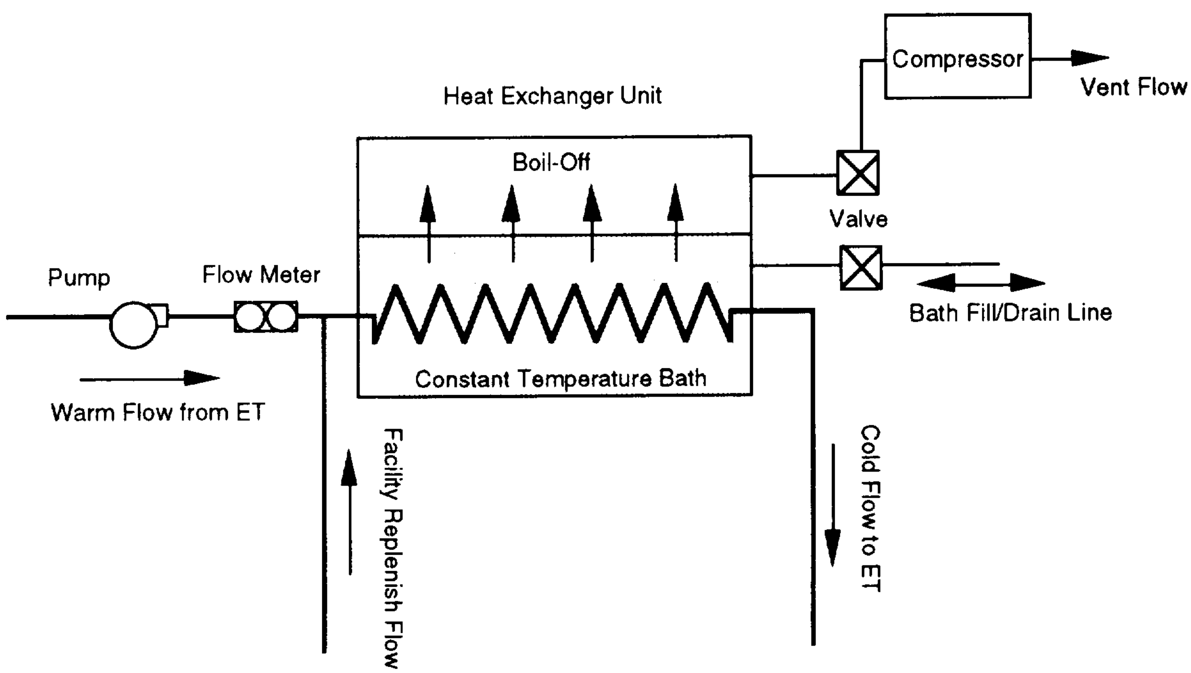


Figure 8. Typical constant temperature bath heat exchanger.

1. <u>LO_2 Conditioning (LN_2 Bath)</u>. LN_2 can be used on the LO_2 side, since the saturation temperature of LN_2 is approximately 24 °R below the LO_2 saturation temperature at the same pressure. Table 11 gives saturation temperatures for various LN_2 pressures.

Table 11. LN_2 saturation temperature versus pressure.

Pressure (lb/in^2 absolute)	Temperature (°R)
5.0	124.6
10.0	133.6
14.7	139.3

For option No. 1, no subcooling of the LN_2 is required; therefore, a LN_2 bath at ambient temperature, 139.3 °R and pressure, 14.7 lb/in^2 absolute can be used.

For option No. 2, the LN_2 subcooling required to achieve the 132 °R conditioning level is approximately 8 lb/in^2 absolute or a temperature of 130 °R.

2. LH_2 Conditioning (Subcooled LH_2 Bath). In order to condition the LH_2, a subcooled LH_2 bath will be required. Table 12 gives saturation temperatures for various LH_2 pressures.

Table 12. LH_2 saturation temperature versus pressure.

Pressure (lb/in^2 absolute)	Temperature (°R)
1.0	25.0
5.0	30.8
10.0	34.3
14.7	36.5

For the LH_2 conditioning, the LH_2 bath must be subcooled to approximately 1.5 lb/in^2 absolute , or a temperature of 26 °R.

B. Conditioning Timeline Analysis

The time required to condition the propellant is critical in the development of a loading and pre-launch STS timeline. The following sections will examine the time required for both the LH_2 and LO_2 as a function of circulation flow rate and the conditioning system efficiency. Both tank conditions were modeled using an energy and mass balance on the system assuming complete mixing in the ET, as shown in figure 9.

An alternate approach to estimating the required mixing time is to assume no mixing at all, i.e., the warm fluid is pushed out of the tank or displaced by the cold fluid. This would demote the shortest conditioning time since only one change of tank mass would be required (fig. 10).

Based on the analysis in section VI.A, two LO_2 temperatures and one LH_2 temperature will be examined. These temperatures are shown in table 12.

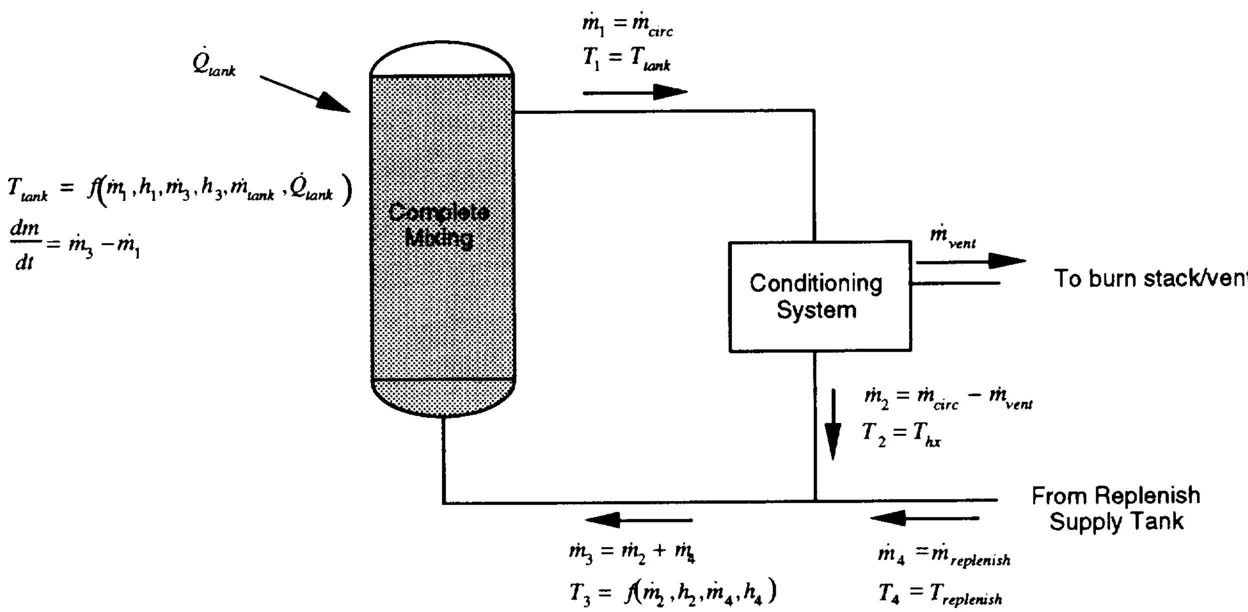


Figure 9. Thermodynamic analysis loop.

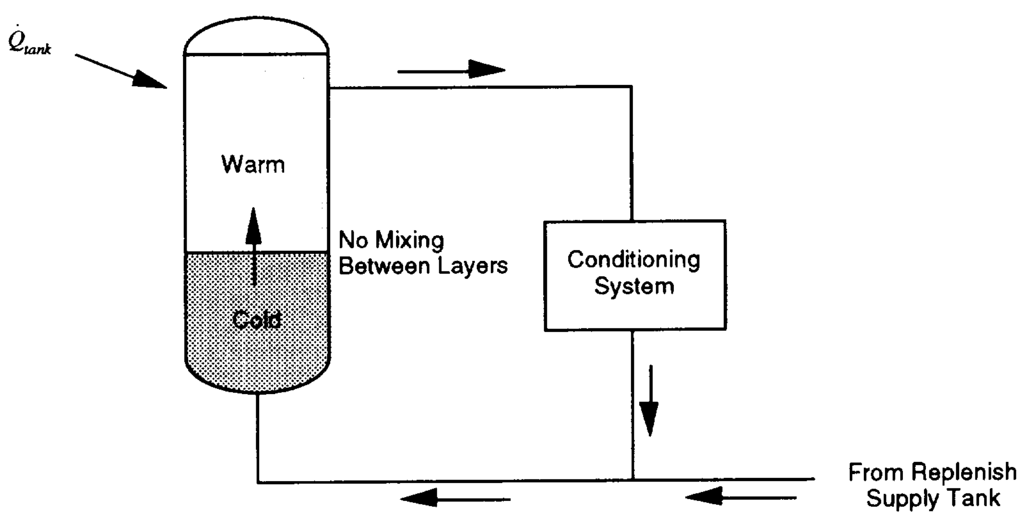


Figure 10. Propellant displacement analysis.

Table 13. LO_2 and LH_2 temperatures.

LO_2 (°R)	LH_2 (°R)
141.5	28.5
132.1	28.5

1. <u>LN_2/LO_2 Cooler (LO_2 Temperature = 141.5 °R)</u>. The initial conditions for the LO_2 cooler conditioning analysis are given in table 14. Circulation flow rate was varied to determine the minimum flow rate that satisfies the densification performance criteria. This system is relatively inexpensive, since a LN_2 ambient bath will provide the temperature difference required. Therefore, no expensive or complicated vacuum systems are required.

Table 14. Typical LN_2/LO_2 cooler input file.

Ifluid (1 = LH_2/2 = LO_2)	= 2
Tank Liquid Volume	= 19,672.00 ft^3
Compressibility Factor	= 1.0
Tank Heat Flux	= 110.00 Btu/s
Initial Liquid Temp	= 164.00 °R
Supply Tank Temp	= 165.00 °R
Circulation Flow Rate	= as shown on plot
Heat Exchanger Exit Temp	= 140.00 °R
Simulation Time	= 30,000.00 s

The predicted temperature versus conditioning time is shown in figure 11.

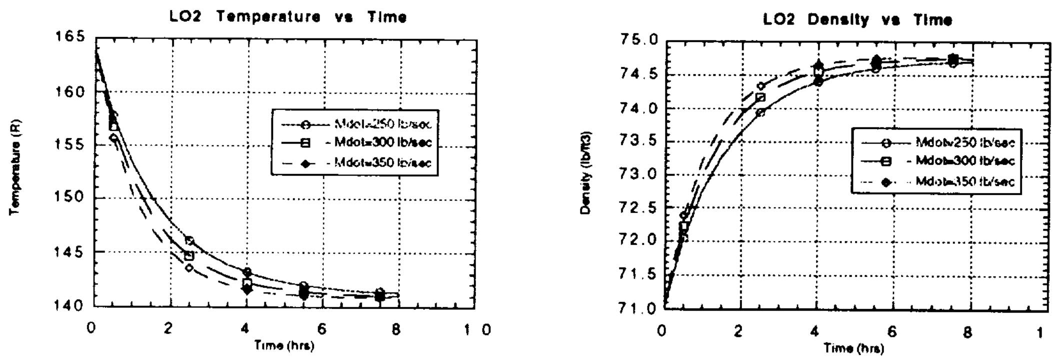


Figure 11. Predicted temperature versus conditioning time.

Based on figure 11, in order to meet the performance criteria of reaching the reference temperature of 141.5 °R in 6 h, a LO_2 flow rate of 300 lb/s will be used.

Based on the alternate analysis, i.e., colder fluid displacing the warmer fluid, the time required for the conditioning will be approximately 1.5 h. A detailed computational fluid dynamics (CFD) code and testing will be required to assess the extent of the mixing taking place. This leaves a range of conditioning time of 1.5 to 5.5 h for the LO_2, option No. 1.

The initial conditions for the LH_2 conditioning analysis are given in table 15. Circulation flow rate was varied to determine the minimum flow rate that satisfies the densification performance criteria. The LH_2 system is similar to the LO_2 system in that it uses a constant temperature bath to reject the heat. The major difference is that the bath must be subcooled LH_2, approximately 1.5 lb/in^2 absolute. This requires a compressor to subcool the LH_2.

Table 15. Typical LH_2 input file.

Ifluid (1 = LH_2/2 = LO_2)	= 1
Tank Liquid Volume	= 53,152.00 ft^3
Compressibility Factor	= 0.995
Tank Heat Flux	= 154.00 Btu/s
Initial Liquid Temp	= 36.44 °R
Supply Tank Temp	= 38.00 °R
Circulation Flow Rate	= as shown on plot
Heat Exchanger Exit Temp	= 27.5 °R
Simulation Time	= 30,000.00 s

The predicted temperature versus conditioning time for various flow rates is shown in figure 12.

