CR-184204

SRS/STD-TR89-92
6670-13

EVALUATION OF ADVANCED PROPULSION OPTIONS
FOR THE NEXT MANNED TRANSPORTATION SYSTEM

Propulsion Evolution Study

FINAL REPORT

PERFORMED FOR:

George C. Marshall Space Flight Center
Program Development Directorate
Marshall Space Flight Center, AL 35812

UNDER:

Contract NAS8-36643
Modification No. 8 - Task 2

March 30, 1990

Prepared by: L. T. Spears
R. D. Kramer

Approved by: Jay H. Lane
J. H. Lane
Director, Aerospace Systems

Approved by: Charles W Mead
C. W. Mead
Sr. Vice President and
General Manager
Systems Technology Group

SRS TECHNOLOGIES

SYSTEMS TECHNOLOGY DIVISION
990 EXPLORER BLVD. N.W.
CUMMINGS RESEARCH PARK WEST
HUNTSVILLE, ALABAMA 35806
(205) 895-7000

(NASA-CR-184204) EVALUATION OF ADVANCED PROPULSION OPTIONS FOR THE NEXT MANNED TRANSPORTATION SYSTEM: PROPULSION EVOLUTION STUDY Final Report, Apr. 1989 - Mar. 1990 (Spectra Research Systems) 150 p CSCL 21H
N92-14106
Unclas
G3/20 0040107

FOREWORD

Evaluation of Advanced Propulsion Options for Next Manned Transportation Systems (Propulsion Evolution Study)

This study is one of two propulsion-related study tasks performed by SRS Technologies over the period April1989 thru March 1990 under contract to the NASA George C. Marshall Space Flight Center.

Dr. Richard D. Kramer served as study task manager for SRS for these two propulsion-related studies.

Mr. Bruce Wiegmann of the Space Transportation and Exploration Office (Office Code PT41) served as Study Manager and COTR for MSFC.

Mr. Robert Champion of the MSFC Preliminary Design Office (Office Code PD13) served as Technical Advisor to the MSFC Study Manager.

The following SRS Technologies personnel contributed to this effort:

Mr. Luke Spears - Task Leader	(205)	895-7020
Dr. R. D. Kramer	(205)	895-7837
Mr. James Pearson, Jr.		
Mr. James Moore.		

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF ACRONYMNS AND ABBREVIATIONS

ACRC	-	Assured Crew Return Capability
ACRV	-	Assured Crew Return Vehicle
AGC	-	Aerojet-General Corporation
ALS	-	Advanced Launch System
AMLS	-	Advanced Manned Launch System
ASRM	-	Advanced Solid Rocket Motor
ATP	-	Authority to Proceed
Cert.	-	Certification
CRV	-	Cargo Return Vehicle
CSTI	-	The NASA Civil Space Technology Initiative
Delta-V	-	Velocity Increase to Be Imparted by a Propulsive Vehicle or Stage
Dev.	-	Development
E	-	Nozzle Expansion Ratio or Area Ratio
E-Hex	-	External Heat Exchanger (for SSME Engine)
Exp	-	Expendable
F.O.	-	Fail Operational
F.R.	-	Fully Reusable
F.S.	-	Fail Safe
F/W	-	Thrust-to-Weight Ratio
FCE	-	Flight Certification Engine
G.G.	-	Gas Generator Rocket Engine Cycle
g's	-	Acceleration Levels Experienced During Ascent or Descent Phases of Launch Vehicle Operations
ICD	-	Interface Control Document
Isp	-	Specific Impulse
LeRC	-	The NASA-Lewis Research Center
LOX/HC	-	Combination of Liquid Oxygen and a Hydrocarbon Fuel as Rocket Engine Propellants
LOX/LH_2	-	Combination of Liquid Oxygen and Liquid Hydrogen as Rocket Engine Propellants
LRB	-	Liquid Rocket Booster
M.R.	-	Mixture Ratio
MSFC	-	The NASA George C. Marshall Space Flight Center
N/A	-	Not Applicable
NASA	-	National Aeronautics and Space Administration
NMTS	-	Next Manned Transportation System
OMS	-	Orbit Maneuvering System
P/A	-	A Propulsion/Avionics Module for Engine and Avionics Recovery
P.O.P.	-	Program Operating Plan
P.U.	-	Propellant Utilization
P&W	-	Pratt & Whitney Division Of United Technologies Corp.
PLS	-	Personnel Launch System
PLS/LRB	-	PLS Launch Vehicles Using LRB as the Booster Stage
PLS/ND	-	PLS Launch Vehicles of New Design, with Booster Stage Not Common with LRB for STS
psia	-	Pressure in Pounds Per Square Inch, Absolute
q-Alpha	-	An Indicator of Aerodynamic Loads Experienced During Launch Vehicle Ascent
R&T	-	Research and Technology

RD	-	Rocketdyne Division of Rockwell International
S.C.	-	Staged Combustion Rocket Engine Cycle
S/L	-	Sea Level
SD/HLV	-	Shuttle-Derived Heavy Lift Launch Vehicle
SSME	-	Space Shuttle Main Engine
SSME-35	-	SSME Engine with 35:1 Area Ratio Nozzle
STBE	-	Space Transportation Booster Engine
STEP	-	Space Transportation Engine Program
STME	-	Space Transportation Main Engine
STME-20	-	STME Engine with 20:1 Area Ratio Nozzle
STME-40	-	STME Engine with 40:1 Area Ratio Nozzle
STME-62	-	STME Engine with 62:1 Area Ratio Nozzle
STS	-	Space Transportation System or Space Shuttle
STS "C"	-	Shuttle "C" or Cargo Version of the Space Shuttle
STS/LRB	-	Liquid Rocket Booster Designed for Use on the Space Shuttle
TBD	-	To Be Determined
TSFR	-	Two-Stage, Fully Reusable Launch Vehicle Concepts
Vac	-	Vacuum

1.0 INTRODUCTION

The Space Shuttle Main Engine (SSME) is a large (half-million pound thrust class), high-performance, reusable, hydrogen-fueled rocket engine, currently in flight operations as a part of the Space Shuttle vehicle, or Space Transportation System (STS). Definition studies and advanced development work are currently in progress toward possible development of another large, hydrogen-fueled engine for use in Advanced Launch System (ALS) and/or other launch vehicle applications. This latter engine has been designated as the Space Transportation Main Engine or STME, and is currently being defined in the joint NASA-DoD "Space Transportation Engine Program" (STEP).

The objectives of this study task were to examine launch vehicle applications and propulsion requirements for potential future manned space transportation systems, and to support planning toward evolution of SSME and STME engines beyond their current or initial launch vehicle applications. The six tasks that made up this study effort are shown in Figure 1-1, in correlation with other related launch vehicle and propulsion activities.

As a basis for examinations of potential future manned launch vehicle applications, we have used the three classes of manned space transportation concepts currently under study by NASA under the Next Manned Transportation System or NMTS study program, e.g., STS Evolution, Personnel Launch System (PLS), and Advanced Manned Launch System (AMLS).

The approximate division of study effort among these study tasks is as follows:

Task No. 1 - Vehicle Applications and Propulsion Requirements (50 percent) - Studies of launch vehicle applications and requirements for hydrogen-oxygen rocket engines.

Task No. 2 - SSME Engine Evolution (5-10 percent) - Development of suggestions for STME Engine evolution beyond the mid-1990's.

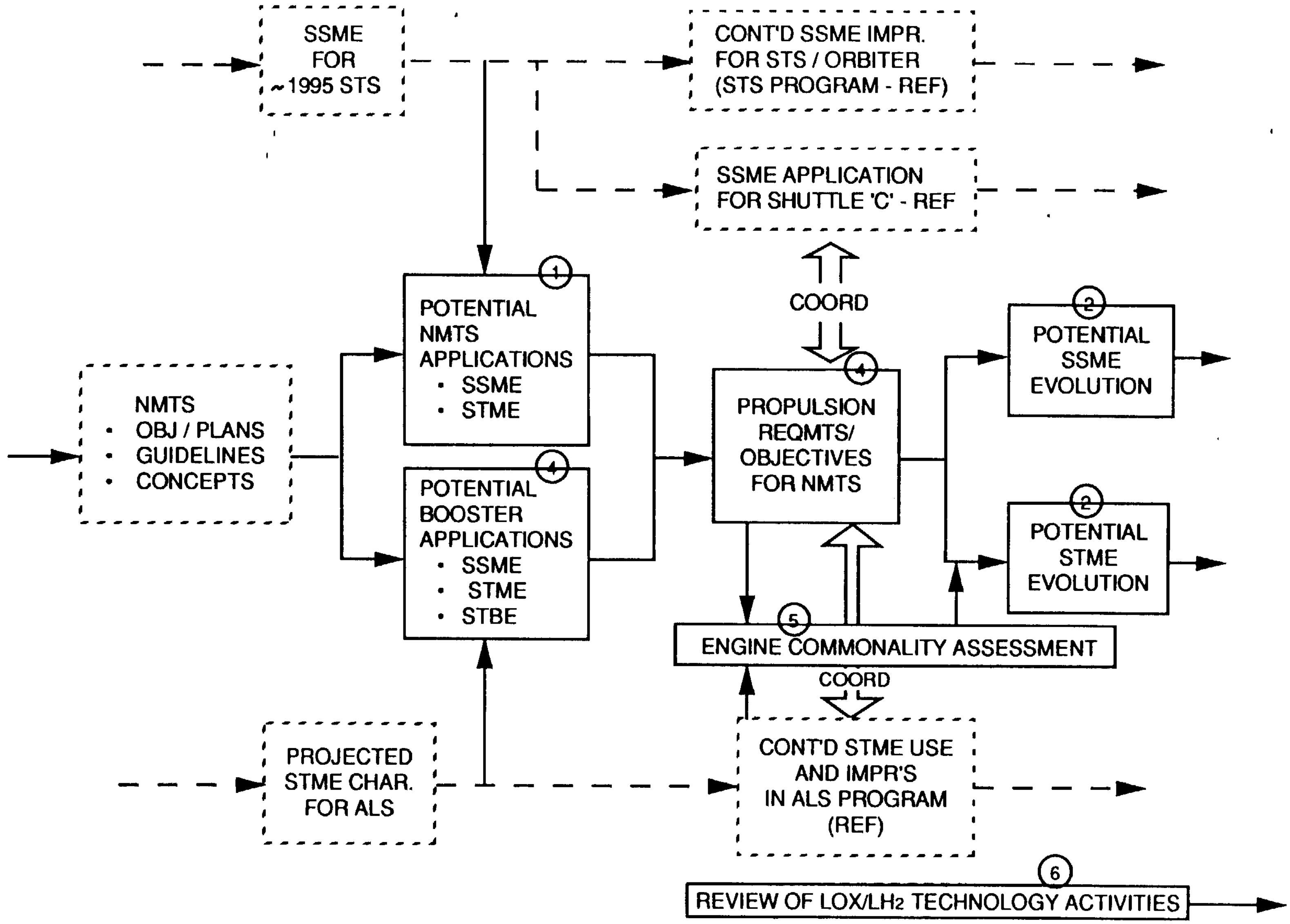
Task No. 3 - STME Engine Evolution (5-10 percent) - Development of suggestions for STME Engine evolution beyond the ALS application.

Task No. 4 - Booster Propulsion Options (5 percent) - A brief study of booster propulsion options, including LOX-Hydrocarbon options.

Task No. 5 - Common Engine Study (25 percent) - Analysis of prospects and requirements for utilization of a single engine configuration over the full range of vehicle applications, including manned vehicles plus ALS and Shuttle "C".

Task No. 6 - LOX-Hydrogen Technologies (5 percent) - A brief review of on-going and planned LOX-Hydrogen propulsion technology activities.

STUDY FLOW DIAGRAM



890623LS1700

FIGURE 1-1 PROPULSION EVOLUTION STUDY FLOW

A significantly larger part of the effort has been devoted to studies of potential launch vehicle applications for different versions of the STME engine, than for SSME applications. This has been due to the number of open questions to be addressed, and not to any perception of prospects for launch vehicle applications. Most of the work by others to date on STME engines has been for cargo launch vehicle applications; the SSME engine is already established for operations in manned launch vehicles. And, the efforts devoted to studies of STME engine compatibility for integration into STS vehicles would obviously not be required for SSME engines.

This study was funded at a level of approximately $140K over a period of twelve months. When applied over the broad scope of several classes of launch vehicles, several rocket engine approaches and a range of objectives, the study depth in any area is necessarily limited. We have attempted to use launch vehicle/concept data and requirements where available, and to augment with broad-based parametric analyses and trade studies where appropriate. We believe that analyses of this nature can help identify the areas of propulsion characteristics of primary interest, and where analyses in more depth can be most useful. We have pursued a few areas in more depth than others, where available data and the nature of the tasks seemed to warrant.

Propulsion requirements and launch vehicle-propulsion interactions are important considerations in planning for the future in rocket propulsion and manned space transportation systems. We at SRS appreciate the opportunity to participate in analyses and planning of this nature. We hope that examination of some of these factors by an "independent" participant (SRS produces neither rocket engines nor launch vehicles) can add some data and insight for further planning by NASA and the Propulsion/Launch Vehicle community.

2.0 SUMMARY

The Space Shuttle Main Engine (SSME) is currently flying in the Space Shuttle (STS), and changes are planned into the mid-1990's to improve its operations and to reduce costs. Work is in progress toward potential development of one or more new liquid rocket engines for launch vehicle applications (The joint NASA-DoD program - Space Transportation Engine Program, or STEP). This latter effort is currently focusing on a new hydrogen-oxygen engine for use in both booster and upper stages, with the potential for application in the Advanced Launch System (ALS) around the turn of the Century.

The objectives of this Propulsion Evolution study were to examine potential engine applications in manned launch systems beyond the 1995-2000 time period, to determine propulsion requirements for such applications, and to suggest evolution paths for SSME and STME engines as candidates for use in these manned launch systems.

The classes of vehicle concepts currently under study by NASA for future manned space transportation, e.g., the "Next Manned Transportation System" were the basis for these studies. These include: (l) STS Evolution, (2) Personnel Launch System (PLS)", and (3) Advanced Manned Launch System (AMLS). And, because of its interaction with STS Evolution planning, we have included some discussion of Shuttle "C" engine applications and requirements. In examining these vehicle applications, we have used as guidance the NMTS objectives including: adaptability for physical integration into the vehicle under discussion; improved system reliability, safety and margins; an acceptable level of performance or improvement; enhanced operations; and reduced costs.

Through the use of available data on manned vehicle concepts in combination with top-level trade studies performed as a part of this study, we have compiled a summary set of suggested propulsion requirements for each of these classes of vehicle concepts. These data are provided in summary matrix form in Figure 3-7 (SSME applications) and in Figures 3-54A and 3-54B (STME engine applications). Summary information from the trade studies in this report, is provided to indicate rationale for these requirements, and to aid in further vehicle and propulsion studies.

A low level of effort task was included in this study to examine propulsion options for booster applications, including Lox-Hydrocarbon engines as well as booster (low area ratio) versions of Hydrogen-Oxygen engines. Use of one of these versions would be highly preferable and possibly mandatory (in lieu of an upper stage version of a hydrogen engine) for Liquid

Rocket Booster and AMLS booster applications. The choice between the two will be highly dependent upon the approach selected for orbiter or core stage propulsion.

As one of the major tasks in this study (Common Engine study task), we have examined prospects for use of a single engine configuration over this full range of vehicle applications, including ALS. A program of this typc is illustrated as "Scenario no. 2 in Figure 2-1. Studies under this and other tasks indicated that a number of changes from the basic STEP/STME engine requirements would be necessary to adapt it for use in any of the manned vehicles, and that additional engine or vehicle changes would be necessary for its use in STS/Shuttle "C". It would be very difficult if not impossible to utilize a singe engine/nozzle configuration over this full range of boosters and upper stages, as is currently planned in ALS; it appears that two nozzle configurations would be required as a minimum.

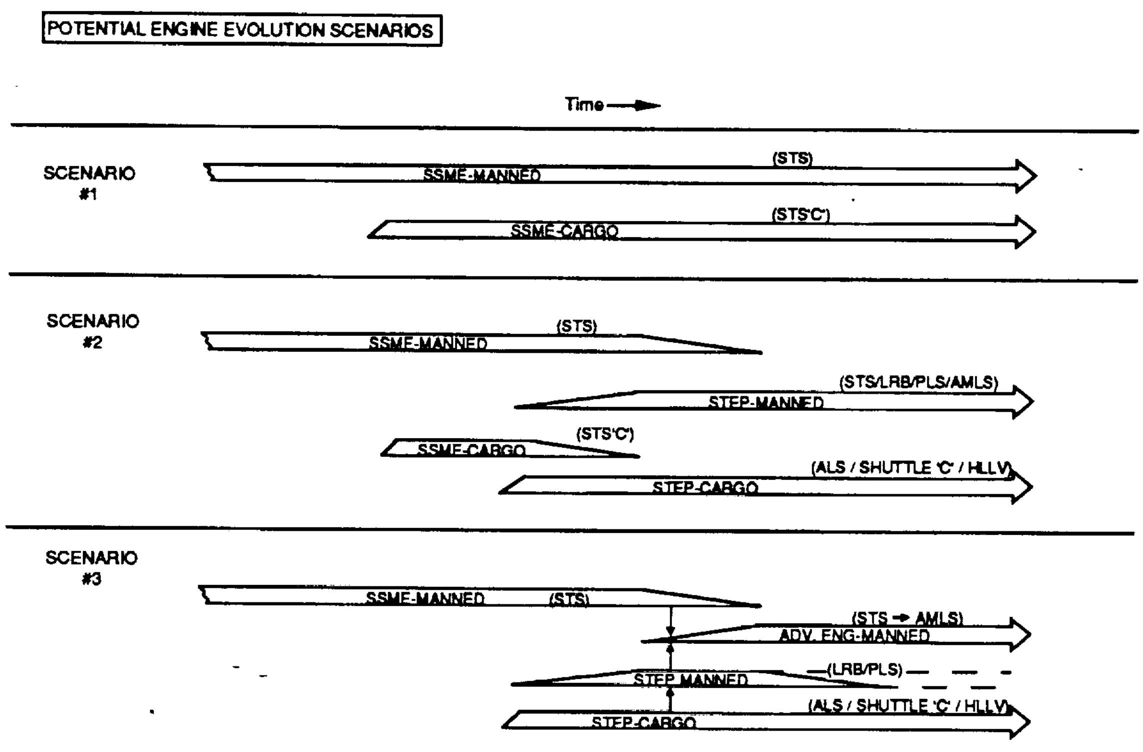


Figure 2-1 Potential Engine Evolution Scenarios

900326LS1010-2

All engines and vehicle applications naturally will want high reliability, high performance, low weight, and low costs. However, the relative importance of some of these characteristics suggests two companion categories of engine applications out of the range studied here. The category including emphasis on more rugged design, adaptability for water recovery, and lower unit costs would best fit the ALS, the Liquid Rocket Booster, and PLS launch vehicle applications. The group with more emphasis on higher performance, smaller engine sizes, and longer engine life would best fit STS orbiters and AMLS vehicle applications. Shuttle "C" in an expendable engine mode would likely prefer the former category, for lower unit costs. The new engine development under STEP/STME is geared more strongly to the characteristics of the first category, while the SSME is already established in the latter.

The alternative shown as "scenario no. 3" in Figure 2-1 suggests continued use of SSME engines in manned, reusable vehicles, to be followed (later) by a successor to the SSME engine that can incorporate some of the characteristics from the STEP engine experience without changing its character completely. The extent to which the current SSME engine can attain the objectives of longer life, improved operations and lower costs, and therefore the timing that would be desirable for conversion to a successor engine, remain yet to be established (as are all the target objectives for a new engine development).

We believe it is important to implement increased levels of margins in vehicles and systems, as a means to improve safety/reliability, to improve operations and maintenance, and to reduce costs. The brief study of margins in propulsion and vehicle systems in this study again points up the higher levels of performance sensitivities for manned, reusable vehicle systems, and the greater degree of care and prioritizing necessary in the selection and application of margins. Secondly, the level of sensitivity to increased margins should be a more prominent factor in future trade studies and selections of baseline approaches for propulsion and other vehicle systems.

Based on these studies of future manned vehicle applications, we have outlined suggestions for SSME evolution beyond that currently scheduled in the STS program (Section 3.4 of the report) and for STME engine evolution beyond its initial application in ALS launch vehicles (Section 3.5 of report). As the final task in this study, we have summarized and reviewed the Lox-Hydrogen technology efforts that are currently in progress or planned under NASA propulsion technology programs and the ALS advanced development program, in comparison with the evolution trends suggested here.

3.0 ANALYSES AND RESULTS

3.1 Launch Vehicle Applications and Propulsion Requirements

3.1.1 Introduction

Three candidate classes of manned transportation systems are currently being studied by NASA, as options for U.S. manned space transportation into the next century: (1) STS Evolution, or planning toward the characteristics that the Space Shuttle should have for continued operations into the next century, (2) Personnel Launch Systems or PLS, which includes a manned spacecraft plus launch vehicle, and (3) Advanced Manned Launch System or AMLS, envisioned as the next generation successor to the current Space Shuttle. Concepts typical of these three categories are illustrated in Figure 3-1, and one set of timelines for potential introduction of such vehicles into the U.S. launch capability is shown in Figure 3-2, as a back-drop for examinations of future propulsion options.

Available information on guidelines, assumptions and plans for NASA analyses of these candidate vehicle concepts was reviewed for implications to propulsion requirements. One version of top-level requirements or objectives for future manned transportation systems is shown in Figure 3-3. For purposes of this study, the first objective (satisfy people and payload requirements) has been subdivided into the three parts as shown. Figure 3-3 also correlates engine and propulsion characteristics with these four NMTS objectives. During the remainder of this study and report, the following objectives for each of the launch vehicle applications under consideration are addressed:

1 - Adaptability for integration into the launch vehicle or stage under consideration (fit and function in a vehicle),

2 - Performance capabilities in the vehicle application,

3 - Features or characteristics to improve operations and cost effectiveness, and

4 - Steps to improve operations and reduce costs via increased margins.

Potential launch vehicle applications for SSME engines are discussed in Section 3.1.2, and for STME engines in Section 3.1.3. Selected aspects of propulsion requirements for these launch vehicle applications are compiled in summary matrix format in Figure 3-7 (for SSME Engine applications) and in Figures 3-54A and 3-54B (for STME Engine applications). A discussion of propulsion and vehicle margins, on an across-the-board basis, is provided in Section 3.1.4.

NEXT MANNED TRANSPORTATION SYSTEM
CANDIDATE VEHICLE CONCEPTS/APPROACHES

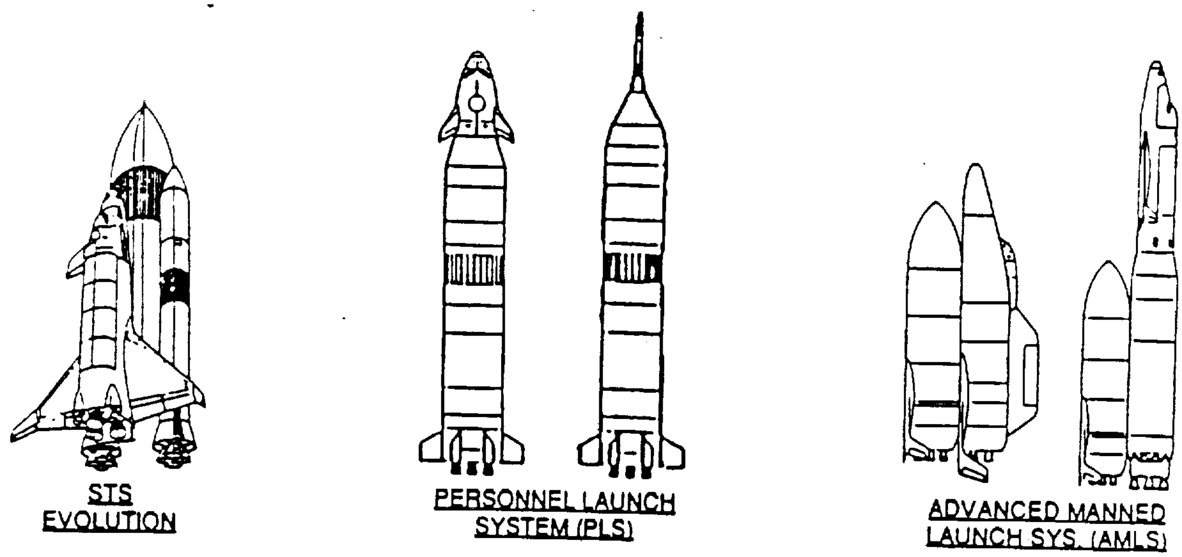
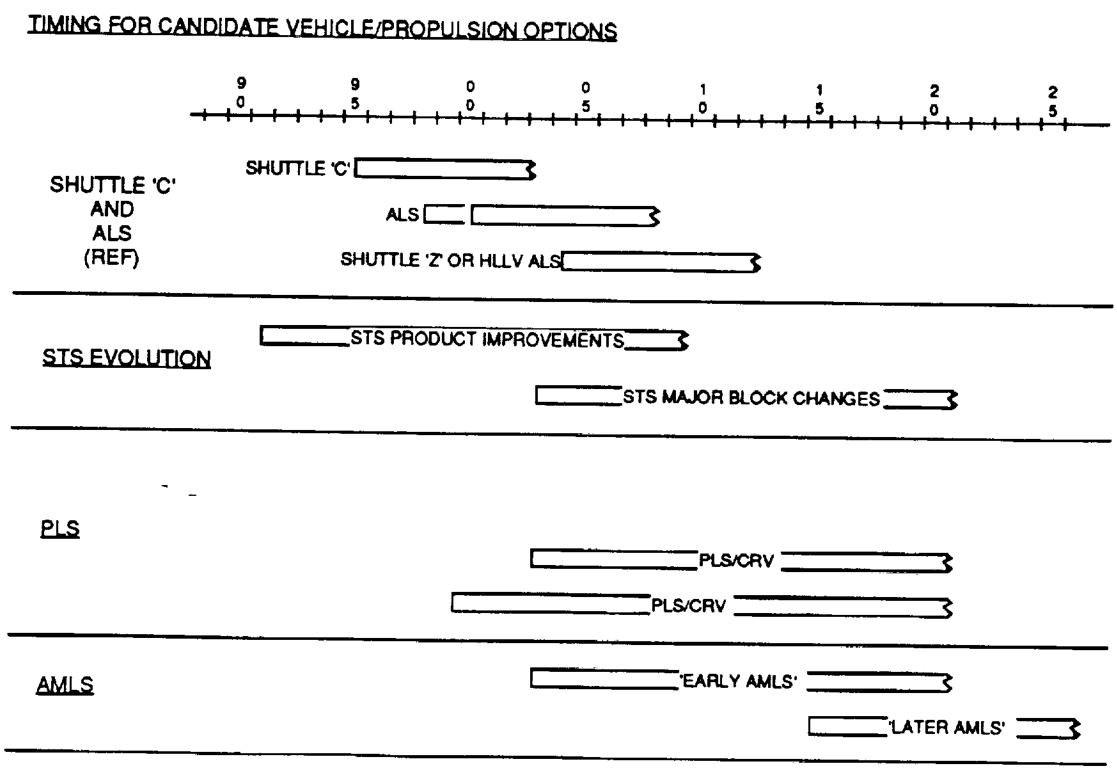


FIGURE 3-1 NMTS VEHICLE CONCEPTS



NOTE: • EARLIEST INTRO DATE SHOWN FOR EACH OPTION.
• MANNED VEHICLE OPTIONS BASED ON NMTS STUDY OPTIONS/GUIDELINES.

FIGURE 3-2 POTENTIAL NMTS TIMELINE

NEXT MANNED TRANSPORTATION SYSTEM (NMTS)
TOP-LEVEL OBJECTIVES

1- SATISFY PEOPLE - PAYLOAD REQMTS

* 1A - FIT AND FUNCTION IN STAGE/VEHICLE
1B - PERFORM FUNCTIONS REQ'D
1C - PROVIDE NEEDED PERFORMANCE LEVEL

2 - IMPROVE OPS AND COST EFFECTIVENESS

3 - INCREASE RELIABILITY

4 - INCREASE MARGINS

* SUB-DIVISIONS ADDED FOR PURPOSE OF THIS STUDY.

