CR-184155

NASA

National Aeronautics and Space Administration
Marshall Space Flight Center
Michoud Assembly Facility

MARTIN MARIETTA
MANNED SPACE SYSTEMS

NAS8-37136

Volume II - Final Report
Addendum 2

March 1991

Liquid Rocket Booster (LRB) for the Space Transportation System (STS) Systems Study

(NASA-CR-184155) LIQUID ROCKET BOOSTER (LRB) FOR THE SPACE TRANSPORTATION SYSTEM (STS) SYSTEMS STUDY, VOLUME 2, ADDENDUM 2 Final Report (Martin Marietta Corp.) 61 p
CSCL 21H G3/20
N91-22374
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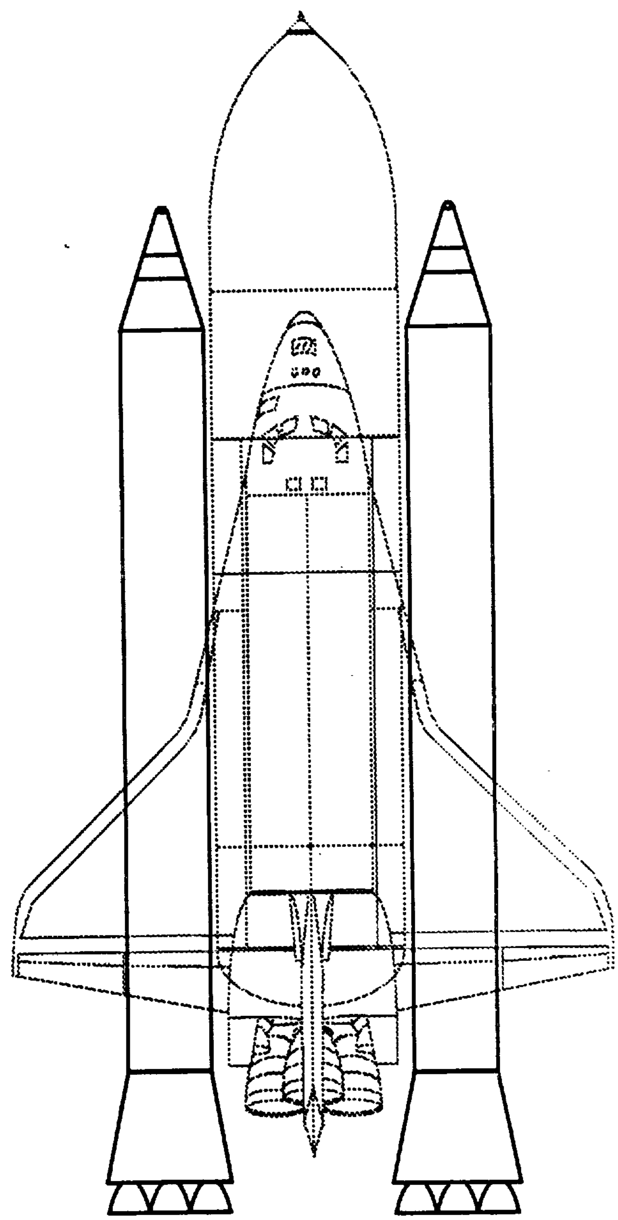

FOREWORD

This document provides the Final Report, Volume II, Addendum 2, for the Liquid Rocket Booster (LRB) for the Space Transportation System (STS) Study performed under the NASA Contract NAS8-37136. The report was prepared by Manned Space Systems, Martin Marietta Corporation, New Orleans, Louisiana, for the NASA/Marshall Space Flight Center (MSFC).

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ACRONYMS AND ABBREVIATIONS

AMLS	Advanced Manned Launch System
ATP	Authority to Proceed
CDR	Critical Design Review
DDT&E	Design, Development, Test, and Evaluation
DM	Data Management
EPS	Electrical Power System
ET	External Tank
GN&C	Guidance, Navigation & Control
GO2	Gaseous Oxygen
GVTA	Ground Vibration Test Article
ID	Inside Dimension
ILC	Initial Launch Capability
INS	Inertial Navigation System
LaRC	Langley Research Center
L/D	Lift to Drag Ratio
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LN2	Liquid Nitrogen
LO2	Liquid Oxygen
LRB	Liquid Rocket Booster
MAF	Michoud Assembly Facility
MPTA	Main Propulsion Test Article
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NCFI	North Carolina Foam Industries
NDE	Nondestructive Evaluation
OD	Outside Dimension
OMS	Orbital Maneuvering System
P/A	Propulsion Avionics
PDR	Preliminary Design Review
PLS	Personnel Launch System
ROM	Rough Order of Magnitude
S-HABP	Supersonic-Hypersonic Arbitrary Body Program
SDR	Systems Design Review
SOFI	Spray-on Foam Insulation

ACRONYMS AND ABBREVIATIONS

SOW	Statement of Work
SRB	Solid Rocket Booster
SSC	Stennis Space Center
SSME	Space Shuttle Main Engine
STA	Structural Test Article
STE	Special Test Equipment
STME	Space Transportation Main Engine
STS	Space Transportation System
T&T	Telemetry & Tracking
TPS	Thermal Protection System
TVC	Thrust Vector Control

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1.0 INTRODUCTION

1.1 BACKGROUND

The principal role of the personnel launch system (PLS) is to provide assured manned access to space. This approach involves a small man-carrying vehicle and has been studied under the NASA Advanced Manned Launch System (AMLS) Study with two vehicle designs having been conceptualized for performing the mission. One concept is a high lift-to-drag (L/D) ratio vehicle while the other is a craft configured more like the Apollo and Gemini spacecrafts of the past which had low L/D ratios. With these vehicle designs now conceptually defined, a major issue outstanding at this time is the lack of a man-rated, cost effective launch system for the PLS missions.

1.2 STUDY OBJECTIVE

The objective of this study extension to the Liquid Rocket Booster (LRB) for the Space Transportation System (STS) Systems Study contract was to assess the feasibility of developing and producing a launch vehicle derived from an external tank (ET). The primary mission of this launch vehicle would be to place a PLS vehicle into low Earth orbit (LEO).

1.3 MISSION SCENARIO

The ascent portion of the PLS reference mission is shown in Figure 1.3-1. The high lift-to-drag

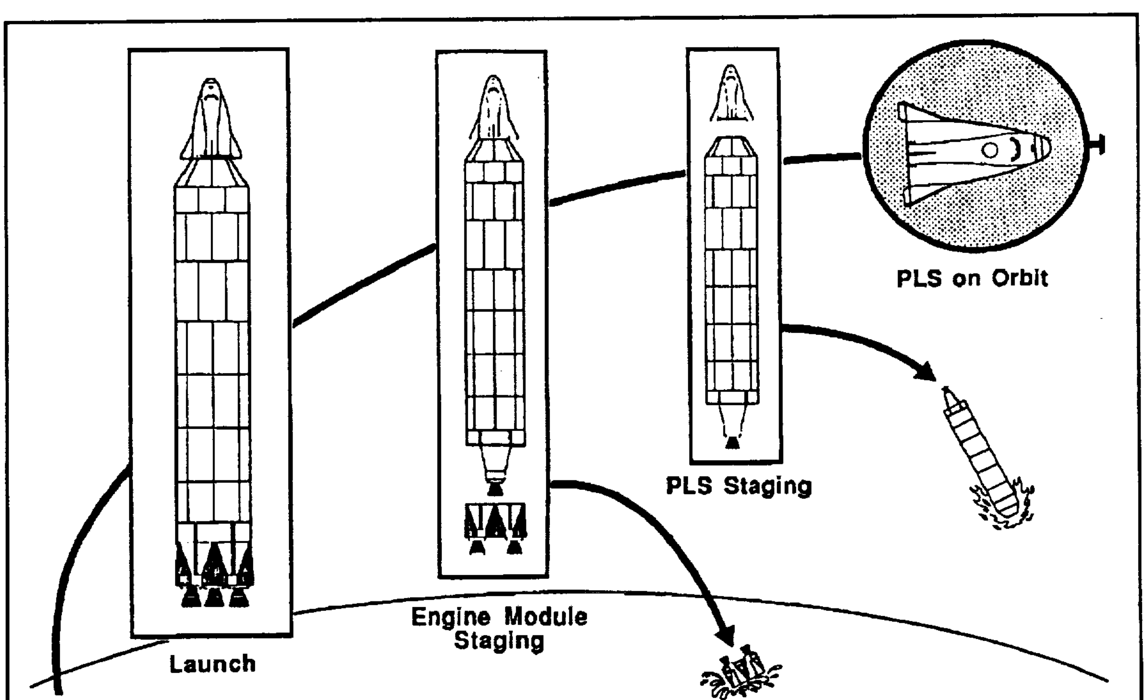

Figure 1.3-1 Mission Scenario–Ascent Phase

PLS glider is shown mounted atop an ET-derived launch vehicle. Early in ascent the booster portion of the 1.5 stage vehicle would be staged leaving the two sustainer engines to provide the final velocity required to place the PLS glider into an elliptical transfer orbit. After achieving orbital velocity, the PLS glider separates from the sustainer portion of the launch vehicle and maneuvers to a final orbit using its on board orbital maneuvering system (OMS). The sustainer portion of the launch vehicle continues in the initial orbit until it reenters and breaks up over the Pacific ocean.

1.4 GROUND RULES AND ASSUMPTIONS

The ground rules and assumptions used as the basis for this study follow.

1) Man-rated vehicle
2) PLS weight targets: 35 klb min; 60 klb maximum
3) Engine out capability at liftoff
4) PLS insertion orbit of 35 x 160 nm @ 57 nm
5) PLS constraints
    a) Maximum dynamic pressure of 900 psf (goal ≤800 psf)
    b) Maximum Q-Alpha of 5000 psf-deg (goal ≤3500 psf-deg)
    c) Maximum acceleration of 4g
6) Unpressurized stability - LO2 & LH2 tanks unpressurized on launch pad
7) Launch vehicle engine module uses STMEs
8) Concurrent build of 12 ETs + 7 PLS launch vehicles @ MAF
9) Vehicle integration options
    a) Total integration at MAF
    b) Vehicle and engine module integration at KSC

1.5 STUDY TASKS

The stated study tasks follow.

1) Task 5a - Design

    Develop a conceptual design for a 1.5 stage inline launch vehicle derived from the Space Shuttle configuration ET to determine the design differences on the ET.

2) Task 5b - Manufacturing/Production

    Define manufacturing/production impacts at Michoud Assembly Facility (MAF) for ET-derived 1.5 stage launch vehicle.

3) Task 5c - Test Program/Certification

    Quantify the delta test certification program required due to the 1.5 stage launch vehicle changes.

1.6 STUDY RESULTS SUMMARY

A launch vehicle concept was developed for placing a PLS vehicle into LEO. The vehicle concept developed derives its tankage from the ET and has an engine module that mounts inline to the tankage at the aft end and contains six space transportation main engines (STME). A PLS adapter is supplied for mounting the PLS vehicle to the forward end of the launch vehicle. This vehicle is shown in Figure 1.6-1.

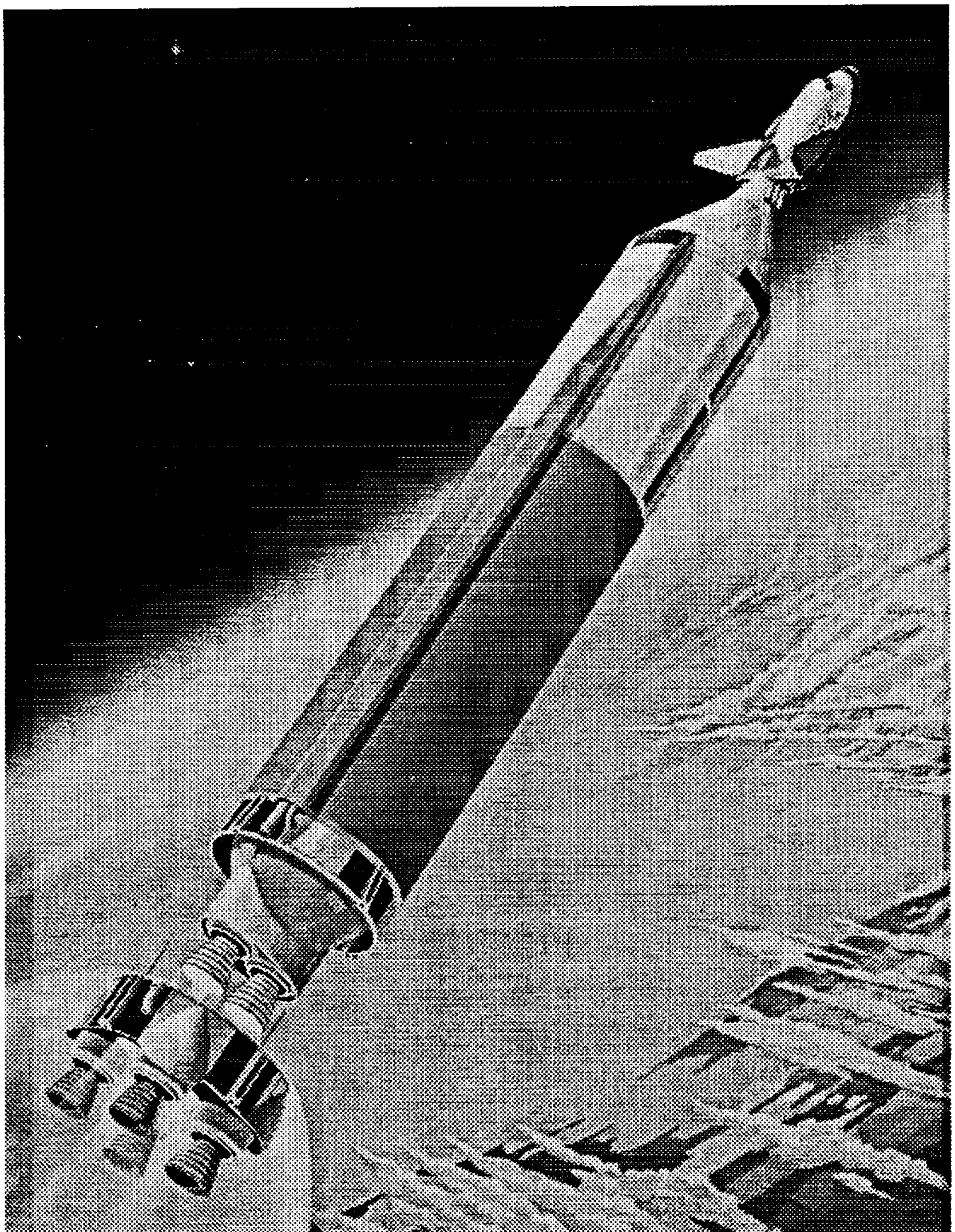

Figure 1.6-1 PLS Launch Vehicle

The vehicle tankage and the assembly of the engine module, was evaluated to determine what, if any, manufacturing/production impacts would be incurred if this vehicle were built along side the current ET at MAF. It was determined that there would be no significant impacts to produce seven of these vehicles per year while concurrently producing 12 ETs per year.

The test program defined is preliminary, but draws heavily on existing ET test knowledge and attempts to be innovative in ways to use fewer test articles to meet all test requirements.

Preliminary estimates of both nonrecurring and recurring costs for this vehicle concept were made. The nonrecurring cost was estimated in the range of $450 to $560M and the average unit cost was estimated to be in a range from $35 to $45M.

2.0 TASK 5a - DESIGN

2.1 TASK SUMMARY

A concept design was developed for a 1.5 stage launch vehicle. This vehicle is configured so that four of its six STMEs can be staged during ascent and continue on to orbit with its remaining two engines. Detailed structural sizings were made for the vehicle tankage and engine module utilizing vehicle loads that were generated. A propulsion system was devised for feeding propellant to the six engines that incorporated externally mounted disconnects for separating the booster engine feedlines at staging. The thermal protection system as well as others, such as avionics and electrical, were defined for this vehicle. Vehicle performance was evaluated using detail weight statements and preliminary vehicle aerodynamics.

A detailed description of the 1.5 stage PLS launch vehicle is provided in Section 2.2 and the criteria used for the design in Section 2.3. Structural descriptions of the ET-derived tankage and the engine module are included in Sections 2.4.1 and 2.4.2. The main propulsion, thermal protection, avionics, and electrical power systems are described in Sections 2.5, 2.6, 2.7, and 2.8. Vehicle mass properties are provided in Section 2.9, and vehicle aerodynamics and flight performance are discussed in Sections 2.10 and 2.11.

2.2 VEHICLE CONFIGURATION

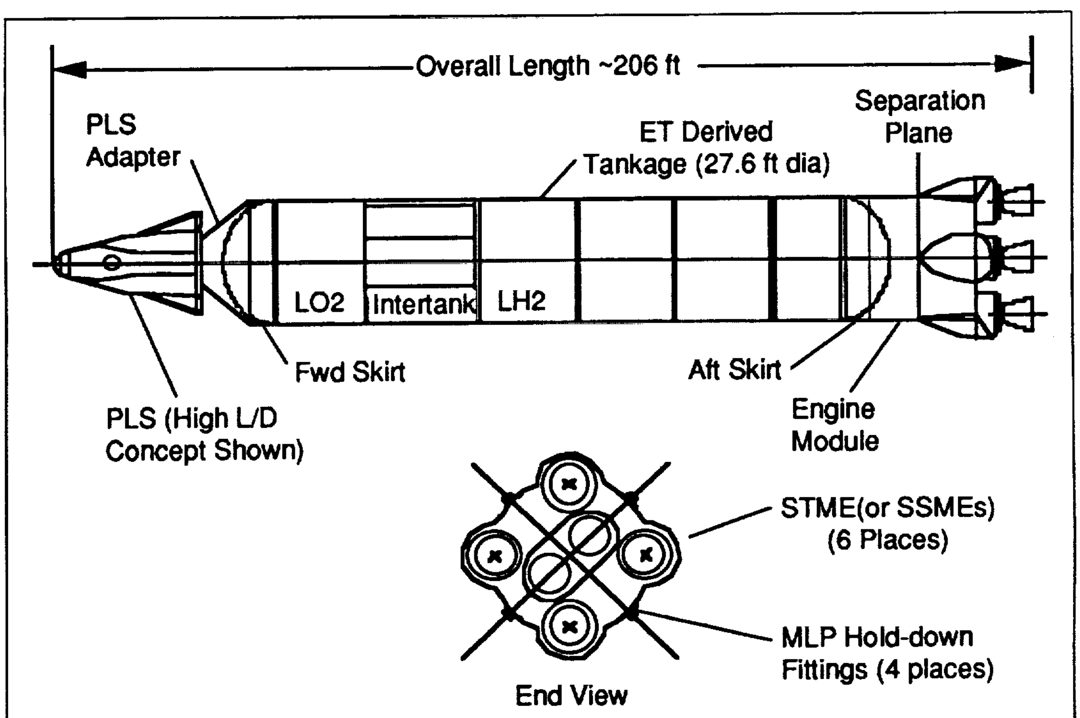

Figure 2.2-1 ET Derived 1.5 Stage Launch Vehicle For PLS

The 1.5 stage launch vehicle consists of the PLS vehicle, PLS adapter, ET-derived tankage, and an engine module and is shown with the high L/D PLS vehicle in Figure 2.2-1. The vehicle is approximately 206 ft overall in length and has a diameter of 27.6 ft. The launch vehicle structures are the forward skirt, oxidizer (LO2) tank, intertank, fuel (LH2) tank, aft skirt and engine module thrust structure. Attached to the thrust structure are six STMEs which produce a combined nominal sea level thrust of 3,000,000 lb. Four of these engines are spaced 90° apart on a 25 ft diameter circle and comprise the booster stage propulsion which is staged during ascent. The remaining two STMEs are mounted inboard equidistant above and below the vehicle pitch axis and remain with the vehicle throughout flight. The intertank provides structural continuity between the fuel and oxidizer tanks, which provide propellant storage. The forward and aft skirts provide structural continuity with the PLS adapter and the engine module respectively. The launch vehicle portion is shown in Figure 2.2-2. The PLS adapter is not a part of this study and will not be discussed further. The assumed adapter weight of 7,524 lb was taken from a Langley Research Center (LaRC) presentation on 7-17-90.