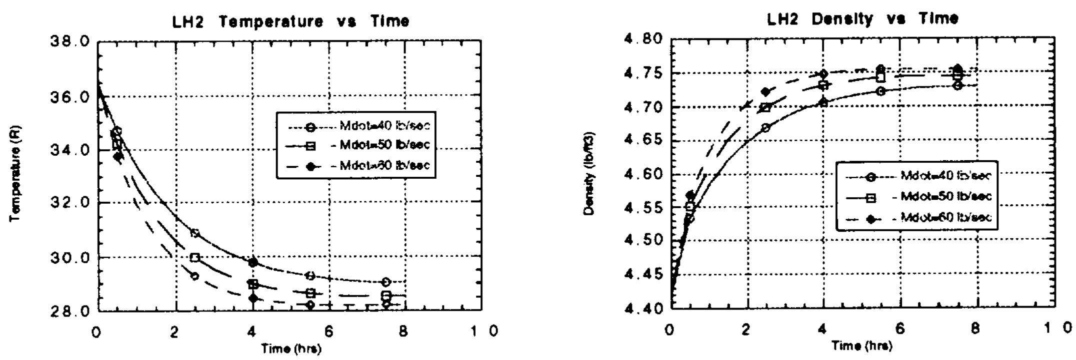


Figure 12. Predicted temperature versus conditioning time at various flow rates.

Based on figure 12, in order to meet the performance criteria of reaching the reference temperature of 28.5 °R in 6 h, a LH_2 flow rate of 50 lb/s will be used.

Based on the alternate analysis, i.e., colder fluid displacing the warm fluid, the time required for the conditioning will be approximately 1.5 h. A detailed CFD code and testing will be required to assess the extent of the mixing taking place. This leaves a range of conditioning time of 1.5 to 5.5 h for the LH_2.

2. LO_2/LN_2 Heat Exchanger (LO_2 Temperature = 132 °R). The initial conditions for the LO_2 heat exchanger conditioning analysis is given in table 16. Circulation flow rate was varied to determine the minimum flow rate that satisfies the densification performance criteria.

Table 16. Typical LN_2/LO_2 heat exchanger input file.

Ifluid (1 = LH_2/2 = LO_2)	= 2
Tank Liquid Volume	= 19,672.00 ft^3
Compressibility Factor	= 1.0
Tank Heat Flux	= 110.00 Btu/s
Initial Liquid Temp	= 164.00 °R
Supply Tank Temp	= 165.00 °R
Circulation Flow Rate	= as shown on plot
Heat Exchanger Exit Temp	= 131.0 °R
Simulation Time	= 30,000.00 s

The predicted temperature versus conditioning time for various flow rates is shown in figure 13.

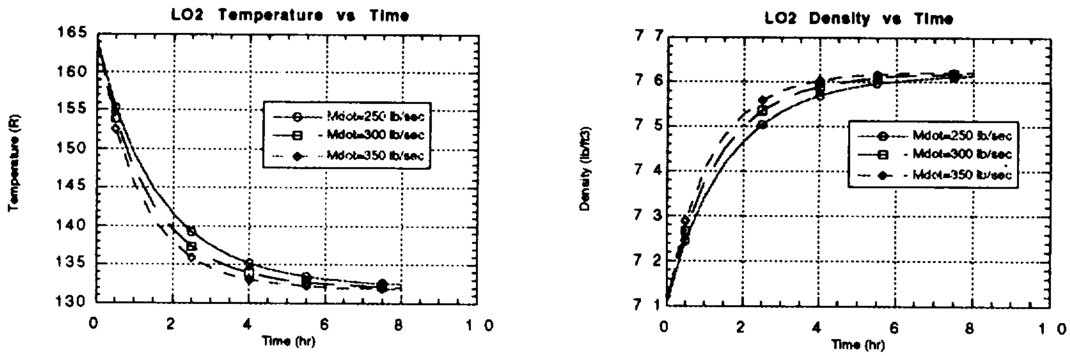


Figure 13. Predicted temperature versus conditioning time.

Based on figure 13, in order to meet the performance criteria of reaching the reference temperature of 130 °R in 6 h, a LO_2 flow rate of 350 lb/s (2210 gal/min at nominal conditions) will be used.

C. Propellant Temperature Uncertainty Analysis

Figure 14 shows the effect of the uncertainty in the liquid temperature of LO_2 and LH_2 on the uncertainty of the onboard propellant mass. As shown, large uncertainties in temperature produce smaller uncertainties in mass.

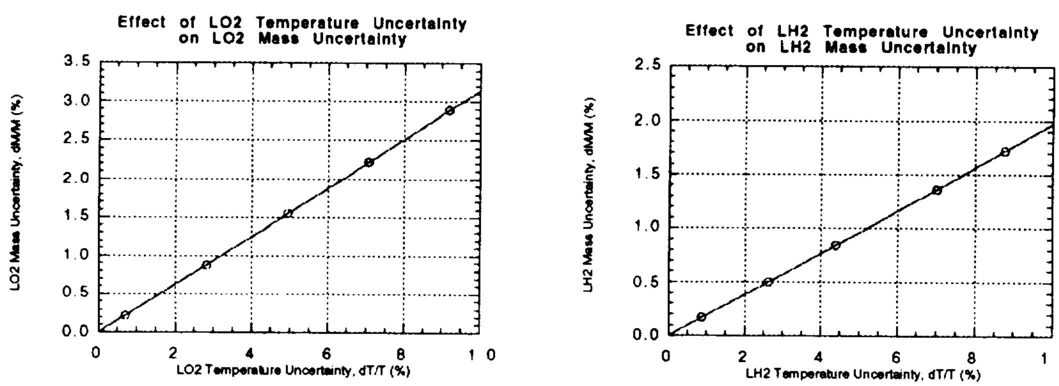


Figure 14. Effects of uncertainty.

D. Overall System Energy Balance

Given the preliminary nature of the overall designs, this study looked solely into the energy balance or heat transfer of the piping network necessary to supply the appropriate fluid to/from the heat exchanger. To perform this analysis, a System Improved Numerical Differencing Analyzer (SINDA) model was developed primarily from the analysis shown is section VI.B, with the addition of terms and equations to calculate heat transfer through the pipe network.

1. Assumptions. There were many assumptions made and boundary conditions had to be set in order to begin this analysis. To be consistent with previous analyses, the flow rates used for the LO_2 and

the LH_2 were set to 250 and 40 lbm/s and heat exchanger outlet temperatures (fluid outlet temperature) were set at 139 °R and 27 °R for LO_2 and LH_2, respectively. The approximate 600/200 ft of pipe was modeled with an inner diameter of about 8.5 in and outer diameter of about 10.25 in. The entire pipe network was modeled as a vacuum-jacketed system which consists of two pipes containing an evacuated space between them. The inner pipe was SS 304 with a multilayer insulation on its outer surface, while the surface of the outer SS 316L pipe was exposed to ambient outdoor conditions of 100 °F. Other parameters used were identical to those used in section VI.B.

2. Equations. The main emphasis in a vacuum-jacketed pipe is heat transfer via radiation. We assumed steady, uniform flow and a perfect vacuum space between the two pipes, thus eliminating any connective or conductive modes of heat transfer. It was first necessary to determine the effective emissivity of the whole pipe and to use that to determine the lost heat:

$$Q_{rad} = \sigma F_e A F\left(T_{in}^4 - T_{out}^4\right) ,$$

where

$$Q_{rad} = \text{heat due to radiation} ,$$

$$A = \text{surface area (ft}^2\text{)} ,$$

$$\sigma = \text{Stefan-Boltzman constant} = 0.1713\text{E-8 Btu/ft}^2\text{-°R}^4 ,$$

$$F = \text{Form Factor to space} = 1.0 ,$$

$$T_{in}^4 = \text{fluid or pipe temperature (°R)} ,$$

$$T_{out}^4 = \text{outside temperature (°R)} ,$$

$$F_e = \text{effective emissivity} ,$$

where

$$F_e = \left[\frac{1}{\varepsilon_1} + \frac{A_1}{A_2}\left(\frac{1}{\varepsilon_2} - 1\right)\right]^{-1} ,$$

$$\frac{A_1}{A_2} = \text{surface area inside/surface area outside} ,$$

$$\varepsilon_1 = \text{inside emissivity} = 0.04 ,$$

$$\varepsilon_2 = \text{outside emissivity} = 0.85 .$$

These equations were placed in the model and added to energy balance at the tank. If one were to calculate a steady-state (nontimė-dependent) heat loss due to radiation, the figures would be approximately 11,000 Btu/h for LO_2 and 4,000 Btu/h for LH_2. Compared to the 300,000 Btu/h plus loss through the tank insulation (see Mission Management Center (MMC) ET Thermal Data Book), these line losses are negligible. Figures 15 and 16 show the system used in this analysis.

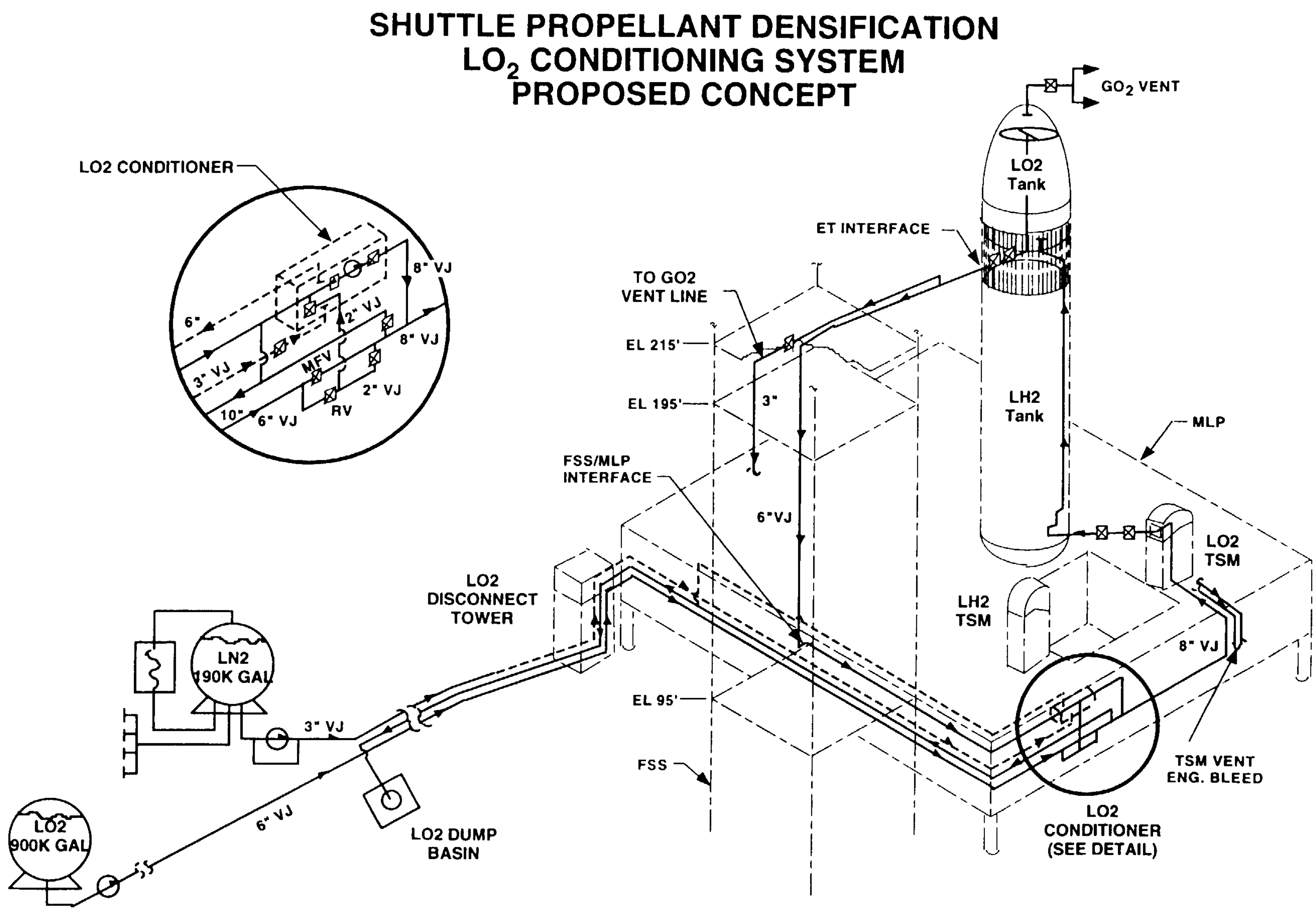


Figure 15. KSC LO_2 system configuration.