	NMTS OBJECTIVES					
	1A	1B	1C	2	3	4
• FUEL			✓			
• ENGINE CYCLE			✓	✓		
• THRUST LEVEL			✓			
• THROTTLE RANGE		✓				
• MIXTURE RATIO			✓			
• RELIABILITY					✓	
• REDUNDANCY					✓	
• RECOVERY MODE				✓		
• ENGINE LIFE				✓		
• PROP. INLET COND.	✓					
• ENGINE ENVELOPE	✓					
• GIMBAL LIMITS	✓	✓				
• EXPANSION RATIO	✓		✓			
• SPECIFIC IMPULSE			✓			
• PRESSURIZ. GASES		✓				
• POWER TAKE-OFF		✓				
• P.U. CONTROL			✓	✓		
• FACILITATE SAFETY				✓	✓	
• FACILITATE MAINT/OPS				✓		
• MARGINS						
- ENGINE PERF.			✓			✓
- ENGINE WT			✓			✓
- OPS COND (REF)				✓		✓
- VEH. PERF (REF)			✓			✓
- VEH. INERTS (REF)			✓			✓

FIGURE 3-3 NMTS OBJECTIVES

891221LS0945

3.1.2 Potential Future Vehicle Applications for SSME Engines

3.1.2.1 Introduction

Potential future launch vehicle applications and corresponding propulsion requirements are examined for SSME engines in this section, and for STME engines in the following Section 3.1.3. Additional examinations of some aspects of vehicle applications and requirements are addressed in Section 3.1.4 (Propulsion and Vehicle Margins), Section 3.2 (Analysis of Booster Propulsion Options) and in Section 3.3 (Engine Commonality Analyses). Changes and improvements in SSME engines already planned and in process in the STS/SSME program are identified in Section 3.4 (Evolution Requirements for SSME Engines), serving as a starting point for analyses of potential SSME applications and improvements beyond the mid-1990's in this study. We have compiled propulsion requirements from vehicle application studies in these parts of the study into a summary matrix form adopted for use in this study. These application studies and requirements, along with analyses of design approaches for specific engines, form the basis for suggestions for future SSME and STME evolution paths in Sections 3.4 and 3.5, respectively.

3.1.2.2 STS Evolution and Shuttle "C"

It is anticipated that Space Shuttle operations will continue well into the next Century. NASA studies and planning to determine vehicle and operation features that will best serve the Nation's needs in this later time period are referred to in part as "STS Evolution". Requirements or objectives for STS Evolution have been stated in several forms, including some of the following:

- Increased reliability and crew safety,
- Reduced operations and life-cycle costs, and
- Increased operations capability, with larger performance margins.

Objectives for a part of this study are to project engine applicatons and requirements beyond the STS and SSME improvements that are planned and scheduled in the STS program, e.g., beyond the mid-1990's. Shuttle "C" is not included in the scope of this study; however, some of the STS and Shuttle "C" considerations are interrelated to such an extent that some comments are offered on Shuttle "C" applications in these discussions.

Performance Capabilities

Increases in vehicle performance capabiltities could be utilized either in the form of increased lift capability (within vehicle structural capabilities), higher altitude orbits as destinations, or in the form of increased margins. We assume that potential for increased lift capability via Orbiter engine/main engine improvements will be fairly limited. Nozzle extensions have been considered previously as a candidate means to improve vacuum specific impulse. Other means to increase specific impulse do not seem readily available without major redesign. Increased vehicle performance could be achieved by increased engine thrust levels; however, it is assumed that up-rating beyond the 109% power level would involve major engine redevelopment, and would not be warranted. Secondly, unless futher analyses show the thrust structure load capability to be higher than presently understood (approx. lll% of SSME rated thrust), the vehicles ability to utilize higher thrust levels would be strongly limited. Therefore, any large increases in vehicle performance capability would more likely come via vehicle inert weight reductions and/or booster stage improvements. One such improvement is the ASRM development. A second major candidate of this nature is the use of liquid rocket boosters, which were the subject of the recent Phase A studies, performed by General Dynamics and Martin-Marietta.

Fit and Function in Vehicles

The capability for SSME engines to "fit and function" in the STS has obviously already been established, and does not require further analysis here. Analyses of this nature are devoted to potential use of STME engines in the STS and are addressed in the following section of this report.

Engine Life and Cost Trades

Potential for vehicle improvements via main engine improvements are more likely to focus on improvements in reliability, safety, engine lifetime, support requirements, or costs. Major steps in these directions are already being initiated or planned in the STS program, including use of an externally located heat exchanger to provide propellant tank pressurization, improved turbopumps, and a larger-throat version of the engine that would allow required thrust levels at reduced chamber pressure and corresponding pumping requirements. Candidate engine improvements beyond these are outlined in Section 3.4 (SSME Evolution).

The STS program would obviously benefit from longer SSME engine life, preferably into the range of 30-50 flights per engine (Ref upper LH part of Figure 3-4). Engine life is currently limited, first by the high-pressure turbopumps, and then by other elements. This has of course led to the current emphasis on SSME turbopump improvements, and to initiation of the alternate turbopump developments. (SRS Technologies has supported MSFC for nearly ten years in analytical modeling, testing, and test data analysis in the development of SSME turbopump bearings/materials, and candidate improvements).

Use of engines in an expendable mode on Shuttle "C" would benefit from reduced unit costs of the engines. Operation of STS and Shuttle "C" as companion vehicles, where engines are switched to the (expendable) Shuttle "C" after some number of flights on the (reusable) STS would provide a good opportunity for "middle ground". A part of our analyses of this prospect is also depicted in Figure 3-4. The upper RH portion of the figure shows the average number of flights realized per engine for a range of STS and Shuttle "C" flight rates.This indicates that a life of 10-12 flights per engine would cover the ranges of flight rates considered, and with some margin, suggests that an engine life on the order of 15 flights would be adequate (in lieu of the life of 30-50 flights if to be operated in the STS, alone). The bottom of Figure 3-5A shows engine costs for operation of Shuttle "C" in the mode where engines are used jointly with STS, in comparison with a hypothetical case in which unit costs for an expendable version of SSME were reduced to $20M, with an additional investment of $200M, for example.

3.1.2.3 LRB and PLS Launch Vehicle Applications

Earlier studies of liquid rocket boosters for use on STS examined use of SSME engines, and recommended further consideration of the "booster version" of SSME (SSME with 35:1 area ratio nozzles). However, the more recent LRB Phase A studies examined engine options extensively, leading to a recommendation for use of a more rugged and lower unit cost engine, similar to STME engines with a low area ratio nozzle (approximately 20:1). Although we have examined performance and sizing of PLS launch vehicles using SSME and SSME-35 engines, we assume that SSME engines are not a primary candidate for LRB or PLS launch vehicle applications, unless a form of engine or stage recovery is developed that would assure integrity of the returned engines and would allow use of each engine over several flights. We have

Engine Life and Cost Trades for STS/Shuttle 'C'

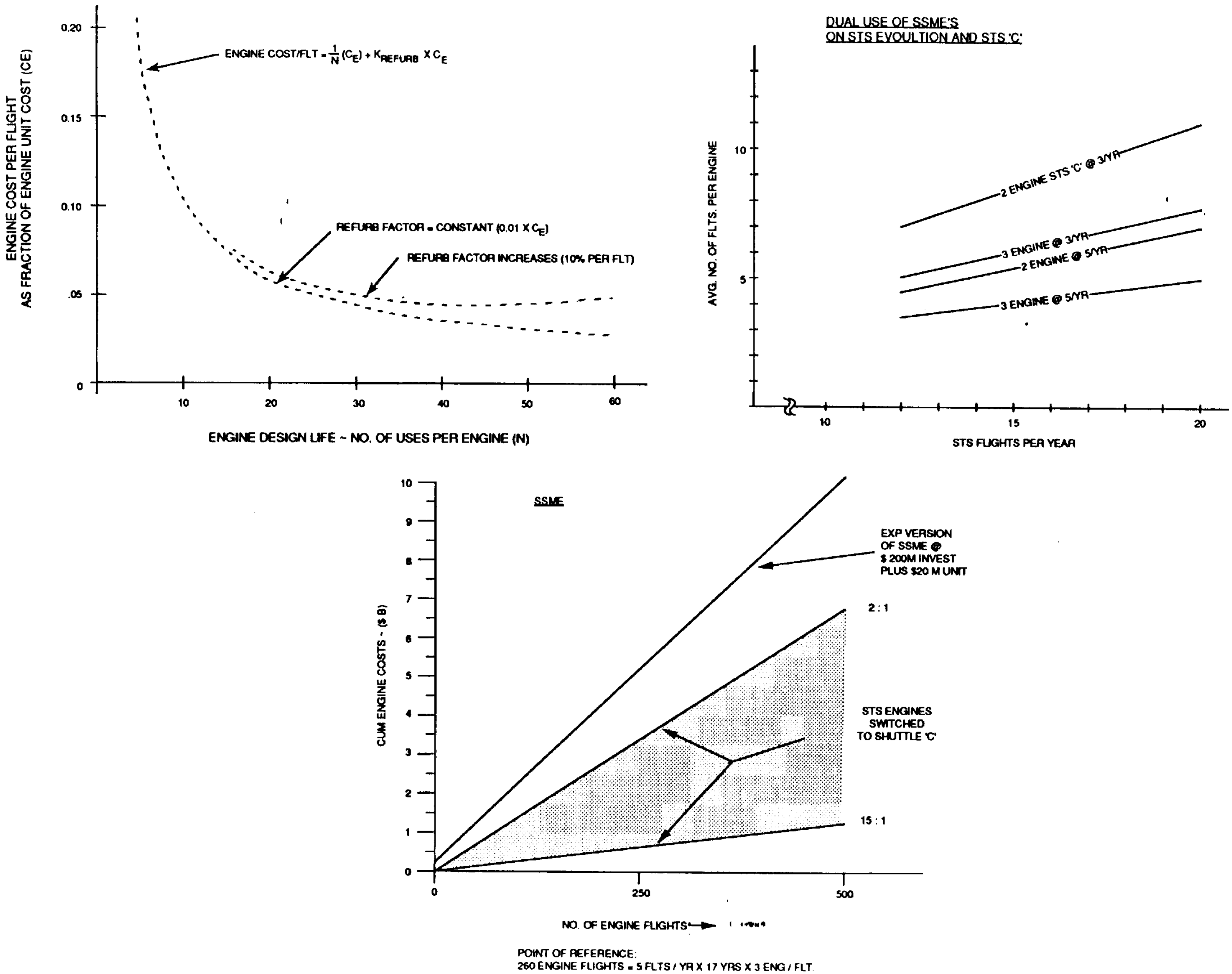


FIGURE 3-4 ENGINE COSTS FOR STS AND SHUTTLE 'C'

900316LS0902

therefore confined this discussion primarily to applications for STS, Shuttle "C" and AMLS vehicles.

3.1.2.4 AMLS Applications

Advanced vehicle concepts are being examined by NASA and in contract studies as candidate next generation successors to the current Space Shuttle (AMLS concepts). Varying degrees of recovery and reuse are being examined (reference Figure 3-1), with the two-stage, fully reusable (TSFR) concept currently used as the baseline concept. We have used the two-stage fully reusable version as the basis for our analyses in this study.

Engine Performance and Vehicle Sizing

AMLS concepts are a very favorable application for SSME engines. The high performance of SSME engines would result in smaller vehicles and lower vehicle dry weights. For example, AMLS vehicles using SSME engines would be 20-25 percent lower in gross weight and nearly 20 percent lower in dry weight than a comparable vehicle using STME engines (reference Section 3.1.3.4, following). In addition, the high operating chamber pressure and corresponding smaller physical size is favorable for vehicle installations and base area requirements. This consideration can be seen by comparison with base area requirements for use of STME engines in Section 3.1.3.4, and will also show by comparison the desirability of a "booster version" of SSME (SSME-35) for use in the booster stage (this aspect is discussed further in Section 3.3 - Booster Propulsion Options).

Results from parametric sizing of AMLS vehicles using SSME engines are summarized in Figure 3-5. The example in this figure uses seven SSME's in the booster stage plus three SSME's in the orbiter stage, the smallest number of engines that would provide full engine-out capability during booster burn or during orbiter burn following separation from the booster stage. Coincidentally, this is the same numbers of engines required when using the higher thrust level STME engines, under the same engine-out assumptions.

SSME Engine Applications

AMLS Type Vehicle Concept (TSFR)

- 50K lbs. Payload
- SSME Engines (77:1 Nozzles)
- Nominal Vehicle Inert Weight Factors

  - Vehicle Gross Weight --------- 2800K lbs.
  - Orbiter ------------------- 3xSSME
    ------------------- 980K lbs.
  - Booster ------------------- 7xSSME
    ------------------- 1780K lbs.
  - Vehicle Dry Weight ----------- 496K lbs.
  - (F/W) @ Lift-Off ------------- 1.39
  - (F/W) Engine-Out ------------ 1.25

900316LS0920

FIGURE 3-5 AMLS VEHICLE USING SSME ENGINES

Thrust Levels and Throttle Requirements

Acceleration levels and throttling requirements for an AMLS vehicle equipped with (7+3) SSME engines are shown schematically in Figure 3-6, assuming the 3 'g' acceleration limit used in the STS program. No throttling would be required during booster burn in order to limit acceleration. Detailed vehicle concept studies will be necessary to determine whether throttling is required for q-alpha limits during early part of ascent. With all three engines operating in the orbiter stage, throttling would have to start soon after booster stage separation, and throttling down to approximately 47% of full thrust would be required shortly before shut-down. An alternative is shown (RH side of Figure) in which one of the three engines is shut down early. In this case, throttling to 70% is adequate to maintain the 3 'g' limit, and would stay within the current SSME throttle capability (65%). We have assumed the latter option in further consideration of AMLS applications of SSME engines.

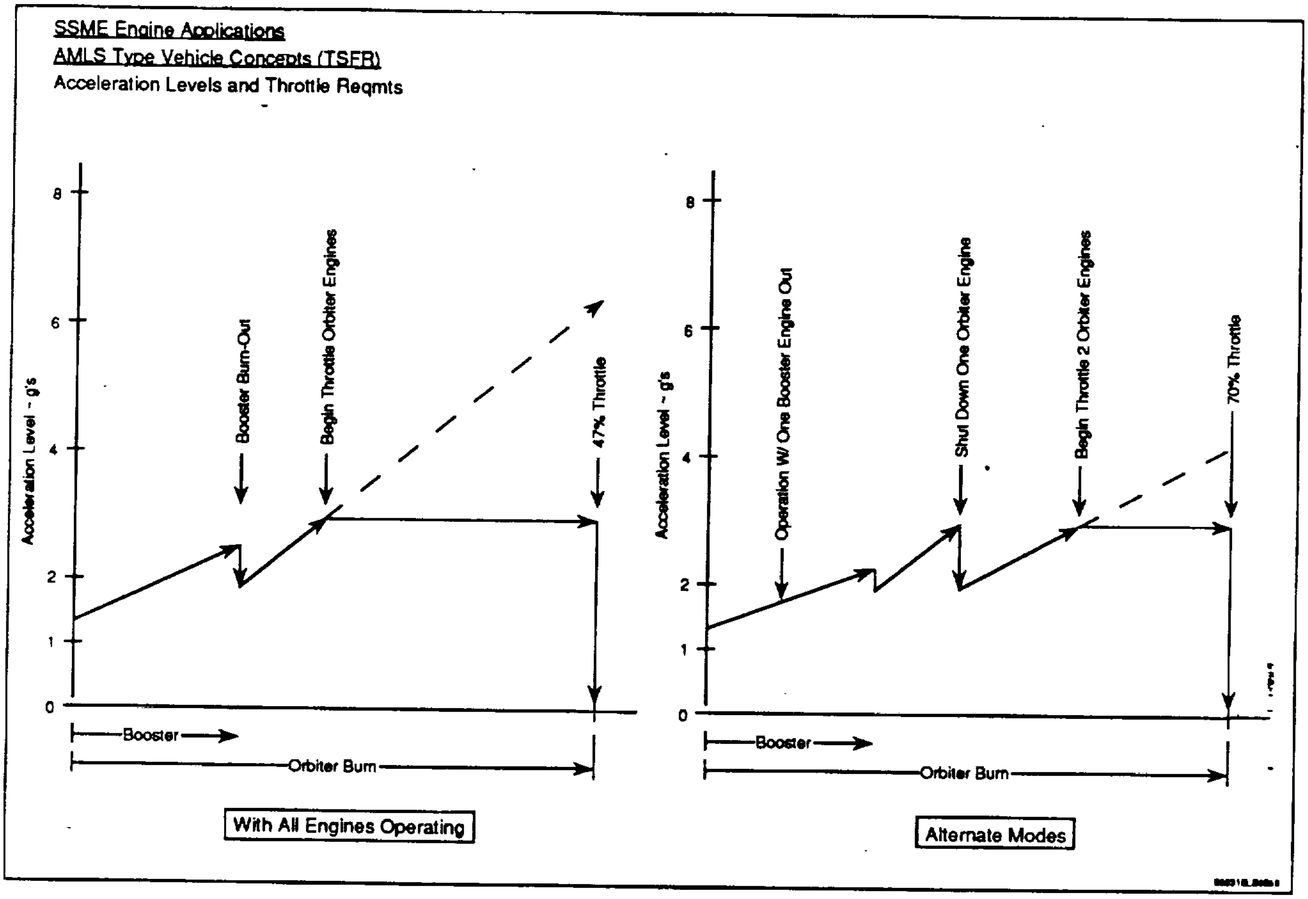


FIGURE 3-6 AMLS ACCELERATION LEVELS AND THROTTLE REQUIREMENTS

This necessity to shut down one of the orbiter engines soon after separation from the booster stage suggests that two engines might be adequate for the orbiter. However, loss of one of these two engines would result in too low a thrust level. This suggests, as in other parts of the study, that the orbiter stage should have three engines at a size/thrust level approximately two-thirds of the existing size.

Engine Life and Operations Characteristics

The current perceptions of SSME engines would indicate limitations for such vehicle applications in terms of unit costs, lifetime and support requirements, reflecting in part its ambitious goals in comparison with our technology capabilities at the time it was developed. However, AMLS development would not occur until some time after the year 2000, and it remains to be seen how much progress can be made in these characteristics by the second half of the 1990's. (The possible desirability of a later version of the SSME engine in combination with a new-development engine for booster and some other applications is discussed in Section 3.3 (Engine Commonality Analyses).

3.1.2.5 Summary - Vehicle Applications for SSME Engines

In this part of the study, we have examined potential for SSME engine applications in STS Evolution/Shuttle "C" and in AMLS launch vehicles. Propulsion requirements based on these potential future vehicle applications are compiled in summary matrix form in Figure 3-7.

Engine Requirements/Objectives
Potential Future Ssme Applications

	Vehicle/Stage Application						
	STS	STS 'C'	STS Evolution	STS/LRB **	PLS/LRB **	AMLS Booster	AMLS Orb
• Fuel	LH_2 →	→	→	→	→	→	→
• Engine Cycle	SC →	→	→	→	→	→	→
• Vac Thrust - Nom	470 - 489K	470K	470K	461K	470K	461K	470K
- Abort/Engine Out	512K	512K	512K	503K	512K	512K	512K
• No. Of Engines	3	2 -3	3	8	4	7	3
• Throttle Range							
- Normal Ascent	65 - 100%	65 - 100%	65 - 100%	75 - 100%	75 - 100%	100%	70 - 100%
- Abort/Engine Out	109%	109%	109%	109%	109%	109%	109%
• Expansion Ratio							
- Orbiter/Core	77	77	77	-		-	77
- Booster				35	35	35	-
• Mixture Ratio	6 →	→	→	→	→	→	→
• Reliability	.97 *	.97 *	.99	.99	.99	.99	.99
- Confidence Level	50%	50%	TBD	TBD	TBD	TBD	TBD
• Redundancy	FO/FS	FO	FO/FS	FO/FS	FO/FS	FO/FS	FO/FS
• Isp - Vac	452.9 →	→	→	442.8 →	→	→	452.9
- S/L	361.4 →	→	→	404.0 →	→	→	361.4
• Engine Weight	6999 →	→	→	6705 →	→	→	6999
• Landing Accel (g's)							
- Vertical	4.47	N/A	N/A	TBD	TBD	N/A	N/A
- Horizontal	4.47	N/A	10	N/A	N/A	TBD	TBD
• Recovery Mode							
- Exp		✓					
- P/A - Water				✓	✓		✓
- P/A - Land				✓	✓		✓
- F.R.	✓		✓			✓	
• Inlet Press - Lox	23.3 →	→	→	TBD	TBD	23.3 →	→
- Fuel	19.6 →	→	→	TBD	TBD	19.6 →	→
• Power Head Dia	73.7 →	→	→	→	→	→	→
• Exit Dia	94 →	→	63 →	→	→	94	94
• Engine Length	167 →	→	146 →	→	→	167 →	→
• Inlet g's	30 →	→	→	→	→	→	→
• Gimbal Limits - Pitch	10.5 →	→	→	6 →	→	TBD	TBD
- Yaw	8.5 →	→	→	6 →	→	TBD	TBD
• Engine Life							
- Exp	-	1 - 15	-	1	1	-	-
- P/A - Water	-	-	-	10	10	-	-
- P/A - Land	-	-	-	-	-	-	-
- F.R.	50	-	50 - 15	-	-	30 - 50	30 - 50

* Demonstrated To Date. ** Assume SSME Not A Primary Candidate.

FIGURE 3-7 REQUIREMENTS MATRIX FOR SSME ENGINE APPLICATIONS

3.1.3 Potential Future Vehicle Applications for STME Engines

3.1.3.1 Introduction

The current Space Transportation Engine Program (STEP) has superseded the previous Space Transportation Main Engine (STME) and Space Transportation Booster Engine (STBE) designations used in previous study phases. The STEP program includes the gas generator cycle version as the baseline, and the split-expander cycle as the "baseline alternate". In this study task and report, we have dealt with the gas generator version exclusively, and have continued to use the "STME" terminology. SRS studies of Split Expander Cycle engines were performed as part of a companion task (Analyses of Undeveloped Rocket Engine Cycles) that is also a part of the same contract (See Figure 3-8). Results from that study task are provided in a separate report. This latter task has included limited analyses of launch vehicle applications, and further analyses of this nature are anticipated.

Analyses of potential vehicle applications for STME engines has been a major part of this study effort. We have used as the starting point STME engine characteristics as defined for the Advanced Launch System (ALS) application. During most of the period for this study, the STME "baseline" was an STME version configured primarily for the ALS core stage application, e.g., an engine with 62:1 area nozzle and other features. This baseline has more recently been changed to a "common nozzle" concept (40:1 area ratio nozzle) and a revised set of features. A comparison of these two sets of "baseline" characteristics is shown in Figure 3-9. We have attempted to adapt to these changes as information has become available to us, in some cases by examining a range of values or features that span both versions of STME baseline. For example, we have examined vehicle applications for STME engines with three nozzle sizes, as shown in Figure 3-10. These three include the previous STME baseline (62:1 area ratio), the current STME baseline (40:1), along with 20:1 area ratio for LRB or other booster applications. Although engine weight and other parameter values were not yet available from the STME/STEP program for the current baseline engine, we have used the values as shown in the bottom of Figure 3-10 for these three versions.

As one example, we used the "ALS Core" version of the STME for analyses of STME compatibility with installation and use in the Space Shuttle, including the stipulation that its baseline version would be equipped with scissor ducts and capability for ± 6 degrees gimbal. As will be noted later, increased gimbal capability and addition of wrap-around ducts would be needed for an STS installation. Although we did not have configuration or weight data for this version, the new STME baseline is to be capable of ± 10 degrees gimbal, and flexible ducting is to be vehicle supplied.

Scope of Study Tasks

	Propulsion Evolution Study	Undeveloped Cycles Study
• SSME	√	-
STME/STEP		
• Gas Generator (LH_2)	√	-
• Split Expander (LH_2)	-	√
• STBE (LoX/HC)	√	-
• Full-Flow Staged Combustion	-	√
• Hybrid FFSC/EC	-	√

Figure 3 - 8 Scope of Study Tasks

STME BASELINE CHARACTERISTICS
(Gas Generator Cycle Version) *

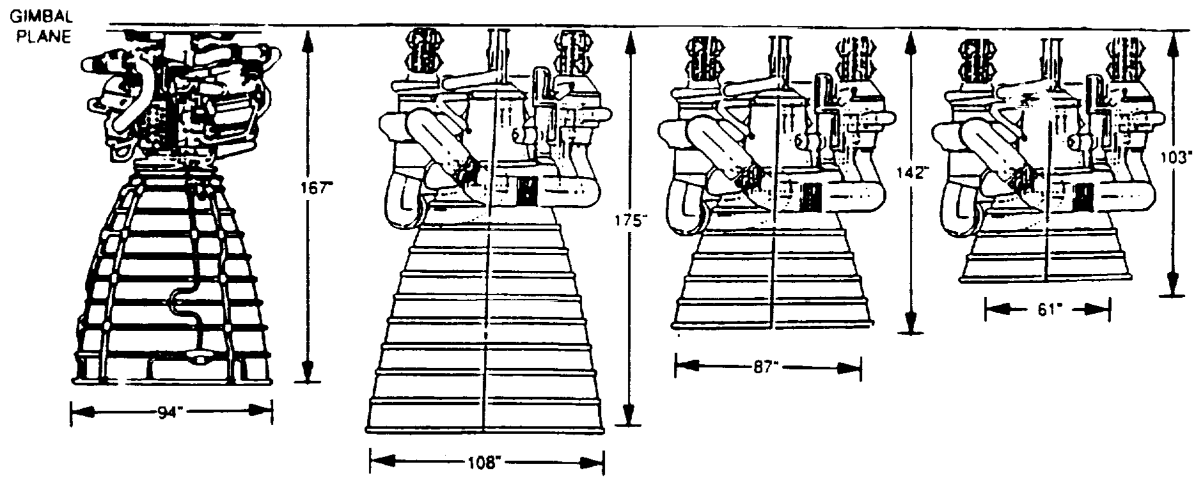
	Previous STME Baseline (ICD) (1989)	Current STME Baseline ** (1990)	
		Nominal	Option
• Thrust (lbs)	580K/435K	580K	
• Throttle Range	Dual	Fixed	Dual Thrust
• Expansion Ratio	62:1	40:1	Dual Nozzle
• Vacuum Isp (Sec's)	438	429	
• Thrust Tolerance	±3%	TBD	
• Engine Weight (lbs)	7800	7300	
• Recovery	Recoverable	Expendable	Ocean Recovery
• Engine Life	15 Flts	10 Flts, Equiv.	
• Gimbal Capability (P&Y)	±6°	±10°	
• Feed Ducts/Joints	Scissor Ducts	Integrated Flexible Feed Sys-On Veh.	
• Engine Inlet Pressure (LH_2)	24.5 psia (min)	30 psia (min)	
• Engine Inlet Pressures (LOX)	47 psia (min)	47 psia (min)	
• Boost Pumps	No Boost Pumps	No Boost Pumps	
• Mixture Ratio	6.0 ±3%	6.0	
• Mixture Ratio Control	Open Loop	Open Loop	
• Single Engine Reliability	0.99	TBD	
• Confidence Level	90%	TBD	
• Chamber Pressure	2250 psia	2250 psia	
• Engine Bleeds	For Tank Pressurization	No Bleeds	

Notes: * Separate set of characteristics for Split-Exapnder cycle version
** An additional range of values is specified by NASA for development of parametric data

900221LS1306

Figure 3 - 9 STME Engine Characteristics

ASSUMED STME ENGINE CHARACTERISTICS



	SSME (REF)	STME CORE ENGINE	STME WITH "COMMON NOZZLE" FOR ALS	LRB BOOSTER ENGINE
VAC THRUST	470K	580K	580K	580K
NOZZLE ε	77.5:1	62:1	40:1	20:1

891130LS1545

	NOZZLE AREA RATIO		
	62:1	40:1	20:1
• VAC ISP (secs)	438	429	414
• S/L ISP (secs)	344	368	387
• ENG. WT. (lbs)	7800	7245	6615
• EXIT DIA (ins)	108	87	61
• LENGTH (ins)	175	142	103

• ADAPTED FROM NASA-MSFC DATA

FIGURE 3-10 ASSUMED STME ENGINE CHARACTERISTICS

Some of the information developed as a part of vehicle application studies under Task No. 4 (Booster Propulsion Options) and under Task No. 5 (Common Engine Study) have been included in this section of the report (Section 3.1.3) for convenience.