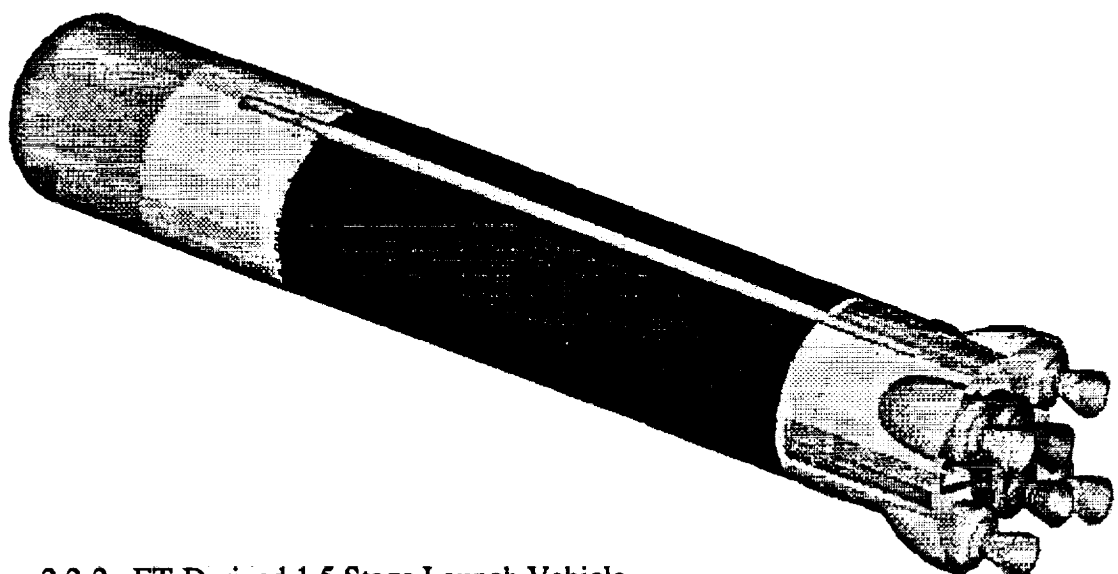

Figure 2.2-2 ET-Derived 1.5 Stage Launch Vehicle

The LO2 tank capacity is of sufficient size to contain the same amount of propellant contained in the ET LO2 tank. The LH2 tank capacity remains identical to that of the ET LH2 tank. Details of the structural design of the tankage and engine module for the 1.5 stage launch vehicle are described in Sections 2.4.1 and 2.4.2.

2.3 DESIGN CRITERIA/CRITICAL LOAD CONDITIONS

Both structural and mechanical design criteria that affected the basic design of the vehicle are presented in Section 2.3.1. Critical load conditions affecting the design of the vehicle shell structure is discussed in Section 2.3.2.

2.3.1 Design Criteria

The following are structural design criteria used in conjunction with the performance ground rules and assumptions described in Section 1.4.

1) Maximum Q-Alpha was limited to 4,000 psf-deg for the structural design.

2) Factors of safety used are taken from MSFC-HDBK-505A for metallic flight structures except for the ultimate safety factor of 1.25 used for well defined loads such as dead weight, axial accelerations, engine thrust, and well defined pressure such as propellant tank operating pressure. This 1.25 ultimate safety factor criteria is taken from the ET end item specification, CPTO1M09A.

   a) Structure verified by analysis and static test
      Ultimate = 1.25 x Limit - for well defined loads and pressures
      = 1.40 x Limit - for all other loads
      Yield = 1.10 x Limit
   b) Structure verified by analysis only
      Ultimate = 2.0 x Limit
      Yield = 1.25 x Limit

3) Maximum propellant tank ullage pressures during flight (same as ET)
   a) LO2 tank = 29.5 psia
   b) LH2 tank = 34.0 psia

4) Winds at launch pad–prelaunch conditions
   a) 60 kt wind with payload, no fuel, tanks unpressurized
   b) 49 kt wind with payload, fully fueled, tanks unpressurized (simulates sudden loss of pressure)
   c) 30 kt wind with payload, fully fueled, tanks pressurized, vehicle held down to launch pad, six STMEs running at 100% RPL (Worst case thrust loads for structural design of engine module only)

5) An additional load factor of 1.3 was applied to the maximum Q-Alpha loads to cover t he uncertainty of the load condition.

6) No skin panels buckling at limit load. Skin panels may buckle above limit load provided the column (skin/stringer combination) does not fail at ultimate load.

7) Dynamic factors on loads–simulates quasi-static loads resulting from dynamic events.
   a) A dynamic amplification factor of 1.5 applied to prelaunch loads caused by wind
   b) A dynamic amplification factor of 1.2 applied to engine startup loads
   c) A dynamic rebound factor of 1.2 on vehicle dead weight for engine shutdown case

2.3.2 Critical Shell Load Conditions

A number of loading conditions were investigated to determine critical loads for the major structural elements of the 1.5 stage vehicle. These conditions were:

1) Prelaunch unpressurized conditions
2) Prelaunch with maximum engine thrust
3) Liftoff
4) Maximum Q
5) Maximum axial acceleration
6) Maximum Q-Alpha
7) Pre-separation
8) Postseparation
9) Burnout
10) Engine out (all conditions).

Table 2.3.2-1 Critical Shell Load Conditions

Vehicle Elements	Critical Load Conditions	
	Prelaunch	Flight
Fwd skirt		Max Q-alpha (t=85 sec)
LO2 tank	60 kn wind, dry, unpressurized	
Intertank		Max Q-alpha (t=85 sec)
LH2 tank	49 kn wind, fully fueled, unpressurized	
Aft skirt		Max Q-alpha with engine thrust @ t=85 sec
Engine module	30 kn wind, 6 engines @ 100% RPL	Lift-off, 6 engines @ 100% RPL + 20% dynamic factor on thrust

Prelaunch unpressurized conditions were judged most critical in governing the thickness of the tanks and therefore most of the vehicle weight The wind requirements on the launch pad are specified in Section 2.3.1. The LO2 tank was found to have maximum axial compressive loads in the shell for the 60 kt wind case with the 60 klb PLS mounted on top. The LH2 tank was also found to be critical for prelaunch winds of 49 kts with payload and full LO2 tank above. This condition can occur from 4 to 24 hours before launch when tanks are fully loaded. Table 2.3.2-1 shows the major structural elements and the critical shell load conditions.

As shown in Table 2.3.2-1, the intertank is critical for the maximum Q-Alpha condition where flight loads on the PLS during a maximum angle of attack occur simultaneously with axial acceleration. LO2 and LH2 tanks are not critical for compressive loads at this time in the flight because tank pressures react all external compression loads. The internal operating pressure of the tanks compensates for the axial compression loads caused by axial load and bending and therefore is in tension, not compression. Forward and aft skirts, and the engine module shell are not pressurized and are also critical for the maximum Q-Alpha load case. Much of the engine module shell is also critical for hold-down and engine thrust loads.

2.4 STRUCTURAL ARRANGEMENTS

Details of the ET-derived tankage structure and engine module are described in Sections 2.4.1 and 2.4.2.

2.4.1 ET-Derived Tankage

The ET-derived tankage is very similar to the ET in structural design and arrangement. The major difference between the two vehicles is that the 1.5 stage tankage does not require the complex structural reinforcements required for the attachment of an orbiter and two SRBs. The LH2 tank structure does not require the reinforcements from the orbiter thrust structure and aft SRB attachments and the intertank does not require forward SRB attachments or the crossbeam. The 1.5 stage tankage does have an engine module attached to the aft end of the LH2 tank and a PLS adapter attached to the forward end of the modified LO2 tank but the loads from this arrangement are introduced fairly uniformly to the tankage and complex and/or local reinforcements are not necessary. The result is that the 1.5 stage ET-derived tankage has a more uniform structural thickness and strength distribution.

The ET-derived tankage consists of three major assemblies, an LO2 tank, intertank, and an LH2 tank. Forward and aft skirt-extension barrel structures are added to the forward end of the LO2 tank and the aft end of the LH2 tank respectively to accommodate attachment of the PLS adapter and the

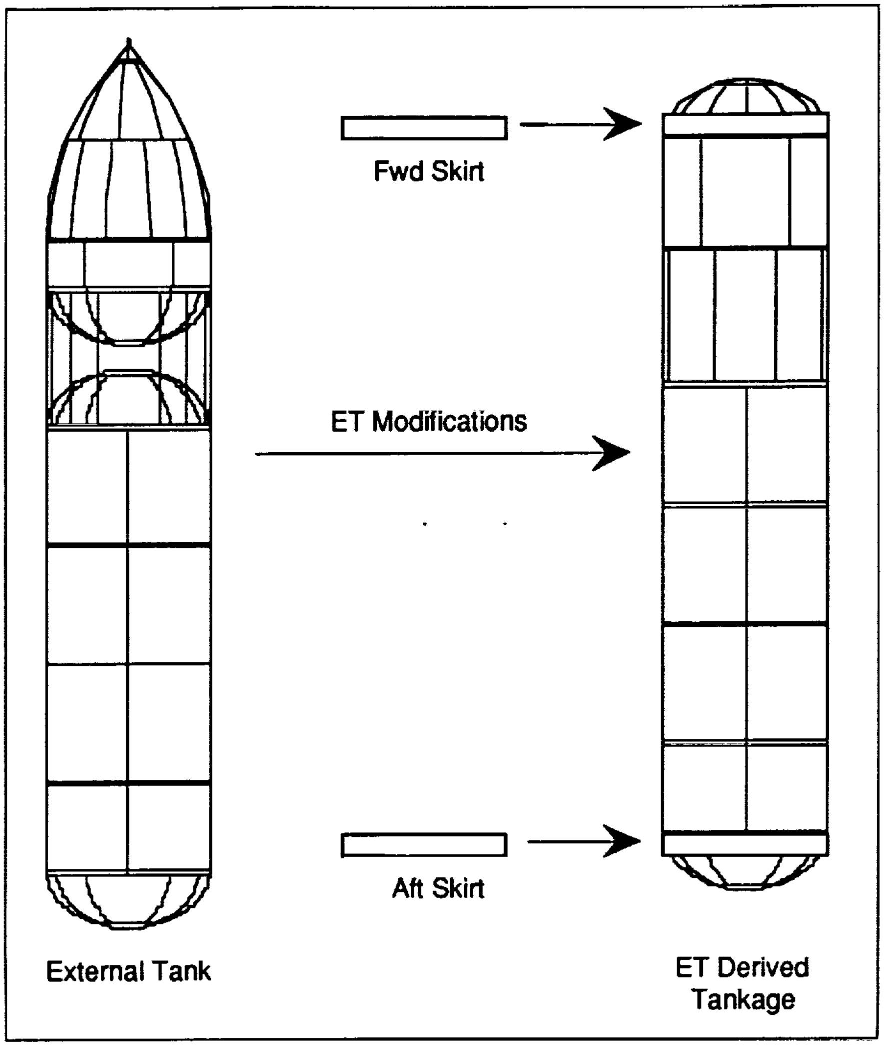

Figure 2.4.1-1 ET Derived 1.5 Stage Tankage

engine module . Figure 2.4.1-1 shows how the tankage is derived from the ET.

2.4.1.1 LO2 Tank

Modifications are made to the all-welded LO2 tank in order to accommodate a PLS vehicle on the front. A 20 ft long stringer stiffened barrel, similar to the 20 ft stiffened barrels used in the LH2 tank and a forward dome similar to the forward dome used on the LH2 tank is used for construction. This simplifies construction for the 1.5 stage since the more complex forward and aft ogive of the ET LO2 tank is replaced with the cylindrical barrel sections.

The 20 ft cylindrical barrel section uses standard ET LH2 "T" stiffened barrel panels. The "T" sections are 1.25 inches deep and are spaced on 10.8 inch centers. Addition of the "T" stringers to the skin panels along with four small ring frames to stabilize the stiffeners on 4 ft. centers, enable the LO2 barrel to carry the axial loads developed by the PLS payload. Fabrication of the longer LO2 barrel will be accomplished on the same tooling used to fabricate the 20 ft LH2 barrels.

An LH2 forward dome is used on the forward end of the LO2 tank. This dome has already been qualified to the higher operating pressures experienced in the LH2 tank.

The aft LO2 dome is the same aft dome used on the present ET except that two feedline outlet fittings are welded into the dome cap instead of one as in the ET. Two separate vortex baffles will be attached to these feedline outlets. Both LO2 domes are ellipsoidal in shape with a minor-to-major axis ratio of 0.75.

Initial review of anti-slosh requirements has led to a full length slosh baffle being included in the preliminary weights. A more in-depth analysis of sloshing will be conducted when a control analysis is performed and tis expected to lead to a shorter length baffle and a lower weight. For preliminary design purposes the conservative higher weight has been used.

Figure 2.4.1.1-1 shows a cutaway view of LO2 tank construction details. All material used in the LO2 tank is 2219 aluminum alloy.

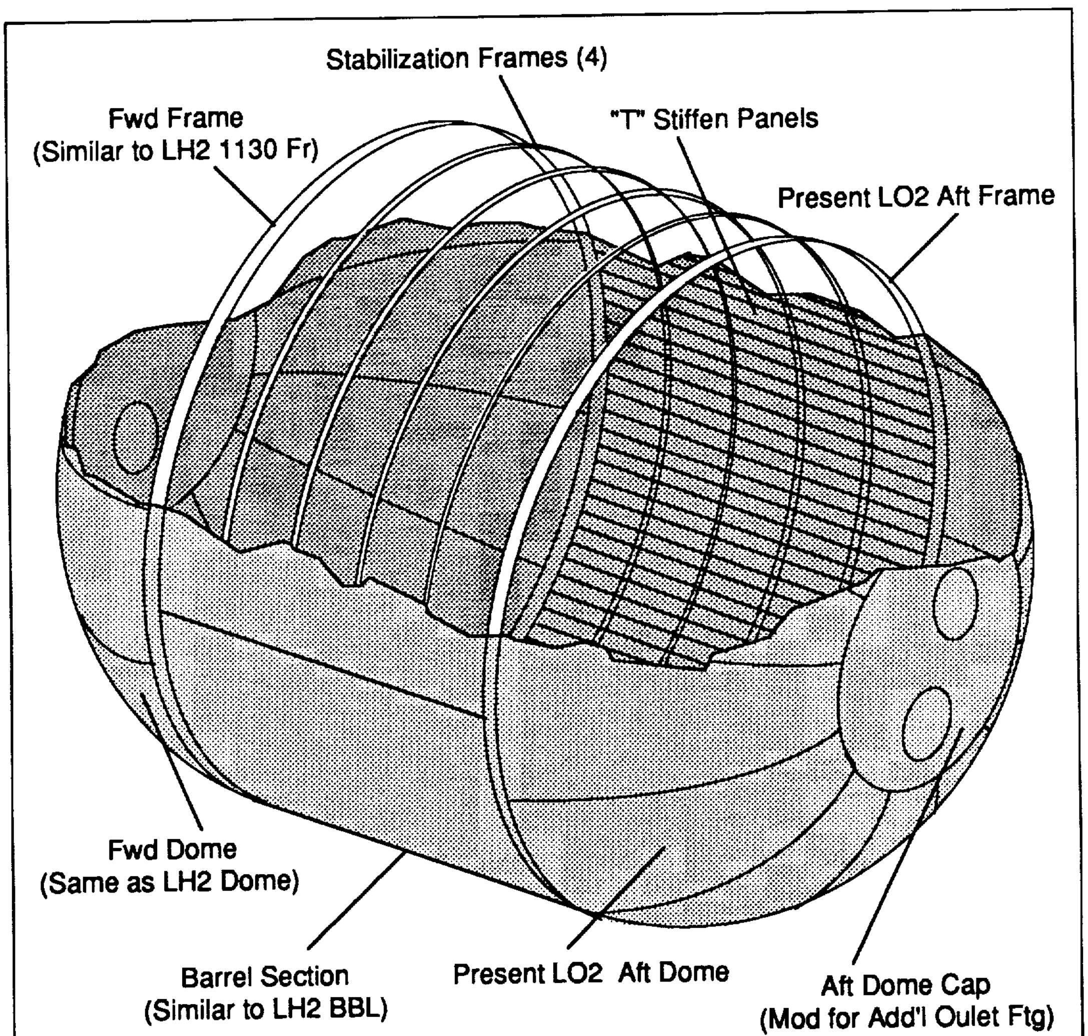

Figure 2.4.1.1-1 Cutaway View of LO2 Tank

2.4.1.2 Intertank

The intertank has the same external hat stiffened skin stringer structure as used on the ET. The 1.5 stage vehicle does not have SRBs attached so the forward SRB attach fittings, the machined thrust panels, and the SRB crossbeam have been eliminated. Ring frames, shown in the cutaway view of the intertank in Figure 2.4.1.2-1, and their spacing are identical to those in the ET. Regular hat stiffened panels such as those used in six of the ET intertank barrel panels are substituted for the two machined thrust panels that were eliminated. In order to carry the PLS and the LO2 tank loads, nominal skin thicknesses for the skin stringer panels have been increased over ET thicknesses.

Handling/lift fittings are shown in Figure 2.4.1.2-1 where the SRB forward attach fittings would normally be located. The SRB fittings on the ET also doubled as lift fittings. The main ring frame on the center line of the intertank has been reinforced locally to react the handling fitting loads.