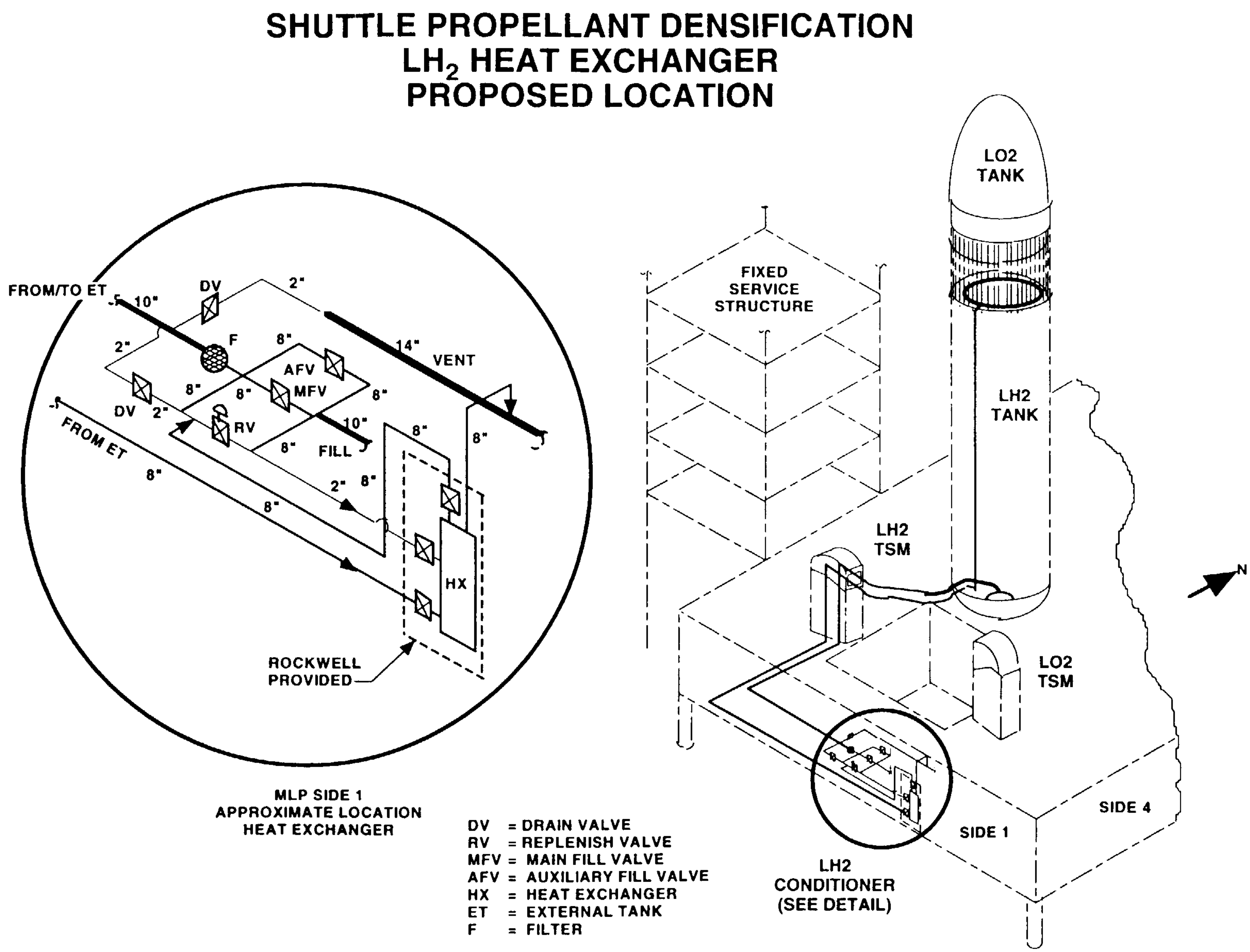


Figure 16. KSC LH_2 system configuration.

VII. STS SYSTEMS IMPACTS

A. Fluid System Integration

In order to adequately condition the propellants, they must be circulated into and out of the ET through an external conditioning system or heat exchanger to provide the required temperature drop. Figures 17 and 18 provide a representative fluid loop within the STS system.

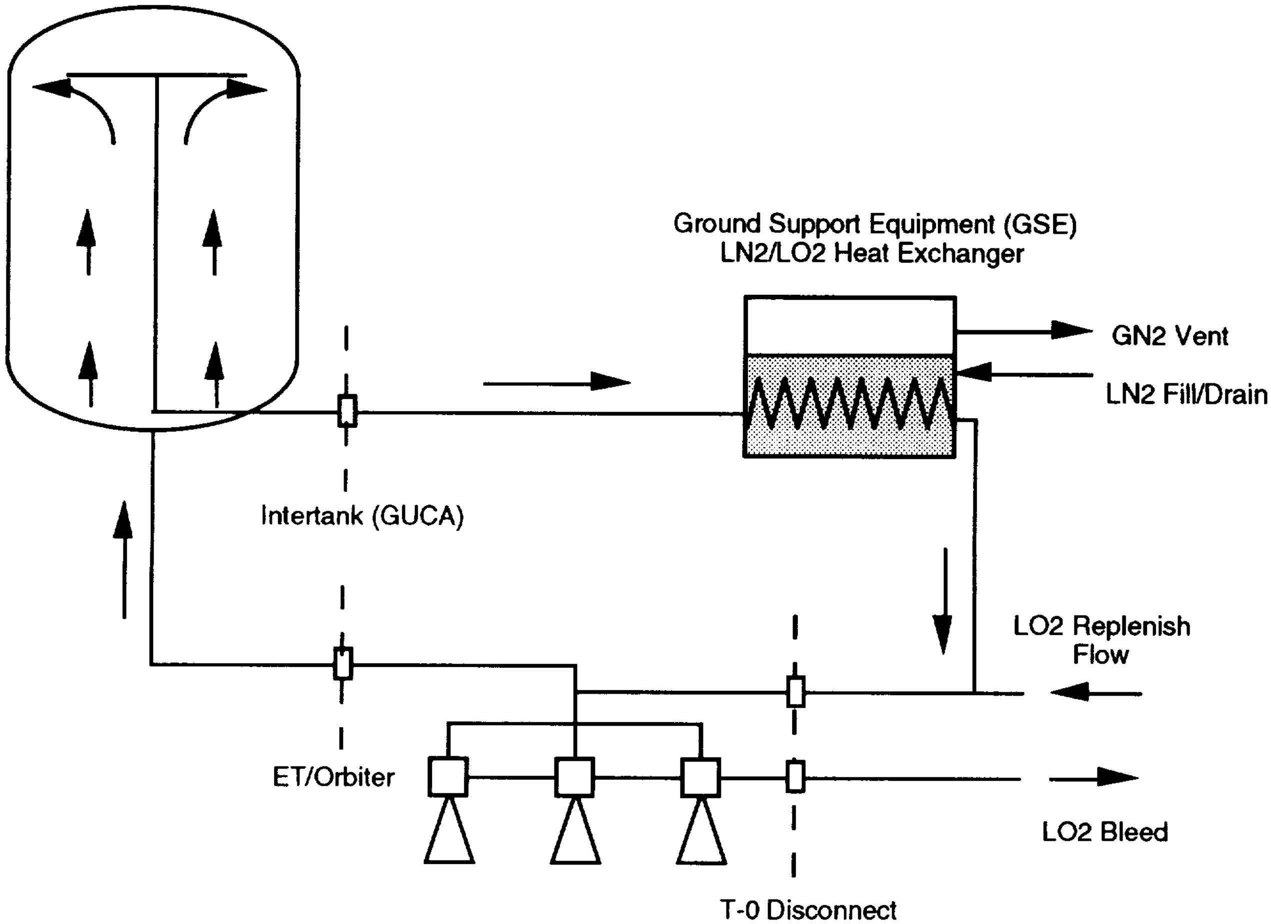


Figure 17. External conditioning system.

1. Description. As shown in figure 17, the conditioning system can be integrated within the current LO_2 fill system. The LO_2 will be circulated out of the tank, passed through a conditioning system to lower its temperature, and injected back into the tank. This loop will continue until the desired bulk temperature is reached. Internal to the ET will be a manifold system which will remove the fluid near the liquid surface and route it out of the tank through the intertank.

2. Hardware Modifications.
   (a) An ET LO_2 internal manifold system
   (b) LO_2 tank penetration near LO_2 feedline
   (c) Additional disconnect at the ground umbilical carrier assembly (GUCA)
   (d) Liquid level sensors for ±100 percent.

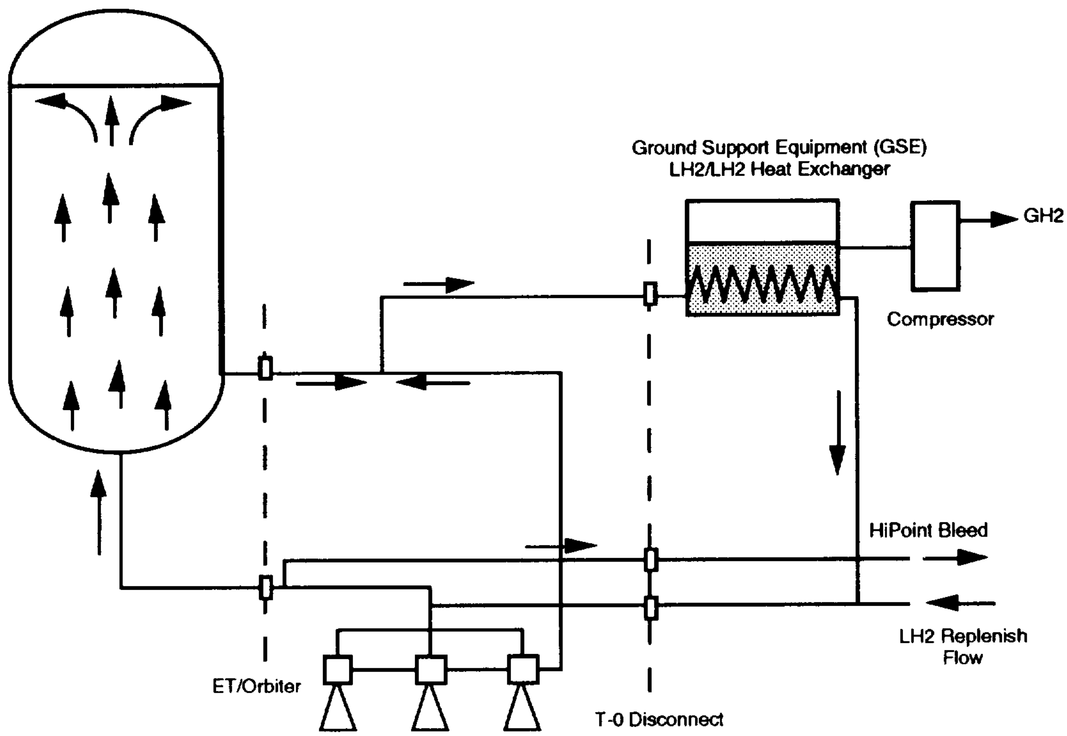


Figure 18. External conditioning system.

3. Description. As shown in figure 18, the conditioning system can be integrated within the current LH_2 fill system. As with the LO_2, the LH_2 will be circulated out of the tank, passed through a conditioning system to lower its temperature, and injected back into the tank. This loop will continue until the desired bulk temperature is reached. Internal to the ET will be a manifold system which will remove the fluid near the liquid surface and route it out of the tank through the intertank.

4. Hardware Modifications.
   (a) An ET LH_2 internal manifold system
   (b) Additional line within the orbiter boat tail
   (c) Additional disconnect at the T–0 plate
   (d) Liquid level sensors for ±100 percent.

B. MPS Impact

Work on a steady-state model using denser LH_2 and LO_2 propellant to determine the minimum ullage pressure necessary to satisfy NPSP requirements for the SSME was performed. The model was built using data from Rockwell, the principles of basic fluids, and the EXCEL™ spreadsheet format to calculate the NPSP for each of the three engines of the shuttle.

Two options were considered for propellant densification: LO_2 temperatures at 141.5 and 132.1 °R. The LH_2 temperature remained constant at 28.5 °R for both LO_2 temperature options. The mixture ratio was 5.93 and 6.05, based on the temperatures set in options 1 and 2, respectively. Thus, in spite of the constant temperature of 28.5 °R for LH_2, two conditions would be generated for LH_2, based on the value of the mixture ratio. The guideline set for this model development was that the minimum NPSP for each of the shuttle engines would be no less than 6 lb/in^2 absolute for LH_2. The LH_2 value of 6 lb/in^2

absolute is also being used for the current shuttle system. An ullage pressure was chosen arbitrarily to meet this minimum NPSP requirement. LO_2 actually has a minimum and maximum range of NPSP, which is currently being determined. However, for our model development, we again set the minimum NPSP at 6 lb/in^2 absolute. It was determined that flow control valves would be used for both LO_2 and LH_2. Therefore, a "press" model was deemed unnecessary for the LO_2 case. A "press" model would have been necessary if a fixed orifice application were used for LO_2. In that particular situation, results from the "press" model would be input into the spread sheet to assure that the NPSP requirements were met throughout the flight.

Results of this model development include four figures (figs. 19, 20, 21, and 22) of NPSP versus time generated for each of the conditions stated above. The general trends obtained from the figures are very similar to what is exhibited in NPSP versus time for the current shuttle system. This similarity in feedline characteristics shows that densifying the propellant should therefore be a feasible concept to apply in this respect, since feedline performance does not appear to be modified by the use of denser propellant. The EXCEL™ spreadsheet data which was used to compile the needed information and LH_2 and LO_2 tanking table data for use in the model development may all be found in the appendix. The EXCEL™ data also includes tank bottom pressures calculated for all of the above conditions.