Potential vehicle applications for STME engines will be addressed in this order:

1 - STS Evolution and Shuttle 'C'
2 - PLS Launch Vehicles (PLS Launch Vehicles using STS/LRB as a booster stage and PLS Launch Vehicles of New Design), and
3 - AMLS Launch Vehicles

3.1.3.2 STS Evolution and Shuttle 'C' Applications

When looking at possible utilization of STME engines in the Space Shuttle, we must first look at physical compatibility with installation in the STS and the level of performance attainable with these engines, and then to operations and cost benefits that might be available with these engines. The questions of physical installation and compatibility are most pronounced, since the STS hardware obviously already exists. We will address some of these considerations first, followed by discussion of the performance and operations costs considerations. Discussion of some aspects of propulsion and vehicle margins will be addressed in Section 3.1.4 of the report. Considerations of engine design features and margins that might be related to reliability and safety will be addressed in Section 3.5 (STME Evolution).

Engine Envelope and Gimbal Capabilities (STS Evolution/Shuttle "C")

Gimbal Capabilities with SSME Engines (Ref Info)

Gimbal capabilities and limits for the current STS using SSME engines have been examined first, as a starting point for analyses of STME engines in this application.

- Normal operation of STS/SSME, along with engine positioning during mission phases, are shown in Figure 3-11.
- Gimbal limits based on contact between SSME nozzles are shown in Figure 3-12.
- Gimbal limits based on contact between SSME nozzles and the Orbiter body flap are shown in Figure 3-13.
- Gimbal limits based on contact between SSME nozzles and orbit maneuvering system (OMS) pods and with OMS engines are shown in Figures 3-14 and 3-15, respectively.
- Our understanding of the resulting gimbal capabilities and limits is summarized in Figure 3-16.

COMMON ENGINE STUDY
STS/SSME ENGINE GIMBAL POSITIONING (REF)*

DURING NORMAL OPERATIONS

- WITHIN ±10.5° PITCH GIMBAL AND ±8.5° YAW GIMBAL LIMITS, WITH ADDITIONAL LIMITATIONS TO AVOID INTERFERENCE BETWEEN ENGINE NOZZLES AND ADJACENT ORBITER ELEMENTS

SUBSEQUENT TO MAIN ENGINE SHUT-DOWN

- ENGINES TO MAX DOWN (PITCH) POSITION.
  (MINIMIZE ORBITER PITCH MOMENT DUE TO MPS PROPELLANT DUMP)

PRIOR TO ENTRY:

- ENGINE #1 - NULL POSITION IN PITCH AND YAW
- ENGINES 2,3 - PARALLEL TO ORBITER ℄ IN YAW.
  - UP 10° FROM NULL IN PITCH
  (MINIMIZES AEROHEATING ON ENGINE NOZZLES DURING ENTRY)

* REF: STS/SSME PROPULSION DOCUMENT, SECTION 3.4.3.1

801214LS1045

FIGURE 3-11 STS/SSME ENGINE GIMBAL POSITIONING

COMMON ENGINE STUDY

STS/SSME GIMBAL LIMITATIONS (REF)*

COMBINATION OF GIMBAL ANGLES THAT RESULT IN ZERO CLEARANCE BETWEEN NOZZLES

Case	Combinations of gimbal angles that result in zero clearance between nozzles: SSME 1 Pitch (δ_{p1}), degrees	SSME 1 Yaw (δ_{y1}), degrees	SSME 2 Pitch (δ_{p2}), degrees	SSME 2 Yaw (δ_{y2}), degrees
1	10.5[a]	0	-10.5[a]	2.95
2	10.5[a]	0	-7.52	0
3	10.5[a]	0	-1.95	-8.5[a]
4	10.5[a]	8.5[a]	0.69	-8.5[a]
5	10.5[a]	8.5[a]	0	-5.40
6	10.5[a]	8.5[a]	-1.96	0
7	10.5[a]	8.5[a]	-7.47	8.5[a]
8	10.5[a]	-8.5[a]	-10.5[a]	-5.53
9	10.5[a]	-8.5[a]	-7.50	-8.5[a]
10	0	8.5[a]	-10.5[a]	-5.40
11	0	8.5[a]	-9.01	-8.5[a]
12	10.5[a]	-2.94	-10.5[a]	0
13	7.52	0	-10.5[a]	0
14	1.96	8.5[a]	-10.5[a]	0
15	-0.69	8.5[a]	-10.5[a]	-8.5[a]
16	0	5.38	-10.5[a]	-8.5[a]
17	1.95	0	-10.5[a]	-8.5[a]
18	7.50	-8.5[a]	-10.5[a]	-8.5[a]
19	10.5[a]	5.48	-10.5[a]	8.5[a]
20	7.47	8.5[a]	-10.5[a]	8.5[a]
21	10.5[a]	5.38	0	-8.5[a]
22	9.01	8.5[a]	0	-8.5[a]

Case	Combinations of gimbal angles that result in zero clearance between nozzles: SSME 1 Pitch (δ_{p1}), degrees	SSME 1 Yaw (δ_{y1}), degrees	SSME 3 Pitch (δ_{p3}), degrees	SSME 3 Yaw (δ_{y3}), degrees
1	10.5[a]	0	-10.5[a]	-2.95
2	10.5[a]	0	-7.52	0
3	10.5[a]	0	-1.95	8.5[a]
4	10.5[a]	-8.5[a]	0.69	8.5[a]
5	10.5[a]	-8.5[a]	0	5.40
6	10.5[a]	-8.5[a]	-1.96	0
7	10.5[a]	-8.5[a]	-7.47	-8.5[a]
8	10.5[a]	8.5[a]	-10.5[a]	5.53
9	10.5[a]	8.5[a]	-7.50	8.5[a]
10	0	-8.5[a]	-10.5[a]	5.40
11	0	-8.5[a]	-9.01	8.5[a]
12	10.5[a]	2.94	-10.5[a]	0
13	7.52	0	-10.5[a]	0
14	1.96	-8.5[a]	-10.5[a]	0
15	-0.69	-8.5[a]	-10.5[a]	8.5[a]
16	0	-5.38	-10.5[a]	8.5[a]
17	1.95	0	-10.5[a]	8.5[a]
18	7.50	8.5[a]	-10.5[a]	8.5[a]
19	10.5[a]	-5.48	-10.5[a]	-8.5[a]
20	7.47	-8.5[a]	-10.5[a]	-8.5[a]
21	10.5[a]	-5.38	0	8.5[a]
22	9.01	-8.5[a]	0	8.5[a]

Case	Combinations of gimbal angles that result in zero clearance between nozzles: SSME 2 Pitch (δ_{p2}), degrees	SSME 2 Yaw (δ_{y2}), degrees	SSME 3 Pitch (δ_{p3}), degrees	SSME 3 Yaw (δ_{y3}), degrees
1[b]	0	-5.69	0	5.69
2[b]	0	-8.5	0	2.89
3[b]	0	-2.89	0	8.5[a]
4	-9.45	-8.5[a]	9.45	8.5[a]
5	9.45	-8.5[a]	-9.45	8.5[a]
6	-10.5[a]	-8.5[a]	8.39	8.5[a]
7	-10.5[a]	-8.5[a]	0	4.32
8	10.5[a]	-8.5[a]	-8.43	8.5[a]
9	10.5[a]	-8.5[a]	0	4.49
10	8.39	-8.5[a]	-10.5[a]	8.5[a]
11	0	-4.32	-10.5[a]	8.5[a]
12	-8.43	-8.5[a]	10.5[a]	8.5[a]
13	0	-4.49	10.5[a]	8.5[a]

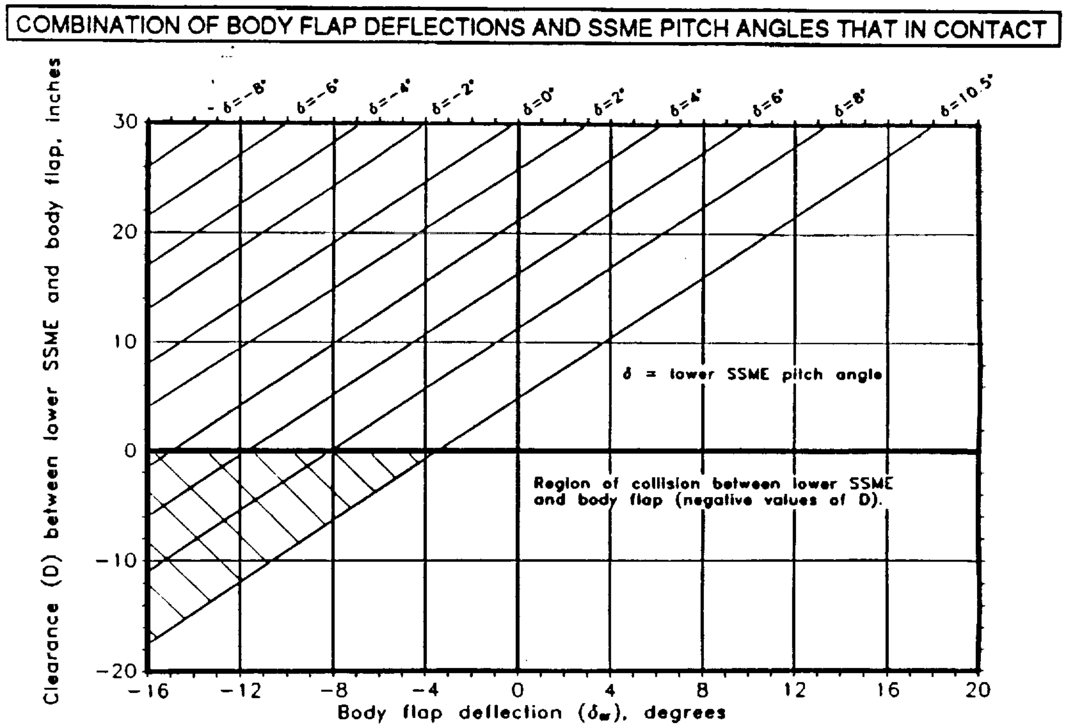
*REF: STS/SSME MPS DOCUMENT, SECTION 3.4.3

FIGURE 3-12 STS/SSME GIMBAL LIMITS (CONTACTS BETWEEN NOZZLES)

891215LS1335

COMMON ENGINE STUDY

STS/SSME ENGINE GIMBAL/BODY-FLAP DEFLECTION LIMITS (REF)*

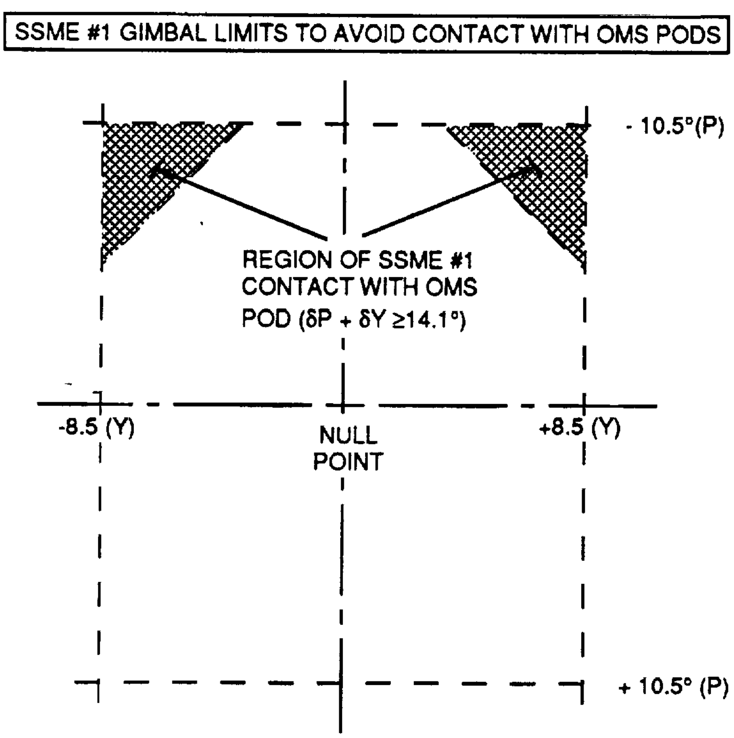


*REF: STS/SSME PROPULSION DOCUMENT, SECTION 3.4.3.1

891215LS134A

FIGURE 3-13 STS/SSME GIMBAL LIMITS (BODY FLAP)

COMMON ENGINE STUDY
STS/SSME GIMBAL LIMITS (REF)*



*REF: STS/SSME PROPULSION DOCUMENT, SECTION 3.4.3.1

891214LS1325

FIGURE 3-14 STS/SSME GIMBAL LIMITS (SSME-OMS PODS)

STS - SSME OMS ENGINE GIMBAL LIMITS (REF)*

SSME AND OMS ENGINE GIMBAL ANGLES THAT RESULT IN CONTACT

Case 3 - SSME 1 Pitch: δ_p = -5.6 degrees
Yaw: δ_y = 0.5 degrees

Left OMS pitch angle (δ_{pL}), degrees

Left OMS yaw angle (δ_{yL}), degrees: δ_{yL} \ δ_{pL}	-7°	-4°	-2°	0°	2°	4°	7°
0°	6.10	5.56	5.26				
-2°	4.46	3.89	3.56	3.28			
-4°	2.86	2.25	1.90	1.60	1.36	1.15	0.94
-6°	1.29	0.66	0.27	-0.05	-0.32	-0.54	-0.78
-8°	-0.24	-0.93	-1.32	-1.66	-1.95	-2.27	-2.45

Case 4 - SSME 1 Pitch: δ_p = -4.5 degrees
Yaw: δ_y = 0.5 degrees

Left OMS pitch angle (δ_{pL}), degrees

Left OMS yaw angle (δ_{yL}), degrees: δ_{yL} \ δ_{pL}	-7°	-4°	-2°	0°	2°	4°	7°
0°	6.73	6.09	5.72				
-2°	5.11	4.43	4.03	3.69			
-4°	3.51	2.80	2.38	2.01	1.70	1.43	1.11
-6°	1.96	1.20	0.76	0.38	0.04	-0.25	-0.59
-8°	0.43	-0.35	-0.81	-1.22	-1.58	-1.89	-2.25

Case 5 - SSME 1 Pitch: δ_p = 0 degrees
Yaw: δ_y = 0.5 degrees

Left OMS pitch angle (δ_{pL}), degrees

Left OMS yaw angle (δ_{yL}), degrees: δ_{yL} \ δ_{pL}	-7°	-4°	-2°	0°	2°	4°	7°
0°	10.3	9.30	8.67				
2°	8.75	7.68	7.03	6.42			
-4°	7.21	6.11	5.43	4.80	4.22	[illegible]	
-6°	5.70	4.57	3.87	3.22	2.61	[illegible]	1.48
8°	4.24	3.07	2.36	1.55	1.05	[illegible]	-0.70

Notes:
- Diagonally lined blocks correspond to regions of collision between nozzles of OMS and SSME 1.
- Clearances between the nozzle of the SSME 1 and the right OMS can be determined from the table by changing the signs of the yaw gimbal angles for SSME 1 and the OMS engine and replacing left OMS with right OMS.
- Clearance between the OMS and SSME 1 nozzle are shown in inches.

*Ref: STS/SSME Document, Section 3.4.3.1

FIGURE 3-15 STS/SSME GIMBAL LIMITS(SSME & OMS)

891215LS1330

PROPULSION EVOLUTION STUDY

STS/SSME GIMBAL CAPABILITIES AND LIMITS (REF)*

CONTACT BETWEEN ENGINE NOZZLES:

- MANY AREAS OF NOZZLE CONTACT (INTERFERENCE) WITHIN THE ±10.5° (P) AND ±8.5° (Y) GIMBAL REGIONS.
- HOWEVER, NO INTERFERENCE WITH ADJACENT ENGINE IN NULL POSITION.

CONTACT BETWEEN ENGINE NOZZLES (#'S 2&3) AND ORBITER BODY FLAP:

- BODY FLAP CAN NOT OPERATE OVER FULL RANGE (±11.7°) WITH ENGINES IN FULL-DOWN POSITION (P=10.5° DOWN)
- REGION OF INTERFERENCE IS BODY-FLAP UP 3.5 TO 11.7 DEGREES, COMBINED WITH SSME PITCH DOWN OF 6 TO 10.5 DEGREES.

(BODY FLAP NOT ACTIVE DURING ASCENT - POSSIBLE MOTION DUE TO VIBRATION/LOADS)

CONTACT BETWEEN SSME NOZZLES AND OMS ENGINES

- ANY SSME YAW DEFLECTION IN COMBINATION WITH ANY PITCH UP- LIMITS - RANGE OF GIMBAL FOR OMS ENGINES (P&Y)
- WITH SSME IN NULL (PITCH) POSITION, INTERFERENCE IS MINIMAL (SSME'S NORMALLY IN FULL-UP PITCH AND ZERO YAW FOR DE-ORBIT AND RE-ENTRY.)

CONTACT BETWEEN SSME NOZZLES AND OMS PODS:

- SSME GIMBAL REGION LIMITED TO δ(PITCH-UP) + δ(YAW) ≤ 14.1°, AVOID CONTACT WITH OMS PODS

* REF: STS/SSME PROPULSION DOCUMENT, SECTION 3.4.3.1.

891214LS1100

FIGURE 3-16 STS/SSME GIMBAL CAPABILITIES LIMITS

As shown in Figure 3-17, gimbal requirements for STS are ±8.5° in yaw and ±10.5° in pitch. As is also shown, gimbal excursions during the first 24 flights fall within a band of ±2° in yaw and ±8.5° in pitch. A good part of the pitch gimbal requirement is necessary to track vertical movement of vehicle c.g. during flight. Of the factors subject to random variations, larger excursions could reasonably be expected to occur in a sample larger than 24 flights.

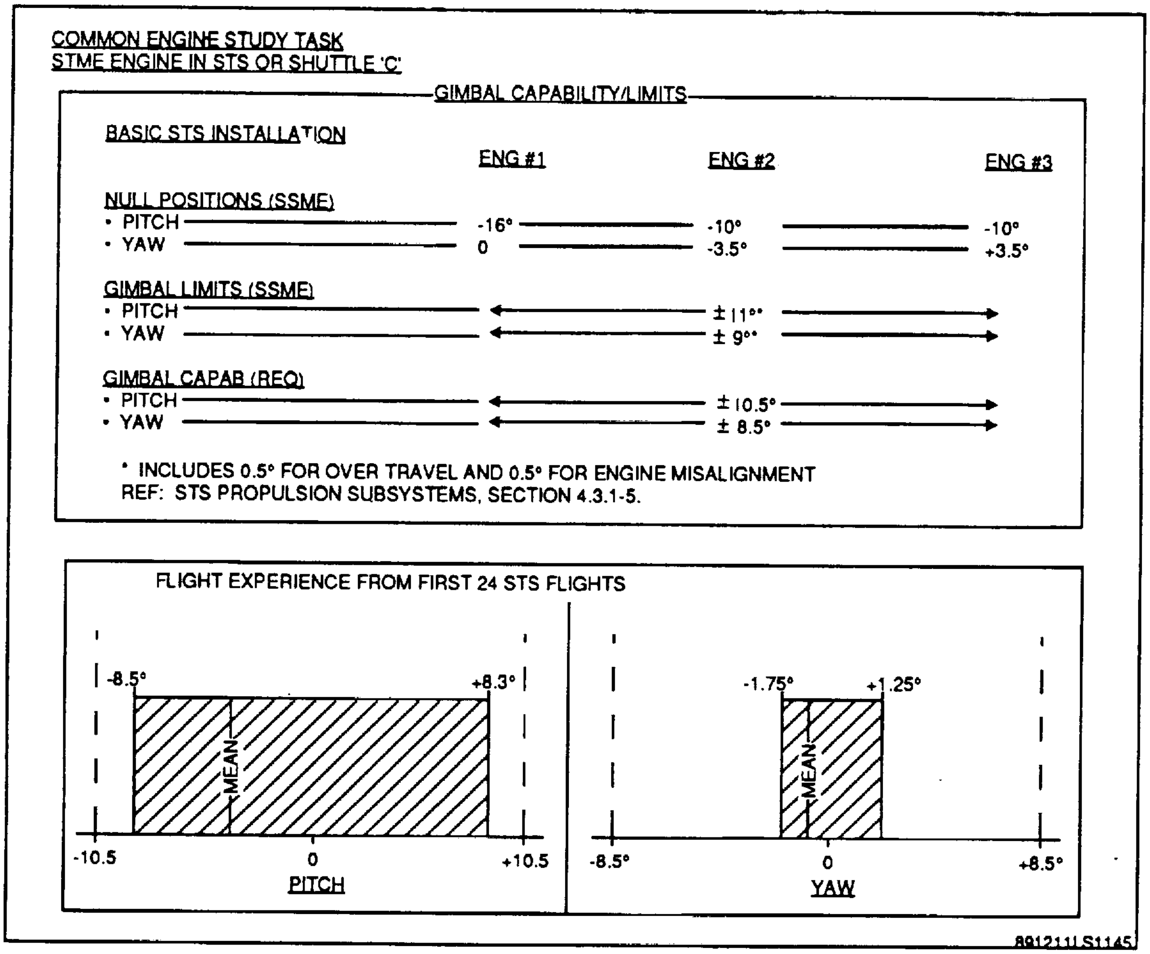


FIGURE 3-17 GIMBAL REQUIREMENTS AND FLIGHT EXPERIENCE

As shown in Figure 3-18 (from the STME-ALS Interface Control Document), STME engines are configured for ±6 degrees gimbal in pitch and yaw using "straight in" propellant feed ducts and scissor joints. In vehicle applications requiring more than 6 degrees gimbal capability such as STS/Shuttle "C", "wrap-around " propellant ducts are required. Depending on how these "wrap-around" ducts are packaged around the engine power head, they could increase problems in fitting the engines into available space in the STS boat-tail. The ducting arrangement shown in this illustration (RH side) would require additional length for engine inlet ducting, and assumes that the engine-vehicle interface could be moved forward by several inches. The arrangement of these wrap-around ducts would need to be worked out for the specific vehicle application.

COMMON ENGINE STUDY
STME INSTL. INSTS

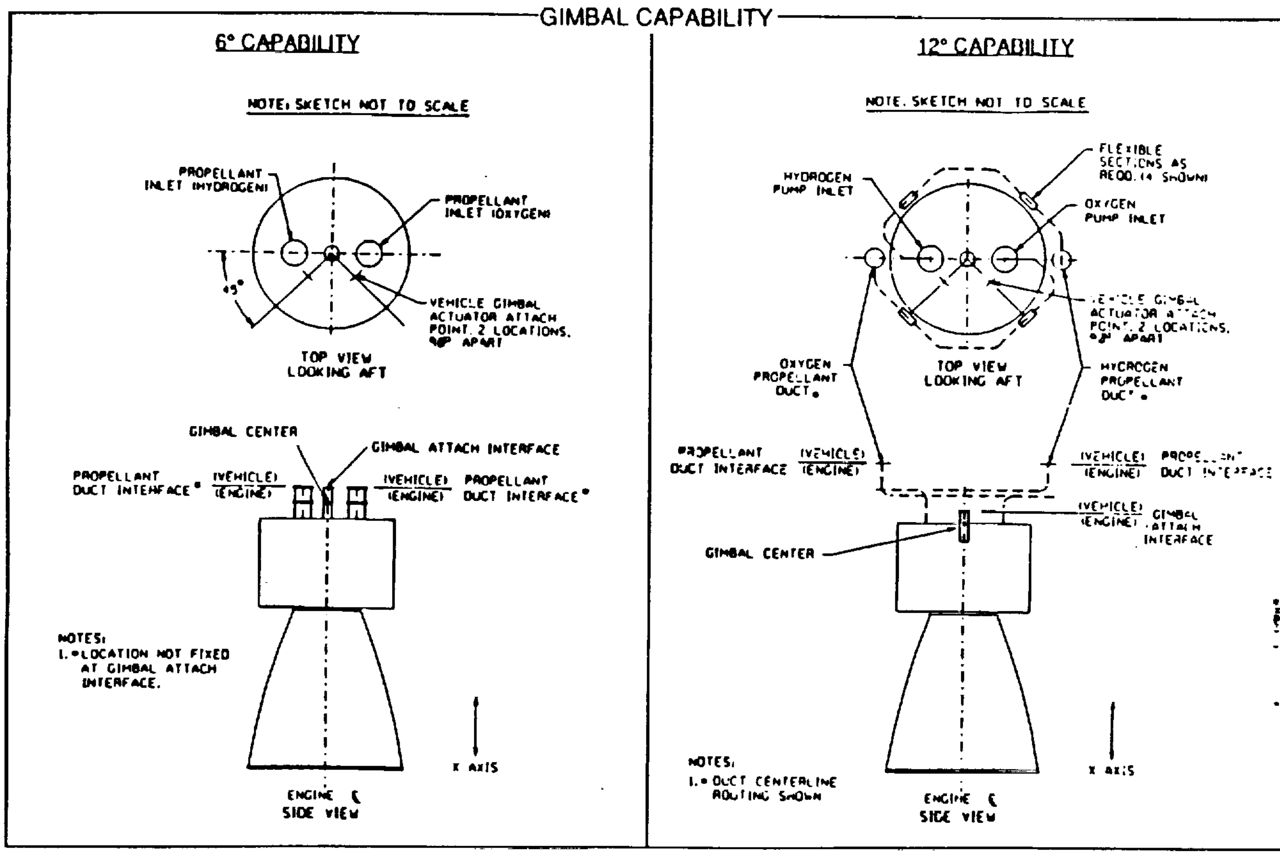


FIGURE 3-18 STME GIMBAL CAPABILITIES

We assume that published STME engine weights do not include the "wrap-around" ducts, and would need to be added for STS/Shuttle "C" applications. We do not have weight data for these ducts; however, it appears that ducts of a similar nature in SSME engines represent a major part of a 1400 lb. weight for "installation plumbing". It would appear, therefore, that additional weight on the order of 1500-3500 lbs. will need to be added for a 3-engine application for STS or Shuttle "C".

Note: This part of the study was performed using STME data that was available at that time, including a "nominal" STME configured for ± 6° gimbal capability. The STME baseline has been changed to ±10° gimbal capability with propellant feed ducting to be vehicle supplied. However, we have not had STME configuration and weight data for ±10° gimbal version for use in this study task.

Because of the complex geometries involved (Engine No. 1 pitched up 10°, Engines 2/3 pitched up 16°, Engines 2/3 yaw out 3.5°, Engine 1 yaw null at 0°), a computer model was developed to examine interactions between engine nozzle bells and interactions between engine nozzles and the Orbiter body flap. The basic arrangement of this program and analysis is shown in Figure 3-19.

Three contractor versions of STME engines (with expansion ratios of approximately 62:1) were examined, as well as a" generic" version of STME, where engine dimensions can be varied parametrically with nozzle area ratio. Results from analyses of the "generic/parametric" versions are presented in this report (based on engine/nozzle dimensions as shown in Figure 3-10).

Gimbal limitations based on contact between STME engine nozzles are shown in Figures 3-20 and 3-21. As shown, engines with 62:1 nozzle can not provide a full 8.5°/10.5° gimbal capability (contact between Engines 2/3 limits yaw gimbal, and contact with Engine 1 limits pitch-up/yaw-in combinations). Gimbal capabilities could exceed those experienced during the first 24 STS flights, as is also shown; but, would not provide margins for larger excursions in later flights. If we back off in nozzle area ratio to see how big a nozzle could be accommodated, we find that approximately 50:1 nozzle would allow full ±8.5°/±10.5° gimbal capability (shown in chart). It naturally follows that the "common nozzle" STME (area ratio of 40:1) could provide the full gimbal capability in the STS installation.

Although not analyzed in detail, it is assumed that gimbal constraints due to contact between Engine No. 1 and the OMS pods would be approximately the same as with SSME engines (contact not at nozzle exit), e.g., sum of pitch-up and yaw ≤14.1°.

Analysis of limitations due to contact between Engines 2/3 nozzle bells and the Orbiter body flap are shown in Figure 3-22. With STME-62, the results appear very similar to those for STS/SSME. There is approximately 3° clearance with the body flap in null position and engines 2/3 in 10.5° down position. With the body flap full-up (11.7°), engine gimbal would be limited to approximately 6° pitch down. Since the body flap would not be active during ascent and the SSME's are in stowed position during descent, it is assumed that these limits do not present a problem (the small clearance between Engines 2/3 and body flap during ascent exists now, on current Shuttle).