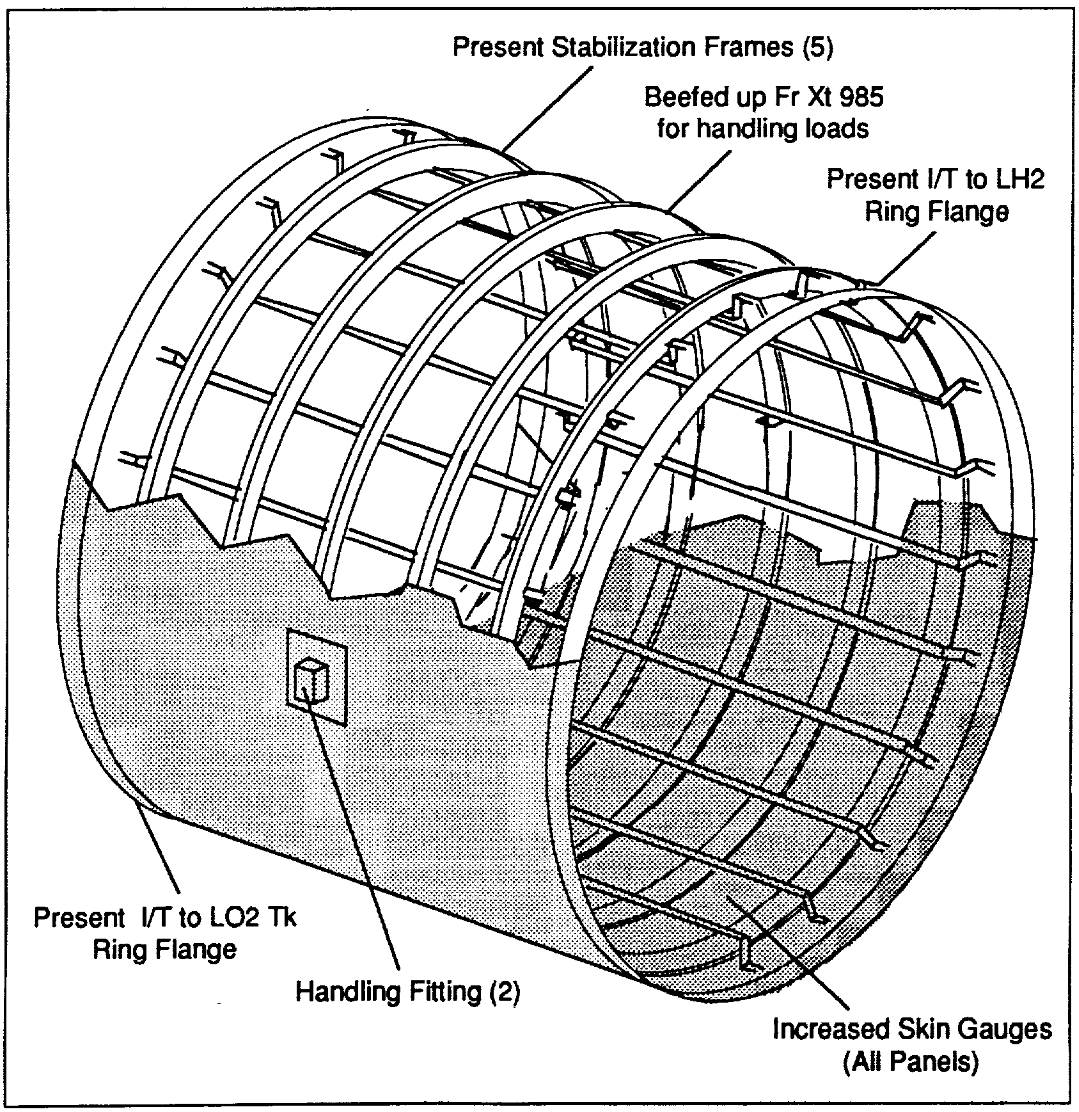

Figure 2.4.1.2-1 Cutaway View of Intertank

The 1.5 stage intertank also requires a penetration for the second LO2 feedline which is located approximately 180 degrees opposite the original feedline. The umbilical carrier plate, the RSS box inside the intertank, and the intertank door remain in the same location as in the ET.

Fabrication is accomplished by mechanically joining all parts of the intertank structure. Aluminum alloys 2024 and 7075 are used throughout the intertank in the form of sheet and extrusions.

2.4.1.3 LH2 Tank

The LH2 tank is an all-welded 2219 aluminum assembly with forward and aft 0.75 ellipsoidal domes, four cylindrical barrel sections, and five main ring frames whose outer flanges are welded integral to the shell. The forward three barrels are approximately 20 ft in length while the aft barrel is approximately 15 ft in length. No changes to overall dimensions from those on the ET have been made.

Construction details of the barrel panels shown in the cutaway drawing (Figure 2.4.1.3-1) are also the same as ET. The skin-stringer panels consist of 1.25 inch deep "T" stringers on 10.8 inch spacing. The membrane skin thickness has been increased from the 0.126 inch minimum used on the ET LH2

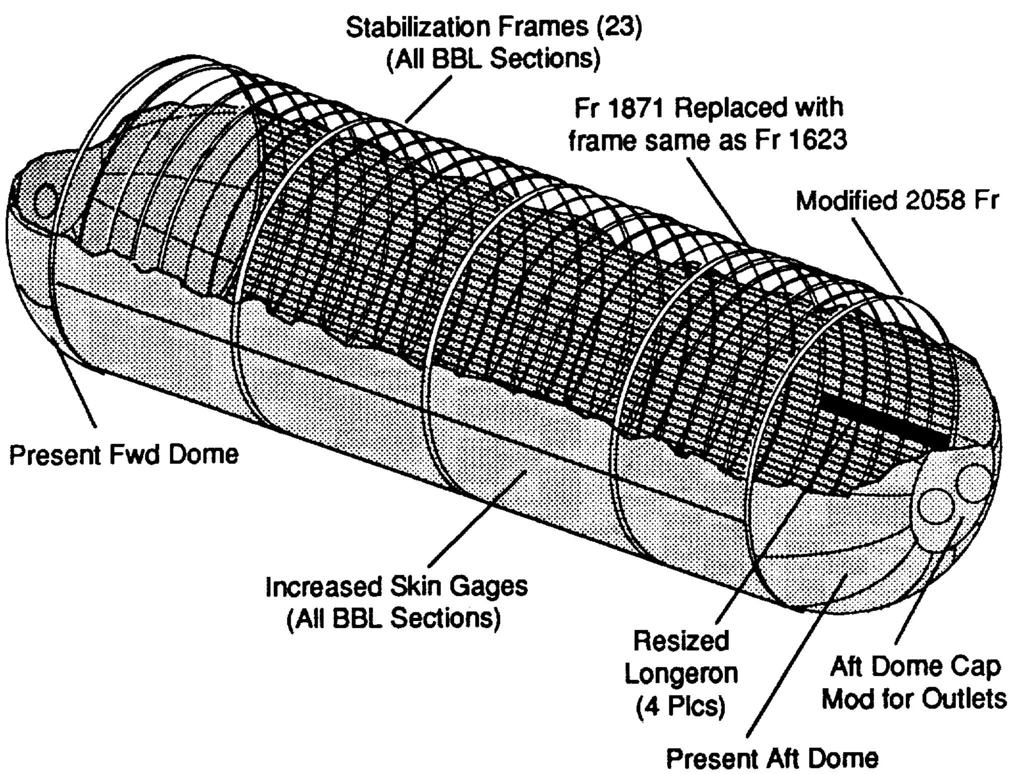

Figure 2.4.1.3-1 Cutaway View of LH2 Tank

tank to 0.180 inchs. This change accommodates the requirement of standing on the launch pad fully loaded but unpressurized. Ring frames were added inside the tank barrel sections to reduce the column length of the "T" stringers to 3.5 ft in order to carry the axial compressive loads which are significantly higher than those experienced on the ET.

The main ring frame at the lower end of the LH2 tank is a modified ET Sta 2058 frame. This frame has to resist the pressure-related discontinuity forces caused by the dome/barrel intersection, and external shear and bending forces caused by load distribution from the engine module. The ET 2058 ring frame provides attachments for the orbiter thrust structure and the aft SRB attachments which put large radial loads into the frame. By eliminating these provisions the frame weighs less than its ET equivalent. Distribution of engine module loads into the first LH2 tank barrel are assisted by four plate longerons inserted into four of the eight barrel panels. All engine module loads are distributed uniformly in the LH2 tank wall by the time they reach the second barrel and longeron reinforcement is no longer required.

Both forward and aft domes on the LH2 tank are the same as used on the ET. The dome cap in the aft dome is modified to accept a second feedline outlet fitting similar to the LO2 aft dome.

2.4.1.4 Forward and Aft Barrel Skirts

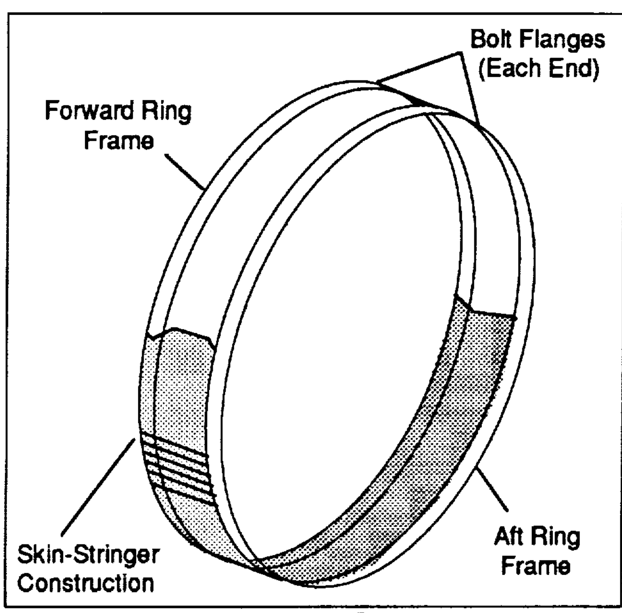

Figure 2.4.1.4-1 Forward Skirt Assembly

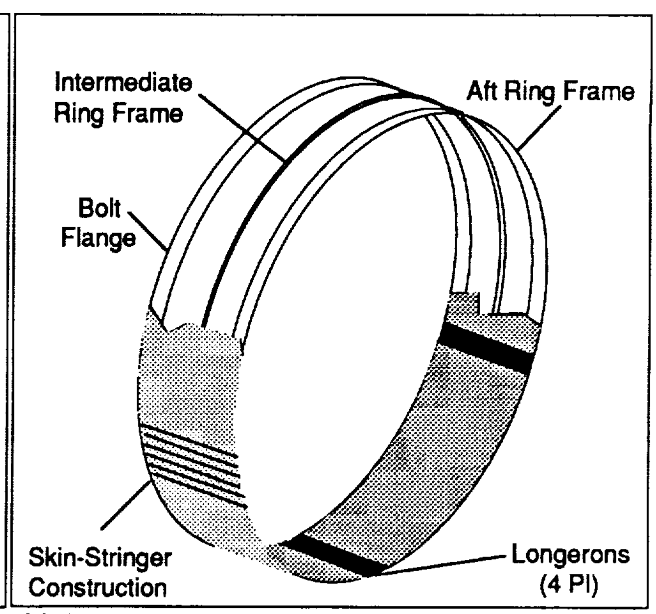

Figure 2.4.1.4-2 Aft Skirt Assembly

Skirt-extensions of 5 and 6 ft are used on the forward end of the LO2 tank and the aft end of the LH2 tank to facilitate attachment of the PLS adapter structure and the engine module to the tankage. These lengths accomodate the placement of a GO2 vent umbilical in the shell of the forward skirt and

Lo2 feedline supports on the aft skirt shell. A bolted flange connection attaches the skirts to the tankage. This arrangement is similar to the bolted flange connection on the intertank. The skirts are skin-stringer construction with hat stiffeners on the outside similar to the intertank construction. Skin gauges and extruded hat stiffeners on the two skirts are proportioned to accommodate the load magnitudes. The end of the skirt away from the tank connection flange incorporates a ring frame to maintain the shape of the skirt assembly during fabrication, handling, and joining of payload adapter and engine module. The forward skirt assembly is shown in Figure 2.4.1.4-1 and the aft skirt in Figure 2.4.1.4-2.

Material used in the skirts is 2024 aluminum and all members are joined mechanically.

2.4.2 Engine Module

The engine module for the 1.5 stage vehicle has four STMEs arranged on the periphery of the module shell and two in the center. The module is constructed so that the four outer engines with supporting structure can be separated at staging leaving only the structure required for the two center sustainer engines. Figures 2.4.2-1 through 2.4.2-4 show details and dimensions of this engine module.

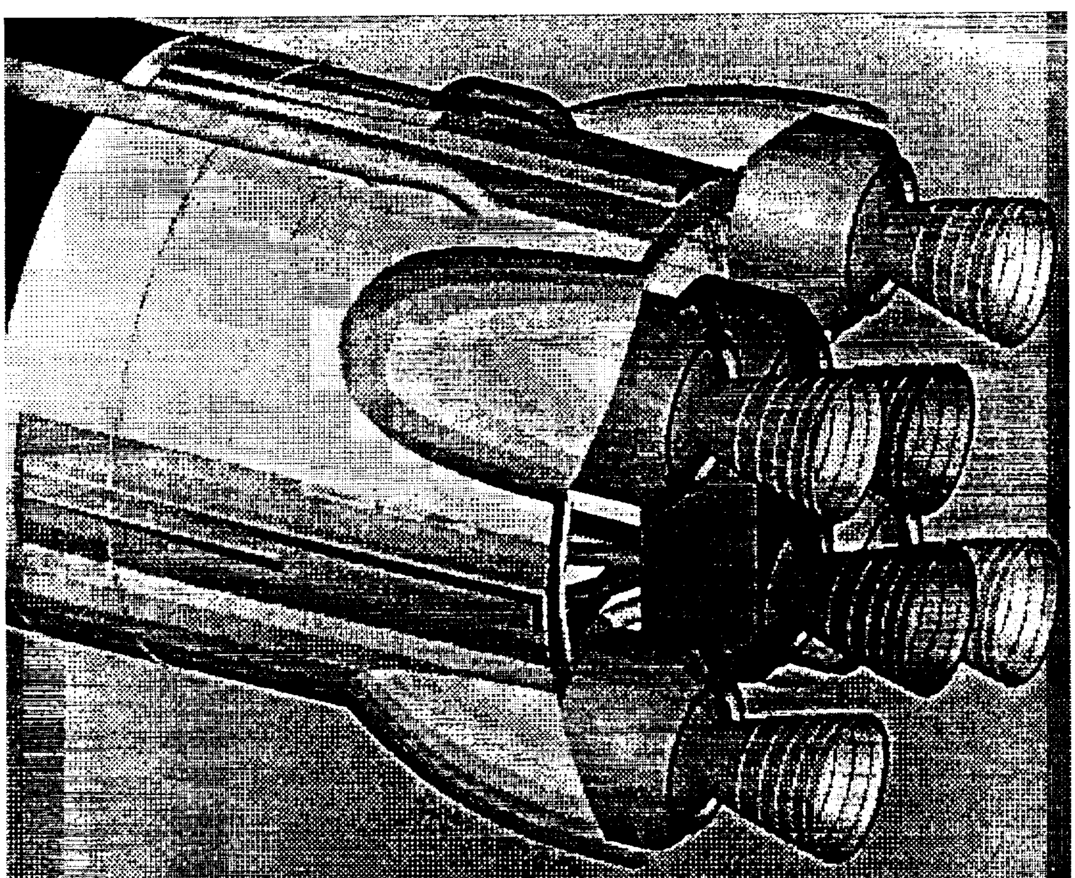

Figure 2.4.2-1 1.5 Stage Engine Module

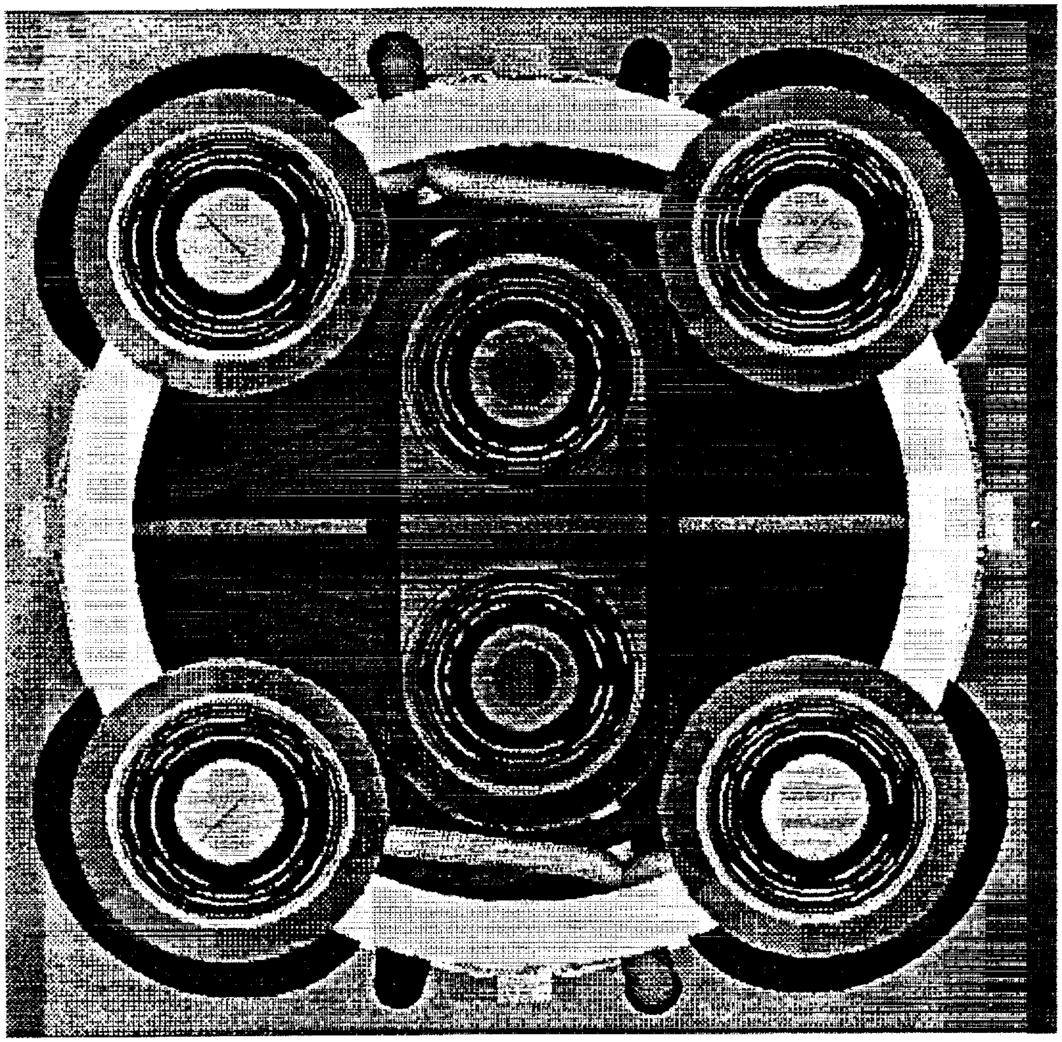

Figure 2.4.2-2 Propulsion Module–Rear View

In order to facilitate service and maintenance on LH2 and LO2 feedline disconnects necessary for staging of the four outer engines, the LH2 feedlines are routed outside of the engine module as shown in Figures 2.4.2-3 and 2.4.2-5. The umbilical disconnects for both LO2 and LH2 feedlines are then located at the module separation plane as shown in Figure 2.4.2-3. The portion of the module staged connects to the fixed upper half through four explosive bolt connections which are the same type as the four explosive bolt connections in the hold-down fittings to the launch pad. Engine mount longerons for the four outer engines, similar to the hold-down fittings in design although smaller in cross section and weight, are integrated into both the staged and fixed portions of the engine module shell as shown in Figure 2.4.2-6. The connection at the separation plane is a lateral-shear type connection and is accomplished by a single large dowel pin which pulls out of a socket in the upper member when the lower section is staged. Matching ring frames on both sides of the separation plane integral to the two shells also are connected with dowel pins which carry only shear loads and pull out at separation.