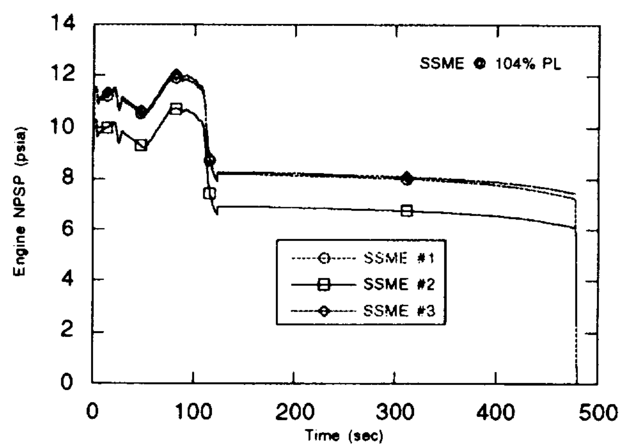


Figure 19. LH_2 NPSP for LO_2 at 132.2 °R.

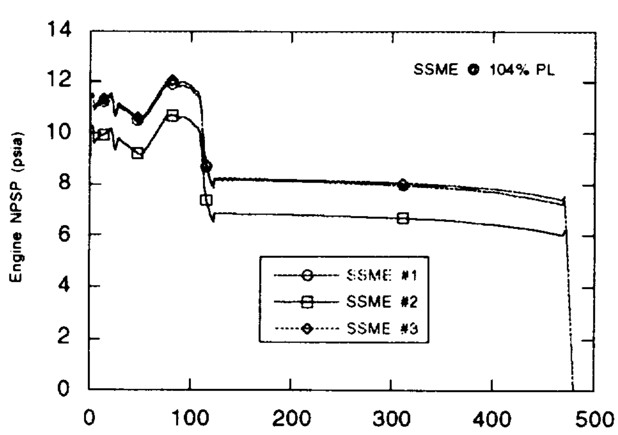


Figure 20. LH_2 NPSP for LO_2 at 141.5 °R.

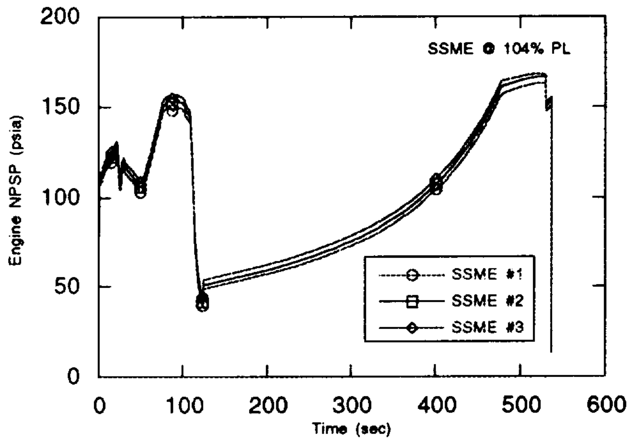


Figure 21. LO_2 NPSP at 132.1 °R.

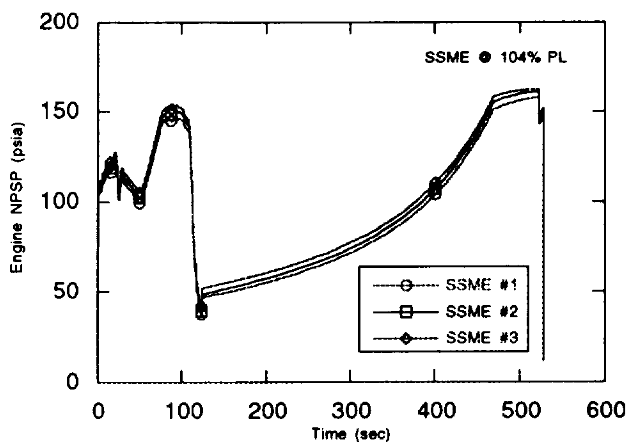


Figure 22. LO_2 NPSP at 141.5 °R.

C. Engine (SSME) Impact

The use of higher-density propellants will have an impact on the SSME start and operation due to their lower temperature. This impact will be assessed for LH_2/LO_2 densification and LH_2 only densification.

1. LH_2/LO_2 Conditioning. In order to maximize the total mass of propellant that may be added to the STS, operating at a higher mixture may be required. The following analysis gives the engine impact due to the higher mixture ratio shown in section IV.A.1.

2. LH_2 Only Conditioning. In order to obtain a propellant mass gain by conditioning the LH_2 only, the engine mixture ratio must be lowered to accommodate the increased LH_2 mass. Analysis was performed to identify the minimum mixture ratio that the engine can tolerate without violating high-pressure pump turbine temperatures or current redlines.

(a) SSME Phase II. Table 17 is an analysis of the current SSME phase II configuration. In order to find the minimum mixture ratio, a set of gains per percent mixture ratio variation were obtained from the Liquid Engine Branch at the MSFC's Propulsion Laboratory. The constraint imposed on this analysis was that the high pressure fuel turbine (HPFT) discharge temperature does not exceed 30 °R for 104-percent power level and that the high pressure oxygen turbine (HPOT) discharge temperature does not violate the low limit redline of 720 °R throughout the throttle range.

Table 17. SSME parameter sensitivity to mixture ratio.

Engine Sensitivity To Mixture Ratio
(Current Engine Configuration - Phase II)

Del HPFT =	30 (°R)	Turbine Temp Red Lines	
Percent MR Decrease =	6.61 (Percent)		
		HPFT R.L. =	1900 (°R) High
		HPOT R.L. =	720 (°R) Low

Current SSME (104 percent)

Engine Parameter	Baseline	dy/y per Percent MR	Del. Param.	Parameter
Specific Impulse =	452.862 (s)	0.05	1.566	454.43
Thrust =	488,369 (lbf)	–0.13	–4,276.918	484,092.08
Mixture Ratio =	6.011	-1.00	–0.397	5.61
Fuel Flow Rate =	154.15 (lbm/s)	0.65	6.660	160.81
Lox Flow Rate =	926.593 (lbm/s)	–0.33	–20.416	906.18
Total Flow Rate =	1,080.743 (lbm/s)	–0.18	–13.073	1,067.67
HPFT Disch Temp =	1,693.67 (°R)	0.27	30.000	1,723.67
HPOT Disch Temp =	1,335.35 (°R)	-2.69	–237.684	1,097.67
FPOV Position =	80.51 (percent)	1.05	5.600	86.11
OPOV Position =	66.43 (percent)	–0.59	–2.583	63.85
LPFP Speed =	15,804.4 (r/min)	0.20	204.837	16,009.24
HPFP Speed =	34,936.3 (r/min)	0.27	633.921	35,570.22
HPFP Tot Ds Press =	6,348.27 (lb/in^2 absolute)	0.35	148.101	6,496.37

Table 17. SSME parameter sensitivity to mixture ratio (continued).

Current SSME (65 percent)				
Engine Parameter	Baseline	dy/y per Percent MR	Del. Param.	Parameter
Specific Impulse =	451.486 (s)	0.05	1.561	453.05
Thrust =	303,228 (lbf)	–0.13	–2,655.536	300,572.46
Mixture Ratio =	6.011	-1.00	–0.397	5.61
Fuel Flow Rate =	96.0239 (lbm/s)	0.65	4.148	100.17
Lox Flow Rate =	577.2 (lbm/s)	–0.33	–12.718	564.48
Total Flow Rate =	673.2239 (lbm/s)	–0.18	–8.144	665.08
HPFT Disch Temp =	1,484.85 (°R)	0.27	26.301	1,511.15
HPOT Disch Temp =	995.988 (°R)	-2.69	–177.280	818.71
FPOV Position =	68.034 (percent)	1.05	4.732	72.77
OPOV Position =	53.757 (percent)	–0.59	–2.090	51.67
LPFP Speed =	13,260.8 (r/min)	0.20	171.870	13,432.67
HPFP Speed =	27,029.4 (r/min)	0.27	490.450	27,519.85
HPFP Tot Ds Press =	3,926 (lb/in^2 absolute)	0.35	91.591	4,017.59

Data Obtained from the Space Shuttle Main Engine Phase II Nominal Engine Power Balance & Operating Maximums Handbook, Jan. 31, 1990.

D. Tank Structural Impact

Due to the increased propellant mass, both LO_2 and LH_2, and the required circulation manifold system in the tanks, the super light weight tank (SLWT) or the current light weight tank (LWT) must be strengthened and will require additional hardware components to support propellant densification. Martin Marietta Corporation, the current ET contractor has assessed the impact of densification on the tank system. Figures 23 and 24 show the required manifold system routing and additional hardware required in the SLWT design.

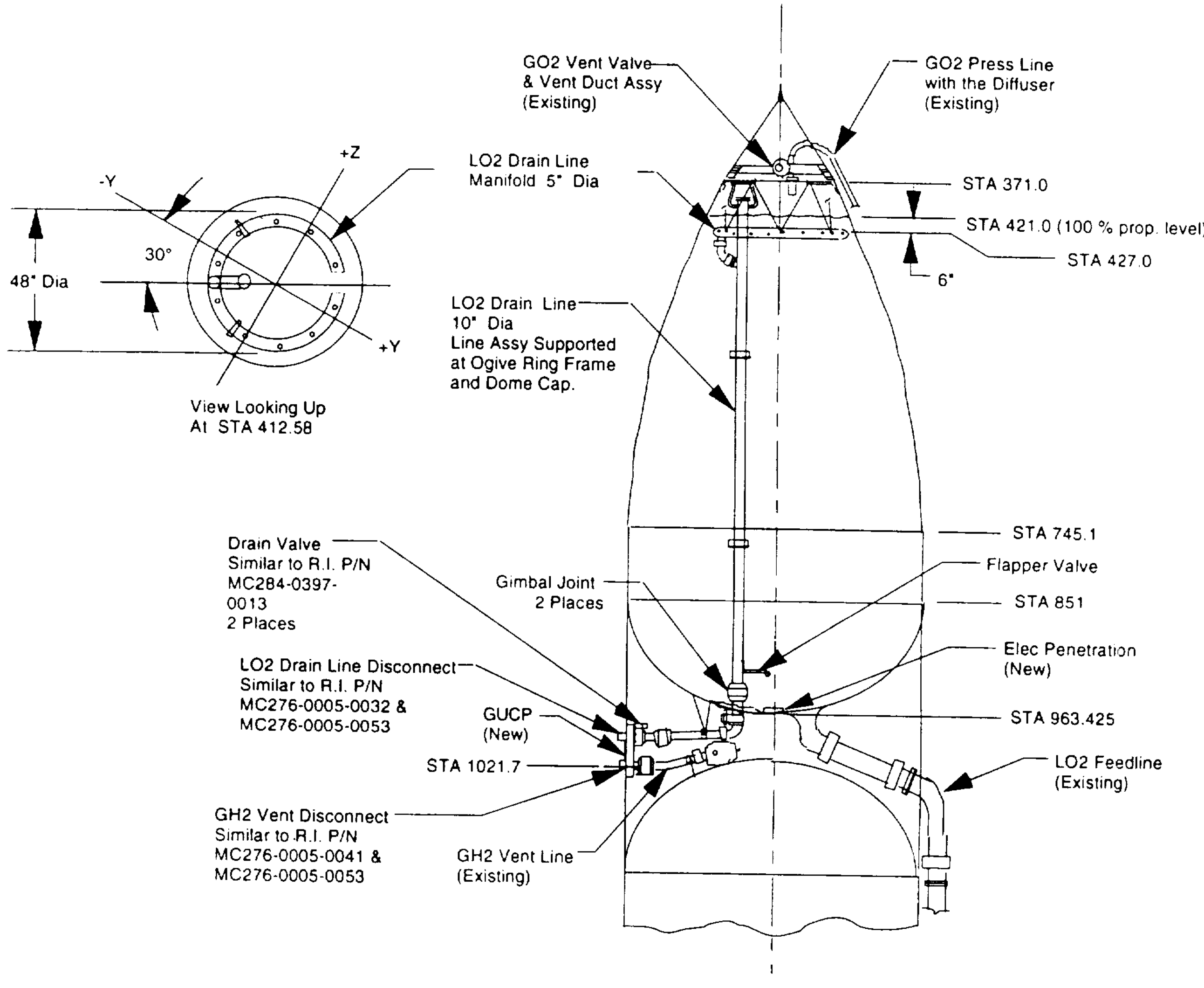


Figure 23. SLWT LO_2 tank design.