A summary of results from analyses of STS/STME gimbal capabilities and limitations is shown in Figure 3-23. Assuming that ±8.5/±10.5° gimbal capability is a firm requirement, engines with full 62:1 area ratio could not be utilized in STS geometry. If used in the STS, some reduction in area ratio could be necessary (something approaching 50:1 area ratio). There should be greater flexibility, however, in adapting STME engines into Shuttle 'C' vehicles. In the first place, gimbal requirements will likely be somewhat lower for Shuttle 'C' than for STS

GIMBAL CAPABILITIES / LIMITS
ANALYSIS / APPROACH

FEATURES OF GIMBAL PROGRAM

Nozzle Bell Collision - footprints for #1, #2, #3, OMS pod

Body Flap Interference with Nozzle Bell - (gimbal angle)

Works for any similar 3 engine boat tail

Must provide: - gimbal point coordinates
- engine length and exit diameter
- nozzle wall thickness
- initial and null pitch and yaw coordinates

ANALYTICAL TECHNIQUES

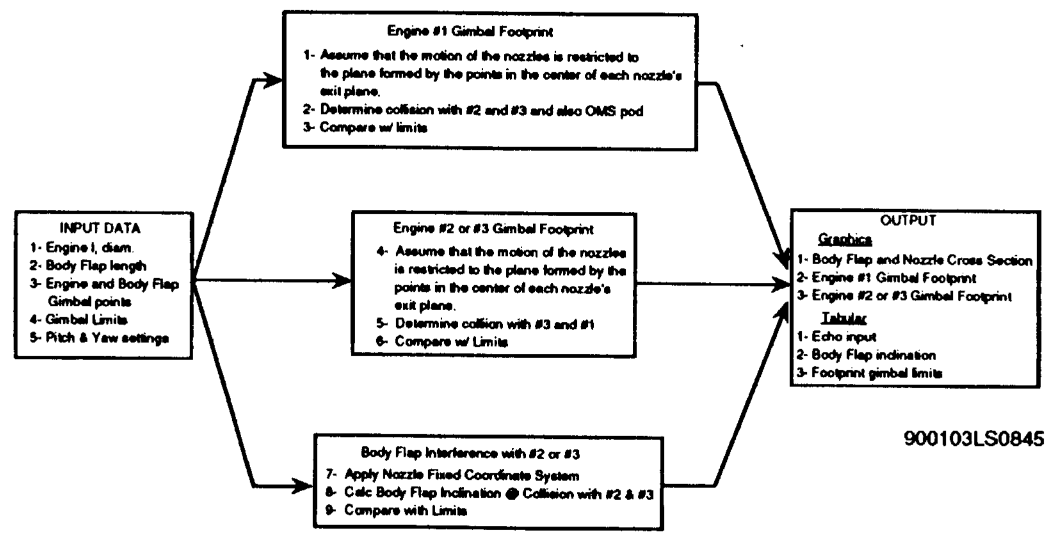
Symphony / Lotus Spread Sheet for IBM PC

Newton - Raphson Solution Method

Linear / Vector Algebra

Parametric Engine Sizing

GIMBAL PROGRAM ELEMENTS & ATTRIBUTES



900103LS0845

FIGURE 3-19 ANALYTICAL MODEL - GIMBAL GAPABILITIES

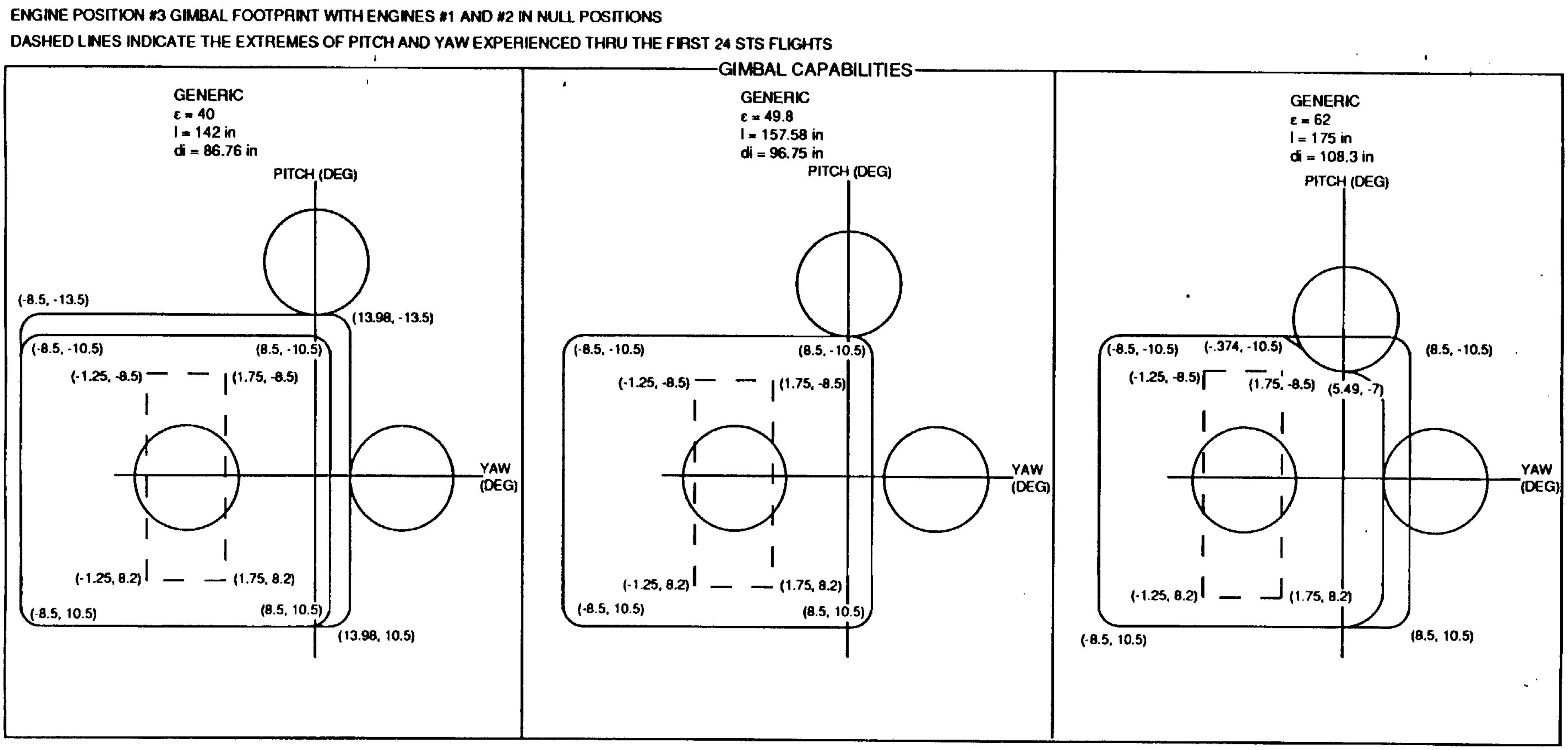


Figure 3-20 STS/STME Gimbal Capabilities (Contact Between Engine Nozzles)

891212jp0810

GIMBAL CAPABILITY / LIMITS
CONTACT BETWEEN ENGINE NOZZLE BELLS
ENGINE NO. 1 - WITH ADJOINING ENGINES IN NULL POSITION

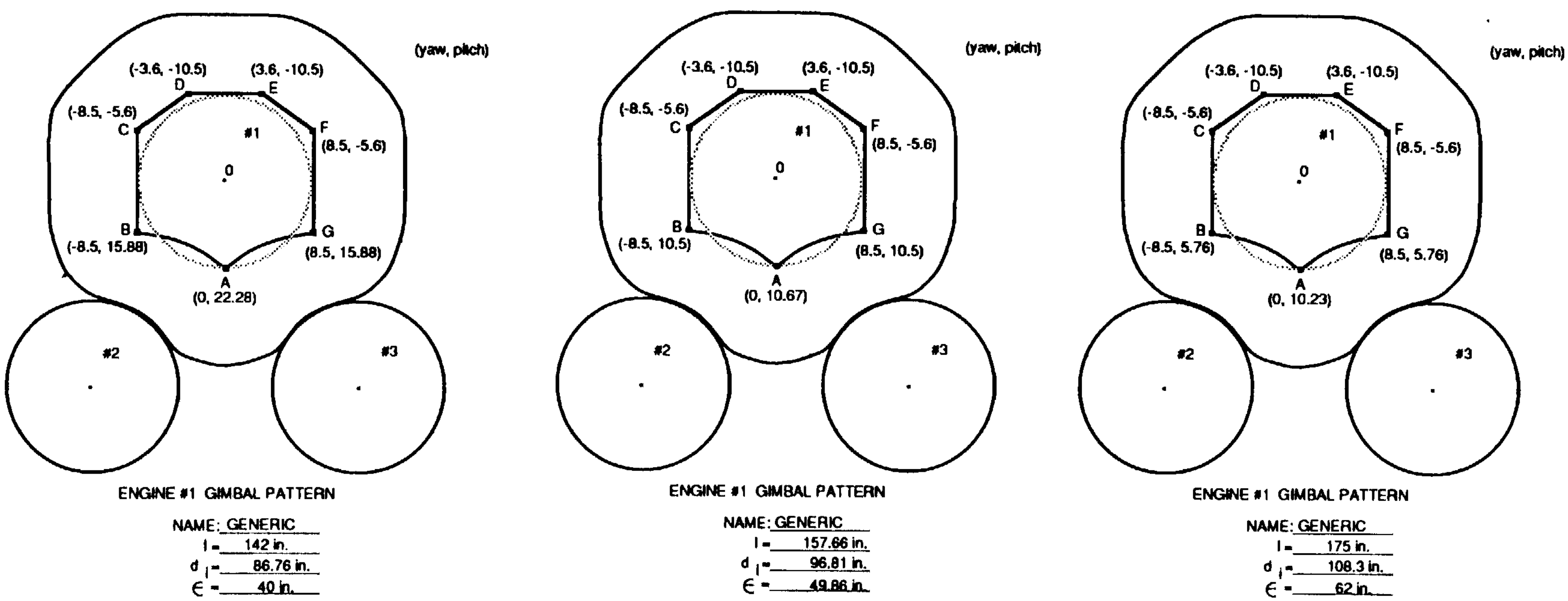
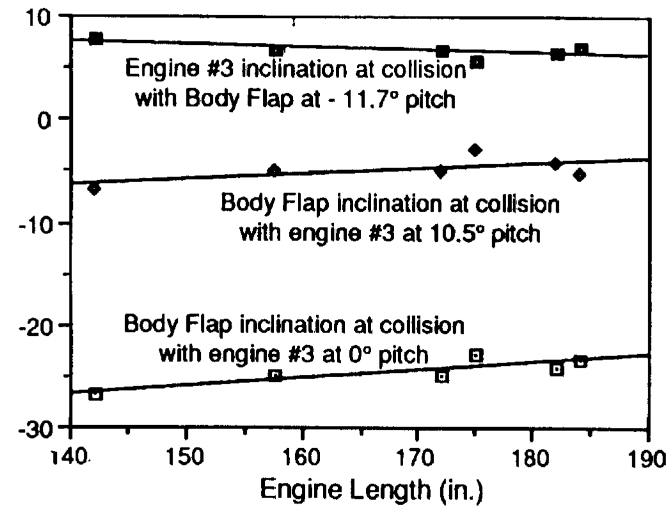


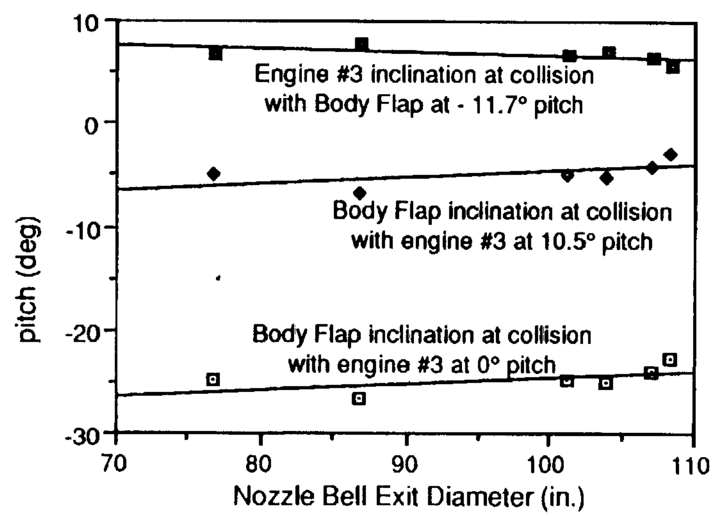
Figure 3-21 STS/STME Gimbal Capabilities (Contact Between Engine Nozzles)

900223LS1600

GIMBAL CAPABILITY / LIMITS
ENGINE BELL CONTACT WITH ORBITER BODY FLAP



STME Concept	Engine Length	#3 @ 0° p incl = □	#3 @ 10.5° p incl = ◆	BF @ - 11.7° p incl = ■
C	182	-23.9	-4.015	6.488
B	184	-25.1	-5.17	7.094
A	172	-24.8	-4.9	6.95
e=40	142	-26.71	-6.76	7.93
e=49.86	157.66	-24.86	-4.93	6.97
e=62	175	-22.8	-2.9	5.90



STME Concept	Engine Nozzle Exit Diameter	#3 @ 0° p incl = □	#3 @ 10.5° p incl = ◆	BF @ - 11.7° p incl = ■
C	107	-23.9	-4.015	6.488
B	104	-25.1	-5.17	7.094
A	101.3	-24.8	-4.9	6.95
e=40	86.76	-26.71	-6.76	7.93
e=49.86	96.81	-24.86	-4.93	6.97
e=62	108.3	-22.8	-2.9	5.90

Figure 3-22 STS/STME Gimbal Capabilities/Limits(Body Flap)

900104LS1105

(large aerodynamic surfaces of the Orbiter not in the Shuttle 'C' configuration). Secondly, some of the Orbiter equipment surrounding the engine installations would not necessarily be present in Shuttle 'C' configurations (Orbiter body flap, etc.). And, thirdly, it should be easier to make physical changes in the areas surrounding the engine installations (if strongly needed), and, in some cases might be made in conjunction with configuration changes being made for other purposes.

STS OR SHUTTLE 'C'/STME ENGINES

GIMBAL CAPABILITY LIMITS
SUMMARY OF RESULTS FROM ANALYSES

CONTACT BETWEEN ENGINE BELLS (WITH ADJ. ENGINE(S) IN NULL POSITION):

- NONE OF STME/62:1 ENGINES PROVIDE FULL 8.5/10.5° GIMBAL CAPABILITY:
  - ALL OF ENGINES EXAMINED COULD PROVIDE GIMBAL CAPABILITY ≥ VALUES EXPERIENCED DURING FIRST 24 STS FLIGHTS.
  - HOWEVER, NOT MUCH MARGINS.
- BACKING OFF TO AREA RATIO OF APPROX 50:1 WOULD REMOVE THESE CONSTRAINTS (STME/40:1 OK IN THIS RESPECT).

CONTACT WITH OMS POD:

- NOT EXAMINED IN DETAIL; ASSUMED TO BE APPROXIMATELY SAME LIMITS AS WITH SSME ENGINES (PITCH UP + YAW ≤ 14.1°).

CONTACT WITH ORBITER BODY FLAP

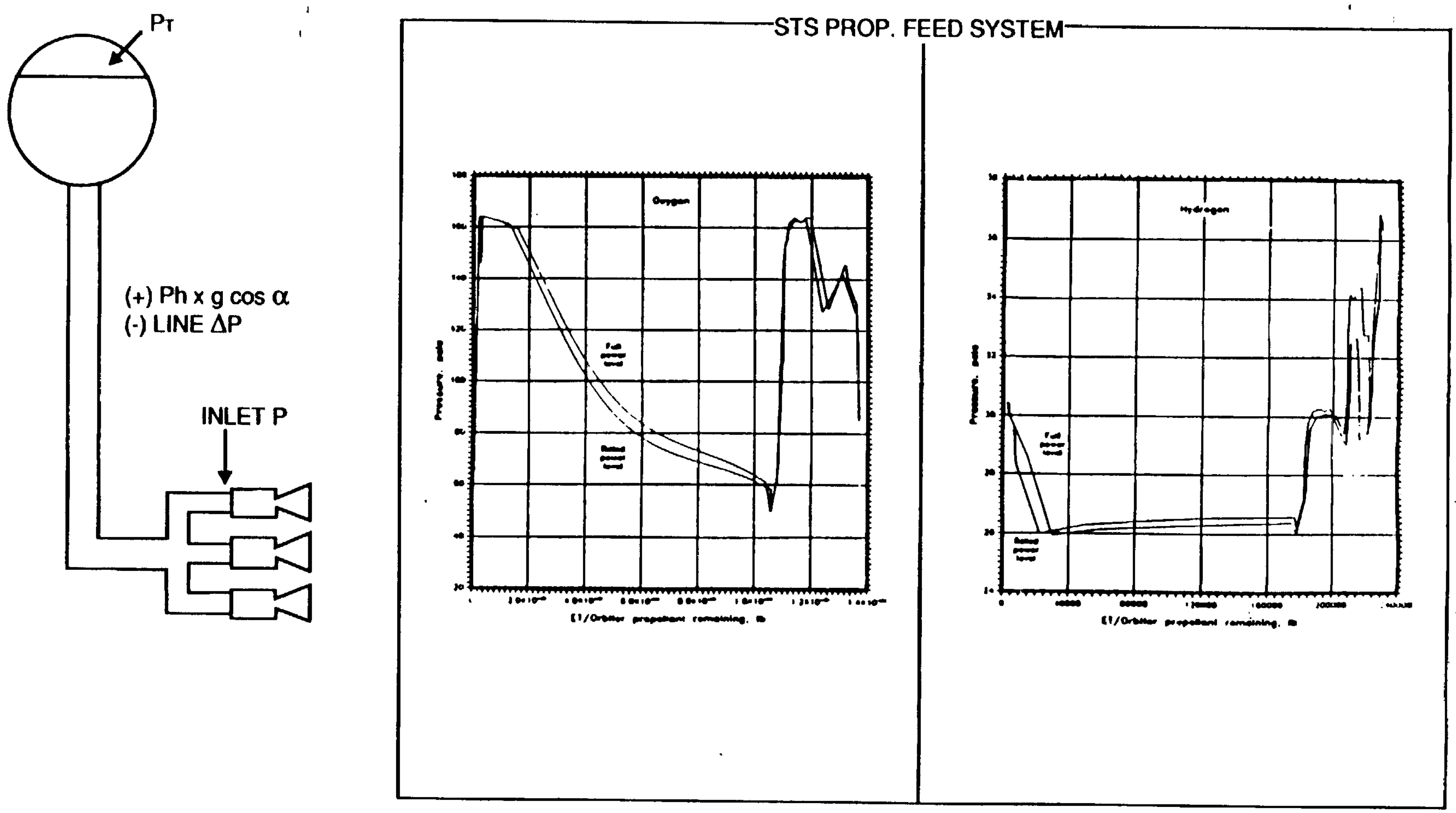
- WITH STME/62:1 ENGINES, BODY FLAP LIMITS VERY SIMILAR TO THOSE WITH SSME ENGINES:
  - 2.9 TO 5.7 DEGREES UP ROTATION, WITH ENGINE NOS. 2/3 10.5° DOWN.
  - 22.8 TO 25.1 DEGREES UP ROTATION, WITH ENGINE NOS. 2/3 IN NULL POSITION (BODY FLAP LIMITED TO 11.7 DEGREES UP).
- WITH STME/40:1 ENGINES, BODY FLAP LIMITS GO UP TO APPROX 7 DEGREES AND 27 DEGREES, RESPECTIVELY.

9001CSL81431

FIGURE 3-23 STS/STME GIMBAL CAPABILITIES/LIMITS (SUMMARY)

Propellant Feed System (STS Evolution/Shuttle "C")

The STS propellant feed system is shown schematically in Figure 3-24, along with engine inlet pressure histories over a typical STS flight sequence. Minimum inlet pressures for SSME engines operating in the STS (as shown in Figure 3-25) are 19.6 on the fuel side and



891208LS1330

FIGURE 3-24 STS PROPELLANT FEED AND PRESSURES

23.3 psi on the LOX side. As also shown in Figure 3-25, requirements for STME engines have been set at 30 psi (fuel) and 47 psi (LOX), to minimize pumping requirements upon the engine and to avoid necessity for boost pumps. It seems likely that the engine would have to operate with inlet pressures lower than the ICD values, and boost pumps would likely be required in some form.

Propellant flow rates will be higher with STME engines than with the current SSME engines. If the STME engines are operated at thrust levels equivalent to current SSME thrust levels (see later discussion on engine thrust levels and vehicle performance), propellant flow rates would be only marginally higher (due to lower specific impulse of the STME engines). This would increase line pressure drop and would add to the engine inlet pressure problem noted above, but should be within the rated flow capability of the propellant feed lines. If on the other hand, we should be able to operate the STME's at higher thrust levels for performance benefits, the much higher flow rates and pressure drops (see Figure 3-25) would contribute much more to the engine inlet pressure problem, and would likely require verification or redevelopment of propellant feed lines for these much higher flow rates (up to 28 percent higher).

PROPELLANT SUPPLY
AND ENGINE INLET CONDITIONS

• PROPELLANT FLOW RATES:

SSME	STME
LOX = 886 LB/SEC	LOX = 1135 LB/SEC (1056 @ 93%)
LH2 = 148 LB/SEC	LH2 = 189 LB/SEC (176 @ 93%)

- 28% INCREASE IN MASS FLOW RATES
- 28% INCREASE IN LINE FLOW VELOCITIES
- ~ 64% INCREASE IN FEED-LINE PRESSURE DROPS

• ENGINE INLET PRESSURE REQMTS

SSME*	FUEL	LOX	STME**	FUEL	LOX
MAX	125	285	MAX	38	285
			RATED	35	130
MIN	19.6	23.3	MIN	30	47

• STS PROPELLANT FEED

- AT SSME FLOW RATES ~ APPROX 50 psia (LOX-MIN) AND 26 psia (LH2 MIN)*
- WOULD BE SIGNIFICANTLY LOWER AT STME FLOW RATES
- WOULD NOT MEET STME INLET PRESSURE REQMTS/OBJECTIVES
- WOULD BE NECESSARY TO:
  - REDUCE STME ENGINE INLETPRESSURE REQMTS
    AND/OR
  - INCREASE E.T. TANK PRESSURES (ALLOWABLE INCR = TBD)
    AND/OR
  - UTILIZE BOOST PUMPS

* REF: STS PROPULSION SUB-SYSTEM DOCUMENT, SECTION 4.3
** REF: PHASE B ERR REFERENCE ENGINE DESIGN REQUIREMENTS

FIGURE 3-25 PROPELLANT FEED WITH SSME OR STME ENGINES

Fluid System Requirements (STS Evolution/Shuttle "C")

A partial listing of fluid requirements for operations in STS/Shuttle 'C' and other vehicles is shown in Figure 3-26. The following requirements for LOX tank pressurant are stated in the STME/ALS ICD:

- 1.10 to 2.35 lbs/sec
- 850±50°R
- 1000 to 3000 psia

Although higher pressurant flow rates will be required, we assume no problems of STS and STME compatibility in this respect.

Some of the functional requirements listed in Figure 3-26 are, however, unique to the Shuttle, AMLS, or other reusable vehicles (propellant dump and line purges for abort or return for reuse). It is assumed that these requirements can be met with no compatibility problems.

COMMON ENGINE STUDY

ASSUMPTIONS - FLUID SYSTEM REQUIREMENTS

	STS/ ORBITER	SHUTTLE 'C'	STS/LRB	PLS/ BOOST	PLS/ SECOND	AMLS/ BOOST	AMLS/ ORBITER
• PROVIDE PROPELLANT TANK PRESSURANTS (LOX AND LH2)	√	√	√	√	√	√	√
• MAIN ENGINE PURGE - GN2 - ON GROUND	√	√	√	√	√	√	√
• PROPELLANT DUMP							
- NORMAL, POST-MECO	√		*	*	*	√	√
- RTLS ABORT	√					√	√
- TAL ABORT	√						√
• HELIUM PURGE & PRESSURE MPS LINES	√		*	*	*	√	√

* POTENTIAL RQMT - IF RECOVERED

\- - IF MISSION PHASE/TIMING ALLOWS.

891214LS1630

FIGURE 3-26 FLUID SYSTEM REQUIREMENTS

Loads for Engine Installation

Load factor requirements for normal operations in STS and for ground handling are shown for STS/SSME in Figure 3-27, in comparison with current load factor requirements for STME engines. The STME requirements seem more than adequate for installation and operation in STS, unless there is an abort landing requirement that might impose higher 'y plane' requirements (horizontal landings) than the engines would see an ALS application.

COMMON ENGINE STUDY
STME - STS INSTL

LOADS

STS

STS INSTL LOADS*

(x) – (-)1.75 TO (+)3.24
(y) – (-)4.47 TO (+)2.05
(z) – (-)2.05 TO (+)4.47

GROUNDING HANDLING
± 4 g's - ANY DIRECTION

ABORT LANDING LOADS
- TBD -

STME
(STME ICD)

- AXIAL (x) -------- ±10g's
- LATERAL (y) --- ±5g's
- LATERAL (z) --- ±5g's

*REF: TELECON INFO FROM RI-HSVL

FIGURE 3-27 LOADS FOR ENGINE INSTALLATION

Orbiter c.g. Location (STS Evolution/Shuttle "C")

The extreme aft location of the weight of three SSME engines added to the difficulty of the original STS orbiter design and development. Although we are not in a position to assess the extent, higher weights for STME engines would likely add to this problem. Three of STME engines would be some 2400-3000 lbs heavier than SSME's, and addition of "wrap-around" propellant feed ducts (included in SSME weights) could possibly double that weight difference.

Thrust Levels and Throttle Requirements (STS Evolution/Shuttle "C")

The basic STME has been planned for two operating thrust levels, e.g., at 100% (580K lbs. vacuum thrust) or at 75% (435K lbs. vacuum thrust) power settings. Corresponding values for STS/SSME operations are at 470K (100%), 489K (104%), and at approximately 512K (109%) under engine-out or abort conditions. The higher thrust capability of the STME would be a performance advantage for STS or 3-Engine Shuttle 'C'; however, capability of the current STS thrust structure may limit or prevent taking advantage of this thrust capability.

As we understand, the current STS thrust structure is limited to approximately 111% x SSME thrust (522K lbs) per engine; or could be increased to approximately 115% x SSME (540K lbs) with minimum redesign. Moving the operating thrust level closer to the thrust structure limit would seem contrary to the established objective of getting larger margins into the NMTS systems where ever possible or practical. We have therefore assumed that normal operation of STME engines in STS would be at a thrust level equivalent to 104% x SSME thrust (approximately 489K lbs per engine).

A thrust profile under these assumptions is shown in Figure 3-28, along with a sketch showing STS/Shuttle 'C' operating thrust levels on an STME thrust level scale. If it is of significant advantage, the STME engines could be operated at a higher throttle setting at lift-off and during initial part of ascent phase (thrust output reduced by atmospheric back pressure). This is noted schematically by the shaded area in Figure 3-28. It is assumed that STME's would need to be throttled to the equivalent of 65% x SSME thrust for $q\alpha$ control (approximately 53%), and to a somewhat higher setting (value = TBD) for 3x Engine Shuttle 'C' flights. Limiting 'g' levels during the latter part of Orbiter burn phase could be achieved by deep throttling of three engines or shut-down of one engine.

If more refined analyses of STS thrust structure capability should show larger margins than currently assumed, then operating thrust levels could be increased correspondingly.