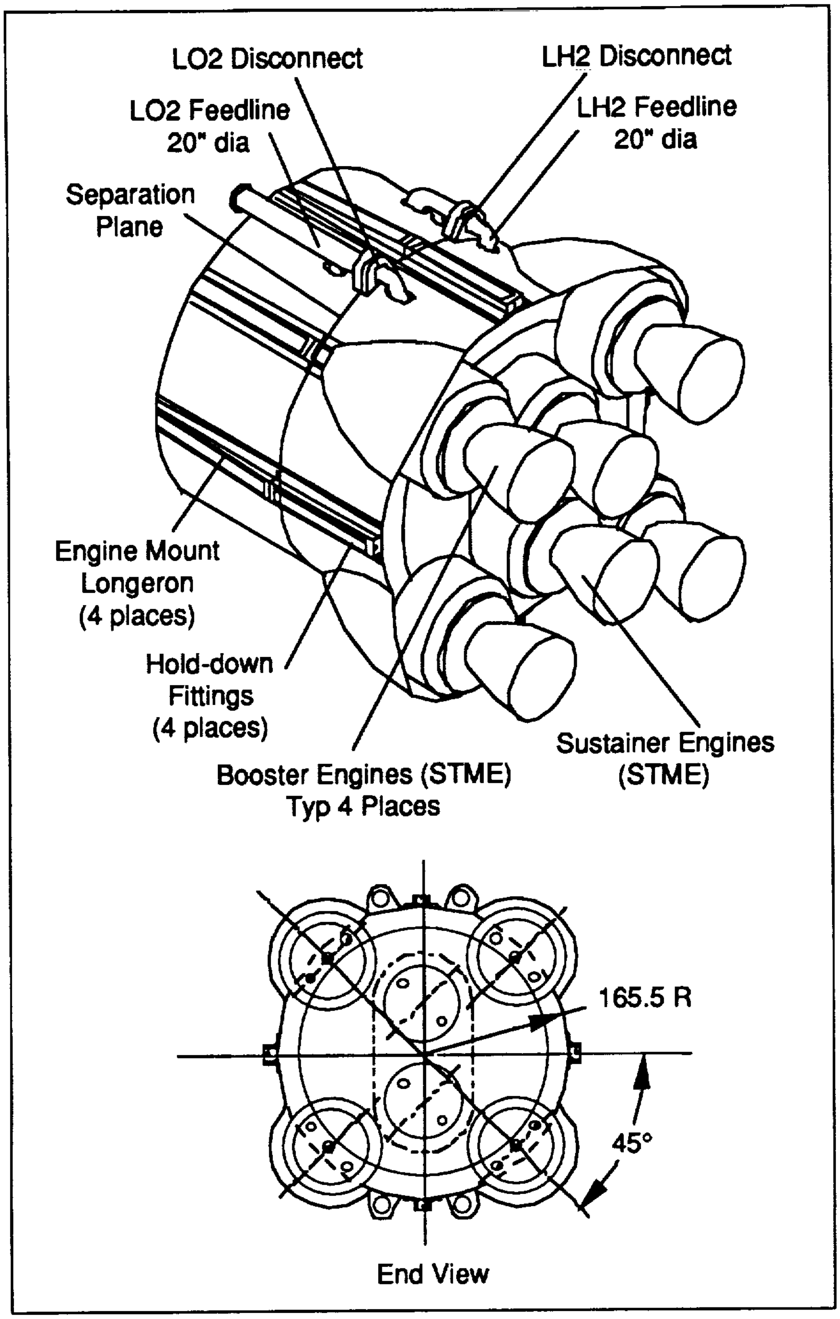

Figure 2.4.2-3 1.5 Stage Engine Module General Arrangement

A large ring frame located at the bottom of the staged portion of the module maintains the shape of the module as it passes the two sustainer engines and provides a path for lateral-shear loads from wind to be reacted at the four hold-down fittings on the launch pad. The four staged engines are not gimbaled and lateral engine loads are consequently not introduced to the lower ring. The ring, however, does have substantial depth and cross section to provide a lateral stiffness to the engine mount and shell structure.

Four guide rails are used around the periphery of the staged module to assist in guiding the module past the sustainer engines.

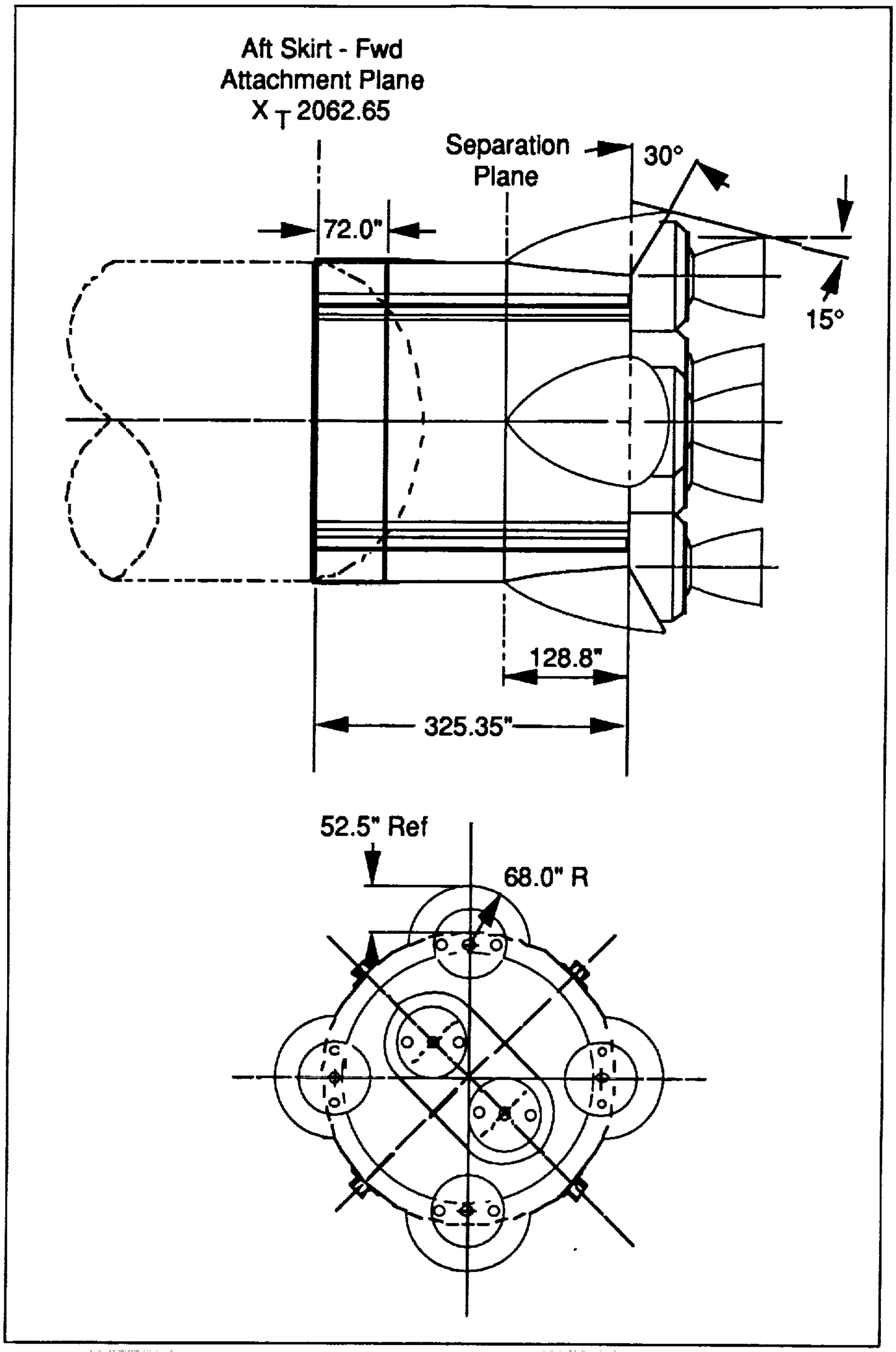

Figure 2.4.2-4 1.5 Stage Propulsion Module Dimensions

The two sustainer engines are mounted off the retained upper portion of the module by two tubular members attached to the upper shell where a large ring frame intersects the four main hold-down longerons as shown in Figure 2.4.2-7. A tension member, in the form of a tubular strut, also connects directly across the ring frame station to the opposite side so that the large engine mount lateral loads are not introduced to the ring frame except during one sustainer engine out operation. To minimize vibration loadings on the engine mount struts, small braces will be used between struts to change spans and frequencies as required.

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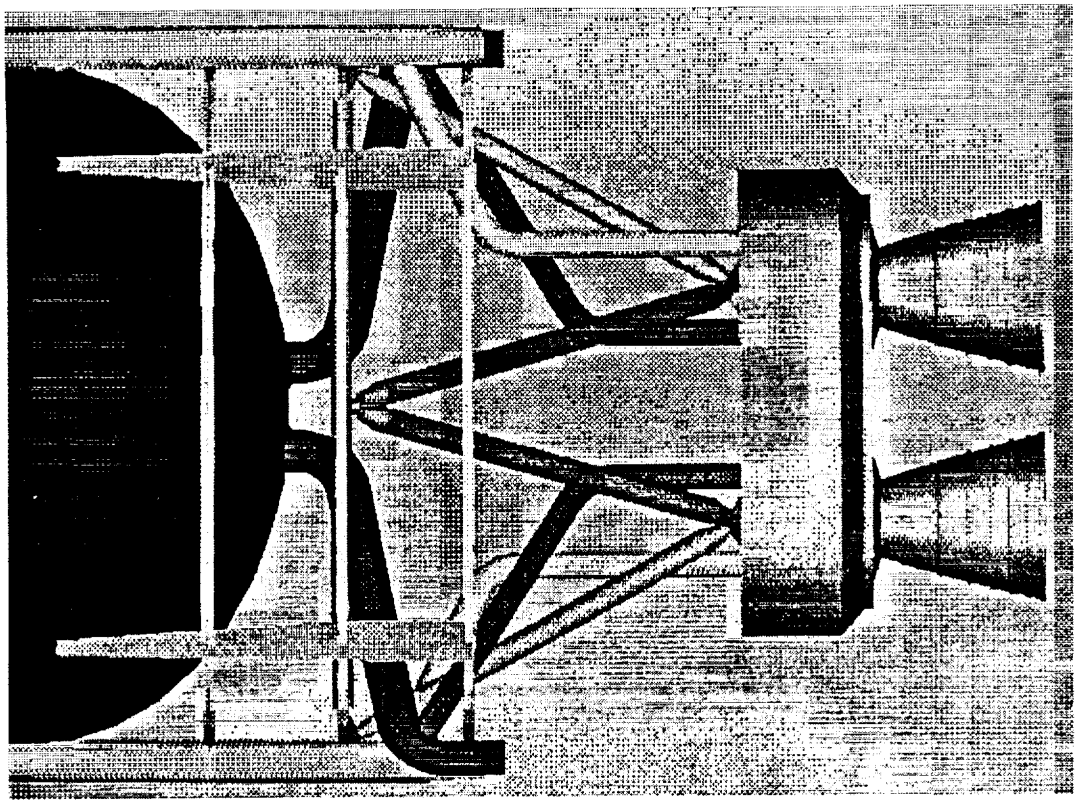
Figure 2.4.2-5 Sustainer Engines

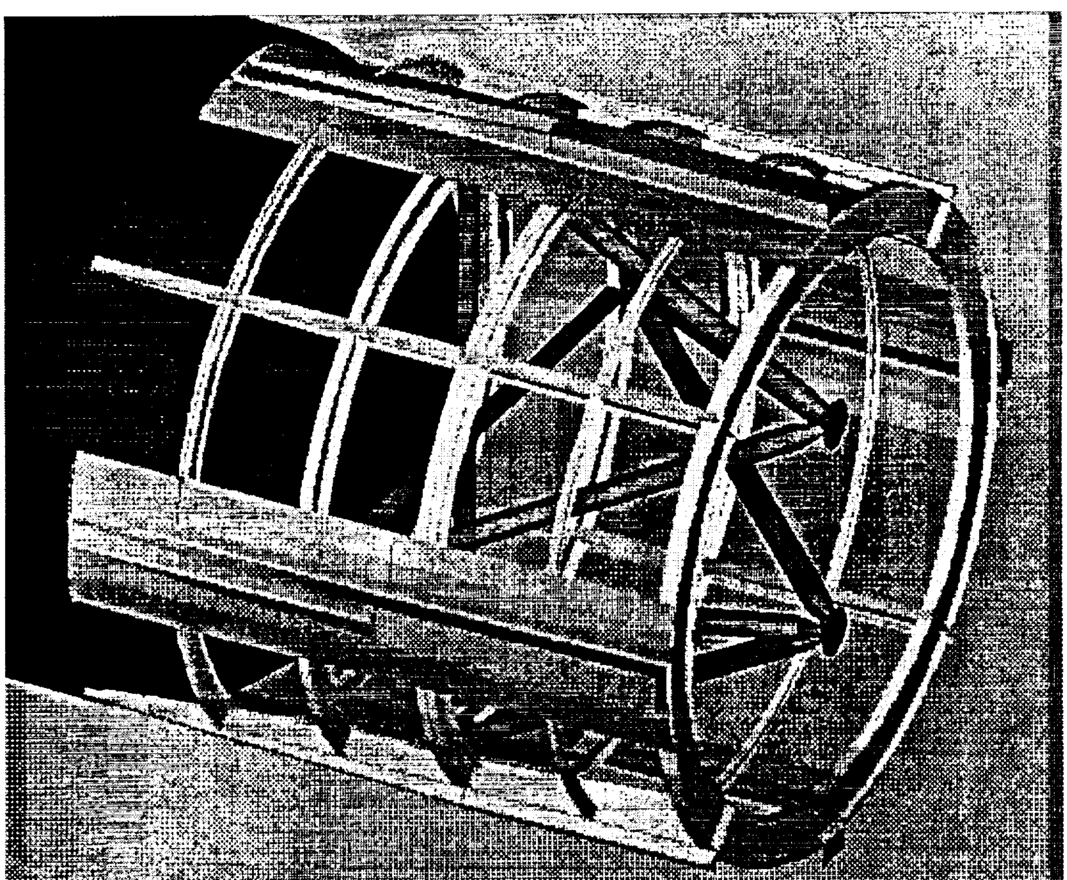
Figure 2.4.2-6 Thrust Structure

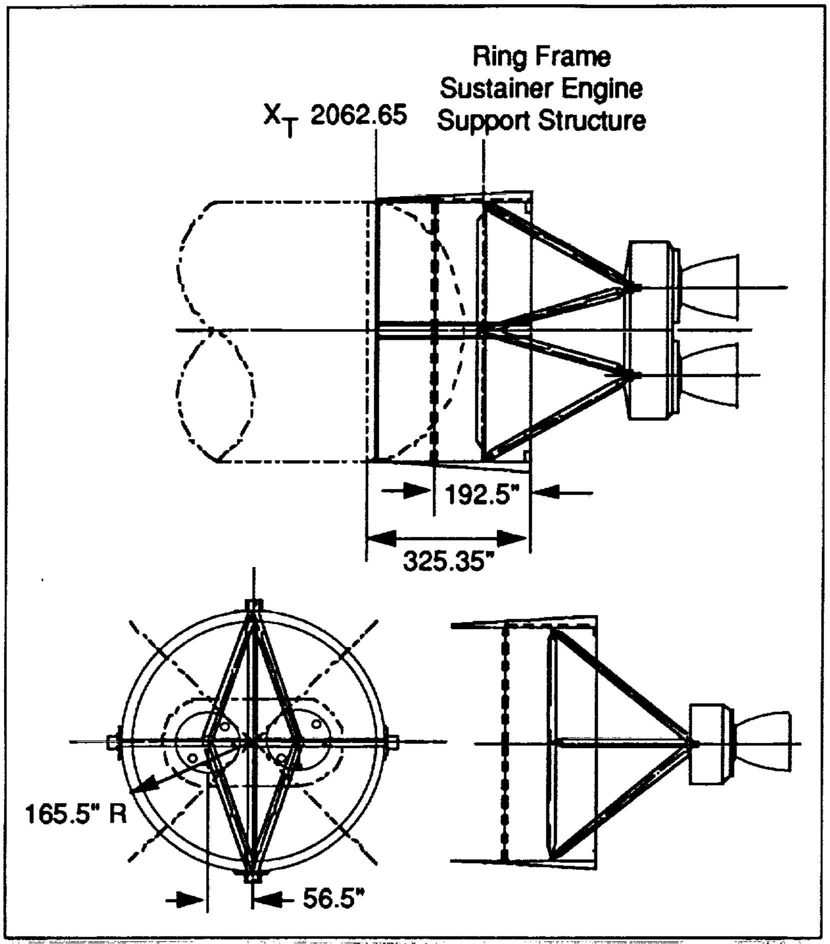

Figure 2.4.2-7 Thrust Structure—Sustainer Engines

The shell for both the upper and lower parts of the module is constructed using skin-stringer panels. Hat stiffeners are used for stringers and are mechanically fastened to sheet and plate material forming the skin The hat stiffeners are located on the outside of the shell, similar to the ET intertank construction, so that complicated intersections to the internal ring frames are eliminated.

All material in the engine module is aluminum alloy. Skin-stringer panels are 2024 sheet, plate and extrusions. Ring frames are 7075 sheet, plate and extrusions, struts for engine mount are 7050 forged and extruded, and hold-down and engine mount longerons are 7050 forgings.