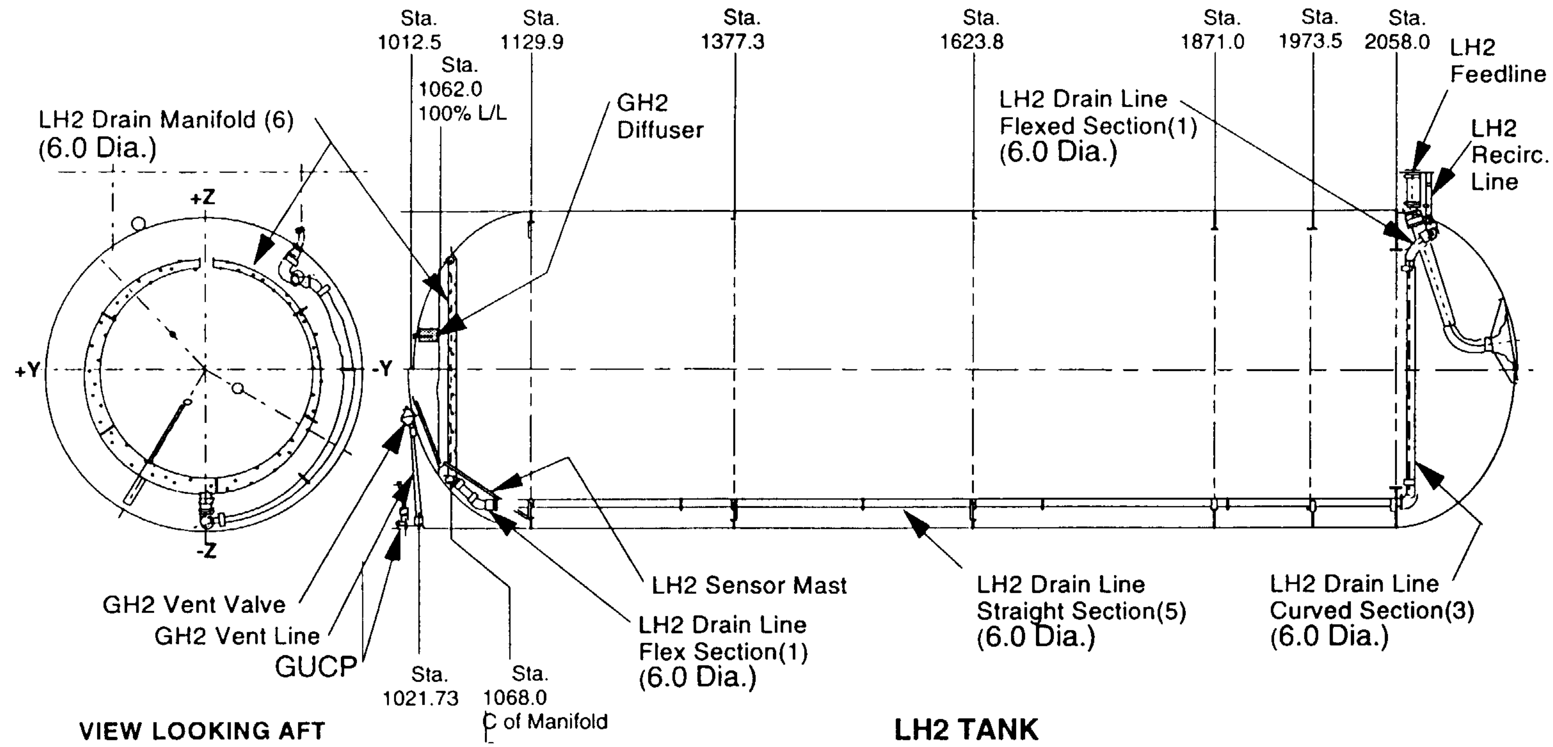


Figure 24. SLWT LH_2 tank design.

Table 18 summarizes the estimated weight and structural impacts to the SLWT due to densification.

Table 18. Major structural impacts.

Item	Est. Wt (lb)	Growth (lb)	Total (lb)
LO_2 Structure			
• Aft Dome	77.0		
• Ogive	128.0		
	205.0	10.0	215.0
LH_2 Structure			
• Barrel Sections	220.0	10.0	230.0
Intertank Structure			
• Thrust Panels	289.0		
• Skin/stringer Panels	86.0		
	375.0	19.0	394.0
Total Structural Impact			839.0

Table 19 summarizes the estimated weight of the LO_2 configuration, i.e., additional hardware required to support densification.

Table 19. LO_2 tank configuration.

Item	Qty	Est. Wt. (lb)	Growth (lb)	Total (lb)
Modify Sta 372 frame		0.0	0.0	0.0
Modify LO_2 aft dome cap		0.0	0.0	0.0
Modify aft dome gore		20.0	3.0	23.0
New drain line supt.		20.0	3.0	23.0
New drain line bracket		10.0	1.5	11.5
New manifold brackets	12	30.0	4.5	34.5
Down comer line - 10 in. dia.	1	218.7	32.8	251.5
Toroidal manifold - 6 in	1	19.2	2.9	22.1
Flex line assy	1	26.6	0.0	26.6
Gimbal joint - 10 in	2	40.0	6.0	46.0
Drain valves	2	80.0	0.0	80.0
Drain line	1	44.0	0.0	44.0
Drain disconnect	1	15.0	0.0	15.0
Drain disconnect - non flight	1	0.0	0.0	0.0
TPS increase - aft dome		41.0	0.0	41.0
New GUCP - flight		30.4	0.0	30.4
Two stage vent valve		10.0	1.5	11.5
GUCP structure impact		10.0	1.5	11.5
Electrical hardware		8.2	1.2	9.4
Wire/sensors/feedthrough		65.3	9.8	75.1
Total Weight (lb)				756.0

Table 20 summarizes the estimated weight of the LH_2 configuration, i.e., additional hardware required to support densification.

Table 20. LH_2 tank configuration.

Item	Qty	Est. Wt. (lb)	Growth (lb)	Total (lb)
Fwd dome manifold mts		5.0	0.8	5.8
Mounting brackets	24	15.0	2.3	17.3
Frame mounting provisions		12.0	1.8	13.8
Sta 1871 mounting fitting		20.0	3.0	23.0
Sta 2058 hole and doublers		0.0	0.0	0.0
Upper drain line assy	1	21.0	0.0	21.0
Lower drain line assy	1	14.0	0.0	14.0
6-in drain manifold	1	65.6	9.8	75.4
Two stage vent valve		10.0	1.5	11.5
TPS increase-LH_2 fwd dome		41.0	0.0	41.0
Electrical-sensors/wires		84.9	12.7	97.6
Drain reposition line		48.9	7.3	56.3
Down comer line - 6 in	1	153.7	23.1	176.7
Total Weight (lb)				553.0

The total weight impact due to densification is given in table 21.

Table 21. SLWT weight summary.

Item	Total Weight (lb)
LO_2 Tank	971.0
LH_2 Tank	783.0
Intertank	394.0
Total	2,148.0

VIII. PAYLOAD BENEFIT

To determine the performance improvement derived from propellant densification, trajectory analysis was done using MSFC shuttle models. The trajectories were flown using the new propellant inventories, structural and densification subsystem mass. To take full advantage of the changes in propellant loading, the engine mixture ratio was adjusted for each option. Therefore, the new runs also included changes to the SSME thrust and Isp due to the changes in mixture ratio. The trajectories were all flown according to the ground rules set forth in table 1. The performance improvement will be measured in the form of changes in orbiter weight at MECO.

The nominal MECO weight from which all delta payload values will be taken is given in table 22.

Table 22. Nominal payload.

Description	Total Prop	Δ Prop	MECO Wt.
Nominal Mission (104 percent throttle)	1,613,777	0	324,430
Nominal Mission (106 percent throttle)	1,613,777	0	324,817

A. LO_2/LH_2 Conditioning

Table 23 shows the performance gains due to conditioning both propellants. The LH_2 temperature for both options is 28.5 °R.

Table 23. LO_2 and LH_2 densification gross MECO weight gain.

Description	Total Prop	Δ Prop	MECO Wt.	Δ MECO Wt.
LO_2 at 141.5 °R (104 percent throttle)	1,699,781	86,004	330,521	6,091
LO_2at 132.1 °R (104 percent throttle)	1,729,783	116,006	331,271	6,841
LO_2 at 141.5 °R (106 percent throttle)	1,699,781	86,004	331,322	6,505
LO_2 at 132.1 °R (106 percent throttle)	1,729,783	116,006	332,141	7,324

Figure 25 gives the total propellant increase versus gross payload gain, and table 24 gives the LO_2/LH_2 net payload gains.

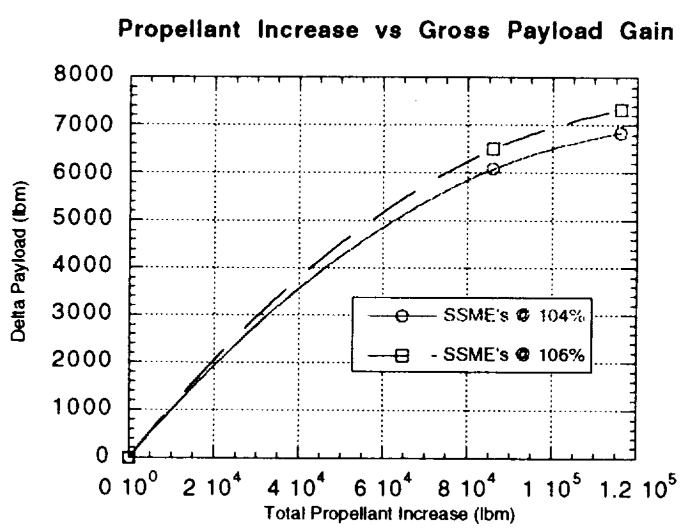


Figure 25. Total propellant increase versus gross payload gain.

Table 24. LO_2/LH_2 net payload gain.

Description	Total Prop	Δ Prop	Δ MECO Wt.
LO_2 at 141.5 °R (104 percent throttle)	1,699,781	86,004	6,091
LO_2 at 132.1 °R (104 percent throttle)	1,729,783	116,006	6,841
LO_2 at 141.5 °R (106 percent throttle)	1,699,781	86,004	6,505
LO_2 at 132.1 °R (106 percent throttle)	1,729,783	116,006	7,324

B. LH_2 Only Conditioning

Table 25 shows the performance gains derived from densifying only the LH_2 based on density values given in section IV.A and engine parameters given in section VII.C.

Table 25. LH_2 only densification gross MECO weight gain.

Description	Total Prop	Δ Prop	MECO Wt.	Δ MECO Wt.
LH_2 Only at 28.5 °R (104 percent throttle)	1,629,774	15,997	325,618	1,188
LH_2 Only at 28.5 °R (106 percent throttle)	1,629,774	15,997	326,120	1,303

IX. SYSTEM TEST/VERIFICATION

Test and verification requirements for the propellant densification systems and affected shuttle and the facility systems are presented in table 26. It should be noted that this test/verification plan does not require MPTA type testing. More detailed information on each item is presented in appendix B, System Test/Verification Detail Analysis.

X. TECHNICAL ISSUES

This section lists some of the technical issues that were raised during this study. This list is not considered complete and should be updated as other issues are raised.

(1) Density Assurance: In order to obtain orbit with the specified payload, the propellant mass must be predictable and known. To ensure adequate propellant mass, the liquid temperature must be known throughout the tank by using temperature sensors or the temperature must be predictable through analysis and/or test.

(2) Liquid Level Control: The existing data base of liquid level as a function of percent wet of the sensor is lost when cryogen is densified. An alternate technique for liquid level control must be developed, tested, and certified.

Table 26. STS propellant densification test/verification matrix.

Item No.	Item	Analysis	Bench Test	Subscale Test	Full Scale Test (1)	KSC Loading Test (2)	KSC FRF	Remarks
1.	GSE Component Performance	X	X					LO_2 and LH_2 densification system components testing.
2.	Propellant Recirculation Line Disconnects	X	X					Densified LO_2 recirc. line disconnect thru intertank. Densified LH_2 recirc. line disconnect thru LH_2 T-0 umbilical.
3.	GSE Propellant Conditioning System Performance	X		X	X	X(P)		Systems testing of Item No. 1 components. Closed-loop control of recirc. flowrates, tank propellant temps, etc.
4.	Liquid Level Sensor Characterization	X	X	X				Liquid surface change due to subcooled propellant and near-zero boiloff. New percent wet algorithms and/or sensor arrangement.
5.	LH_2 Pre-Pressurization Performance	X		X		X(S)		Increased ullage pressure decay due to subcooled LH_2.
6.	LO_2 Pre-Pressurization Performance	X		X		X(S)		Increased ullage pressure decay due to subcooled LO_2.
7.	LH_2 Flight Pressurization Performance	X		X				Ring manifold (heat sink) will be uncovered early in flight. Mainstage LH_2 ullage pressure control band may be lowered with densified LH_2.
8.	LO_2 Flight Pressurization Performance	X		X				LO_2 ullage slump may be worse due to subcooling and uncovered ring manifold (heat sink). Will return to active GOX FCV system.
9.	KSC LH_2 Procedures	X		X		X(P)		Loadings, stop flows, reverts, drains, contingency procedures, etc.
10.	KSC LO_2 Procedures	X		X		X(P)		Loadings, stop flows, reverts, drains, contingency procedures, etc.
11.	LH_2 Tank Stratification Characterization	X		X	X			Good mixing is required for temperature/density assurance.
12.	LO_2 Tank Stratification Characterization	X		X	X			Good mixing is required for temperature/density assurance.
13.	LH_2 Engine Recirculation Performance	X				X(S)		LH_2 recirc. system performance should not be changed unless engine temp or hi-point bleedrate problems are indicated.
14.	LO_2 Bleed Performance	X		X				Verify through analysis and single engine testing. Goal is to minimize bleed rate and thus drainback mass after repl. term.
15.	Orbiter LH_2 Feed and Fill/Drain System Performance	X	X or ->	X				Analyze feed system pressure loss changes. Test valve performance with densified LH_2.
16.	Orbiter LO_2 Feed and Fill/Drain System Performance	X	X or ->	X				Analyze feed system pressure loss changes. Test valve performance with densified LO_2.