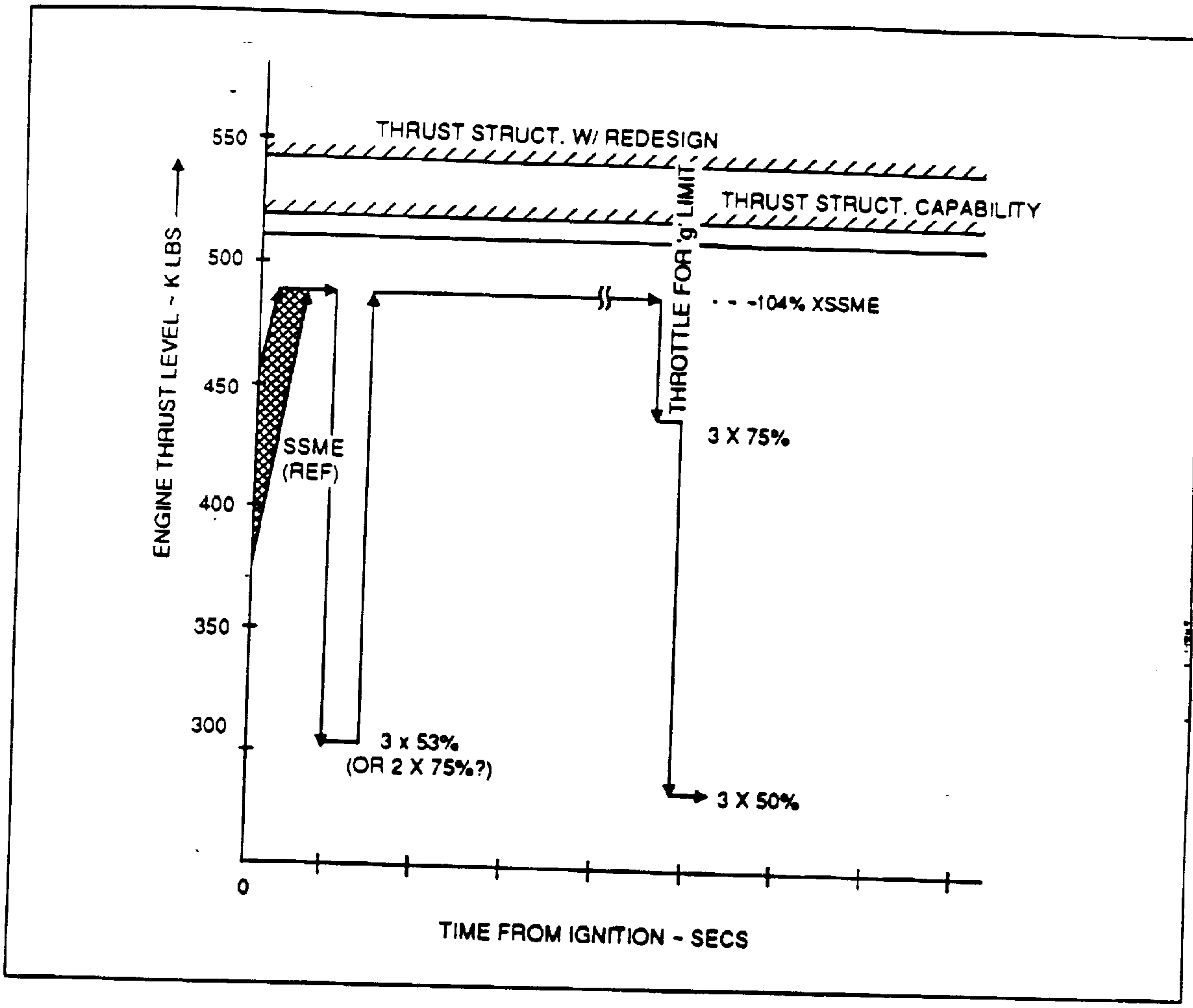
Flight Performance Considerations (STS Evolution/Shuttle "C")

Because of its gas generator cycle and lower operating chamber pressure, vacuum specific impulse of STME engine (at 62:1 area ratio) would be some 12-15 seconds below that for SSME. Performance of the STME with 40:1 area ratio is another 9 seconds lower than that for 62:1. Based on rough order parametric estimates, this results in vehicle performance decrements as shown on Figure 3-29.

The performance/delta estimates are based on use of published STME engine weights which, as we understand, do not include "wrap-around" ducts (see earlier section on "gimbal capabilities and limits"). This additional weight may reduce STS/Shuttle "C" performance by an additional 1500-3500 lbs.

STS performance decrements with STME/62 are significant, and are even larger with STME/40 engines. It is assumed that STS performance delta's of this magnitude would be practical only if implemented in conjunction with incorporation of LRB's or some other off-setting performance gain.

STME ENGINE APPLICATIONS
STS AND SHUTTLE 'C'



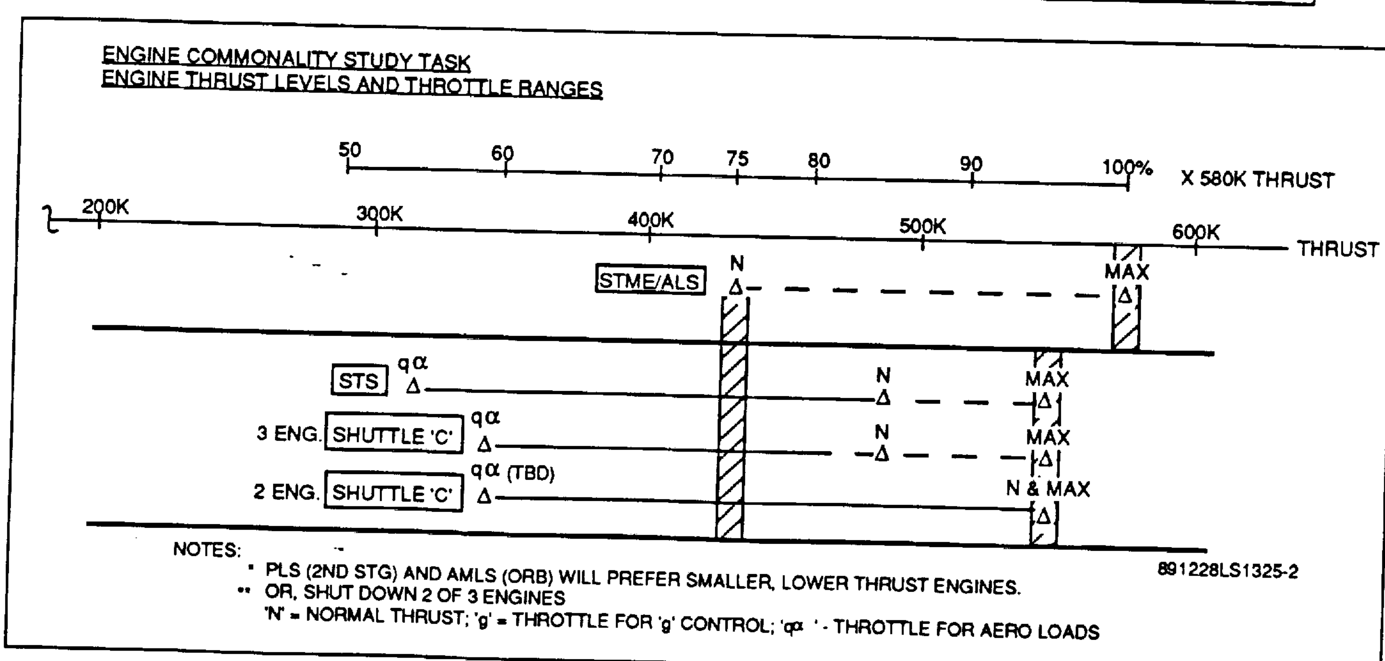
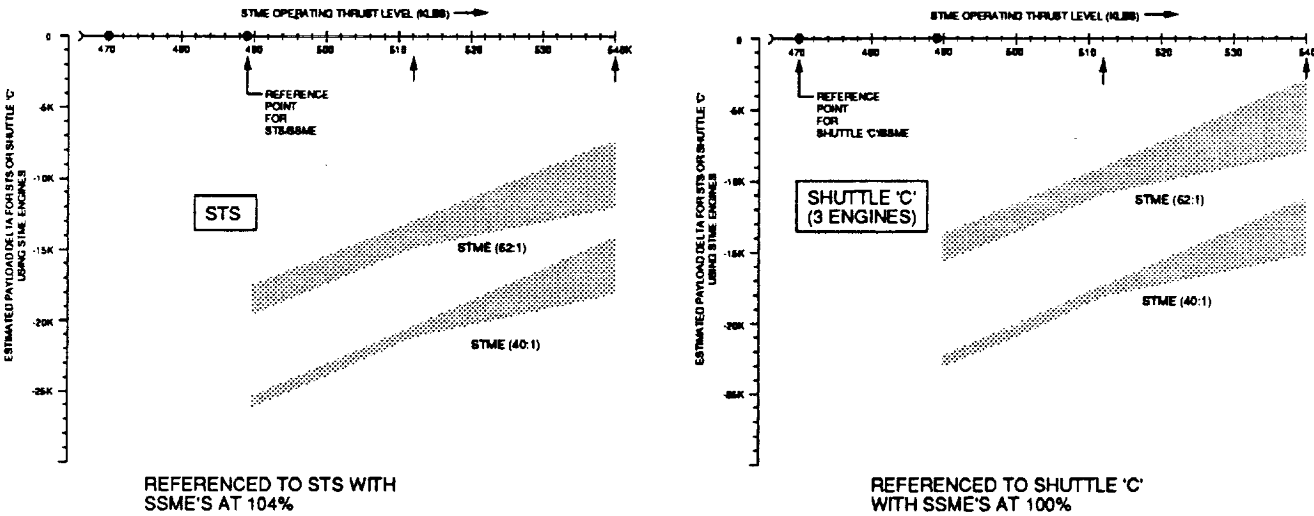


FIGURE 3-28 OPERATING THRUST LEVELS AND THROTTLE REQUIREMENTS

APPROXIMATE PAYLOAD PERFORMANCE DELTA'S
USING STME ENGINES IN STS/STSEVOLUTION/SHUTTLE 'C' VEHICLES



NOTE: (1) SLOPE OF 1K LBS PAYLOAD PER 1% (SSME) THRUST IS USED FROM 470K TO APPROX 512K THRUST. SLOPE AT HIGHER THRUST LEVELS MAY BE LOWER.
(2) INERT WEIGHT FOR "WRAP-AROUND" PROPELLANT FEED DUCTS NOT INCLUDED.

FIGURE 3-29 VEHICLE FLIGHT PERFORMANCE DELTA'S

STS/SHUTTLE 'C' PERFORMANCE WITH STME ENGINES

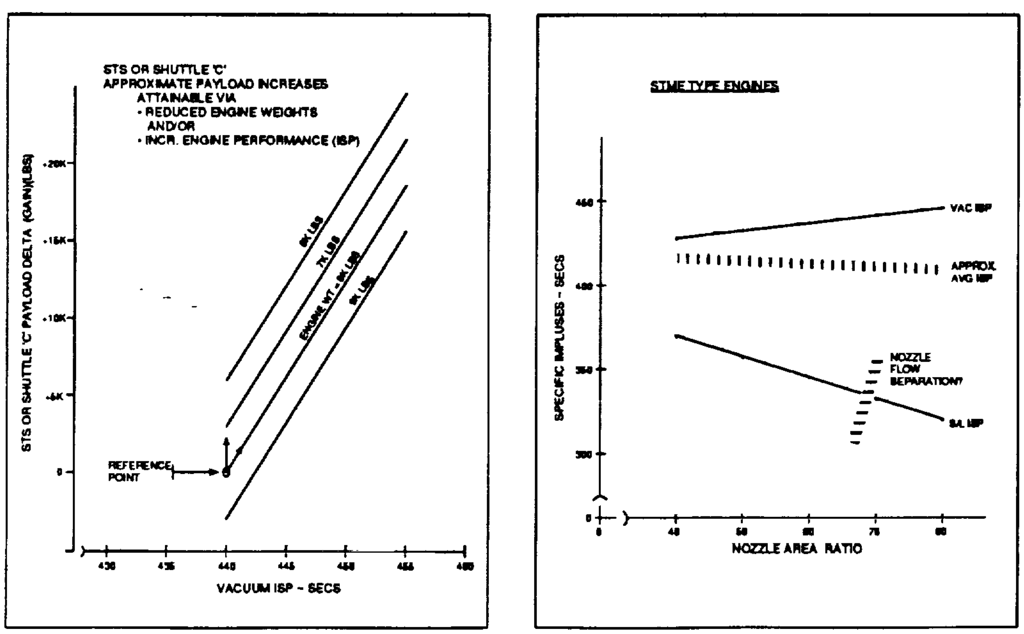


FIGURE 3-30 POTENTIAL PERFORMANCE IMPROVEMENTS

The performance delta's for 3x Engine Shuttle 'C' as shown are somewhat less than for STS, due to the fact that Shuttle 'C' is referenced to SSME's operating at 100% (vs 104% for STS) (Ref: Figure 3-29). We assume that delta's of this magnitude are less critical for Shuttle 'C' than for STS, because it is a much smaller fraction of total payload capability, and missions/payloads have not yet been firmed up to the extent they have for STS. If the Shuttle "C" thrust structure design were modified for other reasons, an increase in payload capability could be realized by use of the STME full thrust capability.

If engine-vehicle trade studies were performed, candidate approaches to reduce the magnitude of the of the STS performance delta's include: (1) Thrust structure analyses or redesign to allow gains from operating at higher STME thrust levels (discussed earlier), (2) Increases in engine performance (Isp), and (3) Engine weight reductions. Parametric estimates in Figure 3-30 (RH side) indicate that little, if any, Isp gains could be achieved by going to a larger nozzle area ratio, even if it could fit into the STS installation. This would likely leave higher chamber pressures as a means to increase Isp. Parametric curves on LH side of Figure 3-30 show, for information, estimates of vehicle performance gains attainable via engine weight reductions and/or increases in specific impulse.

Propellant Utilization (P.U.) (STS Evolution/Shuttle "C")

A mixture ratio tolerance of ±3% is currently indicated for STME engines. If this means that there will be a ±3% uncertainty in M.R. for any given flight, this could have major payload performance implications, as shown in Figure 3-31. The "worst case" impact would be mitigated somewhat by "averaging" of individual engine variances, and could be reduced by use of a "fuel bias" (dashed curve), but would result in a significant propellant residual and payload penalty with nominal mixture ratio operations. This interpretation of the ±3% tolerance suggests strongly to reconsider closed-loop P.U. controls for STME, if used in STS or other performance-sensitive vehicles. If this tolerance means that all engines will fall within a ±3% band, and that the M.R. uncertainty for any given vehicle/flight is much lower than that amount, the performance penalty and motivation for closed-loop P.U. control would be reduced correspondingly. Even if the engine M.R. uncertainty were zero, performance would still be subject to uncertainties in the propellant supply/feed system. A closed-loop P.U. control could handle uncertainties in both parts of the system.

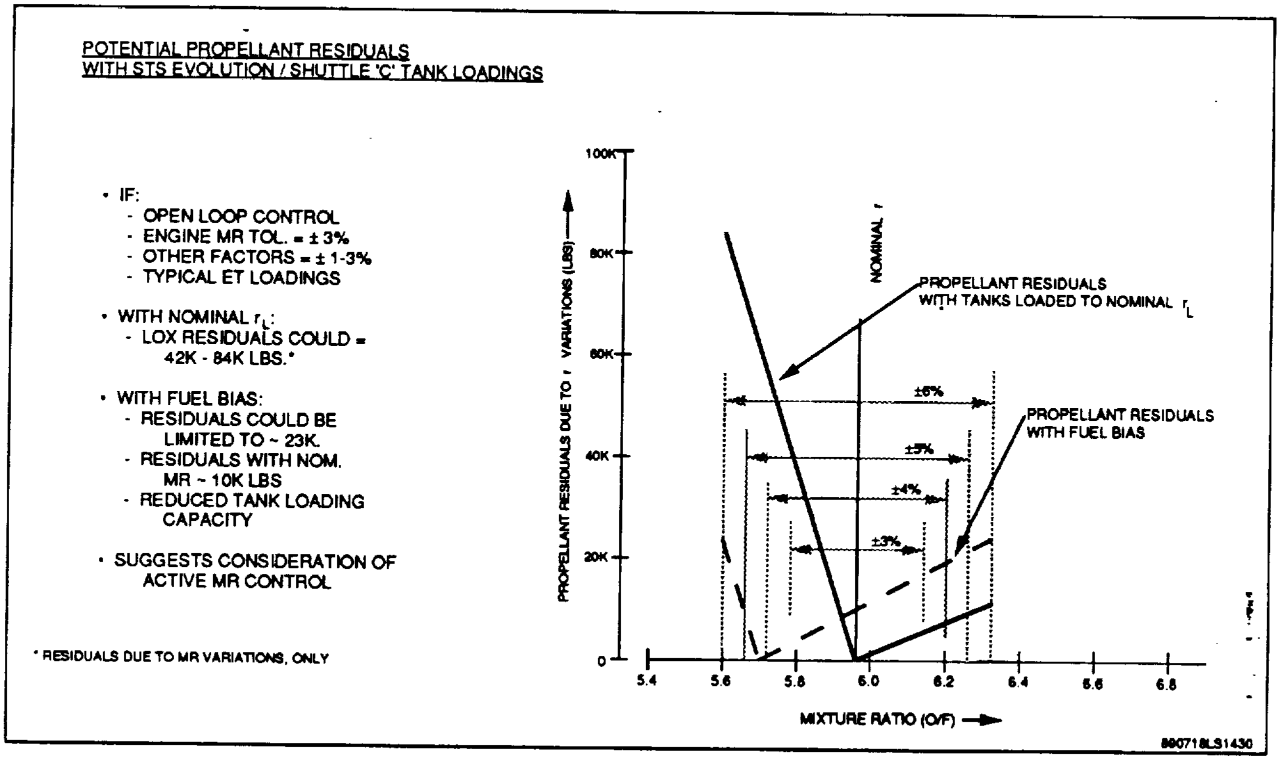


FIGURE 3-31 MIXTURE RATIO TOLERANCE/UNCERTAINTIES

Engine Life Cycle and Cost Trades (STS Evolution/Shuttle "C")

An engine life of 10 flights is used in current STME engine planning (vs. the value of 15 flights used earlier). Earlier parametric studies indicated that an engine life of 30-50 flights is a desirable range for highly reusable vehicles such as the Space Shuttle. The graph in Figure 3-32 (RH side) shows the differences in recurring engine costs with an engine life of 10 flights, in comparison with an engine life of 50 flights. This reduction in recurring engine costs must, of course, be weighed against the additional investment necessary to achieve the higher engine life. Hypothetical values for this additional investment are shown in the shaded band, as an example of such a trade. These data are applicable, under the assumptions shown, for operations in the reusable Shuttle, alone. If the engines are to be operated in the STS and Shuttle 'C' as companions, with engines switched to the (expendable) Shuttle 'C' after some number of flights in the STS, data on the LH side of Figure 3-32 apply. The average number of flights per engine realized in this mode of operation, and over the ranges of STS and Shuttle 'C' flight rates as shown, all fall pretty much within 10 flights per engine. In summary, an engine life of 10-15 flights per engine seems to be the right range for combined operation in STS and Shuttle 'C', but serious trade studies of higher lifetimes (to the 30-50 range) would be needed for operation in the STS alone. If engine recovery were implemented for some version of Shuttle 'C', it seems likely that the 10-15 flight range would fit that case fairly well, depending on specifics of the recovery mode.

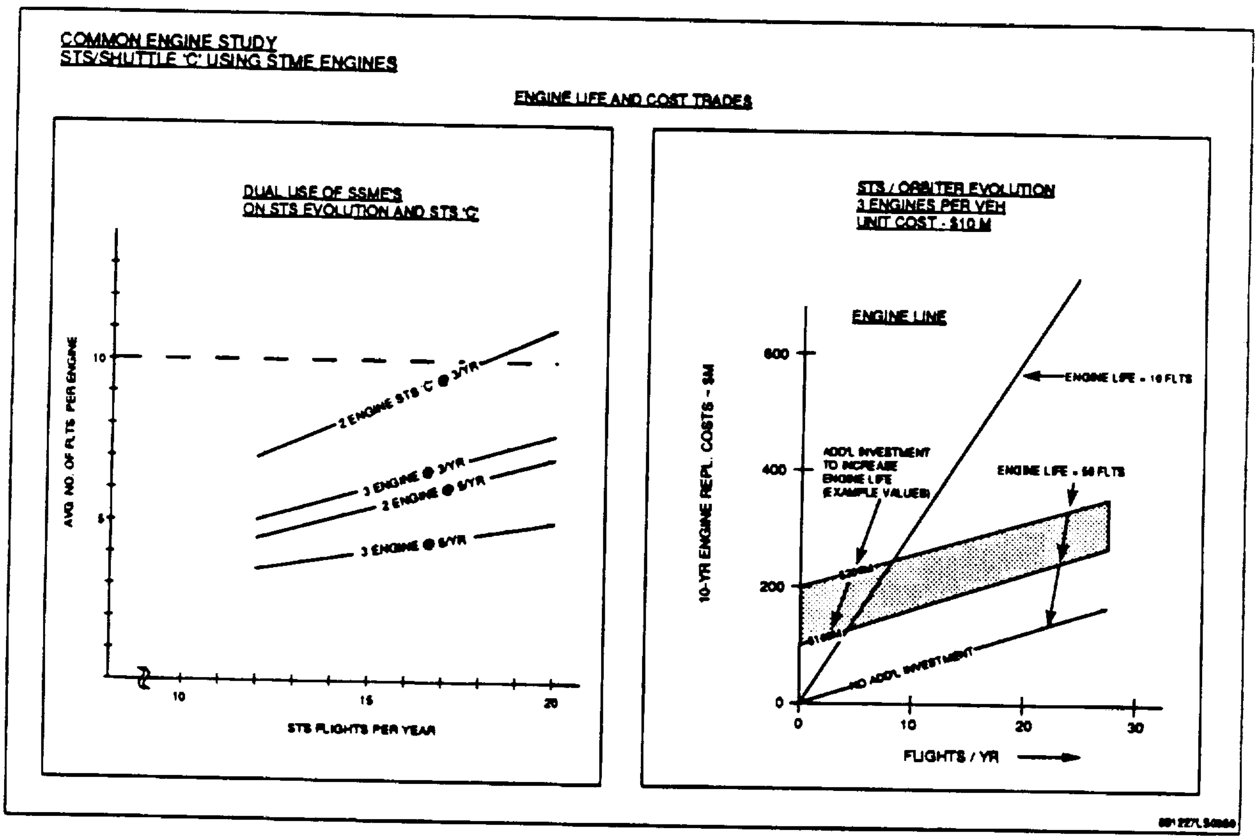


FIGURE 3-32 ENGINE LIFE AND COST TRADES

Summary - STME Engine Applications for STS Evolution/Shuttle "C"

Adaptation of STME engines into the Space Shuttle vehicle would require substantial changes in the vehicle and/ or engine. The STS would need the performance capabilities of the high area ratio (approx. 62:1) version of the engine (plus more performance); however, the large engine size combined with engine gimbal requirements of the STS present distinct hardware installation problems. This could be workable, however, if the Orbiter engine change-out were accomplished in conjunction with another vehicle block change (such as implementation of liquid rocket boosters) that would provide vehicle performance increases to off-set performance decrements from the lower-performing STME engines. If this vehicle performance could allow going to engine expansion ratio lower than 62:1 (preferably into range of 50:1), then many of the physical installation problems could be avoided.

Incorporation of STME engines into Shuttle 'C' vehicles, however, should be much more nearly straightforward. The Shuttle 'C' should be less sensitive to performance reduction associated with lower engine performance. Engine gimbal requirements for Shuttle 'C' may be less than those for STS. Some of the Orbiter hardware surrounding the engine installation may not be present in the Shuttle 'C' configuration (Orbiter body flap, etc.). It might be practical to accept engine performance for a reduced nozzle area ratio (less than 62:1), if necessary to further reduce or avoid physical installation problems. If modifications were still needed in the boat-tail area, these changes could likely be made more easily than in the STS Orbiter, and might be made in conjunction with design changes made for other purposes.

Deeper throttle capability (lower than 75%) would be needed for q-alpha and 'g' control. Changes in the STME pump inlet pressure requirements and/or changes in the STS/Shuttle 'C' propellant feed system would seem to be necessary. Consideration of a closed-loop propellant utilization (PU) system would be advisable, unless engine mixture ratio uncertainties will be considerably lower than the ±3% currently quoted for the STME. An increase in engine life would be needed for operation of STME engines in the STS (from 10 into the range of 30-50 flights); however, the range of 10-15 flights per engine fits quite well for joint operation of STS and Shuttle 'C'.

Suggested propulsion requirements resulting from these studies of STME engines in STS Evolution/Shuttle "C" applications have been compiled in the "matrix" format adopted for use in this study. This compilation/matrix is provided in Section 3.1.3.5 of this report.

Vehicle Applications and Propulsion Requirements
STS and Shuttle 'C'

STS:	SHUTTLE 'C':
• SUBSTANTIAL CHANGES VEHICLE AND/OR ENGINE - - 8.5/10/5 DEGREE GIMBAL REQM'T - WRAP-AROUND DUCTS - CLEARANCE FOR NOZZLE MOVEMENT. - PROPELLANT FEED AND INLET PRESSURES. - FEED LINES/FLOW RATES. - OTHER • STME-62 CLOSEST TO PERFORMANCE REQM'TS - BUT, WOULD LIMIT GIMBAL CAPABILITIES. - PERFORMANCE PENALTIES WITH STME-20 OR WITH STME-40 WOULD BE PROHIBITIVE. • LIMIT OPERATING THRUST LEVELS AND/OR REDESIGN THRUST STRUCTURE. • WIDER THROTTLE CAPABILITY NECESSARY. • NEED MIXTURE RATIO CONTROL OF APPROX. ± 1 PERCENT. • MIGHT IMPLEMENT IN CONJUNCTION WITH OTHER MOD(S)/ PERFORMANCE ENHANCEMENT. • STS/LRB - STME-20 PLUS STME-50.	• SHOULD BE BETTER PROSPE[illegible] R STME APPLICATION. - GIMBAL REQM'TS MAY BE LESS THAN FOR STS. - SOME ORBITER HDWE. (AROUND ENGINE INSTL.) - NOT REQ'D ON SHUTTLE 'C'. - ANY NECESSARY VEH. MODS. COULD BE INCORPORATED WITH LESS IMPACT - POSSIBLY IN CONJUNCTION WITH MODS. FOR OTHER PURPOSES. - LESS SENSITIVE TO PERFORMANCE DECREMENTS (3-ENGINE VEHICLE). - SMALLER PERCENT OF VEHICLE CAPABILITY. - MIGHT GO TO NOZZLE AREA RATIO BETWEEN 50:1 AND 62:1 • SHUTTLE 'C' - STME WITH AREA RATIO 50<R<62.

ENGINE LIFE: • ENGINE LIFE (ALL OPTIONS) -
- 10-15 FLIGHTS PER ENGINE O.K. FOR STS/SHUTTLE 'C' COMBINATION.
- NEED 30-50 LIFE FOR STS OPERATING ALONE.

Figure 3-33 Summary, STS, And Shuttle 'C' Applications

3.1.3.3 LRB and PLS Launch Vehicle Applications

Introduction

A number of launch vehicle approaches are currently under consideration by NASA for launching Personnel Launch System (PLS) spacecraft (see Figure 3-1, in an earlier section of this report). These include:

(1) Adaptation of existing launch vehicles, such as Titan III or IV,
(2) Shuttle 'C',
(3) Vehicles using Liquid Rocket Boosters (LRB) as designed for use with STS,
(4) Vehicles using ALS elements, and
(5) Vehicles of new design.

In this study, we will examine propulsion requirements for two of these categories, e.g., the PLS launch vehicle based on STS/LRB (PLS/LRB), and PLS launch vehicles of new design (PLS/ND). Phase A studies of STS/LRB concepts have been performed by General Dynamics and Martin-Marietta, including studies of a "stand-alone" launch vehicle using the STS/LRB as the booster stage. We have used some of that data as a starting point in looking at propulsion requirements for PLS/LRB launch vehicles.

These studies were initiated at a time when NASA PLS studies were at a preliminary stage and very little data were available on PLS launch vehicle concepts. We performed rough-order parametric studies to determine ball-park areas for propulsion requirements, and to compare with STME engine characteristics. Information is now available on launch vehicle concepts developed recently in NASA PLS studies. We made some comparisons with the NASA data during the remainder of the study.

Some of the PLS spacecraft concepts currently under study fall in the range of 30,000 - 40,000 pounds equivalent LEO payload. We have used a nominal value of 40,000 lbs for parametric launch vehicle sizing. in a few instances, we have extrapolated this sizing into the 80,000 - 100,000 lb payload range to consider implications of launch requirements for the "Cargo Return Vehicle" or "CRV" that is being examined by NASA as a possible complement to the PLS and/or STS.

Since there is no existing hardware in this category as there is for STS/Shuttle 'C', we will have much less basis here for examinations of physical installation considerations. We will address some aspects of engine physical sizes with respect to vehicle/tank sizes, vehicle and engine sizing, and some engine life considerations.