2.5 PROPULSION SYSTEM

A schematic of the proposed main propulsion system for the 1.5 stage launch vehicle is shown in Figure 2.5-1.

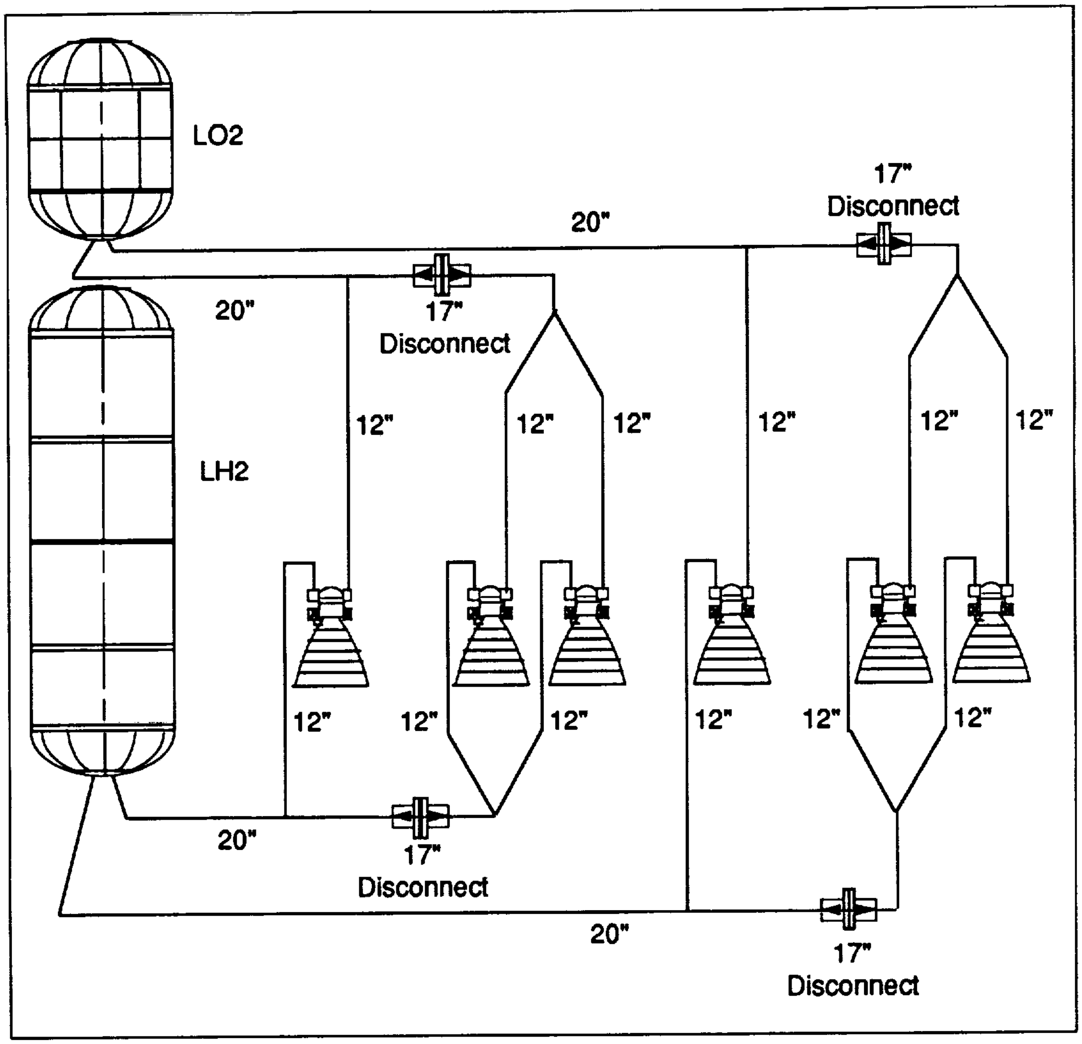

Figure 2.5-1 1.5 Stage MPS Schematic

2.5.1 Liquid Rocket Engine

The baselined liquid rocket engine was the STME. A total of six STMEs were mounted to the engine module thrust structure. Some of the more significant configuration features of this LO2/LH2 engine are as follows:

1) Expendable configuration
2) No boost pumps
3) No required bleeds
4) Open loop control
5) 10° square pattern gimbal capability
6) Straight duct lengths of two diameters required upstream of inlets
7) No engine mounted pogo accumulator
8) Saturated propellant at engine start.

A performance summary for the STME is given in Table 2.5.1-1. It should be noted that throttling was ground ruled for this study.

Table 2.5.1-1 STME Performance Summary

Cycle	Gas generator
Thrust (rated)	
Sea level	502,000 lbf
Vacuum	580,000 lbf
Specific Impulse (rated)	
Sea level	374 sec
Vacuum	432 sec
Propellants	LO2/LH2
Chamber pressure	2250 psia
Mixture ratio	6.0
Area ratio	40
Weight	7300 lbm
Flow rate (rated)	
LO2	1153 lbm/sec
LH2	193 lbm/sec

2.5.2 Propellant Feed System

2.5.2.1 Oxidizer Feed Subsystem

The LO2 feed subsystem shown in Figure 2.5.2.1-1 consists of two 20 inch diameter feedlines connected to separate suction fittings in the LO2 tank aft dome sized to supply LO2 to the six STMEs. The 20 inch feedlines exit the intertank in opposite directions and are routed externally to the propulsion module where 17 inch booster separation disconnects are located. Approximately two line diameters before the disconnects 12 inch feedlines are connected to the 20 inch feedlines to supply LO2 to the sustainer engines. Below each 17 inch disconnect the manifolds split to supply two booster engines. A 10 inch interconnect line connects the 20 inch feedlines to provide a basis for the passive recirculation and antigeyser system. Inside the engine module, feedline routing is based on maintaining a 15° minimum downslope to assist passive recirculation. The dual feedline concept was chosen because it provides a passive recirculation/antigeyser system, reduces protuberance size/loads and permits the use of a three engine main propulsion test article (MPTA).

LO2 feedline sizing is based on Space Shuttle line velocities of 26 ft/sec and a quoted oxidizer mass flow rate of 1153 lb/sec/STME. Gimbal joint selections and the 17 inch disconnects are also based on Space Shuttle technology.

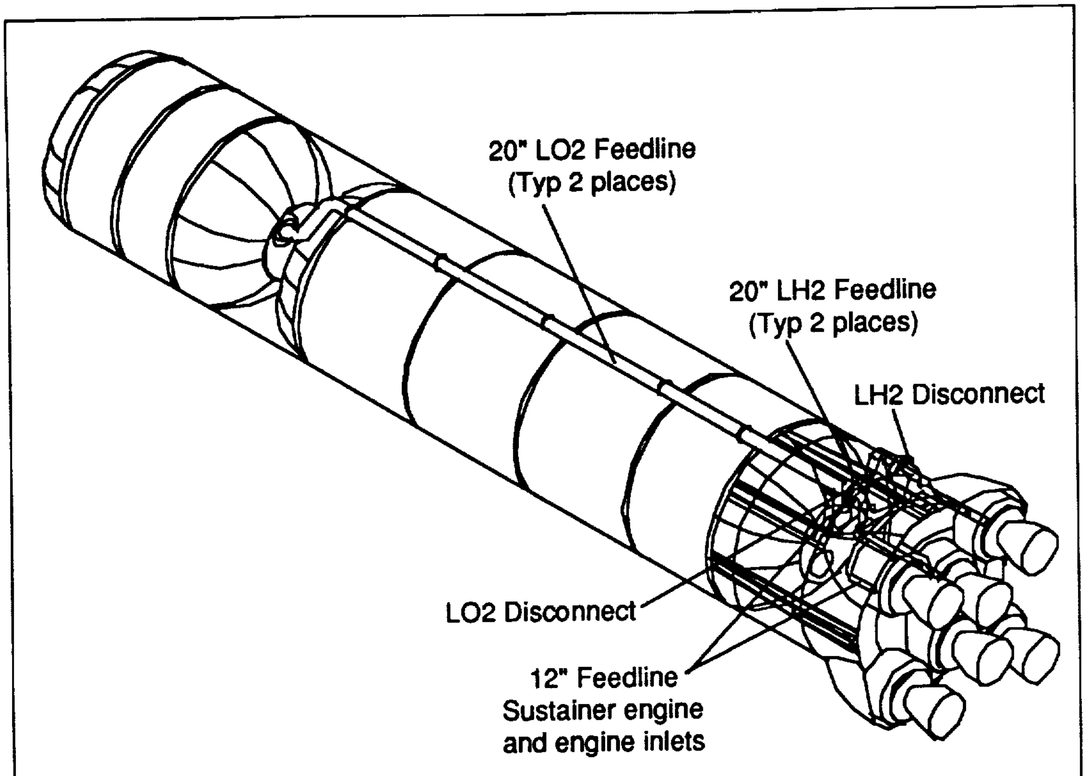

Figure 2.5.2.1-1 1.5 Stage MPS Arrangement

2.5.2.2 Fuel Feed Subsystem

The LH2 feed subsystem shown in Figure 2.5.2.1-1 consists of two 20 inch diameter feedlines connected to separate suction fittings in the LH2 tank aft dome sized to supply LH2 to the six STMEs. The 20 inch feedlines exit the engine module in opposite directions and are routed to the externally mounted 17 inch booster separation disconnects. Approximately two line diameters before the disconnects 12 inch feedlines are connected to the 20 inch feedlines, to supply LH2 to the sustainer engines. Below each 17 inch disconnect the manifolds split to supply two booster engines. Inside the engine module, feedline routing is based on maintaining a 15° minimum downslope to assist passive recirculation. The dual feedline concept was chosen because it permits the use of a three engine MPTA and also minimizes tank penetrations.

LH2 feedline sizing is based on Space Shuttle line velocities of 70 ft/sec and a quoted fuel mass flow rate of 192 lb/sec/STME. Gimbal joint selection and the 17 inch disconnects are based on Space Shuttle technology.

2.5.3 Pressurization System

The oxygen and hydrogen pressurization subsystems are based on current Space Shuttle subsystems and are assumed adequate to meet ullage pressure requirements for each tank. Both subsystems are autogenous, with the oxygen having a fixed orifice control and the hydrogen having an active control valve. Both the GO2 and GH2 pressurization lines are uninsulated 2-inch OD tube fabricated of corrosion resistant steel. Line routing is from the top of each tank, externally down the side of the tankage to a penetration point in the engine module in order to connect with the STMEs.

2.5.4 Vent/Relief System

The oxygen and hydrogen vent and relief subsystems are based on the current ET subsystems and consists of a vent and relief valve at the forward end of each propellant tank. This valve is a dual function valve which can be opened by ground supplied helium (vent) or excessive tank pressure. The LO2 and LH2 tanks will relieve at ullage pressures of 32.0 and 37.0 psi respectively. Subsystem hardware for each tank was assumed to be a 7 inch ID vent/relief valve bolted to the forward dome of each tank with a 5.125 inch ID corrosion resistant steel duct bolted to the valve outlet and extending to the exterior surface of the vehicle.

2.6 THERMAL PROTECTION SYSTEM

The LO2 tank thermal protection system (TPS) configuration consists of spray-on foam insulation (SOFI) covering both the forward and aft domes of the tank. The SOFI was assumed to be required to maintain internal temperatures in both the forward and intertank compartments. The barrel panels have no insulation. The assumed SOFI material was BX-250 which is a 2.0 lb/ft^3 foam. The required foam thickness was estimated to be 0.5-inch.

The intertank TPS configuration consists only of the BX-250 foam used to close out in the area of the flange joining the intertank to the LH2 tank.

The LH2 tank TPS configuration consists of spray-on foam insulation (SOFI) covering the entire exterior of the tank. This insulation was assumed to be required for the following reasons.

1) Prevention of liquifaction/freezing of the nitrogen compartment purge gas
2) Propellant quality requirements
3) Thermal stratification during ascent

The SOFI material assumed for the upper and lower domes was BX-250 while CPR-488 was assumed for the barrel panels. CPR-488 is a 2.4 lb/ft^3 foam that is better suited for areas experiencing aerodynamic heating. Each of these areas were estimated to require 0.5-inch foam.

The base heat shield is covered with approximately 1 inch of 3.0 lb/ft^3 foam. This coverage was assumed adequate for both the flat portion of the shield as well as the power head "nacelles". The insulation material chosen was foam from North Carolina Foam Industries (NCFI) which is currently used on the aft dome of the ET LH2 tank.

The external portions of the LO2 and LH2 feedlines are insulated with CPR-488 foam with the internal sections insulated with BX-250. The propellant feedline insulation was assumed to be required to maintain propellant quality. The estimated thickness of insulation for both the LO2 and LH2 feedlines is 0.5 inch.

2.7 AVIONICS SYSTEM

The major areas of an avionics system assumed to be required for the PLS launch vehicle were guidance, navigation and control (GN&C), data management (DM), instrumentation, and telemetry and tracking (T&T). A block diagram of the avionics system developed for this vehicle is shown in Figure 2.7-1. This system was coordinated with Honeywell, Inc. personnel and features a Hexad Inertial Navigation System (INS) that is currently under development. The Hexad INS has sufficient capability to eliminate the need for a dedicated flight data management computer.

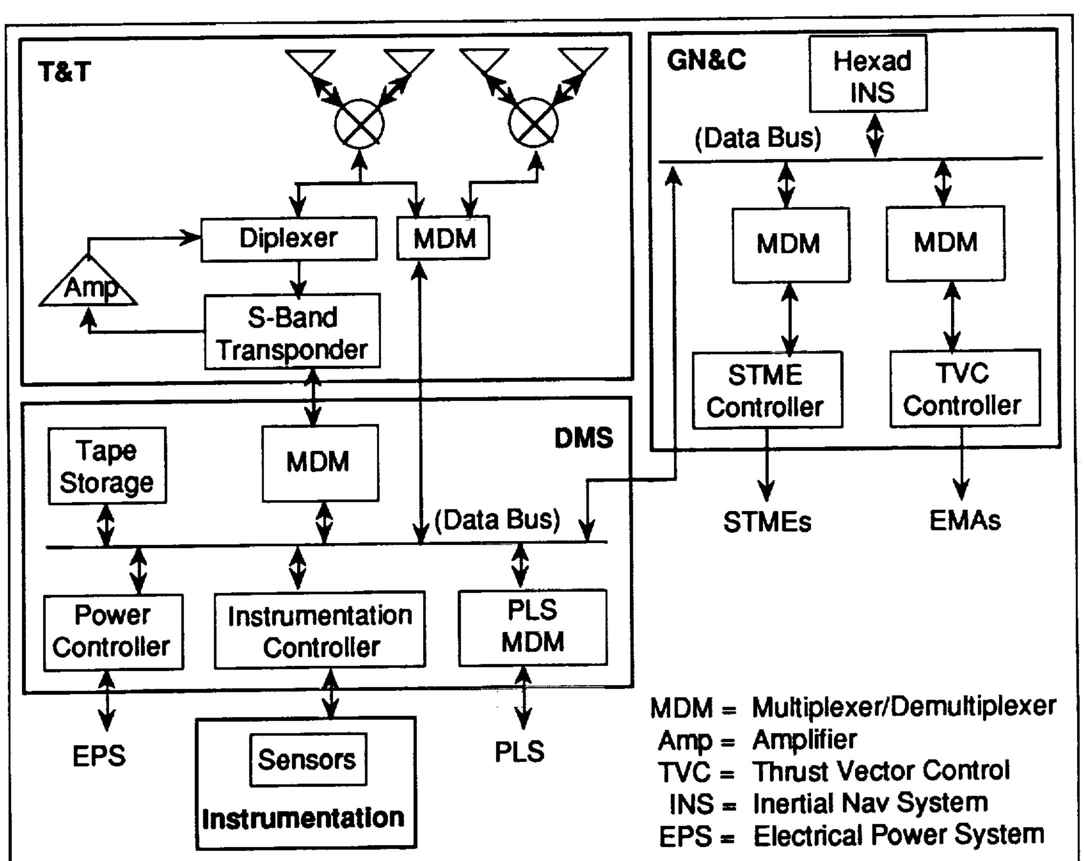

Figure 2.7-1 Avionics Block Diagram

2.8 ELECTRICAL POWER SYSTEM

The electrical power system (EPS) is based on supplying the power required to meet the estimated power and energy requirement for a total mission time of approximately ten minutes. The energy requirement was established assuming a 100% duty cycle for the avionics and environmental control systems. The electromechanical thrust vector control (TVC) system for the two sustainer engines was assumed to have a maximum power requirement for a total of one minute during flight with a nominal requirement during the other approximately nine minutes of flight. The power requirements were estimated to be supplied completely from batteries using Lithium-Carbon monofluoride chemistry. This type battery is currently in an advanced state of development at Eagle Picher and reportedly will exhibit high specific power and energy factors.

2.9 MASS PROPERTIES

2.9.1 Methodology

The weights developed for this study were estimated from 1) dimensional information contained in the preliminary study sketches and layouts, 2) weight related parameters computed from the system level analyses conducted, and 3) existing ET component weights when identified and called out. Allowances ranging from 5 to 20 percent were added to individual weights when appropriate to account for lack of detail in the design concept. A growth allowance was computed to cover any possible insufficient contingency allowances used and/or any inadequate conversion of design information into accurate weight data. This allowance is based on a value of 5 percent applied to all ET-derived delta weights as well as the quoted STME dry weight and a 10 percent factor applied to all systems and new structure weights such as the forward/aft skirts and the engine module.

2.9.2 ET-Derived Tankage Weights

Table 2.9.2-1 ET -Derived Tankage Weights

	Weight (lb)		
	ET Ref	Delta	Derived Tankage
Fwd skirt	N/A	1687	1687
LO2 tank	11903	1108	13011
Intertank	12152	-1275	10877
LH2 tank	27981	6163	34144
Aft skirt	N/A	3878	3878
	52036	11561	63597

Shown in Table 2.9.2-1 are the individual structural assemblies and their estimated weights that comprise the ET-derived tankage for the 1.5 stage launch vehicle. Also shown are the delta weight impacts to the ET elements required to develop this tankage. The total weight increase required is equal to 12 percent of the reference ET structural weight (5,996 lb) added to the forward and aft skirts weights which produces a total tankage weight of 63,579 lb which is 11,561 lb heavier than the ET.