Table 26. STS propellant densification test/verification matrix (continued).

17.	POGO System Performance	X			X			Engine mounted POGO accumulator. Verify performance through analysis and single engine testing.
18.	Nose cone & Intertank Purge Performance Verification	X				X(S)		Propellant densification recirc. lines and colder vent lines may require changes in GN_2 purge gas pressures & temps.
19.	SSME Start/Shut Down Transient Performance	X						Engine start and shutdown at lower LO_2 and LH_2 temperatures.
20.	SSME Mainstage Operation	X		X				Engine operation at lower temperatures, higher densities and higher inlet pressures.
21.	LO_2 Ullage Pressure Slump Verification	X		X				Ullage pressure slump is extremely important item to verify due to potential for loss of vehicle/crew if LO_2 tank buckles.
22.	Systems Integration Verification	X					X	Propellant densification systems, return to active LO_2 press control, change of LO_2 and LH_2 mainstage ullage press control bands, Block II SSME's, SLWT, Orbiter mods, cluster performance, twang verification, etc.

Notes:
(1) Stennis Space Center
(2) P = Primary test requirement, S = Secondary test requirement

(3) Holds/Reverts/Aborts: Liquid temperature control and/or liquid level control is required during extended holds, stop flows and reverts to prevent the venting of liquid. Propellant conditioning GSE must be able to maintain the liquid temperature at nominal levels during extended holds. For holds/stop flows after conditioning is terminated, the ability to reinitiate conditioning or drain back to an appropriate level is required.

(4) Dynamic Response Due to Conditioning Flow Rate: The MPS system, both existing and modified/added components, must be capable of withstanding dynamic regimes and environments due to the conditioning flow rate and densified liquid temperature. MPS system must be tested and certified at the densified conditions.

(5) LO_2 Ullage Slump: LO_2 ullage slump at lift off must be reassessed due to the colder liquid conditions and added heat sink due to the manifolding system required in the LO_2 tank.

(6) Loss of Propellant Conditioning: Ability to safe the system after GSE stop flow or failure during propellant densification operations.

(7) Loss of Tank Pressurization: During densification operations both LO_2 and LH_2 tank must be pressurized to ensure structural stability and to prevent contamination from entering the tank. Assurances must be provided to prevent loss of tank pressurization during densification or provide for safing procedures in case of failure.

XI. CONCLUSIONS

Propellant densification for the space shuttle or the STS is possible, and a payload gain can be realized. In this study, liquid subcooling of 28.5 °R is required for LH_2 and 132.1 and 141.5 °R for LO_2. The nominal liquid temperatures are 36.4 °R and 164 °R for the LH_2 and LO_2, respectively.

An important result of this study is that the most feasible method for conditioning the propellant was determined to be external to the tanks by using GSE located on the MLP. The LH_2 and LO_2 is circulated from the ET to heat exchangers located on the MLP which subcool the propellant prior to flowing back into the tanks. Both heat exchangers can consist of constant temperature baths. For the LH_2, a subcooled hydrogen bath is used, and for the LO_2, a nitrogen bath is used. These are considered the simplest heat exchangers that can be used. In this study, three cases were examined: (1) LH_2 at 28.5 °R and LO_2 at 132.1 °R, (2) LH_2 at 28.5 °R and LO_2 at 141.5 °R and (3) LH_2 at 28.5 °R only. For case (1), the nitrogen bath must be also subcooled below ambient to achieve the lower liquid temperature.

It was shown that for case (1) with the SSME's throttled to 104 percent, a payload increase of 6,841 lb can be obtained, and with the SSME's throttled to 106 percent, a payload increase of 7,324 lb can be obtained. It should be noted that throttling the SSME to 106 percent increases the flight risk to the engines.

It was shown that for case (2) with the SSME's throttled to 104 percent, a payload increase of 6,091 lb can be obtained, and with the SSME's throttled to 106 percent, a payload increase of 6,505 lb can be obtained.

It was shown that for case (3) with the SSME's throttled to 104 percent, a payload increase of 1,188 lb can be obtained, and with the SSME's throttled to 106 percent, a payload increase of 1,303 lb can be obtained. For case (3), it was necessary to decrease the engine mixture ratio to 5.64 due to the extra hydrogen.

The payload increases give for cases (1), (2), and (3) take into account the added weight to the ET from the additional lines necessary for propellant recirculation and the increase in tank structure necessary due to the increase in total propellant load.

A detailed test requirements analysis was performed for the densified STS system, which identified specific tests and test areas that would be required for validation of propellant densification prior to first flight. The test requirements identified in section IX requires component and subsystem tests for the majority of the requirements and large scale testing for certain other subsystems. Although large scale testing is required, a flight ET is not required for use in the test program.

Although a cost estimate was not performed in this study, data obtained from a complimentary study lead by level II determined that the cost for implementation of propellant densification on the STS would run in excess of $500 million. This high cost can be attributed to force fitting propellant densification into a system that was not designed to accommodate it. It should be noted that propellant densification may be viable for a new launch vehicle so that the operations can be designed into the system.

Due to the relatively low payload gain for the cost, propellant densification is not recommended for implementation on the shuttle.

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4. Van Wylen and Sonntag, Fundamentals of Classical Thermodynamics, Third Edition

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APPENDIX A

STS Propellant Inventory

DENS-INV.XLS **MCRE, 02/07/94**

MPS PROPELLANT INVENTORY STS-DENSE TANK **REV HHH**

NOM **CNTR MR** = 5.90223

FUEL BIAS = 976.0 I **THROTTLE SETTING NOM/AOA** = 104/104 **INL MR** = 5.917501

TOTAL FPR = 3,987.68 I **SIGMA** = 3.0 **OBMR = 5.93042** **I**

DELTA FPR = 0

	LH_2	LO_2	TOTAL	
LOADED	247,873	1,457,909	1,705,782	
ORB LINES	266	3,471	3,737	I
SSME X 3	62	1,392	1,454	I
ET (HXT)=1,044.6, HUP=0.20, LXT=412.58, LUP=0.78)	247,544	1,453,046	1,700,590	I
LOAD PRIOR TO ENG START CMD DBT. 4M:55S	*104*	*5,800*	5,904	
BOILOFF, DRAINBACK, ETC.	*104*	*5,800*	5,904	I
LOAD ENGINE START COMMAND	247,769	1,452,109	1,699,878	
ORB LINES	266	3,471	3,737	
SSME x 3	62	1,392	1,454	
ET	247,440	1,447,246	1,694.686	
TRANSFERRED FROM ET TO SSME x3	62	181	243	I
LOSS FOR THRUST BUILDUP & SRB IGN DELAY	1,754	9,498	11,252	I
LOAD AT SRB IGNITION COMMAND	246,015	1,442,611	1,688,626	
ORB LINES	266	3,471	3,737	
SSME x 3	124	1,573	1,697	
ET	245,624	1,437,567	1,683,192	
UNUSABLE	2,050	4,887	6,937	
ORB LINES (LOX ECO T=0.398 NPSP=6.4)	266	513	779	I
SSME x 3	62	1,392	1,454	
ET WET WALLS, BELLOWS	0	175	175	I
ET: LH_2 LINES & TANK; LOX LINES	720	0	720	I
FLIGHT PRESSURIZATION	1,002	2,807	3,809	I
USABLE RESERVES	1,551	3,412	4,964	
ORB LINES (FPR)	0	2,958	2,958	
SSME x 3	0	0	0	
ET (FPR)	575	454	1,030	
BIAS	976	0	976	
USABLE IMPULSE	242,413	1,434,312	1,676,725	
USED AT OBMR (5,93042)	241,603	1,432,808	1,674,411	
SHUTDOWN CONSUMPTION	748	1,323	2,071	
0 SSME's FROM NOM PCT THROTTLE SETTING	0	0	0	I
3 SSME's FROM 67 PCT THROTTLE SETTING	748	1,323	2,071	I
VENTED AFTER SSME VALVE CLOSURE	62	181	243	

Propellant Temperature, °R	28.38	141.69
Propellant Density, Vented Tank (Term Rpln)	4.71791	74.62180
Tank Volume, 100-Percent Level, Vented Tank (Term Rpln)	52,469.09	19,446.08
Propellant Density, Pressurized Tank (ESC)		
Total Tank Volume, Pressurized Tank (ESC)	53,152.43	19,671.92
Delta Usable at OBMR (Ref. Rev. EE)	15,994.9	70,009.0

O2-ONLY.XLS				MCRE, 02/23/94
MPS PROPELLANT INVENTORY STS-DENSE TANK		REV HHH		
NOM		**CNTR MR** = 6.02573		
FUEL BIAS = 957.5 I **THROTTLE SETTING NOM/AOA** = 104/104		**INL MR** = 6.041000		
TOTAL FPR = 4,002.85 **SIGMA** = 3.0		**OBMR = 6.0544**	**I**	
DELTA FPR = 0	**LH_2**	**LO_2**	**TOTAL**	
LOADED	247,856	1,487,988	1,735,844	
ORB LINES	266	3,542	3,809	
SSME X 3	62	1,421	1,483	
ET (HXT)=1,044.6, HUP=0.20, LXT=412.58, LUP=0.78)	247,528	1,483,025	1,730,553	
LOAD PRIOR TO ENG START CMD DBT. 4M:55S	*104*	*5,800*	5,904	
BOILOFF, DRAINBACK, ETC.	*104*	*5,800*	5,904	I
LOAD ENGINE START COMMAND	247,752	1,482,188	1,729,940	
ORB LINES	266	3,542	3,737	
SSME x 3	62	1,421	1,454	
ET	247,424	1,447,225	1,724,649	
TRANSFERRED FROM ET TO SSME x3	62	184	246	
LOSS FOR THRUST BUILDUP & SRB IGN DELAY	1,754	9,498	11,252	I
LOAD AT SRB IGNITION COMMAND	245,998	1,472,690	1,718,688	
ORB LINES	266	3,542	3,809	
SSME x 3	124	1,605	1,729	
ET	245,608	1,467,543	1,713,151	
UNUSABLE	2,050	4,916	6,966	
ORB LINES (LOX ECO T=0.398 NPSP=6.4)	266	513	779	I
SSME x 3	62	1,421	1,483	
ET WET WALLS, BELLOWS	0	175	175	I
ET: LH_2 LINES & TANK; LOX LINES	720	0	720	I
FLIGHT PRESSURIZATION	1,002	2,807	3,809	I
USABLE RESERVES	1,525	3,435	4,960	
ORB LINES (FPR)	0	3,029	3,029	
SSME x 3	0	0	0	
ET (FPR)	575	406	973	
BIAS	958	0	958	
USABLE IMPULSE	242,423	1,464,339	1,706,762	
USED AT OBMR (5,93042)	241,613	1,462,832	1,704,445	
SHUTDOWN CONSUMPTION	748	1,323	2,071	
0 SSME's FROM NOM PCT THROTTLE SETTING	0	0	0	I
3 SSME's FROM 67 PCT THROTTLE SETTING	748	1,323	2,071	I
VENTED AFTER SSME VALVE CLOSURE	62	184	246	

Propellant Temperature, °R	28.39	132.13	I
Propellant Density, Vented Tank (Term Rpln)	4.71760	76.26344	
Tank Volume, 100-Percent Level, Vented Tank (Term Rpln)	52,469.08	19,446.08	I
Propellant Density, Pressurized Tank (ESC)			
Total Tank Volume, Pressurized Tank (ESC)	53,152.43	19,671.92	I
Delta Usable at OBMR (Ref. Rev. EE)	16,002.2	10,004.5	

(LO2 DELTA IS NONE ZERO DUE TO CHANGE IN FB & FPR)