PLS/LRB Launch Vehicle Concepts

A "PLS Stand-Alone Vehicle" concept, developed as a part of the LRB Phase A studies and used as a starting point in these studies, is shown in Figure 3-34. The vehicle uses liquid hydrogen engines of the STME type, with a nozzle area ratio of 20:1. Four engines are used in the booster stage (LRB), and a single engine of the same type is used in the second stage.

One of the first considerations in adapting vehicles for manned flights is the acceleration levels experienced during powered flight. The sketch in Figure 3-34 shows the extent of engine throttling necessary to limit accelerations to 3 g's. Throttling to approximately 75% would be adequate during booster burn; however, throttling to approximately 50% would be necessary during second stage burn. This is a natural result of using one of the booster stage engines, which is bigger than required for the second stage. Note: Some of current NASA planning uses 4 g's as a limit for manned flights, in lieu of the 3-g figure that came into use with the Shuttle program. Throttling to approximately 67% in the second stage would be needed to maintain a 4-g limit. The extent of throttling, if necessary to limit "q-alpha" values during ascent, would have to be determined after further vehicle definition and loads analyses.

REF: GEN SYNAMICS
LRB PHASE 'A' STUDY
FEB 89

LRB 'STAND-ALONE' L/VEH
ADAPTED FOR PLS

LEO PLD	40K LBS
λ'_1	0.851
λ'_2	0.878
ISP (VAC)	412 SECS
ISP (S/L)	373 SECS
W_O	1260K LBS
W_{S2}	400K LBS
W_{S1}	821K LBS
F_2(NOM)	419K LBS
F_2(MAX)	558K LBS
F_1(NOM)	1997K LBS
F_1(MAX)	2076K LBS

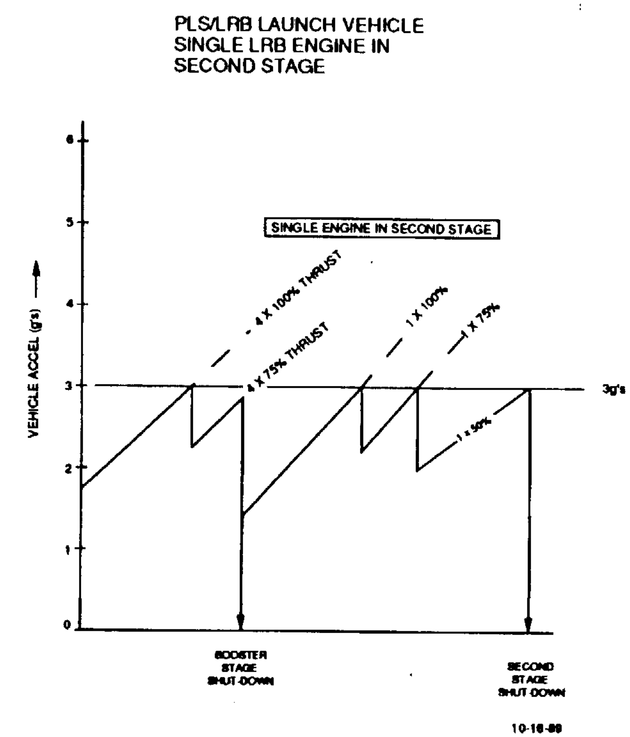


Figure 3-34 LRB 'Stand-Alone' Vehicle Concept

891222LS1300

Second Stage/Propulsion Options (PLS/LRB)

Excursions from this "reference" PLS/LRB launch vehicle concept should be examined, to look at propulsion requirements and implications of questions such as: (1) What size and type engine(s) would the vehicle like to have in the second stage, if given a choice?, (2) What are vehicle and engine implications if it were desired to push to higher payload capabilities?, (3) How well do the STME engine candidates match up in these applications?, (4) What kinds of engine features would be needed for engine applications in vehicles of this type and sizes?

The first of these questions is addressed in part in Figure 3-35. Rough-order analysis indicates engine(s) in the range of 80K to 130K lbs. thrust would be needed for 40K payload capability, depending on second stage specific impulse within a range of 420 to 460 seconds. Indications of engines this small in comparison with the booster/STME engines may be due to (1) to relatively "small" payload requirements for PLS (in comparison with STS, Shuttle "C", ALS, etc.), and (2) the LRB booster stage may be larger than required or "optimum" for this payload requirement when combined with a high performance second stage.

This approach for 40K payload capability (LRB booster stage in combination with a relatively small second stage) suggests a look at possibilities for commonality with upper stages for expendable launch vehicles, or with higher performance engines for STV's or Lunar exploration vehicles (see FIGURE 3-79, in a later section).

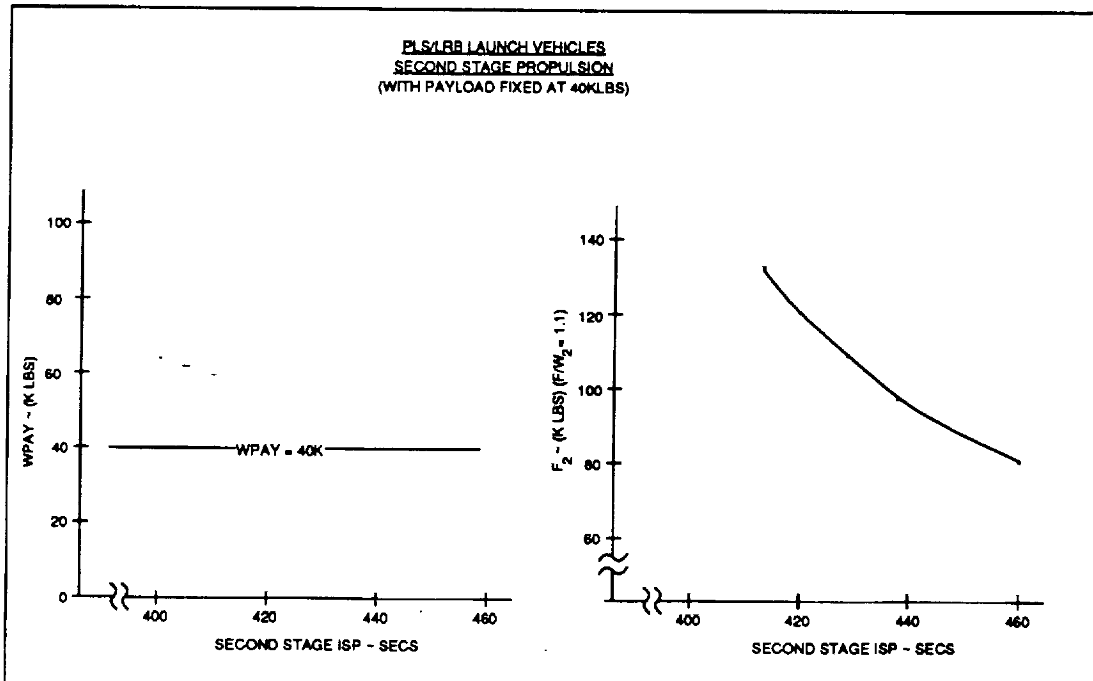


FIGURE 3-35 PLS/LRB SECOND STAGE PROPULSION

We want next to examine a wider range of second stage sizes, to consider the extent to which launch vehicles using LRB as the booster stage could accommodate payload requirements higher than 40K lbs., and to see where STME engine characteristics seem best to match. Results from rough-order parametric analyses over a range of second stage sizes and engine options are shown in Figure 3-36, for both series-burn and parallel-burn vehicles. STME engines with 20:1 area ratio are used in the LRB/booster stage in all cases. Data are shown for variations in second stage engine area ratio; however, we assume that the 20:1 engine would likely be used in the second stage. Data for series-burn vehicles in Figure 3-37 (top) show that payload capability on the order of 60K lbs. could be achieved by increasing second stage size and propellant loading. Operation in this region; however, would be without full engine-out capability in the booster stage. If full engine-out capability is retained, payload capability would be limited to the 40K-50K lb. range, as shown in the shaded area. This series-burn version of the PLS/LRB vehicle does not appear a good prospect to extend into the "CRV" range of payload capabilities (80K lbs. and above).

Because of the height of series-stack vehicles with large second stages (discussed in a later paragraph) and other reasons, it is of interest to examine parallel-staged versions of the PLS launch vehicles. Data from parametric analyses of this approach are shown in Figure 3-36, (bottom) for versions with one or two STME engines in the second stage. Although our analyses indicate the parallel-burn vehicle to be slightly lower in performance than its series-burn counterpart at the same gross weight, the parallel-burn vehicle can accommodate larger second stage sizes, and can therefore achieve higher payload capabilities. This is of course due to the additional thrust of the second stage engine(s) being ignited at lift-off. With the inert weight assumptions used in these analyses, these vehicles could extend into the 60K-80K lb. payload range, with full engine-out capability during booster burn (4 out of 5 engines operating). A practical limit may be in the 70K lb. range; however, since second stages beyond that point would become larger than the LRB/booster stage. Note: these data indicating payload capabilities approaching 65-70K lbs., with second stage of the same size as the LRB are not representative of the "Twin-LRB" concept, currently under study for PLS application. Inert weight characteristics assumed for second stages of these vehicles are significantly lower than for LRB stages. As a point of "calibration", studies of the twin-LRB concept in some depth by NASA-MSFC indicates a payload capability of 38K lbs. for that configuration.

PLS/LRB LAUNCH VEHICLES

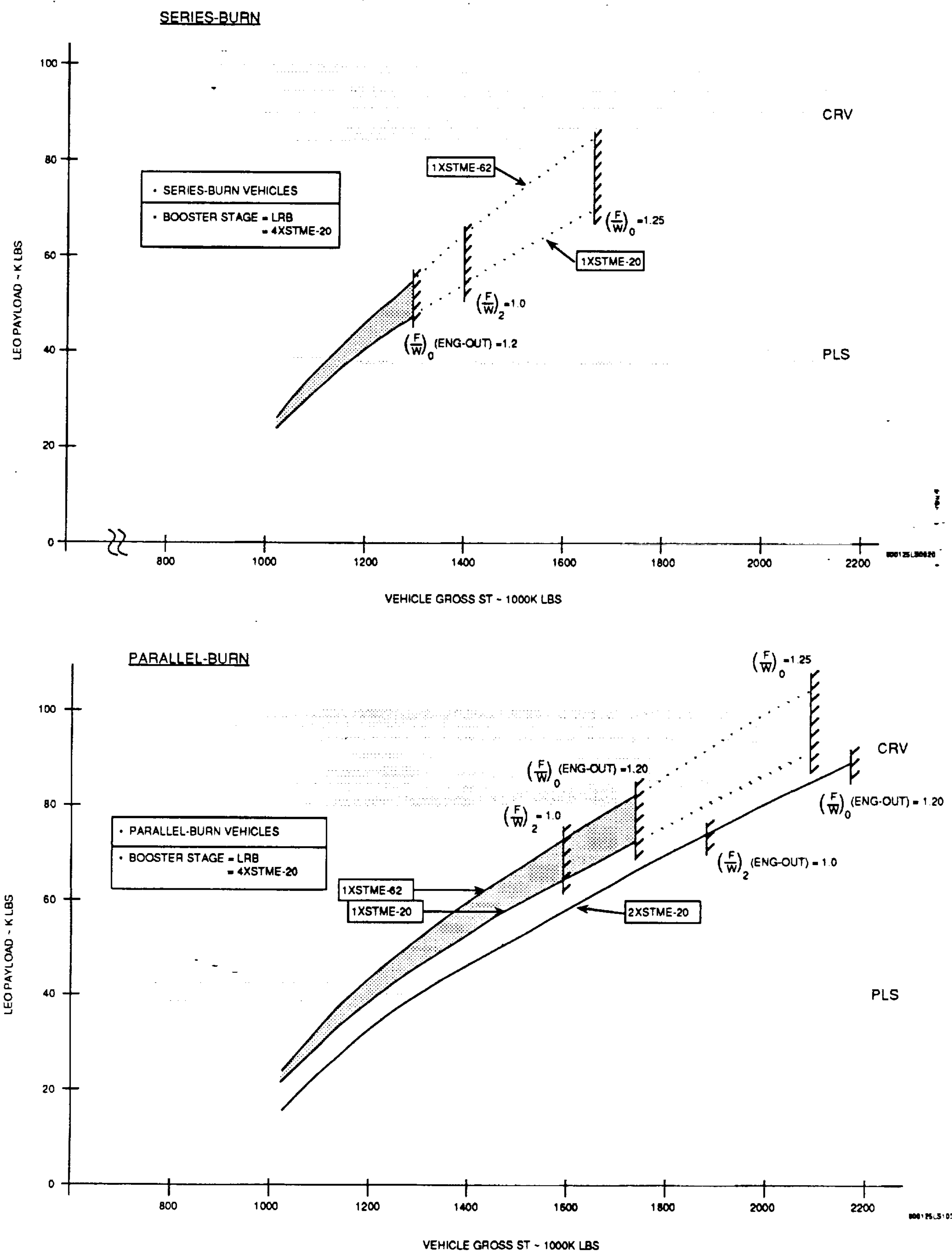


Figure 3-36 PLS/LRB Launch Vehicle Performance

900226LS0907

Vehicle/Tank Sizes (PLS/LRB)

Relative sizes of hydrogen-oxygen tankage for three versions of PLS/LRB launch vehicles are shown in Figure 3-37. These sizes are based on 18-foot diameter tanks, which may be an upper limit for LRB's in the STS application. The launch vehicles would naturally be taller than indicated, when space is added for engines, elliptical tank bulkheads, etc. The series-burn vehicle sized for 40-K payload with a small second stage is of moderate height; however, attempts to push this vehicle to higher payload capabilities with bigger second stages would result in very tall vehicles, as is shown in the "60K payload" case. Although of no significant benefit for the "40K payload" case shown, parallel mounting of stages should be a strong consideration for vehicles with larger second stages, for reasons of vehicle height (shown here), performance factors discussed in the preceding section, and potential for stage hardware commonality.

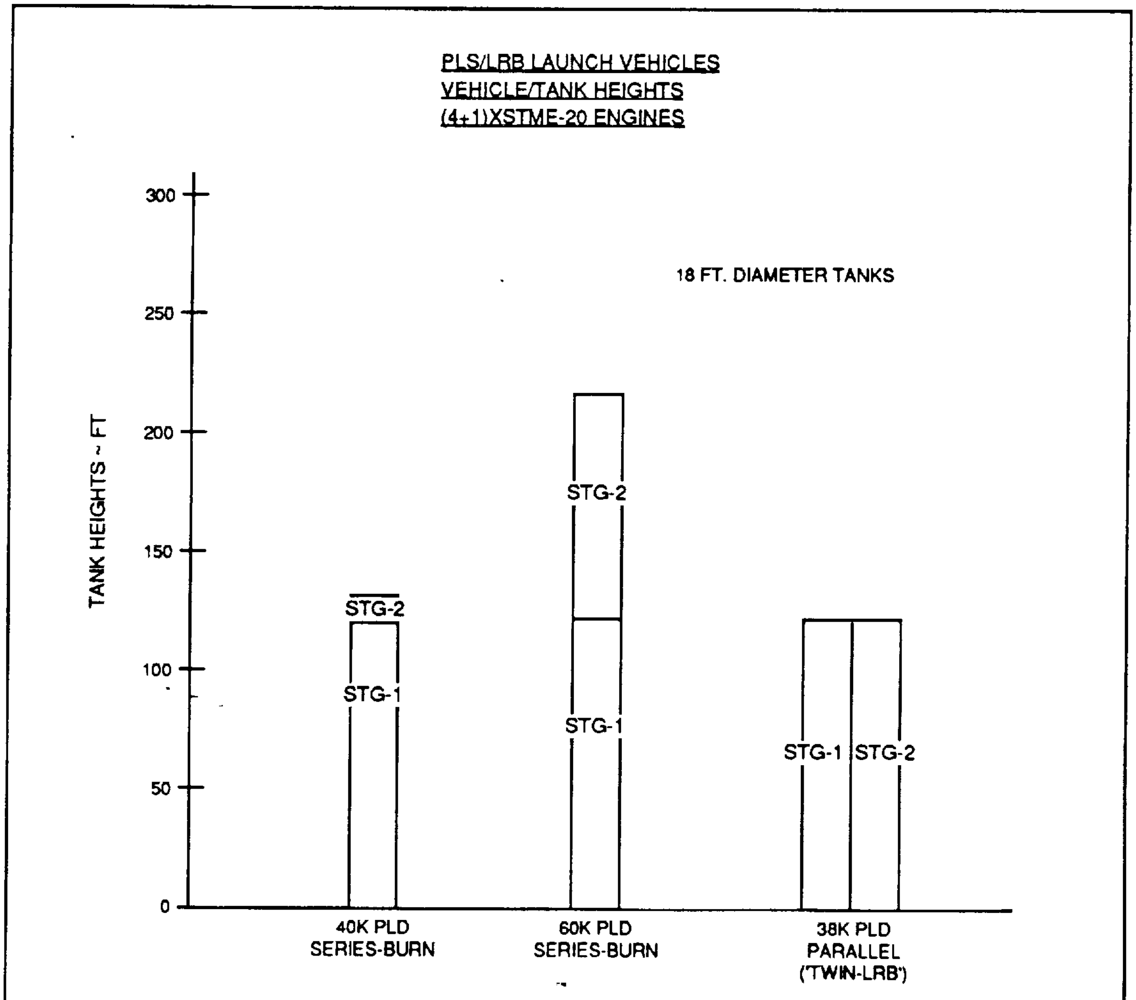


FIGURE 3-37 VEHICLE TANK HEIGHTS FOR PLS/LRB LAUNCH VEHICLES

PLS New Design Launch Vehicles (PLS/ND)

In the preceding section, second stage/propulsion options were considered, with the STS/LRB fixed as the first stage. In this section, we will open and examine stage and engine options for both stages. We will again follow the pattern: (1) If given a choice, what size and type engines would the vehicle want, (2) What if the vehicles are extrapolated into the CRV range of payload capabilities, and (3) If full-size STME engines are used, where do they best fit, and what requirements are indicated.

Booster and Second Stage/Propulsion Options (PLS/ND)

Data from parametric analyses are shown in Figure 3-38 for PLS launch vehicles (40K payload) and for varying degrees of engine-out capability. This indicates that vehicles sized for PLS/40K payload and for series-burn mode of operation (top part of Figure 3-38) would prefer engines in the 350-500K lb. thrust class (vacuum thrust). Sizing for 80K payload (CRV) and using five engines in the booster stage; however, indicates engine sizes in the 500K-600K thrust range, closely bracketing the 580K nominal thrust level for STME engines. Similar data are shown in the bottom part of Figure 3-38 for parallel-burn vehicles. Not surprisingly, this shows engine-size preferences slightly lower than that for the series-burn counterpart (due to use of the second stage thrust starting at lift-off). Engines in the 350K-400K thrust range are indicated for PLS/40K payload, for "minimum gross weight" design. A second case is shown for comparison, in which the two stages of the parallel-burn vehicles are of the same size (propellant capacity/loading). A surprisingly small "penalty" in gross weight is indicated for this option; an engine in the 500K thrust class is indicated for the bigger second stage.

PLS/CRV (NEW DESIGN) LAUNCH VEHICLES
PROPULSION APPLICATIONS
(STME-40 CHARACTERISTICS)

	PLS/40K PLD			CRV/80K PLD
ENGINE-OUT	NO/NO	YES/NO	YES/YES	YES/NO
• W_O	1024K	1037K	1060K	1622K
• W_{S1}	664K	677K	691K	1092K
• W_{S2}	320K	320K	329K	450K
• F_2	1X360K	1X360K	4X123K	1X530K
• F_1	4X320K	4X485K	4X495K	5X607K

PLS/NEW DESIGN LAUNCH VEHICLES
(PARALLEL-BURN) (STME-40 CHARACTERISTICS)

PLS/40K PLD

	PARALLEL-BURN	
	MIN. W_O	$W_{P2}=W_{P1}$
W_O	1048K	1095K
W_{S1}	680K	542K
W_{S2}	328K	513K
F_2	1X331K	1X498K
F_1	4X380K	4X347K

NOTE : ENGINE-OUT IN BOOSTER STAGE, ONLY

FIGURE 3-38 ENGINE THRUST LEVELS FOR PLS/CRV LAUNCH VEHICLES

Although the preceding discussion indicated that PLS launch vehicles sized for 40K payload capability would "prefer" engine sizes somewhat smaller than the STME baseline (580K), these analyses indicate a small penalty in vehicle gross weight for use of "full-size" STME's (by a few percent). Data in Figures 3-39 and 3-40 show vehicle sizes and payload capabilities for using discrete numbers of STME engines. Figure 3-39 indicates vehicle/tank sizes for three versions of vehicles sized for 40K payload capability. At the 18-foot tank diameters as shown, vehicle (tank) heights are quite moderate. Note: If there is an advantage to do so, it is assumed here that "PLS/New Design" vehicles could go to larger tank diameter, since there would be no commonality with the STS/LRB stage.

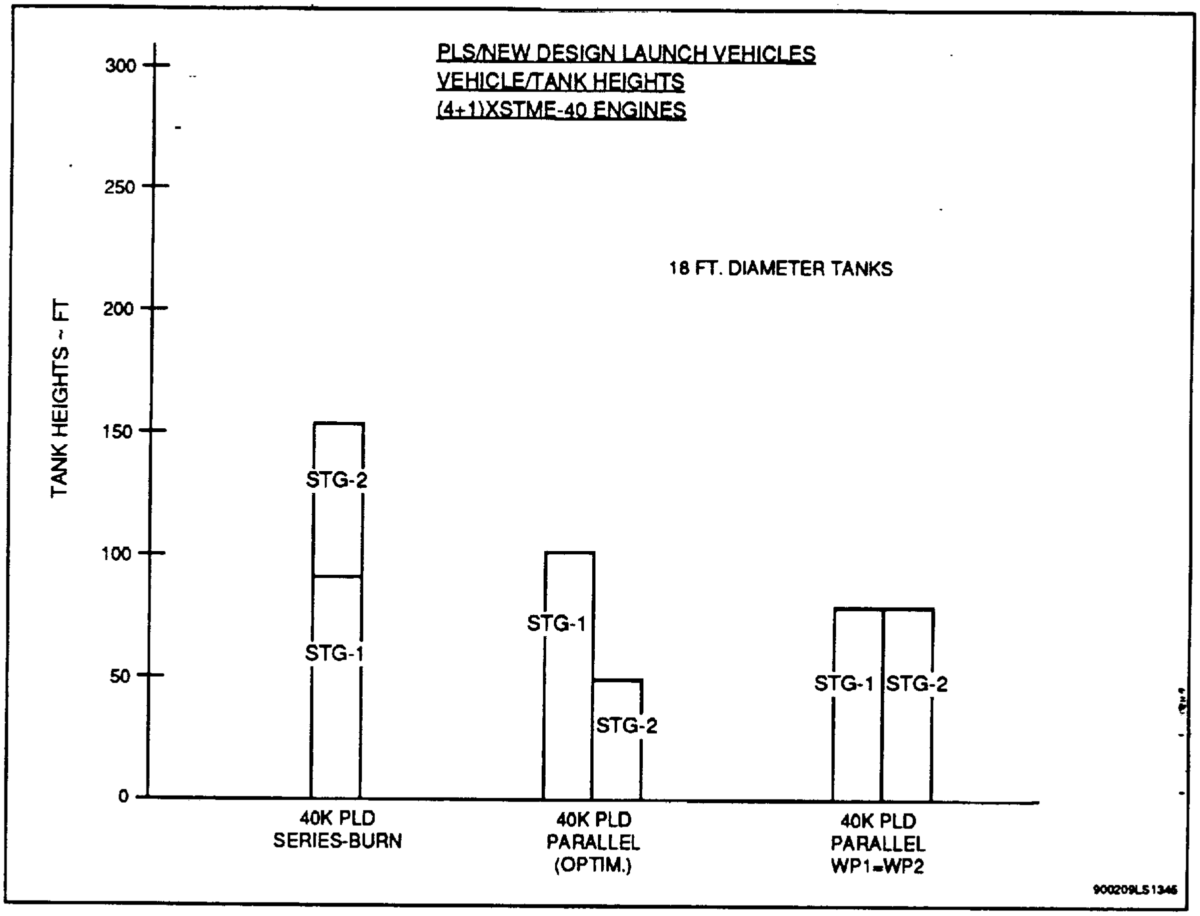


FIGURE 3 - 39 Tank Heights for PLS/ND Launch Vehicles

Parametric data in Figure 3-40 show the extent to which the PLS/New Design vehicles could be extrapolated into payload capabilities higher than the basic 40K value (vehicles with 4 STME's in the booster stage plus a single STME in the second stage). This indicates for series-burn vehicles: payload capability of up to approximately 50K lbs. with full engine-out capability in the booster stage; or payload capabilities approaching 80K lbs. if vehicle gross weight is increased further, without retaining booster engine-out capability. These data again show that larger vehicle gross weights, and corresponding larger payload capabilities could be achieved with parallel-burn vehicles, due to the additional thrust of the second stage engine being ignited at lift-off. In the parallel-burn case, payload capabilities of 80K lbs. and above are indicated with full or some degree of engine-out capability in the booster stage. It should be noted again that these cases do not compare directly with the "twin-LRB" vehicle concept. In this case, we have assumed inert weights characteristics for both stages that are lower than inert weights for the LRB stage. A data point is shown for reference for a series-burn CRV launch vehicle using (5+1)xSTME engines.

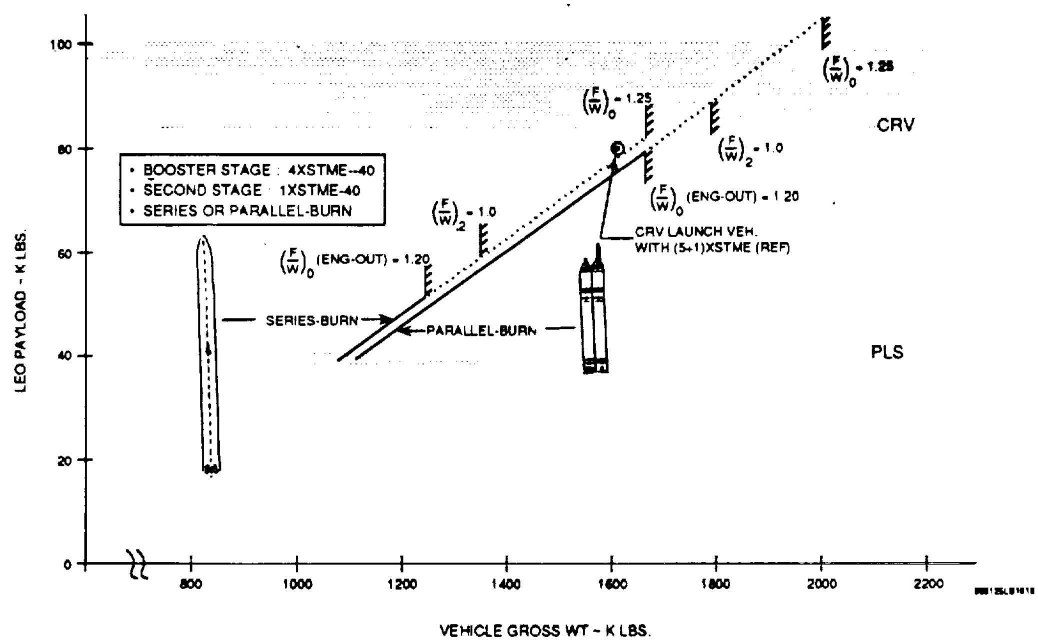


FIGURE 3-40 PLS/ND LAUNCH VEHICLE PERFORMANCE

One obvious implication of use of "full-size" STME engines in PLS/40K payload vehicles of new design if that the vehicle will be over-thrusted, and will require throttling capability to limit acceleration levels for manned space flight. As shown in Figure 3-41, throttling to approximately 50% would be required for the booster stage and to approximately 37% for the second stage, in order to limit accelerations during ascent to 3 g's. Values for a 4-g limit are 65% and approximately 50%, respectively. A second case, using 3 STME's in the booster stage is shown for comparison.