2.9.3 1.5 Stage Launch Vehicle Weight Statement

The buildup and summation of the major weight categories comprising the launch vehicle dry weight is shown in Table 2.9.3-1. The total dry weight of 161,519 lb includes the weight growth allowance discussed in Paragraph 2.9.1 and represents approximately 5 percent of the total vehicle

Table 2.9.3-1 1.5 Stage Launch Vehicle Weights

Total dry weight			161519
Primary structure		87042	
Forward skirt	1687		
LO2 tank	13011		
Intertank	10877		
LH2 tank	34144		
Aft skirt	3878		
Thrust structure	23445		
Secondary structure		2536	
Thermal protection		2668	
Systems		17313	
Main engines (6 STMEs)		43800	
Growth		8160	

Above weights do not include PLS vehicle or adapter

Table 2.9.3-2 PLS Launch Vehicle Liftoff Weight

	PLS Weight (lb)	
	Minimum	Maximum
Launch vehicle at liftoff	1,805,974	1,833,474
Booster & sustainer stages	1,759,950	1,759,950
Dry weight	161,519	161,519
Residual	42,154	16,909
Usable	33,904	8,659
Unusable	8,250	8,250
Usable propellant	1,556,277	1,581,522
PLS adapter	7,524	7,524
PLS vehicle & margin	38,500	66,000

weight. Detailed in Table 2.9.3-2 are the items and their estimated weights contributing to the buildup of the PLS launch vehicle gross liftoff weight. Included in this buildup is the breakdown of the vehicle residuals into two categories; 1) propellant considered unusable and 2) propellant remaining as a result of under utilized vehicle performance. The performance analyses conducted revealed that the specified PLS payloads do not create a weight critical condition for this vehicle with an equivalent ET propellant load.

2.10 AERODYNAMICS

Preliminary six-degree of freedom aerodynamic coefficients were computed for the proposed PLS launch vehicle at mach numbers from 0.05 to 10. Viscous, shielding, and power-on base effects were not included. The PLS configuration used was the NASA/LaRC lifting body version and a computer model of this vehicle was provided by Christopher Cruz from NASA/LaRC.

For this analysis, the supersonic-hypersonic arbitrary body program (S-HABP) was used to

Table 2.10-1 PLS Vehicle Aero Coefficients

Mach Number	Coefficients					
	Axial Force	Normal Force	Pitching Moment	Side Force	Yawing Moment	Rolling Moment
0.05	0.4260	0.0116	0.0043	0.0000	0.0000	0.0000
0.40	0.4204	0.0122	0.0044	0.0000	0.0000	0.0000
0.60	0.4217	0.0125	0.0045	0.0000	0.0000	0.0000
0.80	0.4505	0.0142	0.0051	0.0000	0.0000	0.0000
0.90	0.4899	0.0152	0.0055	0.0000	0.0000	0.0000
0.95	0.5135	0.0165	0.0061	0.0000	0.0000	0.0000
1.10	0.6119	0.0192	0.0077	0.0000	0.0000	0.0000
1.20	0.6198	0.0278	0.0112	0.0000	0.0000	0.0000
1.40	0.6041	0.0320	0.0138	0.0000	0.0000	0.0000
1.53	0.5699	0.0325	0.0144	0.0000	0.0000	0.0000
2.00	0.5080	0.0222	0.0090	0.0000	0.0000	0.0000
2.50	0.4836	0.0171	0.0062	0.0000	0.0000	0.0000
3.00	0.4723	0.0143	0.0047	0.0000	0.0000	0.0000
3.50	0.4652	0.0125	0.0037	0.0000	0.0000	0.0000
4.00	0.4602	0.0113	0.0030	0.0000	0.0000	0.0000
4.50	0.4571	0.0104	0.0025	0.0000	0.0000	0.0000
10.00	0.4475	0.0168	0.0055	0.0000	0.0000	0.0000

Sref = 86153.03 sq. in. X-MRP = 1585.0 in.
Lref = 2437.38 in. Y-MRP = 0.0 in.
Span = 331.20 in. Z-MRP = 0.0 in.

Angle of Attack = Angle of Sideslip = 0.0 Deg.
Power-on base drag, viscous and interference effects not included.

compute the aerodynamic characteristics of the PLS configuration above Mach 2. Wind tunnel test data supplied by Mr. Cruz for the PLS lifting body was used to determine the accuracy of the theoretical methods that were applied to the vehicle configuration. Above Mach 2 relatively good agreement was obtained between wind tunnel test results for the PLS lifting body and theoretical computations. Therefore, identical theoretical methods were implemented for the PLS vehicle configuration. Wind tunnel test results for the PLS lifting body and the Titan Dyna-Soar launch vehicle were used to determine the relative aerodynamic characteristics below Mach 2. The Titan Dyna-Soar concept which was studied in the early 1960s is similar in design to the proposed 1.5 stage PLS launch vehicle configuration.

Table 2.10-1 presents tabulated longitudinal aerodynamic characteristics for the vehicle configuration at an angle of attack and sideslip of zero degrees. Since the PLS configuration is symmetrical about the X-Z plane, lateral aerodynamic forces and moments were zero at the aforementioned angles. The normal force and pitching moment coefficients are relatively linear with angle of attack up to plus or minus eight degrees. The side force, yawing moment, and rolling moment coefficients

Table 2.10-2 PLS Vehicle Aero Slope Coefficients

Mach Number	Slope Coefficients (+/- 4 Deg.)				
	Normal Force	Pitching Moment	Side Force	Yawing Moment	Rolling Moment
0.05	0.1770	0.0248	-0.1050	-0.1340	-0.0009
0.40	0.1800	0.0251	-0.1055	-0.1352	-0.0009
0.60	0.1817	0.0258	-0.1065	-0.1355	-0.0009
0.80	0.1890	0.0270	-0.1130	-0.1370	-0.0009
0.90	0.1910	0.0282	-0.1138	-0.1378	-0.0009
0.95	0.1915	0.0283	-0.1140	-0.1380	-0.0009
1.10	0.1920	0.0280	-0.1139	-0.1376	-0.0014
1.20	0.1922	0.0274	-0.1081	-0.1358	-0.0014
1.40	0.1880	0.0251	-0.0965	-0.1300	-0.0011
1.53	0.1875	0.0245	-0.0941	-0.1281	-0.0009
2.00	0.1611	0.0211	-0.0700	-0.1148	-0.0007
2.50	0.1309	0.0189	-0.0615	-0.1055	-0.0005
3.00	0.1130	0.0178	-0.0530	-0.1000	-0.0005
3.50	0.1010	0.0170	-0.0472	-0.0950	-0.0004
4.00	0.0922	0.0165	-0.0430	-0.0930	-0.0004
4.50	0.0856	0.0161	-0.0399	-0.0900	-0.0004
10.00	0.0579	0.0145	-0.0265	-0.0850	-0.0002

Sref = 86153.03 sq. in.	X-MRP = 1585.0 in.
Lref = 2437.38 in.	Y-MRP = 0.0 in.
Span = 331.20 in.	Z-MRP = 0.0 in.

Power-on base drag, viscous and interference effects not included.

are also linear with respect to the sideslip angle within plus or minus eight degrees. Table 2.10-2 provides slopes for the normal and side forces along with the pitching, yawing, and rolling moments. Slopes were not provided for the axial force component since, at small angles of attack, the differences are minimal.

Preliminary estimates show the launch vehicle configuration to be unstable in both yaw and pitch while stable in roll based on the moment reference point selected for this analysis. A more forward center of gravity (CG) location will increase the stability margin as well as decrease the bending moments. The natural longitudinal trim point occurs between -0.5 and -2.0 degrees angle of attack for the Mach range selected in this analysis. For inline configurations, the CG is often aft of the center of pressure which causes an unstable condition. The thrust provided by the gimbaling engines will generally allow the vehicle to fly right through the longitudinal instability. As the vehicle travels through the atmosphere the CG will move forward and the margin of stability will generally increase. The longitudinal center of pressure will also shift relative to the Mach number and angle of attack. Launch vehicles with inline payload configurations and unstable pitching moments have successfully flown in the past (Titan III, etc.).

2.11 FLIGHT PERFORMANCE

The launch vehicle conceptualized during this study was evaluated to determine its capability to meet the PLS lift requirements of 35,000 and 60,000 lb to LEO. The ground rules and assumptions that were applied to this evaluation were as follows:

1) PLS vehicle inserted in 35 x 160 nm elliptical transfer orbit
2) STME has two step throttle capability (75 & 100 % RPL)
3) One engine out at liftoff
4) Total usable propellant of 1,590,181 lb
5) PLS adapter weighs 7,524 lb
6) Max dynamic pressure < 900 psf (Goal ≤ 800 psf)
7) Max acceleration = 4 g
8) Ten percent payload margin considered
9) Equivalent ET propellant load.

The simulated ascent trajectory began at KSC and terminated with the insertion of the PLS vehicle into a 35 x 160 nm elliptical orbit. The orbital insertion point parameters were 1) velocity of 25,871 ft/sec, 2) flight path angle of 0.767°, and 3) an altitude of 57 nm. This simulated trajectory was flown twice; once with a PLS weighing 66,000 lb (10 % payload margin added) and again with a PLS weighing 38,500 lb (margin included). The results indicated that the 1.5 stage launch vehicle design concept developed during this study is capable of placing each of these payloads into the specified orbit. Engine throttling was employed to avoid exceeding the ground ruled maximum acceleration and dynamic pressure values. Ascent trajectory data is shown in Table 2.11-1.

Table 2.11-1 Ascent Trajectory Parameters

Flight Parameter	PLS Weight Min	PLS Weight Max
Liftoff thrust-to-weight	1.38	1.36
Booster max accel (g)	4.00	4.00
Booster staging time (sec)	190	190
Maximum dynamic press (psf)	793	785
Sustainer max accel (g)	2.98	2.95
Sustainer engine cutoff (sec)	433	442

These results provide a basis to conclude that the vehicle has the required lift capability and possesses a performance margin due to the usable propellant remaining. These reserves could be used to compensate for variations in engine thrust/specific impulse and/or vehicle liftoff weight. These reserves then can be viewed as reducing the performance risk associated with this PLS launch vehicle concept. The usable propellant remaining varies depending upon the PLS weight (Figure 2.11-1). Discrete amounts associated with the specified PLS weights are shown in Table 2.9.3-2.

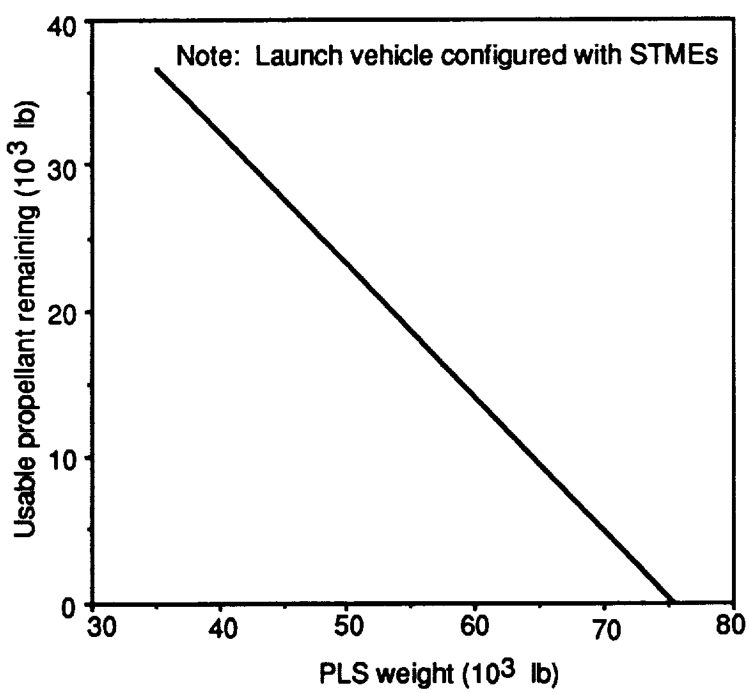

Figure 2.11-1 PLS Launch Vehicle Propellant Reserves

The performance of this launch vehicle was also evaluated using SSMEs rather than STMEs and was found to have sufficient lift capability to carry the specified PLS payloads to orbit.. A plot of usable propellant remaining as a function of payload weight is shown in Figure 2.11-2. It should be

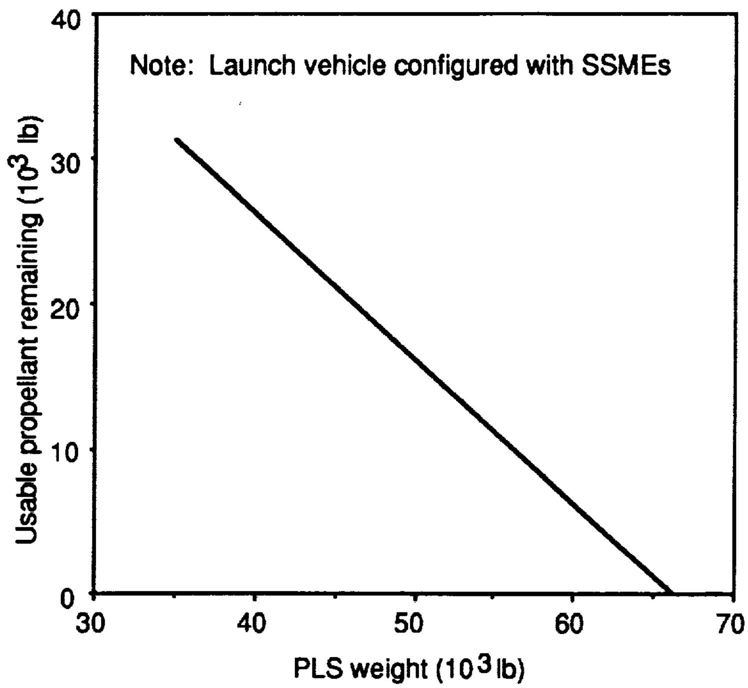

Figure 2.11-2 PLS Launch Vehicle Propellant Reserves

noted that with SSMEs the total propellant loaded was 1,570,000 lb. This was required to obtain a reasonable liftoff thrust-weight ratio.

3.0 TASK 5b - MANUFACTURING/PRODUCTION

3.1 SUMMARY

The 1.5 Stage Launch Vehicle Production Plan has been developed for total assembly and integration at MAF. The approach makes effective use of underutilized manufacturing areas, existing tooling and facility capacities, and infrastructure on a non-interference basis with the ongoing ET project.

Two approaches were considered.

1) The vehicle would be assembled completely and checked out at MAF including the assembly of the propulsion module to the ET-derived tankage and installation of the main engines.

2) The tankage would be fully assembled and partially checkedout, including all system installations to the propulsion module interface. The propulsion module would also be fully assembled and partially checked out at MAF.

A manufacturing approach was devised for the production of seven 1.5 stage PLS launch vehicles per year concurrent with an ET production rate of twelve per year, as defined in the statement of work (SOW). The manufacturing approach involved:

1) Defining manufacturing ground rules and assumptions
2) Analyzing capacities of the existing ET major tooling
3) Developing manufacturing flows
4) Defining tooling impacts
5) Defining schedule impacts
6) Defining facilities impacts.

3.2 MANUFACTURING GROUND RULES AND ASSUMPTIONS:

For study purposes it was necessary to establish ground rules and make assumptions based on the SOW and knowledge of the ET working environment.

Our plan is based on the assumption that an authority to proceed (ATP) would be issued at the start of FY 93 and that the defined ET production rate of 12 ETs per year would be commensurate with the POP 90-2 program operating plan. The POP 90-2 will require a five day, two shifts per day schedule. This will be increased to a five day, three shifts per day work schedule to accommodate the additional seven 1.5 stage vehicles.

The projected schedule assumes that all new and/or modified tooling and facilities will be phased into production with the first tooling available approximately nineteen months after the ATP, and that tool and facility modification windows will be available. The plan also assumes the manufacture of the launch vehicle will use current ET manufacturing technologies and established processes, and that overall ET manufacturing philosophy will prevail, i.e., all construction will be at MAF using vendor-supplied detail parts and sub-assemblies.

3.3 CAPACITY OF ET MAJOR TOOLING

All tools and processing cells are capable of meeting or exceeding the prescribed production rate of 24 ETs per year; however, an analysis of the existing ET tooling was performed to determine the maximum capacity of each tool and/or facility in terms of its major function, in order to evaluate the capability to produce both ET and 1.5 stage vehicle tankage. For example, the maximum number of dome quarter panel assemblies or the number of individual barrel assemblies that could be produced on a specific tools was evaluated and the results of this analysis is shown in Table 3.3-1.

Table 3.3-1 Major Tooling Capacity Analysis

Operation	Capability Per Year	ET Req'mt 12 per yr	PLS LV 7 per yr	Total Req'd	Margin
Dome Assembly Tooling	87 Domes	36	28	64	23
Barrel Weld Tool #5015	52 Barrels	24	7	31	21
Barrel Weld Tool #5016	78 Barrels	36	28	64	14
"T" Ring Assembly	176 Rings	48	21	69	107
Major Weld Fixt #5018	96 Circ Welds	48	14	62	34
Major Weld Fixt #5019	168 Circ Welds	84	56	140	28
Major Weld Fixt #5068	30 Circ Welds	12	14	26	4
Intertank Assembly	24 Assemblies	12	7	19	5
LH2 Tank Clean & TPS Operations	26 Tanks	12	14	26	0
Final Assembly	24 Vehicles	12	7	19	5

3.4 MANUFACTURING FLOWS

3.4.1 ET-Derived Tankage

With the capacity of each major production station defined, manufacturing flow diagrams were prepared to identify the major vehicle production activities through factory test/checkout, and preparation for shipment.

All mechanically fastened subassembly operations, e.g. a ring frame assembly, will use ET fixturing whenever possible. Detail parts will be located and tack fastened in assembly fixtures, then removed to the existing riveting center for automatic rivet installation on a large C-frame riveter. The assemblies will then be moved to off-load fixtures for removal of tack fasteners, installation of flight fasteners, and subsequent overall inspection.

The LH2 and LO2 tank barrel manufacturing sequence flows are identical to the ET and use ET fixtures, tooling, nondestructive evaluation (NDE) facilities, etc. The procured barrel skin panels are cleaned in the existing MAF facility prior to welding. Weld assembly, trim, and frame installation will be accomplished on ET tooling and will use ET roll rings and roll ring installation tooling.

Rings with "H" sections will be procured fully machined, stretch formed and trimmed in 90° sections. These sections will be welded together to form the 360° rings, machined and drilled, etc. in the ET ring tools. Rings with "J" sections will be procured as extrusions, stretch formed, aged and trimmed to 90° sections. These will be spliced into complete rings at MAF prior to assembly in the barrels.