H2-ONLY.XLS **MCRE, 02/10/94**

MPS PROPELLANT INVENTORY STS-DENSE TANK **REV HHH**

NOM

CNTR MR = 5.61373

FUEL BIAS = 978.4 I **THROTTLE SETTING NOM/AOA** = 104/104 **INL MR** = 5.629000

TOTAL FPR = 3,985.71 **SIGMA** = 3.0 **OBMR = 5.64073** I

DELTA FPR = 0

	LH_2	LO_2	TOTAL	
LOADED	247,905	1,387,844	1,635,749	
ORB LINES	266	3,304	3,570	
SSME X 3	62	1,325	1,387	
ET (HXT)=1,044.6, HUP=0.20, LXT=412.58, LUP=0.78)	247,577	1,383,215	1,630,792	
LOAD PRIOR TO ENG START CMD DBT, 4M:55S	*104*	*5,800*	5,904	
BOILOFF, DRAINBACK, ETC.	*104*	*5,800*	5,904	I
LOAD ENGINE START COMMAND	247,801	1,382,044	1,629,845	
ORB LINES	266	3,304	3,570	
SSME x 3	62	1,325	1,387	
ET	247,473	1,377,415	1,624,888	
TRANSFERRED FROM ET TO SSME x3	62	172	234	
LOSS FOR THRUST BUILDUP & SRB IGN DELAY	1,754	9,498	11,252	I
LOAD AT SRB IGNITION COMMAND	246,047	1,372,546	1,618,593	
ORB LINES	266	3,304	3,570	
SSME x 3	124	1,497	1,621	
ET	245,657	1,367,745	1,613,402	
UNUSABLE	2,050	4,820	6,870	
ORB LINES (LOX ECO T=0.398 NPSP=6.4)	266	513	779	I
SSME x 3	62	1,325	1,387	
ET WET WALLS, BELLOWS	0	175	175	I
ET: LH_2 LINES & TANK; LOX LINES	720	0	720	I
FLIGHT PRESSURIZATION	1,002	2,807	3,809	I
USABLE RESERVES	1,579	3,386	4,964	
ORB LINES (FPR)	0	2,791	2,791	
SSME x 3	0	0	0	
ET (FPR)	600	594	1,195	
BIAS	978	0	978	
USABLE IMPULSE	242,418	1,364,340	1,606,759	
USED AT OBMR (5,93042)	241,608	1,362,845	1,604,454	
SHUTDOWN CONSUMPTION	748	1,323	2,071	
0 SSME's FROM NOM PCT THROTTLE SETTING	0	0	0	I
3 SSME's FROM 67 PCT THROTTLE SETTING	748	1,323	2,071	I
VENTED AFTER SSME VALVE CLOSURE	62	172	234	

Propellant Temperature, °R	28.36	163.10	I
Propellant Density, Vented Tank (Term Rpln)	4.71853	71.13078	
Tank Volume, 100-Percent Level, Vented Tank (Term Rpln)	52,469.08	19,446.09	I
Propellant Density, Pressurized Tank (ESC)			
Total Tank Volume, Pressurized Tank (ESC)	53,152.43	19,671.92	I
Delta Usable at OBMR (Ref. Rev. EE)	15,997.1	18.4	

(LO2 DELTA IS NONE ZERO DUE TO CHANGE IN FP & FPR)

APPENDIX B

System Test/Verification Detail Analysis

STS Propellant Densification Test Requirement Analysis

Item No.: 1 Requirement: GSE Component Performance

Description: Component level characterization of the LH_2 and LO_2 GSE heat exchanger, circulation pumps, compressors and valves. Heat exchanger performance characterization/verification in terms of energy removal rates, efficiency and performance throughout the densification range and timeline.

Analytical Models: Analytical models shall be developed by the selected contractor and/or component vendors

Test Requirements: Testing is required on heat exchanger to determine heat transfer surface area capacity/effectiveness, compressor(s) performance with one and two compressors in operation, LH_2 and LO_2 pump and valve operation.

Risk Assessment: Could jeopardize schedule, cost and performance of subsequent densification system testing (see Item 3).

STS Propellant Densification Test Requirement Analysis

Item No.: 2 Requirement: Propellant Recirculation Line Disconnects

Description: Design verification of densified propellant recirculation line disconnects. Preliminary locations of disconnects are through the ET Intertank for LO_2 and the LH_2 T-0 umbilical for LH_2.

Analytical Models: None required

Test Requirements: Test for fit/alignment, leaks, cold flow and separation dynamics. Utilize KSC Launch Equipment Test Facility (LETF).

Risk Assessment: Failure to operate as designed could result in Crit 1 failure from leakage during propellant densification or leakage/rupture during liftoff.

STS Propellant Densification Test Requirement Analysis

Item No.: 3 Requirement: GSE Propellant Conditioning System Performance

Description: System level characterization of the LH_2 and LO_2 GSE conditioning equipment. Chill down, start, operation, shut down and purge operations. Evaluate operation envelop and contingencies for stop flow conditions, reverts, etc.

Analytical Models: System level analytical models shall be developed by the selected contractor.

Test Requirements: System level test on subscale test article as a minimum. Required evaluation/verification of predicted conditioning times and levels. Evaluation and verification of operation coupled with liquid level and temperature control of the LH_2 and LO_2 tanks. Complete subscale verification required prior to KSC propellant loading tests.

Risk Assessment: Inadequate propellant densification system performance during nominal and contingency operations could result in scubbed launches or launching with insufficient propellant margin.

STS Propellant Densification Test Requirement Analysis

Item No.: 4 Requirement: Liquid level sensor characterization

Description: Determine percent wet characterization of level sensors under densified propellant conditions. Design level sensor clustering to provide good liquid level determination during topping and replenish.

Analytical Models: Develop algorithms for level sensor percent wet for subcooled propellant surface. Also, Martin Marietta Nastran model that determines External Tank volumes versus tank height for following cases: (1) ambient vented, (2) ambient pressurized, (3) cryo-loaded, vented and (4) cryo-loaded, pressurized.

Test Requirements: Subscale tank testing using densified LO_2 and LH_2 to determine sensor responses to being cover by propellant surface with little or no boiling. If % wet algorithm that is derived from tests is too "flat", then determine a new ET sensor arrangement that would provide good level determination for precise topping and replenish control.

Risk Assessment: Lack of precise liquid level control during replenish would increase the uncertainty in propellant load and require an increase in the Flight Performance Reserve (FPR) alloted for loading accuracy.

STS Propellant Densification Test Requirement Analysis

Item No.: 5 Requirement: LH_2 Pre-Pressurization Performance

Description: Due to densified LH_2 load with subcooled surface, the ullage pressure decay rate during pre-press will increase. Determine analytically the amount of He (i.e., the number of bursts) required to stabilize the ullage pressure within the required pre-ignition band. Verify with subscale tank test and then with KSC loading test.

Analytical Models: Martin Marietta Single-Node Pressurization Model.

Test Requirements: First, establish pre-press control band required by engines and tank structure. Test initially at SSC on subscale tank with densified LH_2. Pre-press with GHe and determine number of one second bursts required to stabilize ullage pressure. Run several tests to determine variability. Repeat for KSC loading tests to establish final pre-press characterization and max number of He bursts above which a press system or tank leak is indicated.

Risk Assessment: Poor pre-press performance can cause ullage pressure to fall outside of required engine ignition band. Poor characterization of pre-press can cause tank or press system leaks to go unnoticed.

STS Propellant Densification Test Requirement Analysis

Item No.: 6 Requirement: LO_2 Pre-Pressurization Performance

Description: Due to densified LO2 load with subcooled surface, the ullage pressure decay rate during pre-press will increase. Determine analytically the amount of He (i.e., the number of bursts) required to stabilize the ullage pressure within the required pre-ignition band. Verify with subscale tank test and then with KSC loading test.

Analytical Models: Martin Marietta Single-Node Pressurization Model.

Test Requirements: First, establish pre-press control band required by engines and tank structure. Test initially at SSC on subscale tank with densified LO_2. Pre-press with GHe and determine number of one second bursts required to stabilize ullage pressure. Run several tests to determine variability. Repeat for KSC loading tests to establish final pre-press characterization and max number of He bursts above which a press system or tank leak is indicated.

Risk Assessment: Poor pre-press performance can cause ullage pressure to fall outside of required engine ignition band. Poor characterization of pre-press can cause tank or press system leaks to go unnoticed.

STS Propellant Densification Test Requirement Analysis

Item No.: 7 Requirement: LH_2 Flight Pressurization Performance

Description: Two changes may affect LH_2 tank pressurization system performance. (1) A lowering of the mainstage pressure below the current 32-34 psia. This may be implemented along with densified LH_2. (2) The presence of the LH_2 recirculation manifold will likely act as a heat sink when it is uncovered early after liftoff.

Analytical Models: Martin-Marietta Single-Node Pressurization Model. Model will need to be modified to simulate heat transfer from pressurization gases to LH_2 recirculation manifold after it is uncovered.

Test Requirements: Characterize any potential for ullage pressure to slump when recirc manifold is uncovered via analysis and then subscale, single engine testing. Final characterization, plus verification of new GH2 pressurization system control setting, should be made as part of the Systems Integration Verification Test (see Item 22) during FRF.

Risk Assessment: GH2 press system performance margin should be more than adequate to compensate for the possibility of a very slight ullage pressure slump when the cold recirc manifold is uncovered. Should the changes required to maintain the LH_2 ullage pressure at a lower control band not be completely verified, then the worst possible failures would be for all the flow control valves to remain either open or closed throughout the flight. Consequences of overpressurization would be tank venting during ascent which carries the potential for fire/explosion at lower altitudes. Consequences of under pressurization might be failure to meet engine NPSP requirements and possibly the collapse of the LH_2 tank.

STS Propellant Densification Test Requirement Analysis

Item No.: 8 Requirement: LO_2 Flight Pressurization Performance

Description: Changes that will affect LO_2 pressurization system performance are: (1) colder, denser LO_2, (2) SLWT, (3) LO_2 recirculation manifold, and (4) change back to an active GO_2 flow control system. Items (1), (2) and (3) will affect the ullage thermodynamics and tank dynamics and may significantly worsen the LO_2 ullage pressure slump experienced shortly after liftoff. See Item 21 for related test requirements.

Analytical Models: Martin-Marietta Single-Node Pressurization Model.

Test Requirements: Analytically determine the performance of an active GO_2 flow control system with colder LO_2 and a recirc manifold heat sink. Test for effects on ullage pressure when recirc manifold is uncovered during subscale, single engine testing. Final characterization, plus verification of the reactivated GO_2 pressurization system, should be made as part of the Systems Integration Verification Test (see Item 22) during FRF.

Risk Assessment: GO_2 press system performance margin should be more than adequate to compensate for the possibility of a very slight ullage pressure slump when the cold recirc manifold is uncovered. Should reactivation of an active GO_2 flow control system not be completely verified, then the worst possible failures would be for all the flow control valves to remain either open or closed throughout the flight. Consequences of overpressurization would be tank venting of GO_2 during ascent which carries some potential for fire/explosion if an ignition source is available. Consequences of under pressurization might be the collapse of the LO_2 tank.

STS Propellant Densification Test Requirement Analysis

Item No.: 9 Requirement: KSC LH_2 Procedures

Description: All nominal and contingency procedures must be tested for loading and draining densified LH_2. After the densification system is started following topping, procedures which are affected by the densified LH_2 are replenish, stop flows, reverts back to fast fill, topping and earlier stages of replenish, and drain.

Analytical Models: None required

Test Requirements: Obtain KSC support as early as possible to coordinatge testing of effects densified LH_2 would have on loading and draining operations. During series of densification tests with subscale tanks, conduct (1) normal replenish and drain operations, (2) stop flows of varying duration, (3) reverts to various loading phases, and (4) hold time assessment after stop flows, replenish termination and pre-press. Maximum hold times for maintaining subcooled LH_2 should be determined. Transition sequencing back to full flow should be determined. During the KSC loading tests, many of these same subscale tests should be repeated for fullscale tank characterization.

Risk Assessment: Risks involved with insufficient characterization of loading and draining operations for densified LH2 are (1) possible hardware damage during unsuitable flow transition, (2)countdown delays in establishing LH_2 flight mass, and (3) uncertainty in hold time available following stop flows and terminate replenish.

STS Propellant Densification Test Requirement Analysis

Item No.: 10 Requirement: KSC LO_2 Procedures

Description: All nominal and contingency procedures must be tested for loading and draining densified LO_2. After the densification system is started following topping, procedures which are affected by the densified LO_2 are replenish, stop flows, reverts back to fast fill, topping and earlier stages of replenish, and drain.

Analytical Models: None required

Test Requirements: Obtain KSC support as early as possible to coordinatge testing of effects densified LO_2 would have on loading and draining operations. During series of densification tests with subscale tanks, conduct (1) normal replenish and drain operations, (2) stop flows of varying duration, (3) reverts to various loading phases, and (4) hold time assessment after stop flows, replenish termination and pre-press. Maximum hold times for maintaining subcooled LO_2 should be determined. Transition sequencing back to full flow should be determined. During the KSC loading tests, many of these same subscale tests should be repeated for fullscale tank characterization.

Risk Assessment: Risks involved with insufficient characterization of loading and draining operations for densified LO_2 are (1) possible hardware damage during unsuitable flow transition, (2)countdown delays in establishing LO_2 flight mass, and (3) uncertainty in hold time available following stop flows and terminate replenish.