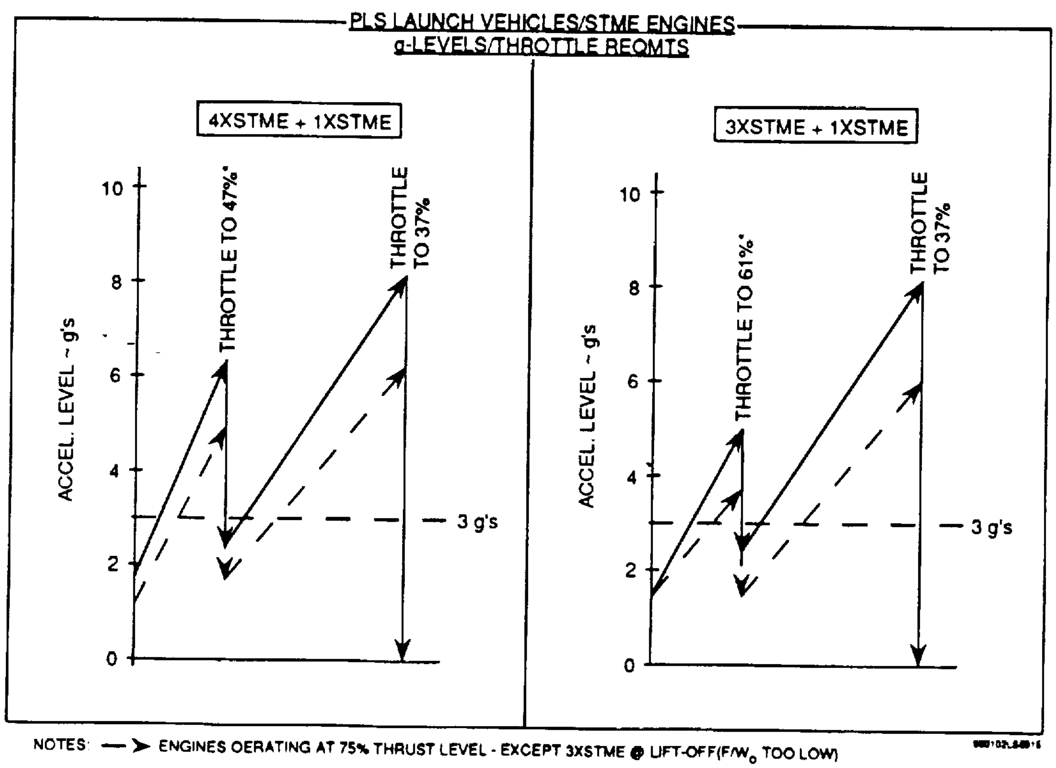


FIGURE 3-41 THROTTLE REQUIREMENTS

Engine Installation Considerations (PLS/LRB AND PLS/ND)

Since there is no existing PLS launch vehicle hardware, there is no basis for examinations of engine installation considerations to the extent that were discussed earlier for STS and Shuttle "C" engine installations. Examinations of these factors were done in some depth for the LRB stage, by other contractors, as a part of the STS/LRB Phase A studies. We will attempt to use and build upon that information here.

Base Area Geometries (PLS/LRB AND PLS/ND)

Analyses of base area geometries, integration with the STS vehicle and integration with the STS launch facilities in the LRB Phase A studies led to the recommendation for use of the STME type engines with 20:1 area ratio. We have used that engine/nozzle size in our analyses of PLS launch vehicles using the STS/LRB stage as the booster stage. However, we have also examined base area geometries for the full range of STME nozzle sizes under consideration here. Base area geometries for booster stage installations, are shown in Figure 3-42A for the three STME engine versions (engines with nozzle area ratio's of 20:1, 40:1, and 62:1). A hypothetical square pattern is shown in each case, with space to allow gimbal capability of ±6 degrees in both pitch and yaw planes, without interference between engine nozzle bells. Note: this spacing would provide full six degree gimbal capability even if the adjacent engine were "stuck" in a hard-over position. This spacing could obviously be reduced to some extent if it were assumed that the adjacent engines would always be in either a "coordinated gimbal" position or "null" position. The base area geometry is shown in each case in comparison with tank diameters of 18 feet, which is perhaps an upper limit in diameter for STS/LRB applications.

As noted, the base area geometries shown in Figure 3-42A are based on nozzle sizes and clearance for gimbal movement. The sketch in Figure 3-42B shows a typical engine configuration with nozzle sized for 20:1 area ratio. Depending on how the pumps and plumbing are packaged, the power head/plumbing dimensions could dictate engine spacing, in lieu of space for gimbal movement/clearance. If this turns out to be the case, this might suggest an area ratio slightly higher than 20:1 for the LRB engines.

In the "PLS-New Design" category of vehicles (not using STS/LRB as the booster stage), we have assumed that the vehicles could go to larger tank diameter if that were of advantage, and would therefore not have the same constraint upon engine area ratio and nozzle sizes utilized. Since there is a performance advantage of a larger area ratio in the second stage, and there is an

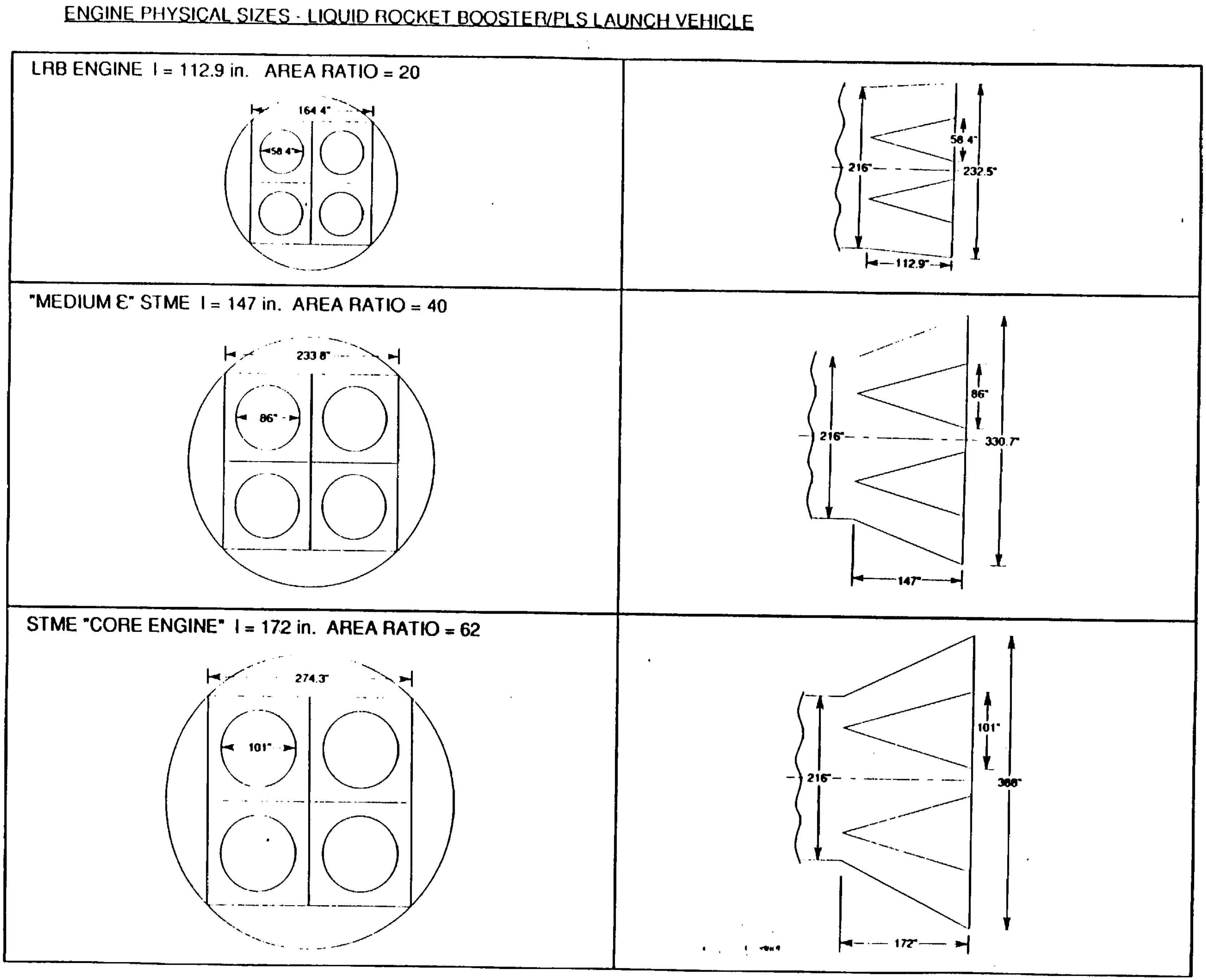


Figure 3-42A Base Area Requirements for PLS Launch Vehicles

0 '151 S0810

obvious advantage of using the same engine in both stages, we have assumed that engines of 40:1 area ratio could be utilized in both stages of the "PLS/ND" vehicles.

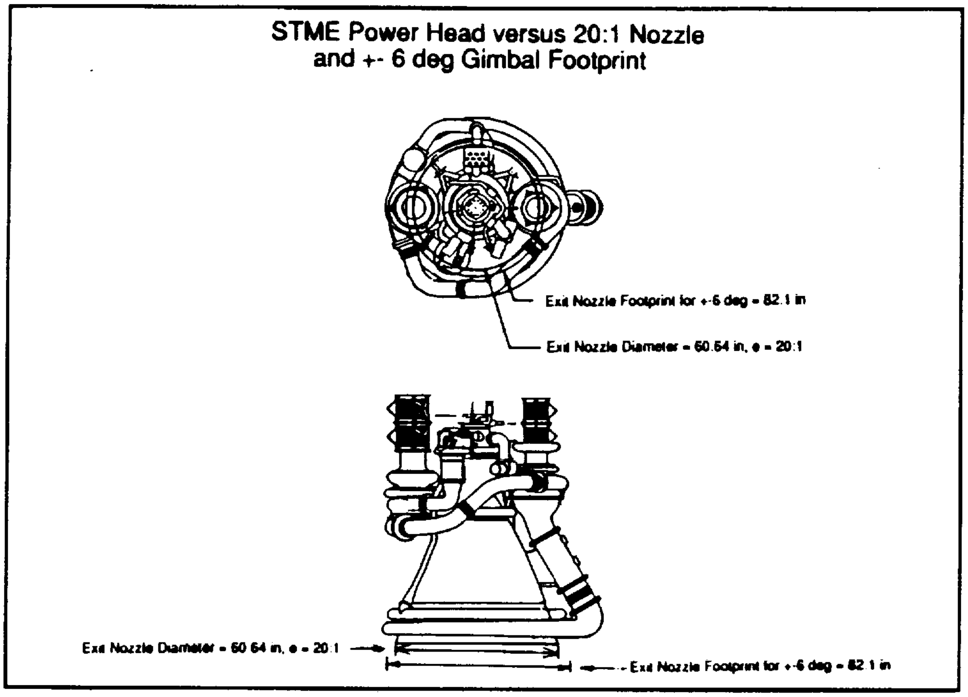


FIGURE 3-42B TYPICAL STME-20 ENGINE ENVELOPE

Engine Installation Requirements (PLS/LRB AND PLS/ND)

Some of the engine installation considerations for PLS launch vehicles are listed in Figure 3-43. PLS launch vehicle studies at MSFC have indicated that ± 6 degrees gimbal capability may be adequate, with approximately 3-degrees cant of the booster engines. This in within the capability of STME engines with scissor ducts, and will therefore not require addition of "wrap-around ducts", as was the case for STS installations. Since the hardware does not already exist, the stages for PLS launch vehicles can be designed to accommodate to the planned design features of STME engines, such as engine inlet pressures. Further trade studies should still be done as the vehicle and engine designs progress, to determine the most eeconomical balance between engine and stage requirements. Particularly for the "PLS/ND" category of vehicles, it would remain to be seen whether it would be more economical to place additional requirements upon the stage pressurization and tankage/plumbing systems, in comparison with inclusion of booster pumps on the engine or stage.

PLS/LRB LAUNCH VEHICLES

ENGINE INSTALLATION REQUIREMENTS

- GIMBAL REQMTS:
  - ± 6° GIMBAL*
  - ~ 3° CANT (BOOSTER) - 2ND STG = TBD*
- 'STRAIGHT-IN' FEED DUCTS ('WRAP-AROUND' DUCTS NOT REQ'D)
- PROPELLANT FEED/ENGINE INLET PRESSURES
  - OPEN, WITH NEW DESIGN VEHICLE.
  - TRADE - ENGINE REQMT. VS STAGE PROVISIONS.
  - LOX-TANK-FWD DESIGN : HELPS WITH LOX INLET PRESSURES.
- ENGINE THERMAL ENVIRONMENT -
  - DESIGN TO.
- FLUID SYSTEM REQMTS:
  - TANK PRESSURIZATION GASES
  - PROPELLANT DUMP/PURGE (DEPENDS ON PROPULSION RECOVERY)
- LOADS:
  - DESIGN TO
  - NO HORIZONTAL LANDING QUESTION.
- REDUNDANCY
  - FO/FS DESIGNS.

* REF - MSFC VEHICLE CONCEPT.

FIGURE 3-43 PLS/LAUNCH VEHICLE ENGINE INSTALLATIONS

Engine Life Considerations (PLS/LRB and PLS/ND)

Average cost per engine flight, as a fraction of engine unit cost, is shown in Figure 3 44 (RH side), as a function of engine life. Current STME requirements call for a life of 10 flights per engine (a value of 15 flight per engine was used earlier). Assuming that refurbishment costs after each flight (in the range of 25% or more of engine replacement cost) would be higher than that for operations with the Shuttle or other highly reusable vehicles, the range of 10-15 flights per engine looks quite appropriate. If the engines were to be switched to the (expendable) second stage after a few flights on the (reusable) booster stage, the average number of flights realized per engine would more likely be limited by the number of engines expended per year in second stages. The curve on the LH side of Figure 3-44 shows this influence. A vehicle with four engines in the booster and a single engine in the second stage would realize 5 flights per engine, and so on. This range of 5-6 flights per engine is also shown by a shaded area in the RH side of the figure. In either mode, it appears that the current target values of 10-15 flights per engine would be in the right range for use in PLS launch vehicles, assuming some degree of recovery of booster engines. If a P/A Module mode of land recovery were implemented for second stage engines, an engine life somewhat higher than 10-15 flights might be "optimum"; but would not likely show a strong motivation to go to a higher life requirement.

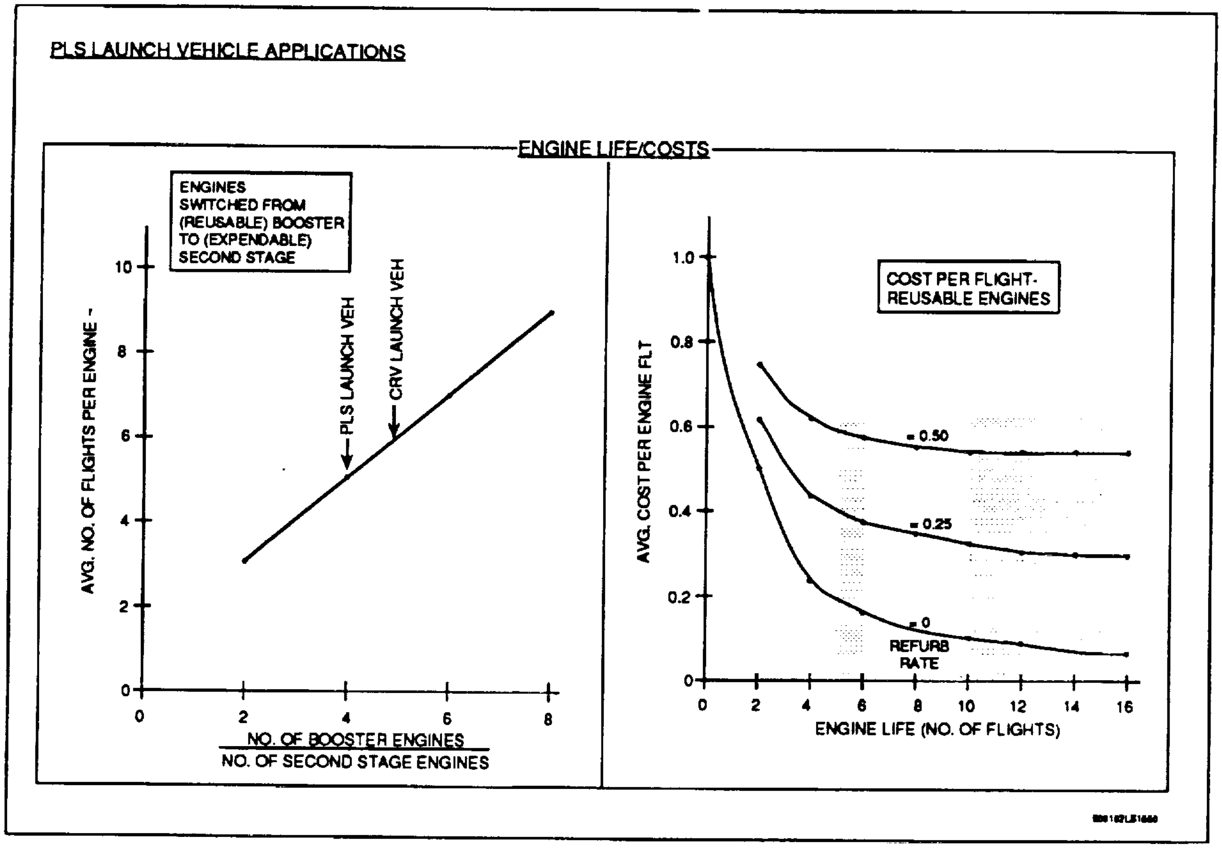


FIGURE 3-44 ENGINE LIFE AND COST TRADES (PLS)

Summary - PLS Launch Vehicle Applications

Studies of PLS launch vehicle concepts are at an early state of definition, and a relatively large number of options still exist. However, some observations can be made from the preliminary examinations of some of these options.

For a PLS Launch Vehicle using the STS LRB as the booster stage: It is assumed that an STME type engine with nozzle area ratio of approximately 20:1 would be used in the booster stage. If the payload requirement is limited to approximately 40K lbs. for PLS, a relatively small second stage could be used, with engine(s) thrust in the range of 80K-130K lbs. However, if higher payload capabilities and/or increased commonality between first and second stage hardware are desired, then full-size STME engines can be utilized better in both stages, and will most likely want to use parallel staging. Increased payload capabilities could be obtained with higher expansion ratio engines in the second stage; however, engines with 20:1 area ratio can be used in both stages with moderate payload penalty.

From the rough-order parametric studies of "PLS New Design" vehicle concepts performed here and based on the inert weight assumptions used, it appears that PLS launch vehicles (40K pld.) would prefer engines lower in thrust than the 580K lb. value baselined for STME engines. With these assumptions, STME engine sizes seem to fit better in vehicles sized for payload capabilities more typical of CRV launch vehicles (in 80K lbm, payload range). However, gross weight penalties for use of full-size STME engines in PLS launch vehicles do not seem large (on the order of 5 percent). Secondly a number of factors could lead toward higher engine thrust requirements. With the option of going to tank diameters higher than 15-18 feet, it appears that STME engines with area ratio of 40:1 could be utilized effectively in both booster and second stages. Use of full size STME engines in PLS/40K vehicles would require deeper than 75 percent throttle capability (perhaps as low as 37 percent for second stage with a single engine and a 3-"g" limit (or 50 percent for a 4-"g" limit).

NASA studies have indicated that parallel staged PLS launch vehicles can operate with ±6 degrees gimbal capability, with some engine cant. This indicates that "wrap-around" engine feed ducts would likely not be required, and would reduce or avoid some of the problems of fitting the engines into the limited base area space. Since the stage hardware does not already exist, the stages can be designed to accommodate to most of the existing engine requirements; however, further trade studies should examine and balance the vehicle vs. engine requirements in areas such as engine inlet/feed pressures. Engine life values of 10-15 flights per engine seem to be an appropriate range for PLS launch vehicles, where booster engines are recovered for reuse, or where engines might be switched to the (expendable) second stages after a few flights on the (recoverable) booster stages.

Based on these preliminary analyses, propulsion or engine requirements for PLS launch vehicle applications have been incorporated into the "requirements matrix" format as shown in Figure 3-54B. Two options each are shown for "PLS/LRB" and "PLS/ND" launch vehicle categories, with variations in second stage propulsion.

3.1.3.4 Advanced Manned Launch System (AMLS) Applications

Introduction

The third of the categories of candidate future manned space transportation systems (Reference Figure 3-1) is referred to as "Advanced Manned Launch Syst ɔn s" or "AMLS". This category of vehicle concepts is perceived as a more advanced and next generation of manned Space Shuttle type vehicles, and would likely be characterized by a higher degree of recovery and reusability, than the current Shuttle. Varying degrees of recovery are being examined, with a two-stage, fully reusable vehicle currently being used as the "baseline" concept. NASA in-house concept studies have been under way for some time (including "Shuttle II" concept studies that preceded the current AMLS concept studies).

Studies of AMLS vehicle concepts have been relatively inactive during the past year or so, while primary emphasis was being placed on the "Shuttle Evolution" and "PLS" categories of concepts. Current information on vehicle concepts, sizes, weights, and propulsion requirements is therefore fairly limited. We have attempted to utilize available information from earlier concept studies where applicable, and have augmented with rough-order parametric studies to identify areas of interest for this class of vehicles, and to examine sensitivities to variations in propulsion parameters.

A sampling from previous studies of AMLS type vehicle concepts indicates vehicle gross weights in the range of 2 1/4 to 3 3/4 million pounds. These vehicles were not all sized to the same payload requirement, and some employ hydrogen-fueled boosters and others hydrocarbon-fueled boosters. From this initial information, a starting point was derived, e.g., a vehicle concept with five engines in the booster stage plus three additional engines in the orbiter stage.

AMLS Vehicle Performance/Sizing and Engine Requirements

For our rough-order parametric vehicle/engine sizing, we have assumed the payload requirement to be in the Space Shuttle class, e.g., on the order of 50K lbs. to low Earth orbit, under the assumption that this would correlate with approximately 40K lbs. payload to the Space Station orbit. Some of the AMLS concepts for which data are available were sized to a considerably lower payload requirement. As noted earlier, this is a part of reasons for the spread in vehicle weights. In these analyses, we have also used moderately low booster stage delta-v's, even though "optimum" or "minimum gross weight" values would usually be indicated at higher staging velocities. This was done under the assumption that this would limit the severity of the re-entry and return requirements upon the fly-back or glide-back boosters.

AMLS Performance with STME Engine Characteristics

Results from parametric vehicle sizing using performance and weight characteristics of the three different versions of STME engines are shown in Figure 3-45, in comparison with a vehicle sized with SSME engine characteristics in both stages. This initial vehicle sizing is done, using "rubber" engine sizes, with performance and weight characteristics of the full-size engines. Vehicle sizing with a discrete number of SSME or STME engines in each stage will be discussed later. This level of analysis shows no major performance/sizing differences between four of the engine combinations shown (62:1 area ratio in both stages vs. 20:1/62:1 vs.40:1/40:1 vs. 20:1/40:1). All four of these cases are in the range of 15-25 % higher in gross weight than their counterpart concept sized using SSME engine characteristics. Only in the 20:1/20:1 case is there a much larger difference in gross weights (41 percent higher than the SSME/SSME counterpart). This information will be correlated in a later discussion with considerations of engine physical sizes and installation requirements.

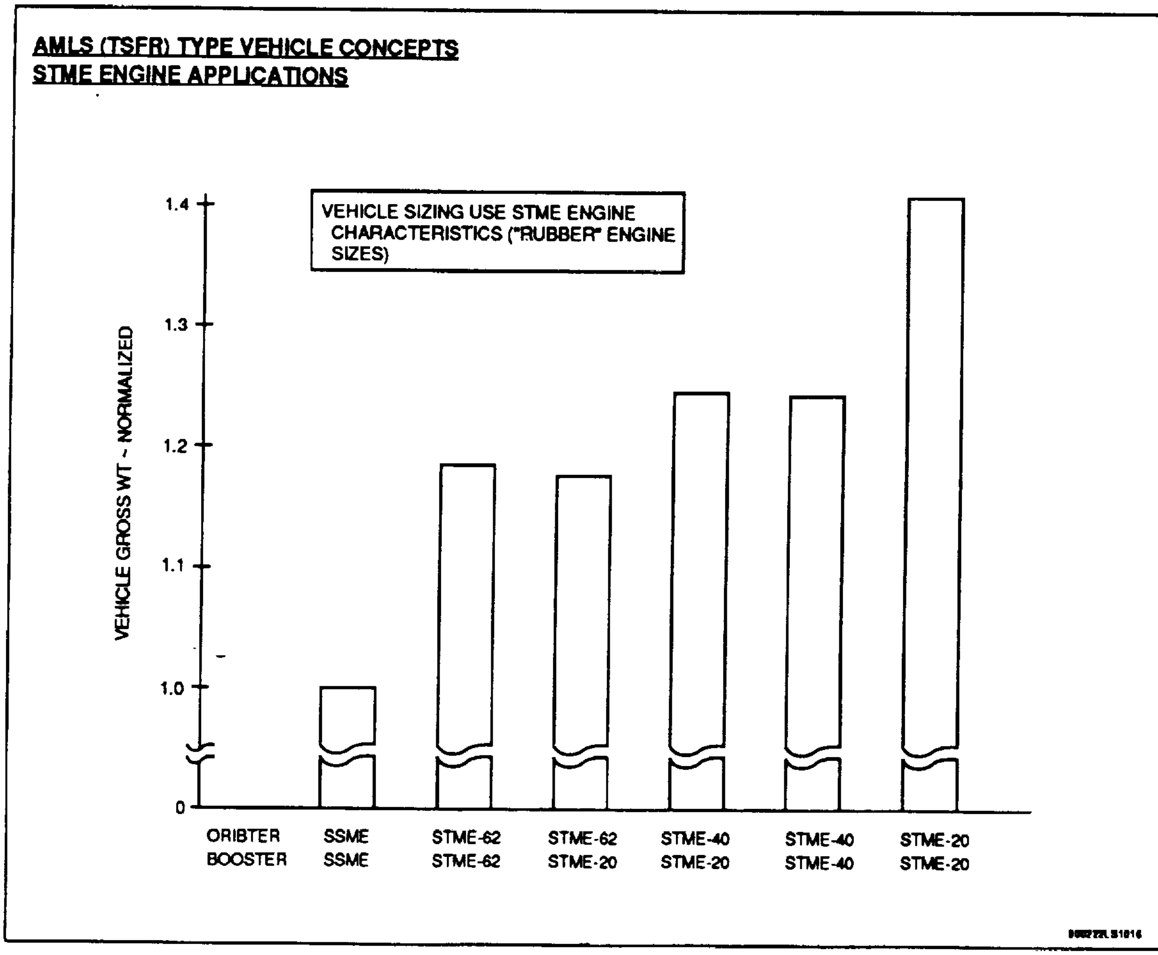


FIGURE 3-45 VEHICLE SIZING USING STME ENGINE CHARACTERISTICS

What Size Engines Would AMLS Vehicles "Want"?

Results from a first step in these parametric analyses (what engine sizes and what number of engines would the vehicle want?) is shown in Figure 3-46. Without including full engine-out capability at this point in the analyses, this indicates seven engines in the booster stage plus two additional engines in the Orbiter, at an engine thrust level approximately that of STME engines.

<u>AMLS (TSFR) TYPE VEHICLE CONDEPT</u>
<u>STME ENGINE APPLICATIONS</u>

<u>VEHICLE/ENGINE SIZING</u>

- 50 K PAYLOAD
- STME-40 ENGINE CHARACTERISTICS
- "RUBBER" ENGINE SIZES
- NOMINAL VEHICLE INERT WEIGHT FACTORS

- VEHICLE GROSS WT ------------- 3290K LBS
- ORBITER --------------------- 1130K LBS
- BOOSTER --------------------- 2115K LBS
- ORBITER ENGINES -------------- 2X590K THRUST
- BOOSTER ENGINES ------------- 7X550K THRUST
- $(F/W)_0$ ----------------------- 1.30
- $(F/W)_2$ ----------------------- 1.36

FIGURE 3-46 "NOMINAL" AMLS VEHICLE SIZE

The numbers of engines and engine sizes noted above and in Figure 3-46 are based on a set of vehicle inert weight scaling factors that we have used as "nominal" values. There is considerable uncertainty in these inert weight factors, due in part to the early state of vehicle definition studies, and also due to uncertainties as to the levels of technology advancements that may be incorporated into the vehicle structures, thermal protection and other subsystems. In view of these uncertainties, we have examined a range of inert weight factors, to determine their effect on engine thrust requirements. Results from this "sensitivity study" are shown in Figure 3-47. Data are shown for inert weight factor reduced by 15 to 25%, in an attempt to represent more advanced technologies in vehicle structure/subsystems; and other cases with vehicle inert weight factors increased by 15 to 25%, to represent much lower state-of-art and more conservative designs. Engine inert weight factors representative of STME engines have been used as fixed values in all these cases, and have not been varied with vehicle inert variations.