Fabrication of the domes will be accomplished using the family of ET dome weld tooling. New

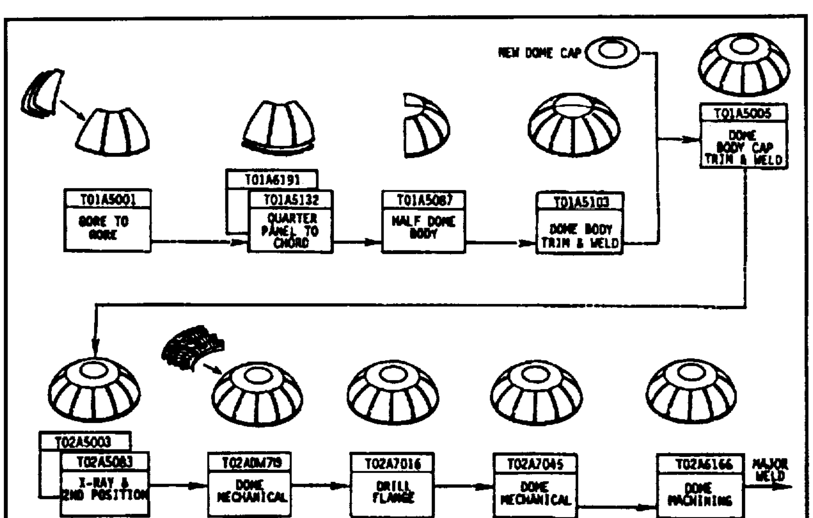

Figure 3.4.1-1 LH2 Tank Aft Dome Manufacturing Flow

adaptive tools will be required for preparation and installation of the new-design dome caps and fittings, and a new tool is required for the LH2 tank aft dome mechanical installations. An illustrated flow diagram of these operations is shown in Figure 3.4.1-1.

Both internal and external cleaning, priming, and TPS application will use the ET LH2 tank processing cells.

New dedicated tooling will be required for the assembly of the anti-vortex and slosh baffle assemblies, and will be located in MAF Bldg 103. Elements of these assemblies will be procured from outside suppliers ready for installation.

The manufacturing flow for the LH2 and LO2 tank assemblies will be similar to the ET process and will use existing tools, equipment and facilities where practical. The flows differ from ET only in that the 1.5 stage vehicle LO2 tank weld operations are performed on ET LO2 tank major weld tooling using a dedicated adapter which permits use of an ET LH2 forward dome attachment basket to locate the LO2 tank forward dome during dome-to-barrel weld operation, slosh baffle installation and aft dome-to-tank weld.

Cleaning, priming, and TPS application will use the ET LH2 tank processing cells, except that the LO2 tank will be processed through Cell P for external clean and prime and Cell K for the application of TPS SOFI on the forward and aft domes only.

Intertank assembly will be performed on the ET family of intertank tooling with the aid of an adapter to simulate the SRB beam and provide a location point for the handling attachments, which simulate the SRB attachment points used in the ET handling and transportation activities. LO2 and LH2 tank interface bolt hole patterns will be identical to ET and will use the existing drill plates incorporated in the ET tooling.

A manufacturing flow developed for the forward skirt subassembly activities will be performed on the ET intertank tooling where possible, and major assembly activities on dedicated assembly fixtures at MAF. LO2 and LH2 tank interface bolt hole patterns will be identical to ET and will use drill plates mastered from existing ET tooling.

The assembly sequence for the 1.5 stage vehicle tankage is similar to the ET except that the forward skirt assembly to LO2 tank to intertank stacking will be accomplished in Cell L. The assembly will then be transferred to Cell A for stacking to the LH2 tank and TPS closeout of the intertank/LH2 tank interface. The completed stack will then be lowered to the horizontal position, mounted onto a transporter and moved to the final assembly station.

3.4.2 Propulsion Module

Approach #1

The propulsion module manufacturing sequence uses ET tooling for interface ring segments splicing and machining operations. Dedicated fixtures will be located in MAF Bldg 303 for module structural assembly and partial systems installation and checkout. Tooling will be installed to secure systems elements which will interface directly with the tankage, e.g. propulsion lines, etc. Following checkout, the modules will be removed from the fixtures, rotated through 90° and secured to a dolly for transfer to the final assembly position.

Approach #2

This propulsion module manufacturing sequence is similar to that for Approach #1. The module is assembled and partial systems installation performed on dedicated tooling in Bldg 303; however, once this is completed, the module would be rotated through 90°, mounted onto a assembly/ transporter fixture, and all systems installed to the maximum extent possible for shipment to KSC.

Mastered tooling will be required to control the propulsion module-to-tankage interfaces and temporary tooling will be installed to secure system elements which will interface directly such as the propulsion feedlines. Test and checkout will be accomplished in a separate facility located within Bldg 303.

3.4.3 1.5 Stage Vehicle Final Assembly, Test and Checkout

Approach #1

The sequence flow uses either of two former ET final assembly positions in MAF Bldg 103 where the aft skirt will be installed to the new aft external flange of the LH2 tank and TPS closeouts made in the dome/ring crotch and the tank/ring flange. Following completion of this operation the propulsion module is attached and all remaining systems installed, including the installation of the engines. Finally, the completed vehicle is moved to one of two test and checkout cells in MAF Bldg 420 where all systems will be verified, a full inspection performed, and the vehicle prepared for shipment.

Approach #2

The manufacturing flow for the ET-derived tankage is similar to Approach #1 except that following installation of the aft skirt all systems are installed to the vehicle tankage and are terminated at the interface to the propulsion module. Mastered interface tooling will be provided to control the locations and, again, the completed tankage will be moved to Bldg 420 for an all systems test and checkout, then prepared for shipment.

Final assembly, test, and checkout of the propulsion module will be a stand alone operation accomplished in Bldg 303 as discussed above.

3.5 TOOLING IMPACTS

Tooling for the vehicle structural assembly and systems installations has been determined for the current conceptual design and will be reviewed and appropriate changes made as the design matures to ensure production rate and improved manufacturing efficiency.

The proposed 1.5 stage launch vehicle schedule of seven vehicles per year and an ET build schedule of 12 ETs/year permit a tooling approach that allows maximum use of existing NASA ET tooling, facilities, and equipment for fabrication and assembly at MAF. Some minor modifications and new adapters will be required to facilitate attachments and/or to provide necessary clearances. Unique hard tooling is provided only for those assembly operations and/or reassembly of subcontracted flight hardware where no comparable ET tooling exists.

Manufacture of the LH2 tank will be similar to the ET process and will use all existing tools, equipment, and facilities. The LO2 tank is similar to the LH2 tank but cannot be constructed on the LH2 major weld tool due to capacity limitation. The ET LO2 tank major weld tool will be modified to accomplish this operation. The modification will involve an adapter to accommodate a forward dome basket in place of the ET ogive basket and a new additional barrel support carriage. The existing dome weld tooling will be modified to accommodate feedline outlet fitting locations and a new dome mechanical installation tool provided for the LH2 tank aft dome.

Internal and external cleaning, external finishing, and TPS operations will all be performed in the existing ET processing cells using established processes and procedures. New adapters will be provided for those tools and cells which use the orbiter or SRB interfaces during ET processing. In addition, new support tooling will be required in Cell L for the forward skirt to LO2 tank to intertank stack operation.

New dedicated fixtures will be required for the forward and aft skirt assemblies and for the non-ET frame assemblies used in the skirts and in the LH2 tank. In addition to handling equipment, a complete set of detail fabrication and structural assembly tools will be required for the manufacture of the propulsion module. For all of these new assemblies, the highly successful assembly methodology developed for the fabrication of the ET components will be used.

A new complement of special test equipment (STE) will be required for the factory test and checkout of the completed vehicle to attain the desired ship and shoot capability. This STE can take advantage of the significant advances in electronics technology over equipment currently used for factory test and checkout of the ET.

3.6 SCHEDULE IMPACTS

No schedule impacts have been identified for either the ET-derived tankage or the propulsion module fabrication; the manufacturing requirements (tools and processing cells) for the proposed mission model of seven 1.5 stage vehicles in addition to 12 ETs per year does not exceed current capacities in place at MAF for 24 ETs per year.

Integration of the propulsion module to the ET-derived tankage at either MAF or KSC has no schedule impacts at MAF.

3.7 FACILITIES IMPACTS

Structural assembly areas within MAF Bldg 103 will be provided for the forward and aft skirt assembly and slosh baffle assembly fixtures. These positions will be located under existing crane coverage and supplied with all necessary utilities.

An additional position with a reinforced foundation will be provided for the new aft dome mechanical installation fixture. This area will be in the northeast corner of MAF Bldg 103 and will require relocation of the tool maintenance facility. Figure 3.7-1 is a layout of MAF showing building locations and is included for reference.

Cells A, E, F and L will require modifications to add platforms and stairs to provide access for installation and removal of handling equipment. Cell E will also require a new probe and cover plate for the LO2 Tank internal cleaning.

Final assembly areas in Bldg 103 will require rework to accommodate vehicle integration and engine installation operations, e.g. additional jacking pad foundations, and foundation reinforcements to support the propulsion module installation.

Since the overall length of the integrated 1.5 stage vehicle is longer than the ET, the test and

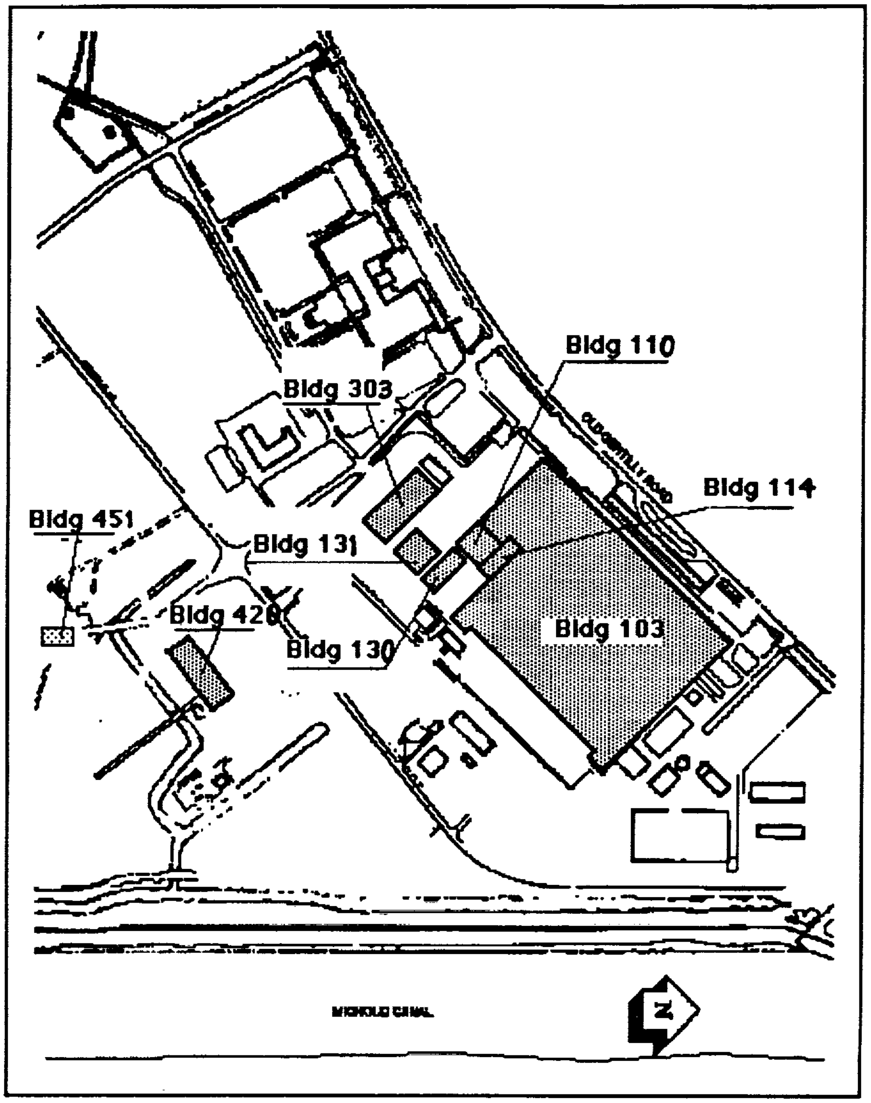

Figure 3.7-1 Layout of MAF Showing Building Locations

checkout facility (Bldg 420), will be extended to accept the increased vehicle length. In addition, a computer room will be constructed to house the new enhanced computer equipment required for the all-systems test and verification requirements of the ship and shoot philosophy.

4.0 TASK 5c - TEST PROGRAM/CERTIFICATION

This section describes the integrated approach taken to design verification for the 1.5 stage PLS vehicle. For an integrated approach, development tests are used to supply data for analytical processes and qualification tests, then major ground tests are used to verify the processes. Section 4.1 describes the overall testing plan for the vehicle, Section 4.2 describes the major ground tests, and Section 4.3 describes the test facilities that have been identified for possible use.

4.1 TASK SUMMARY

In the ET program the approach to verification included an integrated test program which featured:

1) Preplanned development tests to support design and analysis

2) Qualification tests of newly designed components at the component assembly level

3) Major ground tests to verify adequacy of flight-type hardware and substantiate analysis, manufacturing, checkout, handling and transportation procedures

4) Functional and environmental acceptance tests of electrical/electronic equipment components to identify defective components prior to installation

5) Proof pressure tests of all propellant tanks based on fracture control technology

6) Power-on integrated systems tests on DDT&E vehicles prior to delivery, and on all subsequent vehicles at the launch site prior to mating with other elements of the Space Shuttle.

The approach taken for an integrated test program for the 1.5 stage vehicle relies heavily on ET program experience and lessons learned. Overall number of tests has been reduced along with the amount of time required to conduct the tests. Development tests to support the design and analysis tasks have been minimized because many tests for material properties and their design allowables, and TPS/structures compatibility and design allowables have already been accomplished on the ET program and no new materials have been specified for the 1.5 stage vehicle. Major structural ground tests have also been simplified since the 1.5 stage vehicle structure is similar or the same as the ET structure, and ultimate capability has already been determined. Qualification of new components, functional and environmental acceptance tests, proof pressure tests for each propellant tank, and power-on systems tests on all vehicles at the launch site will still be conducted as in the ET program along with a completely new verification program for the engine module and propulsion system.

4.2 MAJOR GROUND TESTS

Major structural ground tests are required to verify design adequacy of the flight hardware, substantiate the various analyses performed for design and to assess checkout, handling and transportation procedures. The major ground test for the propulsion system, the main propulsion test article (MPTA), is required to assess and verify propulsion system performance parameters. In the 1.5 stage PLS launch vehicle program, separate contractors for the vehicle tankage and engine module package may exist. If this is the case (Table 4.2-1), joint responsibility of both contractors

Table 4.2-1 Major Ground Tests

Test requirements
- Verify structural integrity
- Obtain data to substantiate analysis
- Assess checkout, handling, and transportation
- Assess and verify propulsion system performance parameters

Tests	Responsibility	
	Core vehicle Contractor	Engine module Contractor
Component tests	✔	✔
Tie-down fittings		
Engine mounting fittings		
Lift fittings		
Main propulsion test article (MPTA)	✔	✔
Structural test article (STA)	✔	✔
Includes modal tests		
Shock and staging tests	✔	✔

will be necessary in much of the testing program. The structural test program will require structural test articles (STA) for the tankage and engine module. The MPTA will require the engines, engine module and tankage with feedlines to be supplied by each contractor. Each contractor will also perform individual component tests on fittings such as tie-down, engine mount, and lift fittings, that are a unique part of that assembly. Data on load distribution from engine module tie-down fittings into longerons in the lower skirt and LH2 tank of the vehicle is required by both contractors and require coordination of test objectives and results. The STAs are described further in Section 4.2.1 and the MPTA is described in Section 4.2.2.

4.2.1 Structural Test Article

The first vehicle assemblies off the production line will be used for the STA. The STA, as shown in Figure 4.2.1-1, will consist of forward skirt and PLS adapter, an LO2 tank, an intertank structure,

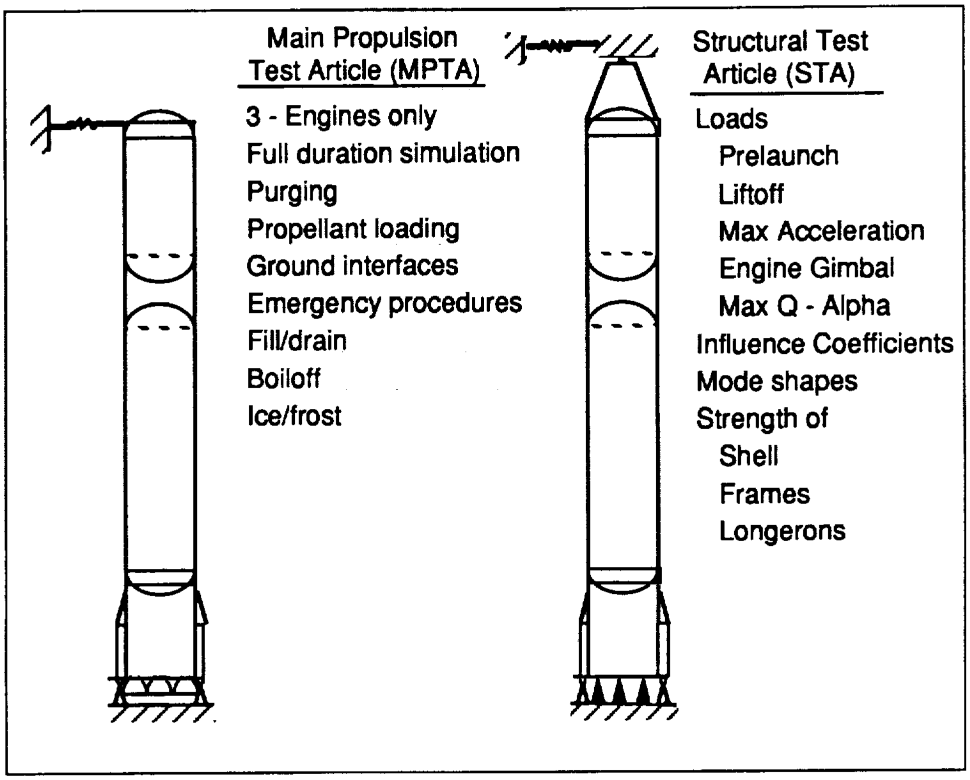

Figure 4.2.1-1 Major Ground Tests—MPTA and STA

LH2 tank and lower skirt, and an engine module less engines. The PLS adapter is shown because it would be advantageous for NASA to test this structure at the same time Propellant feedlines, pressurization lines, and electrical/electronic equipment are not required for the STA. An extensive instrumentation system consisting of strain gauges, pressure and temperature transducers, and accelerometers will be included in the STA. As shown in the figure, loads required to be applied to the STA will be prelaunch, liftoff, maximum g, engine gimbal, and maximum Q-Alpha loads. Data obtained from the STA will verify the strength of the shell structures including the frames and longerons.