STS Propellant Densification Test Requirement Analysis

Item No.: 11 Requirement: LH_2 Tank Stratification Characterization

Description: To maximimize the LH_2 load during the densification process, good temperature mixing within the tank is required. Also, determination of the mean bulk temperature is required to accurately calculate the load on board. Propellant stratification should be investigated both analytically and via propellant tank temperature instrumentation.

Analytical Models: TBD

Test Requirements: Subscale LH_2 tank should be instrumented to determine densified LH_2 temperature profile horizontally and vertically. A major objective is to verify analytically modeling so that a flight tank will not require instrumentation. During densification tests, determine if, how and when proper propellant mixing is accomplished.

Risk Assessment: Lack of accurate temperature characterization would result in uncertainty in the mean bulk density and flight load.

STS Propellant Densification Test Requirement Analysis

Item No.: 12 Requirement: LO_2 Tank Stratification Characterization

Description: To maximimize the LO_2 load during the densification process, good temperature mixing within the tank is required. Also, determination of the mean bulk temperature is required to accurately calculate the load on board. Propellant stratification should be investigated both analytically and via propellant tank temperature instrumentation.

Analytical Models: TBD

Test Requirements: Subscale LO_2 tank should be instrumented to determine densified LO_2 temperature profile horizontally and vertically. A major objective is to verify analytically modeling so that a flight tank will not require instrumentation. During densification tests, determine if, how and when proper propellant mixing is accomplished.

Risk Assessment: Lack of accurate temperature characterization would result in uncertainty in the mean bulk density and flight load.

STS Propellant Densification Test Requirement Analysis

Item No.: 13 Requirement: LH_2 Engine Recirculation Performance

Description: LH_2 recirculation performance via the clustered recirc system must be characterized for densified LH_2. Two objectives apply here: (1) avoid excessive propellant being lost through the hi-point bleed line following replenish termination, and (2) maintain SSME start temperature requirements.

Analytical Models: TBD

Test Requirements: Analytically assess engine LH_2 temperature conditioning during recirc pump operation with densified LH_2 and predict effect on hi-point bleed flow. Recirculation flow should be adjusted only if engine LH_2 temperatures are too cold, which is unlikely. Hi-point bleed flow can be reduced to lower the LH_2 drainback mass after replenish termination if adequate temperature margin is maintained (could be more trouble than it's worth). Verification of engine LH_2 temperature conditions should be made during the KSC loading test.

Risk Assessment: Typical LH_2 drainback mass is 104 lbm. With densified propellants, this may go up slightly and thus reduce the flight load, given the same hi-point bleed system configuration. Too cold LH_2 might increase the LH_2 oscillations during start.

STS Propellant Densification Test Requirement Analysis

Item No.: 14 Requirement: LO_2 Bleed Performance

Description: LO_2 bleed is required to eliminate heat entering the LO_2 feed system and engine. After replenish termination, the bleed goes through a drainback phase of nearly five minutes which reduces the LO_2 load on board by approximately 5,800 lbm. The ability to launch following an extended hold can be affected by the drainback time and rate. With colder LO_2, the bleed rate can probably be reduced to minimize the drainback mass while still meeting SSME temperature requirements.

Analytical Models: TBD

Test Requirements: Analytically assess SSME LO_2 conditioning for varying bleed rates. For densified LO_2, if the bleed rate can be reduced significantly and an adequate temperature margin still be maintained, then modify the engine bleed system and tverify during single engine hot fire testing.

Risk Assessment: A bleed rate that is unnecessarily high sacrifices LO_2 flight mass during drainback. Also, a too high bleed rate (i.e., too cold LO_2 start conditions) may cause problems with the fuel preburner start and result in an oxygen rich start. A low nominal bleed rate could make the engine more sensitive to variations in the flow.

STS Propellant Densification Test Requirement Analysis

Item No.: 15 Requirement: LH_2 Feedline and Fill and Drain Line Performance

Description: Colder, denser LH_2 will affect the feedline pressure losses. These can be determined analytically. Also, valve operation should be verified with densified LH_2. Applicable valves are the 17 inch disconnect valves, the feedline prevalves, and the inboard and outboard fill and drain line valves.

Analytical Models: Develop spreadsheet simulation for feedline pressure losses.

Test Requirements: Determine pressure losses analytically. Determine valve performance with densified LH_2 through component test or by similarity with single engine test stand valving.

Risk Assessment: Pressure loss analysis is straight forward with no significant risk involved. Risk of not verifying proper valve operation under densified LH_2 conditions prior to KSC loading test would be to experience faulty valve operation while on the pad and thus delay schedule to accomodate further valve testing and possible changeout.

STS Propellant Densification Test Requirement Analysis

Item No.: 16 Requirement: LO_2 Feedline and Fill and Drain Line Performance

Description: Colder, denser LO_2 will affect the feedline pressure losses. These can be determined analytically. Also, valve operation should be verified with densified LO_2. Applicable valves are the 17 inch disconnect valves, the feedline prevalves, and the inboard and outboard fill and drain line valves.

Analytical Models: Develop spreadsheet simulation for feedline pressure losses.

Test Requirements: Determine pressure losses analytically. Determine valve performance with densified LO_2 through component test or by similarity with single engine test stand valving.

Risk Assessment: Pressure loss analysis is straight forward with no significant risk involved. Risk of not verifying proper valve operation under densified LO_2 conditions prior to KSC loading test would be to experience faulty valve operation while on the pad and thus delay schedule to accomodate further valve testing and possible changeout.

STS Propellant Densification Test Requirement Analysis

Item No.: 17 Requirement: POGO System Performance

Description: LO_2 POGO suppression is accomplished with an SSME mounted POGO accumulator. Any effect that densified LO_2 might have on accumulator performance should be determined analytically and verified through single engine testing with densified LO_2.

Analytical Models: TBD

Test Requirements: Analytically assess POGO accumulator performance with densified LO_2. Verify proper accumulator performance on single engine test stand. Proper performance would mean elimination of LO_2 feed system oscillations coupled with engine and maintaining proper accumulator He charge performance.

Risk Assessment: Worst case risk would be collapse or loss of accumulator He charge and subsequent coupling of engine oscillations with LO_2 feedlines.

STS Propellant Densification Test Requirement Analysis

Item No.: 18 Requirement: Nose Cone & Intertank Purge Performance Verification

Description: Colder vent lines plus recirculation lines placed in the nose cone and intertank may affect the performance of the heated GN2 purges in these compartments. This may require an increase in the purge supply pressure and/or temperature.

Analytical Models: Martin-Marietta Intertank conditions model.

Test Requirements: Analytically determine if purge system supply pressure and temperature should be modified to maintain required nose cone and intertank conditions. Adjust purge system output prior to KSC loading test and verify during loading with compartment temperature and pressure data.

Risk Assessment: Intertank: Possible RSS battery and electronics problems and structural problem with colder temperatures. Nose cone: Possible icing problem around vent ducts.

STS Propellant Densification Test Requirement Analysis

Item No.: 19 Requirement: SSME Start/Shutdown Transient Performance

Description: Densified propellants will change the SSME inlet temperatures, pressures and densities and will affect SSME transient performance during start and shutdown. These changes may affect preburner performance and require changes in valve scheduling.

Analytical Models: SSME Digital Transient Model

Test Requirements: Analytical simulations are questionable for transient performance. Therefore, short duration single engine hot-fire tests should be conducted at SSC with progressively colder propellants. During start transients, evaluate OPB start pops and any difficulty in igniting all OPB injector elements due to possible reduction in fuel oscillation magnitude and due to the reduced LO_2 manifold boiloff. Adjust OPOV schedule as may be required. Evaluate FPB for increased fuel flow and redu ced preburner LO_2 injector flow at ignition. Adjust FPOV schedule as may be required. During shutdown transients, evaluate possible increase in number of small preburner pops due to colder LO_2 residuals. This is for characterization testing, as there is no known corrective action.

Risk Assessment: Skipping the testing for start and shutdown performance is not an option. Improper testing (e.g., starting with fully densified propellants on first test) could result in such poor preburner performance that a damaging engine shutdown could result.

STS Propellant Densification Test Requirement Analysis

Item No.: 20 Requirement: SSME Mainstage Operation

Description: Densified propellants will change the SSME inlet temperatures, pressures and densities and will affect SSME mainstage performance. These changes may affect mixture ratio, turbine temps and nozzle cooling margins.

Analytical Models: SSME Power Balance Model

Test Requirements: Conduct single engine hot-fire tests at SSC. During mainstage, evaluate for mixture ratio effects and reduced turbine temps and increased MCC/nozzle cooling margins. This testing is to characterize engine performance rather than to adjust for changes.

Risk Assessment: Improper engine mainstage characterization would result in inaccurate redlines, and engine performance errors (i.e., specific impulse, thrust, propellant consumption, etc.) that could effect vehicle velocities and consume propellant reserves.

STS Propellant Densification Test Requirement Analysis

Item No.: 21 Requirement: LO_2 Ullage Pressure Slump Verification

Description: The LO_2 ullage pressure slump that occurs shortly after liftoff is a result primarily of a small ullage and propellant spash caused by the SRM thrust buildup that sets off a tank "breathing motion." Colder LO_2 will contibute to the slump. The LO_2 recirc manifold will act as a heat sink after it is uncovered and may also contribute to the slump. The breathing motion of the SLWT may be different from the ET LWT. All of these things need to be assessed because this is a very critical phenomenon. An ullage pressure slump larger than what the tank is capable of withstanding could result in the loss of the vehicle and crew.

Also, a precise determination of the SLWT LO_2 low pressure structural capabilty is important. This would provide the most accurate margin between what the tank could withstand and the predicted minimum pressure during the period of slump.

Analytical Models: Martin-Marietta Single-Node Pressurization Model. CFD Research , Incorporated's LO_2 Ullage Pressure Slump CFD Model.

Test Requirements: This is a very difficult area to test for but may be extremely important. Of course the dynamics of SRB thrust buildup on the LO_2 tank cannot be tested directly. However, dynamics tests of a subscale tank that could closely duplicate the predicted breathing motion of the ET LO_2 tank (when loaded to various levels with densified LO2) and thus produce the correct "splash" at the LO_2 surface would be required. The resultant ullage pressure slump could then be evaluated.

Risk Assessment: Uncertainties in analytically modeling of the LO_2 ullage pressure slump, coupled with the potentially disastrous results of a slump that would violate LO_2 tank minimum structural capabilities, make it imperative to minimize uncertainties in this area. If this cannot be done, then the first flight with densified propellants might require a larger than normal ullage (i.e., lowered LO_2 load) to reduce the slump potential. This could change mission objectives and affect the Space Station schedule.

STS Propellant Densification Test Requirement Analysis

Item No.: 22 Requirement: Systems Integration Verification

Description: The densified propellant change would likely be incorporated with several other significant shuttle changes: SLWT, Block II SSME's, various orbiter mods, and a return to active GOX flow control system. With the number and nature of the changes, it would be prudent to conduct a short duration Flight Readiness Firing (FRF) on the launch pad. An FRF would verify proper systems integration , and identify correlated performance effects, if any, that would not show up under individual system testing. Also, this would be the only opportunity to test for cluster effects and changes to the vehicle twang.

Analytical Models: Shuttle Integrated Performance Prediction Simulation (SIPPS).

Test Requirements: Conduct normal propellant loading and count down followed by a short duration (20 seconds should suffice) hot-firing. Place priority on evaluating twang, LO_2 pressurization system performance, LH_2 pressurization system performance, and engine inlet conditions and engine control with densified propellants and clustered performance.

Risk Assessment: Risks are difficult to predict. Uncertainties in integration of all systems, especially systems that have been changed, and correlated performance effects that we are not smart enough to identify or cannot test for with systems tests are the primary risks. Problems could conceivably scrub a mission or actually sacrifice a mission if not discovered prior to an actual launch attempt.

APPROVAL

STS PROPELLANT DENSIFICATION FEASIBILITY STUDY DATA BOOK

By M.M. Fazah

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

W.R. Humphries

J.P. McCARTY
Director, Propulsion Laboratory

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The feasibility of using densification or subcooling with respect to standard temperature propellants on the Space Transportation System (STS) in order to achieve a payload gain is discussed in this report. The objective is to determine the magnitude of the payload gain and to identify any system impacts to the space shuttle on either flight systems or ground systems. Results show that a payload benefit can be obtained by subcooling the liquid hydrogen (LH_2) from a nominal temperature of 36.4 °R to 28.5 °R and by subcooling the liquid oxygen (LO_2) from a nominal temperature of 164 °R to either 132.1 °R or 141.4 °R. When the propellants are subcooled to 28.5 °R and 132.1 °R for the LH_2 and LO_2, respectively, a maximum payload gain of 7,324 lb can be achieved, and when the propellants are subcooled to 28.5 °R and 141.5 °R for the LH_2 and LO_2, respectively, a maximum payload gain of 6,841 lb can be achieved. If the LH_2 is subcooled to 28.5 °R while the LH_2 and LO_2 remains at the nominal conditions, a maximum payload gain of 1,303 lb can be achieved.

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