A test fixture that can apply both axial and lateral loads to the STA while the STA is supported off its engine module structure is necessary for the program. A tension leg frame similar to that shown in Figure 4.2.1-2 was considered as one possible means of applying the high axial loads (approximately 400 klb) that are required to load the upper elements. Water in the LO2 tank will be used to increase axial loads for the intertank, LH2 tank, aft skirt, and engine module. If the stand is located

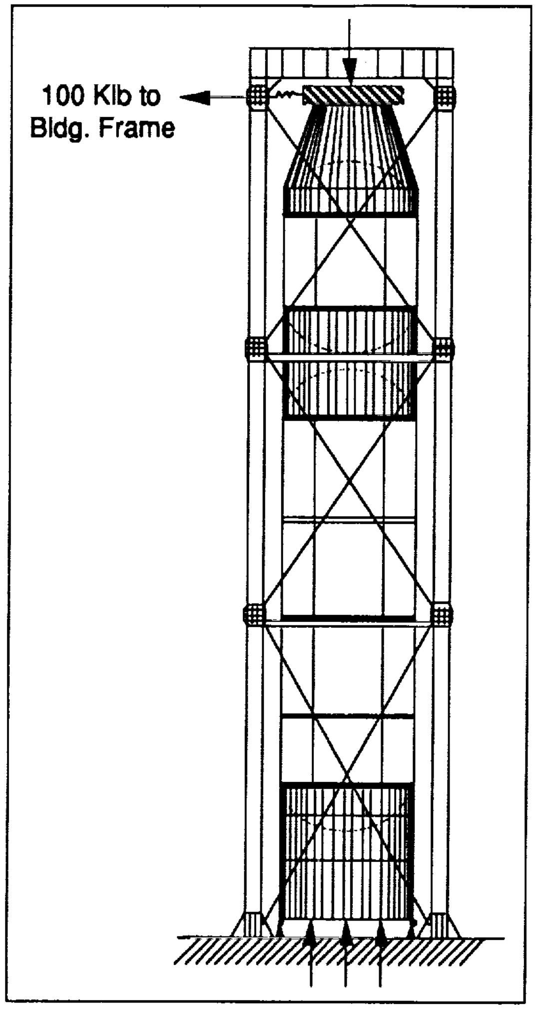

Fig 4.2.1-2 Major Ground Tests - STA

in a suitable test building where structural framing is already present, lateral loads which total a maximum of 100 klb on the stacked vehicle can be applied by the building frame and the tension leg frame will not have to carry the lateral loads.

An important aspect of the STA tests involve applying ultimate loads to the component elements affected by thermal loads and displacements. The intertank will be tested in the cold condition at the LO2/intertank interface by filling the lower end of the LO2 tank with LN2 at -300°F. The LO2 and LH2 tanks can be tested individually with the intertank attached in the same stand by first testing the LO2 tank then turning the specimen upside down. Each tank's lower dome will be filled so that all thermal conditions in the shell can be tested for worst case loads.

Separate modal tests on the tanks were eliminated from the test program because of the similarity of the tanks to the ET tanks in size, shape and construction and because the ET program verified the analytical methods used to predict mode shapes and frequencies. If additional verification is required, the assemblies can be excited while in the STA test stand. Reliance on proven analytical methods for determination of important dynamic parameters will significantly reduce the amount of testing and shorten the overall test program. On this basis, no separate ground vibration test article (GVTA) testing will be specified.

Both tankage and engine module contractors, if different, will be involved in the STA. The engine module's four hold-down fittings for attaching to the launch pad will be used to attach to the test stand floor. Both tankage and engine module are then tested together without the need for simulators, thereby saving time and test hardware. As is the case for all flight tanks, the STA tanks will be proof tested with test factors determined by fracture control technology.

Additional major structural tests involve shock testing of the engine module structure and staging of the lower half of the module. As shown in Figure 4.2.1-3, the shock tests involve the actuation of the explosive bolt devices and the measurement of response spectra and vibration response

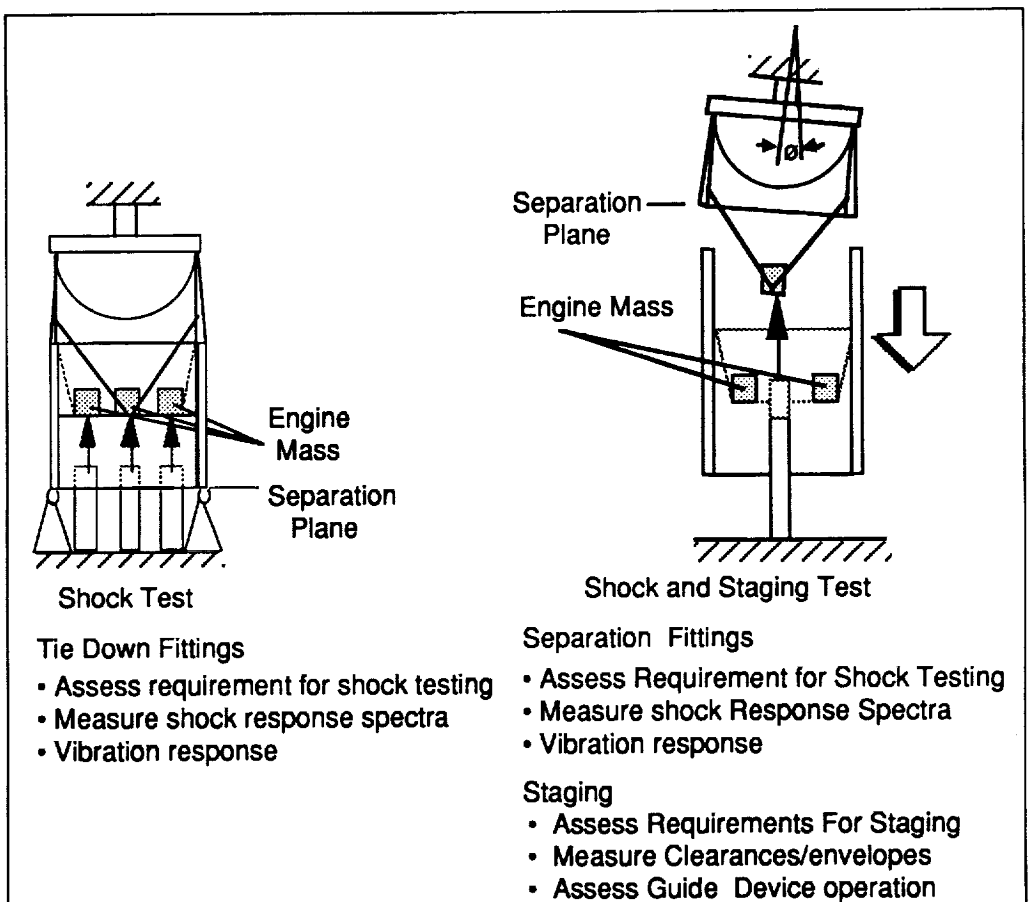

Figure 4.2.1-3 Major Ground Tests - Shock and Staging

throughout the structure. Engine masses will be simulated in the module and hydraulic actuators will be used to supply engine thrust. A simulator will be used with the engine module assembly to provide LH2 dome and barrel stiffness to the assembly.

A second shock test will be combined with the staging test to assess shock and vibration response when the explosive bolts at the separation plane are actuated. Vehicle acceleration at booster staging is approximately 1g. This event will be simulated by allowing the staged portion of the module to drop free until it clears the sustainer engines. The booster will be dropped onto cushioning material to prevent damage. As separation can occur with a pitch or yaw angle present, the worst case angle will be introduced to the assembly tie downs as shown in Figure 4.2.1-3.

4.2.2 Main Propulsion Test Article

The second set of vehicle assemblies off the production line will be assigned to the MPTA. The first set of propellant feedlines, pressurization lines, fill and drain lines produced will also be assigned to this test. A simulated engine module will be required because only three engines will be necessary to develop and test all propulsion system design parameters. A simulated engine module will also be designed to a more robust scale than the flight article so that unlimited testing time can be achieved. If the simulated engine module is mounted to hold-down fittings on the test stand, then engine thrust loads are reacted directly into the test stand and not into the vehicle tankage, thereby preventing premature tank failure and assuring long test life The MPTA schematic is shown in Figure 4.2.1-1.

Besides verifying propulsion system operation, the MPTA will be used to verify thermal analyses for boiloff, stratification, chilldown and fill, and ice/frost formation. Most of these analyses will use parameters from the ET program and the MPTA will substantiate that the parameters used were correct. Fill and drain operation, emergency procedures, and ground interfaces will also be verified during the test program.

4.2.3 Risks to Program

The major ground tests described in Sections 4.2.1 and 4.2.2 are part of an ambitious and innovative approach to certification of the 1.5 stage launch vehicle. The overall test program which entails development, acceptance, qualification, and flight readiness testing for each subsystem in addition to the major ground tests, relies heavily on ET program experience. Since many of the subsystems for the 1.5 stage vehicle will be the same as those on the ET, development and qualification testing of the common components will not be required. There is no additional risk to the program due to the elimination these subsystem tests. Development tests that will not be required include material development/allowable tests including metals, nonmetals, and TPS since the same materials used on the ET will be used on this vehicle.

The most significant difference between the 1.5 stage vehicle and the ET testing program will be the elimination of the requirement for GVTA testing. Individual mode shapes and influence coefficients for vehicle components used to verify math models and analyses will be developed on the STA where required. By installing vibration actuators in the STA test stand, the important lateral and axial modes of the vehicle can be developed. Replacing the vibration actuators with static load actuators will enable the static ultimate loads to be applied to the vehicle, as shown in Figure 4.2.1-1.

STA testing will be conducted for all critical areas of the 1.5 stage vehicle including the engine module. These tests are not as complex as the ET STA tests because this vehicle is uniformly loaded axially. It does not have the large concentrated point loads from an orbiter and SRBs as does the ET. No risks will be incurred by eliminating the GVTA tests and performing simplified STA tests.

A rigorous MPTA test program with one complete feedline system and three engines will be conducted and will verify all propulsion system components and procedures. Risks to the program of using only three of the six engines in the engine module will be minimal because both feedline systems are identical. The structural aspects of using only three engines is not important because the STA will verify module strength under six engine loads and one engine out simulation. All other objectives of the MPTA concerning structural tanks/TPS performance, ground operations and off-nominal operating conditions will be accomplished. Figure 4.2.1-1 shows the MPTA test schematic and the procedures that will be verified.

4.3 TEST FACILITIES

Major ground testing for the 1.5 stage PLS launch vehicle will be conducted at MSFC and at Stennis Space Center (SSC). The STA testing will be conducted on one of the MSFC test stands, and the main propulsion test stand at SSC will be used for the MPTA testing. The B2 side of the stand at SSC will be modified to hold the engine module and the vehicle tankage on the four hold- down fittings similar to the arrangement used for Saturn testing.

STA testing at MSFC may require a new test stand facility because of the present condition of the old static test stands. A consideration for the STA is the 4551, dynamic test stand which currently is not in use. This stand was used for the GVTA testing on the ET program. In order to apply load to the STA elements a separate tension leg loading fixture, shown in Figure 4.2.1-2, may be required since the 4551 building frame was not designed for applying test loads to test articles. A high, modularized test fixture will apply axial loads to high, ultimate load levels but will not be able to apply lateral loads simulating wind loads or maximum Q-Alpha flight loads. The building frame, however, may be capable of applying the lateral load which is approximately 100 klb limit.

The 4551 stand does not have cryogenic fluid delivery capability. This might be overcome by using tanker trucks to act as supplier/storage during testing. Cryo-fluids would have to be limited in quantity for trucks to be feasible and only domes could be filled reasonably.

Full instrumentation and data acquisition systems were originally available in this stand but may need considerable refurbishment and/or replacement. A more suitable STA stand should be found for this program.

The MPTA stand at SSC is currently involved with STS orbiter engine testing and is in good condition. The B2 side of the stand is presently open but would need modification to be able to mount the 1.5 stage vehicle. Extensive instrumentation and data acquisition and reduction systems are currently available and in good condition.

The shock and staging tests will be conducted at one of the MSFC smaller test facilities where instrumentation, data acquisition and reduction is available.

5.0 PROGRAM COSTS

Program costs for the 1.5 stage PLS launch vehicle are engineering rough order of magnitude (ROM) estimates and should be used for top level planning purposes only.

5.1 COST METHODOLOGY

The costs were developed through a combination of parametric cost estimating relationships and analogy to historical ET program costs. The cost estimates assume the advantages of the existing ET infrastructure in both the nonrecurring and recurring costs and includes only the impacts to the ET and MAF.

The following ground rules and assumptions were used to develop the cost estimates.

1) All cost estimates are reported in constant 1991 dollars and are exclusive of fee, government support and government contingencies and reserves.

2) All estimates were developed under the constraints of current ET technology and processes and only includes work accomplished at MAF.

3) The cost estimates assume a production rate not to exceed 12 ETs and 7 PLS vehicles per year.

4) ET-derived tankage assumes,
   a) Tankage inclusive of the forward and aft skirts, and
   b) ET-derived tankage length of approximately 141 feet.

5) Vehicle length (less payload & interstage elements) is approximately 172 feet.

6) Cost estimates include all nonrecurring and average unit cost estimates for
   a) Tankage elements
   b) Final assembly of the propulsion/avionics components to the vehicle. The estimates exclude design, manufacture and procurement of these two subsystems.
   c) Vehicle production integration of the tankage and the propulsion/avionics components in final assembly.

7) Test program cost estimates include only the dedicated test hardware and operations associated with the ET-derived tankage.

5.2 COST ESTIMATES

Cost estimates for both nonrecurring and average unit cost were developed for the 1.5 stage PLS vehicle. The estimates are reported by ET-derived tankage DDT&E and unit cost, final propulsion and avionics subsystem assembly and packaging (component hardware e.g. engines and avionics components are not included), and finally vehicle assembly.

The total nonrecurring cost estimate for the 1.5 stage vehicle is $450 to $560M. The design and development cost estimates range from $210 to $260M and include tankage redesign and integration efforts for the propulsion/avionics element to the tankage. The tooling and facility cost estimates of $160 to $200M include both modified and unique requirements for the production of ET-derived launch vehicle elements at MAF. The tankage tooling/facilities requirements consist primarily of modifications to existing ET tooling. Propulsion and avionics tooling estimates are unique tooling/facilities required for the subsystem assembly of these two subsystems' components. The integration tooling/facilities estimates include the requirements for final assembly of the tankage and propulsion/avionics subsystems before final shipment to the launch site. The test operations/hardware cost estimates of $80 to $100M include only the hardware and operational requirements related directly to the tankage element. All other test costs are excluded.

The cost estimate for an average unit ranges from $35 to $45M and is based on a production rate of 12 ETs and the assembly of seven PLS vehicles per year. The average unit cost includes the ET-derived tankage production which consists of the hardware cost and subsystem assembly of the propulsion/avionics components (excluding subsystem components hardware costs). The integration and final assembly of the tankage element was also included.

6.0 PROGRAM SCHEDULE

The summary schedule (Figure 6.0-1) for the ET-derived 1.5 stage launch vehicle covers a seven year period from ATP until initial launch capability (ILC). The first three years of this program will be basically a design effort including all design changes necessary to progress from the ET design to a an ET-derived tankage for the 1.5 stage vehicle. The next four years include fabrication, assembly, and test of the three test articles and the beginning of flight article production.

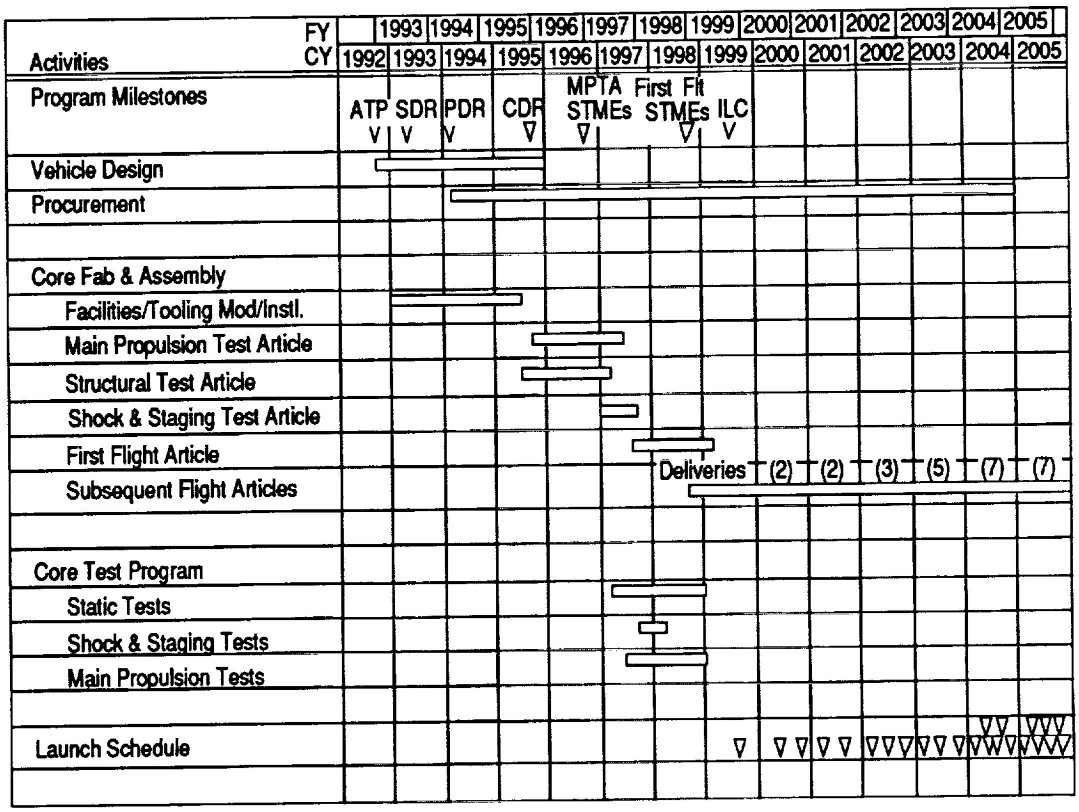

Figure 6.0-1 ET-Derived 1.5 Stage Launch Vehicle Schedule

The design phase begins with a system design review (SDR) six months after ATP. The SDR will provide an approved requirements baseline from which design activities can be initiated and would cover the entire 1.5 stage vehicle. A Phase B system design optimization contract is assumed to precede this schedule which drives the October 1992 ATP date. Approximately one year after SDR a preliminary design review (PDR) would be held to review layout drawings and requirements derived during the preliminary design process. A critical design review (CDR) would follow a PDR 18-22 months later and review the final end item specifications and drawings.

At PDR, authorization will be given for long lead item procurement and upon delivery of these items, assembly of the STA will begin in mid-1995. Twenty-two months was allowed for STA build, since it will be the first unit to go through all production tools. The MPTA and shock and staging test articles will be built following the STA. Test program schedules are approximate since these tests are not well defined at this point. Substantial test data will be available prior to the start of first flight article build. MPTA STMEs will be required at the end of FY96 and production of the first flight article is scheduled to begin in early FY98 with first launch toward the end of FY99. The delivery rate shown will create a smooth transition from strictly ET production which will be at a 12/year rate through test and flight article production of the ET-derived 1.5 stage launch vehicle.