As can be seen, a ±15 percent variation in vehicle inert weight factors results in variations in vehicle gross weights from 73 to 143 percent of the nominal value, with corresponding swings in installed thrust requirements, as will be noted later. Vehicles sized with ±25 percent variation in vehicle inert weight factors results in vehicle gross weight variations from 61 to 193 percent of the nominal value. Vehicles sized with reduced vehicle inert weight factors indicate either progressively lower engine thrust levels (as shown), or a single engine in the orbiter that is considerably higher in thrust than STME engines (750 to 900K lbs. thrust). Vehicles sized with increased vehicle inert weight factors can be accommodated with increased numbers of engines, with engine thrust levels remaining in the STME engine class (increases from 9 to 13 to 17 engines).

AMLS (TSFR) TYPE VEHICLE CONCEPTS
STME ENGINE APPLICATIONS

	INERT WEIGHT FACTORS *				
	(-) 25%	(-) 15%	NOMINAL	(+) 15%	(+) 25%
• VEH. GROSS WT (NORMALIZED)	0.61	0.73	1.0	1.43	1.93
• ORBITER ENG'S (VAC THRUST ~KLBS)	2X375K	2X444K	2X590K	3X549K	4X545K
• BOOSTER ENG'S (VAC THRUST ~KLBS)	6X392K	6X472K	7X550K	10X553K	13X573K
• AVG. THRUST/ENGINE	388K	465K	559K	552K	566K

* INERT WEIGHTS OTHER THAN ENGINES (ENGINE WEIGHT FACTORS HELD CONSTANT)

900221L80800

FIGURE 3-47 EFFECTS OF INERT WEIGHT FACTORS

As was noted earlier, we have used as nominal in these analyses, vehicles sized for approximately 50K lbs. payload to orbit (Space Shuttle class vehicles). Data for vehicle sizing to lower payload requirements are shown in Figure 3-48 for information of the reader. Engine thrust requirements would reduce in proportion to vehicle weights.

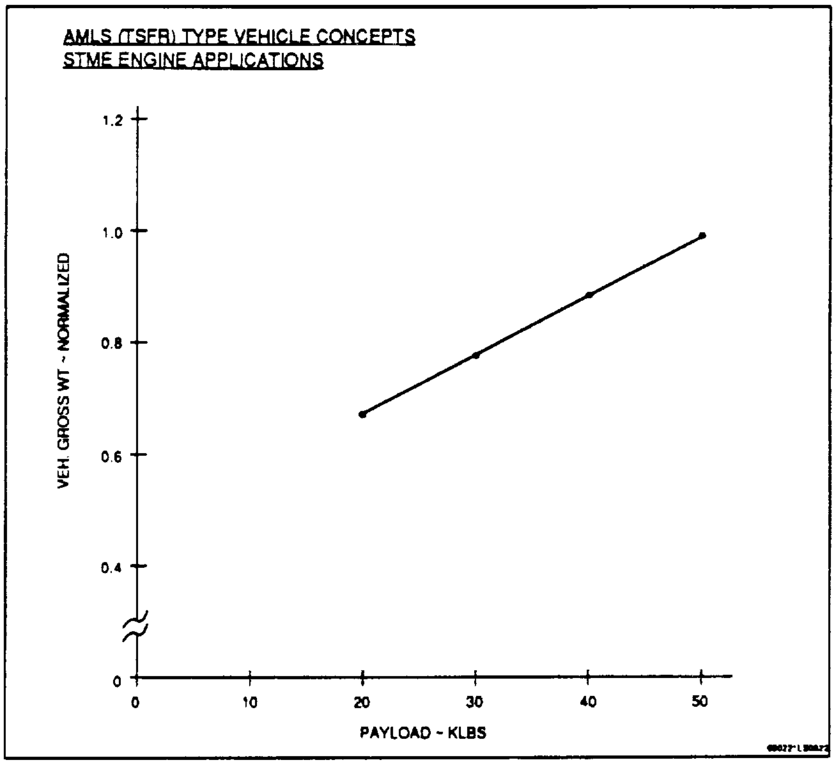


FIGURE 3-48 EFFECTS OF PAYLOAD REQUIREMENTS

The AMLS data and discussions to this point have been based on "rubber" engine sizes, e.g., allowing the engines to be at whatever thrust level they wanted to be (based on STME values for specific impulse and engine inert weight per unit thrust, etc.). We will now examine vehicle size and performance using discrete numbers of STME engines at the nominal thrust level of 580K lbs.. Characteristics for vehicles sized for 50K lbs. payload and using the nominal inert weight factors are shown in Figure 3-49, for a range of numbers of engines in each of the two stages. The configuration with (6+2) engines is marginal in lift-off thrust-to-weight without considering engine-out capability. The configuration with (6+3) engines has adequate lift-off thrust and adequate engine-out thrust during orbiter burn, but does not provide engine-out capability during lift-off. The configuration with (7+2) engines is inadequate for engine-out capability during both lift-off and during orbiter burn. This leads to the (7+3) engine configuration as the first that would provide adequate thrust during normal operations and under engine-out conditions in either the booster or orbiter burn phases. This configuration will then be used as a basis for further discussions.

Acceleration levels at burn-out of the two stages are shown at the bottom of Figure 3-49, for two of the engine combinations. In these cases, acceleration levels at booster burn-out are not excessive, and would require no throttling. Using three engines of this size in the orbiter stage, however. results in acceleration levels in the 6-7 'g' range. This would obviously require either deep throttle capability (to approx. 44 percent thrust), or a combination of engine shut-down and throttling. Shutting down two of the three engines would be adequate, or shutting down one engine and throttling to 66 percent on the remaining two engines. These figures are noted assuming a 3 "g" limit; corresponding figures if a 4 "g" limit were used are 59 percent throttle (with three engines burning) or 88 percent throttle (with two of the three engines burning).

AMLS (TSFR) TYPE VEHICLE CONCEPTS
STME ENGINE APPLICATIONS
(USING STME-40 ENGINES)

	NO. OF ENGINES INSTALLED			
• ORBITER • BOOSTER	2 6	3 6	2 7	3 7
• W_0 (NORMALIZED)	0.933	0.995	0.938	1.00
• $(F/W)_0$	1.2	1.26	1.34	1.39
• $(F/W)_0$ (ENGINE-OUT)	1.05	1.12	1.19	1.25
• $(F/W)_2$	1.34	1.88	1.34	1.88
• $(F/W)_2$ (ENGINE-OUT)	0.67	1.26	0.67	1.26
• $(F/W)_1$	2.46			2.68
• THROTTLE REQM'T (3 g's)	NONE			NONE
• $(F/W)_3$	4.82			6.75
• THROTTLE REQM'T (3 g's)	63% *			44% **

NOTES: * OR SHUT DOWN ONE OF TWO ENGINES
** OR SHUT DOWN TWO OF THREE ENGINES

FIGURE 3-49 NUMBERS OF STME ENGINES

By comparison of the (6+2) and the (7+3) cases above, it can be seen that the orbiter stage would still prefer engines of a lower thrust level. Two of the STME engines provide adequate thrust for normal operations; however. loss of one of the two engines results in loss of too much of its thrust. The orbiter would like to have three engines each of a thrust level about two thirds that of the STME (approx. 390K lbs. thrust, vacuum).

AMLS Engine Installation Requirements

Since AMLS vehicle concepts are at such an early state of definition, there is a very limited basis for examination of physical installation considerations. Physical sizes of engines will naturally be a concern for boat-tail area and installation in both the orbiter and booster stages, since both are designed for lifting entry and horizontal flight. This may be particularly true with STME engines, designed at moderately low chamber pressures, together with advances in vehicle/structures that may tend to reduce the physical size and mass of the vehicle stages. Engine weights will continue to be a concern, not only from the standpoint of performance as discussed earlier, but also from the standpoint of vehicle weight and balance, with engines installed at the aft extreme of the stages.

Engine Sizes and AMLS Booster/Orbiter Base Areas

Without trying to work to specific vehicle configurations, base area requirements in a generic sense are shown in Figures 3-50 and 3-51 for the three sizes of STME engine/nozzle sizes under discussion. How well these base areas would match up would obviously depend upon size and configuration for the two stages. We do not yet have that information; however, a Lox-Hydrogen booster tank for the "nominal" vehicle from our parametric analyses would be approximately 27 1/2 ft. in diameter and 137 ft. in length, or roughly the same size as the STS External Tank. By comparison, the width of a seven-engine booster base area with STME-20 engines (20:1 area ratio) in a "three-four" stack arrangement would be approximately the same as the tank diameter. This would therefore seem to be a reasonable fit with the tank/fuselage. If engines with 40:1 area ratio were used, the booster base area in a "three-four" stack arrangement would be approximately 1.4 times the tank diameter, and would not be a good fit. Other options for STME-40 booster installations might be: (1) using twin propellant tanks in lieu of a single tank (Figure 3-50), or (2) Engines in a "2-3-2" stack arrangement in lieu of a "3-4" stack (also shown in Figure 3-50). The latter arrangement would fit fairly well with the tank diameter. but might be more difficult to integrate into a

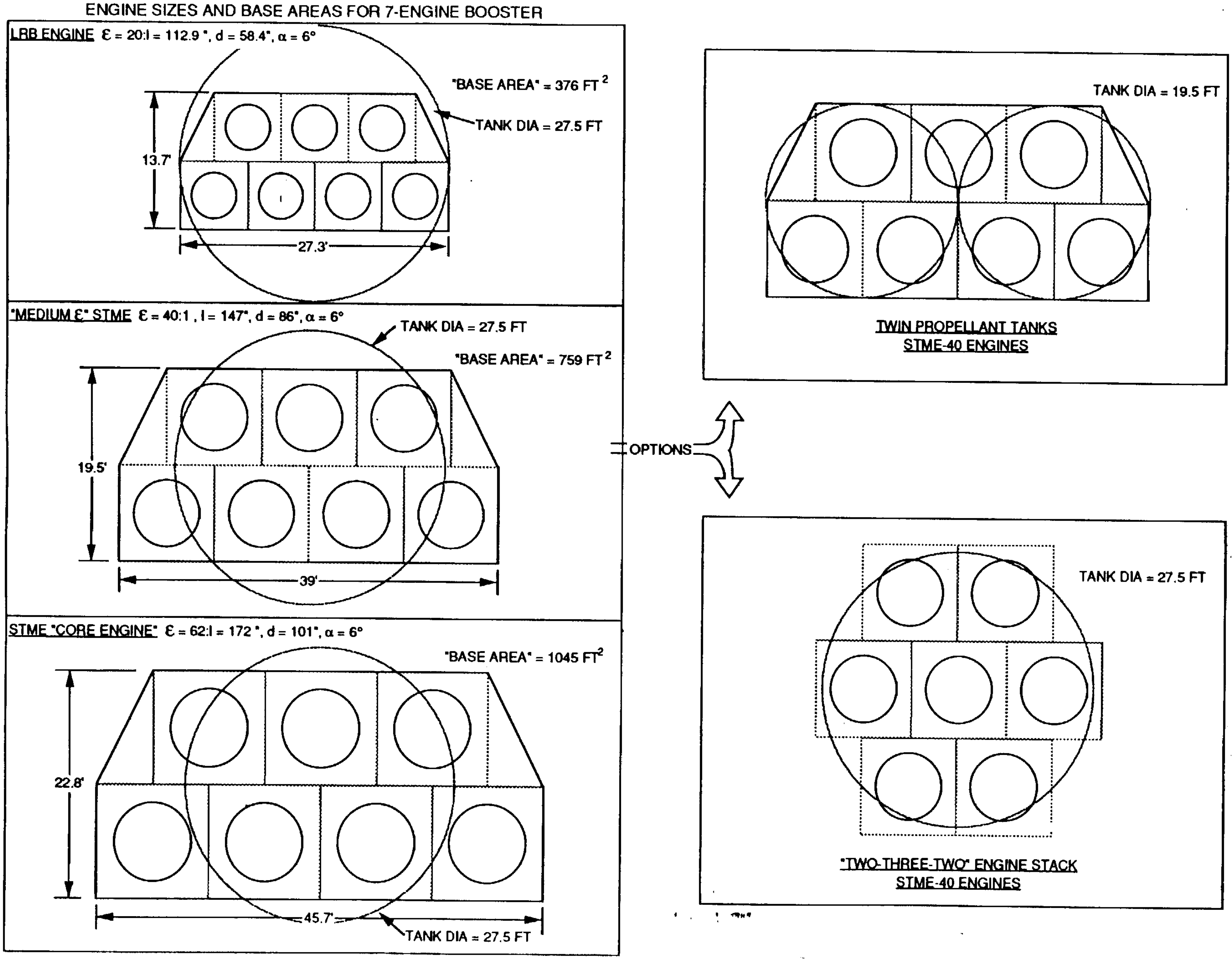


Figure 3-50 Engine Sizes And Booster Base Area (AMLS)

900221LS1038

winged booster configuration. A base area with 62:1 engines would clearly be too big; in addition, there would be no performance motivation for use of this engine in booster stages. For this and following discussions, it will be assumed that the 20:1 nozzle is preferred for this application with the 40:1 nozzle as a possible candidate.

In similar fashion, a Lox-hydrogen tank for the orbiter stage of our "nominal" AMLS vehicle size would be approximately 21 1/2 feet in diameter, by 107 feet in length. The base area for a three-engine orbiter with STME-62 engines (see Figure 3-51, LH side) would just about fit into the projected area of the orbiter tank. This is assumed to be a workable arrangement; however, base drag and vehicle aerodynamics would no doubt prefer a base area smaller than the fuselage/tank dimensions. Use of STME-40 engines in the orbiter stage would be one means to get a smaller base area. Another alternative would be to go to a higher (than 2250 psi) engine chamber pressure at the same nozzle area ratio (example shown on RH side of Figure 3-51).

ENGINE PHYSICAL SIZES
AMLS TYPE ORBITER (WITH 3 ENGINES)

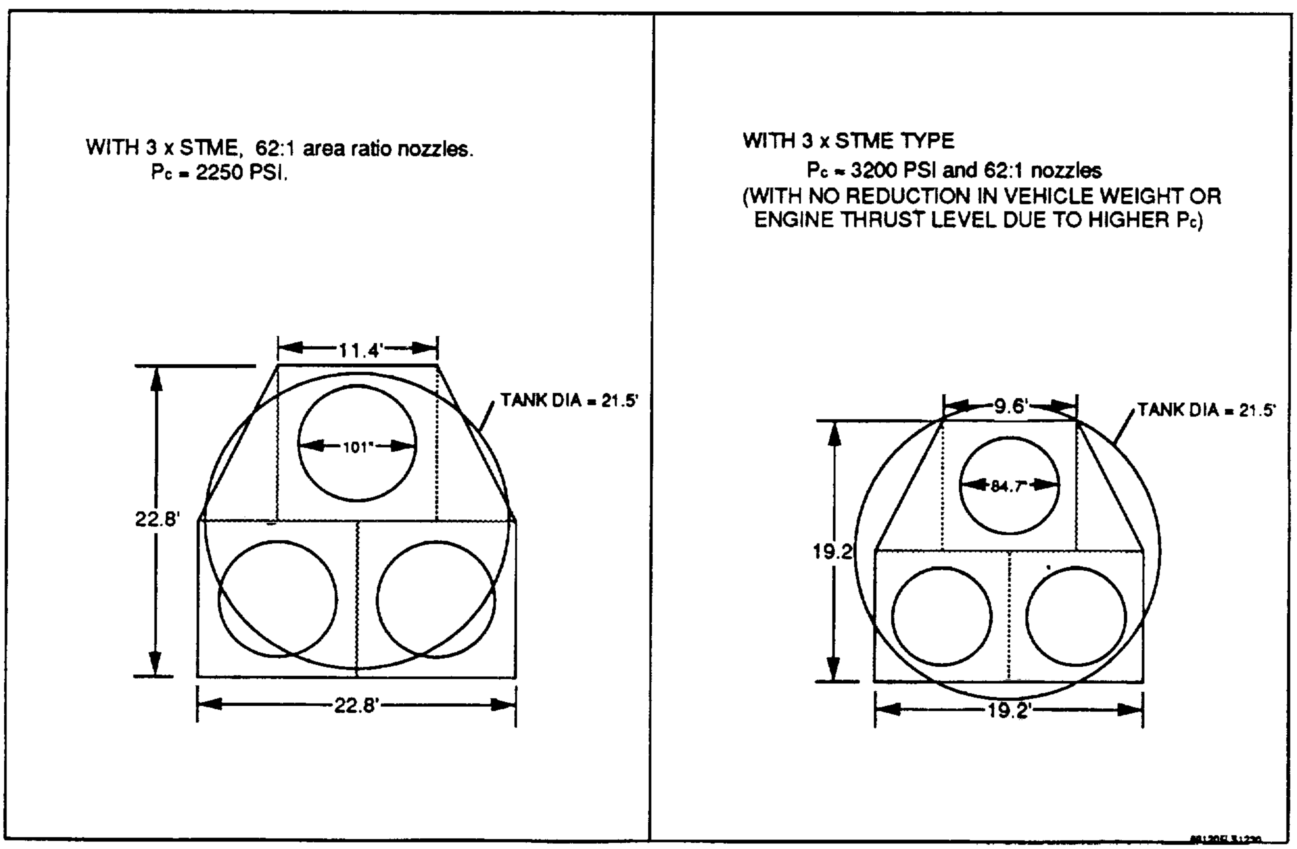


FIGURE 3-51 ORBITER BASE AREA (AMLS)

If lower payload requirements and/or advances in vehicle technologies result in vehicle fuselage sizes smaller than those shown, there would be a stronger motivation to go to 20:1 area ratio engines in the booster stage, and to go either to area ratio lower than 62:l or to higher chamber pressure engines for the orbiter stage. For example, an AMLS vehicle sized for 50K pld. and inert weight factors reduced by some 15% would require booster tankage approximately 24.4 in. diameter ft., and orbiter tankage approximately 20 ft. in diameter (vs. 27.5 ft. and 21.5 ft. as nominal values).

AMLS Gimbal Capability and Provisions

The base areas shown in Figures 3-50 and 3-51 include clearance for ±6 degree gimbal capability in a square pattern. AMLS vehicle configurations with parallel mounting of stages and large aerodynamic surfaces will likely require more than 6 degrees gimbal capability, as is the case with STS. In this event, addition of "wrap-around" propellant feed ducts would be necessary, adding several hundred pounds inert weight for each of the ten engines, with a corresponding increase in vehicle size and weight. This would also require some increase in engine spacing beyond that shown in Figures 3-50 and 3-51; however, this would not be expected to be a major impact in a completely new design, beyond the base area considerations noted earlier.

AMLS Propellant Utilization and Controls

As noted earlier in the STS/Shuttle "C" discussion, ±3 percent is the currently specified as the engine mixture ratio uncertainty band for STME engines. If this means that there will be a ±3 percent uncertainty in the operating mixture ratio for any given engine on any given flight, this could be a significant impact to performance-sensitive vehicles such as STS or AMLS. This uncertainty, combined with some level of additional uncertainty in vehicle/feed system factors, could lead to very large residual propellant weights, as shown in the example in Figure 3-52. This impact would be reduced somewhat by "averaging" effects between multiple engines in each stage, and in "averaging" of the effects of two individual stages of an AMLS vehicle (as shown in the example in Figure 3-52, RH side). The "worst case" condition can be lessened somewhat with a "fuel bias" in propellant loading (dashed curve on LH side of Figure 3-55), but would result in sizeable propellant residual even in the nominal mixture ratio case. If the STME value should be interpreted that all engines will fall within the ±3 percent range and the uncertainty for any given flight will be much lower, then adaptability of engines with "open loop" P.U. control will depend upon the levels of uncertainties expected in the vehicle/feed system factors. From information available at this point, it appears that strong consideration will need to be given for a "closed loop" P.U. system for AMLS applications.

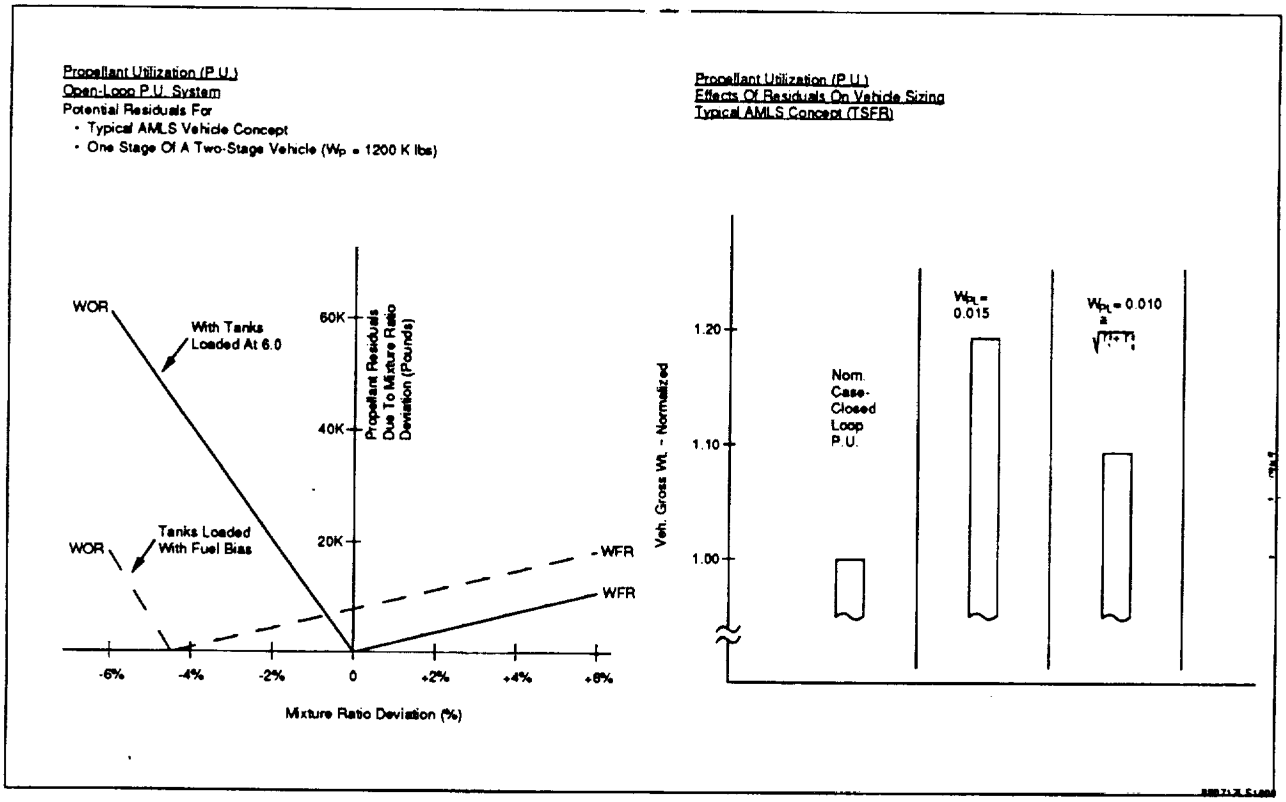


FIGURE 3-52 PROPELLANT UTILIZATION/CONTROLS

AMLS Engine Life Considerations

STME requirements currently include an engine life requirement of 10 flights (in lieu of 15 flight life that was carried earlier as a requirement). Analyses earlier in this study indicated an engine life of 30-50 flights to be desirable for highly reusable vehicles such as STS or AMLS. This is illustrated in Figure 3-53 (LH side), showing engine replacement costs over a ten-year period, for an engine life of 10 flights in comparison with engine life values of 30 or 50 flights. Hopefully this longer life would be inherent in the engine design; however if not, this savings would obviously have to be weighed against any additional investment required to increase engine life. We have no way of knowing at this point what that cost might be; however, an example of such a trade is shown in Figure 3-53 (RH side). This shows that savings could potentially warrant investments on the order of several hundred million dollars.

Note: this illustration was prepared earlier in the study, and was based on an assumption of five-engine booster and three-engine orbiter (total of eight engines per vehicle). Similar curves based on the more recent indications of (7+3) engine configurations would naturally show more pronounced effects of increased engine life.

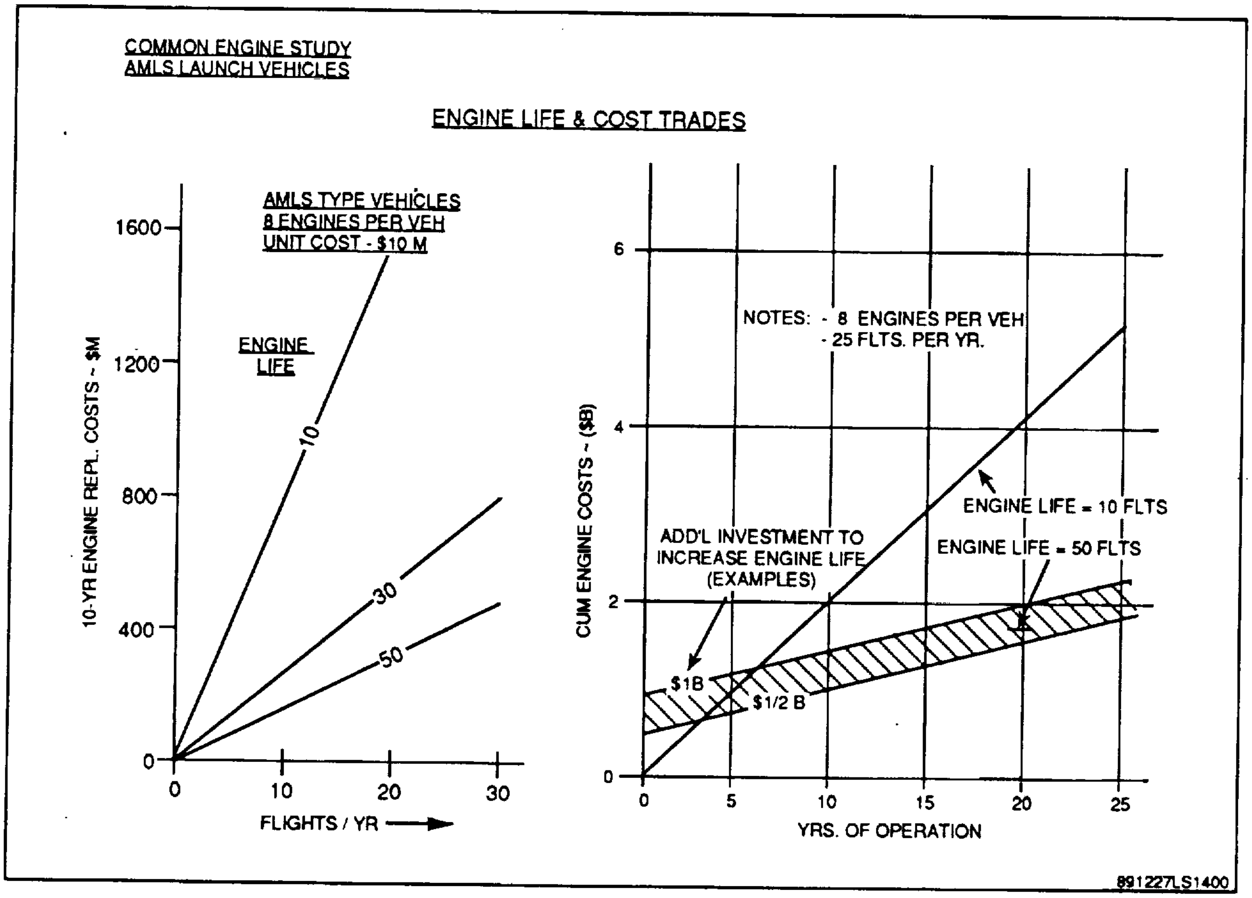


FIGURE 3-53 ENGINE LIFE AND COST TRADES (AMLS)

Summary - STME Applications for AMLS Type Vehicles

As noted earlier, AMLS vehicle concept studies have not been active during the period of this study, while emphasis was being placed on STS Evolution and PLS studies and planning. The preceding discussions based on available data on AMLS vehicle concepts and our own parametric studies can allow a few observations. Further studies of propulsion requirement and applications can be very helpful in conjunction with the additional vehicle concept studies that have been initiated by NASA.

The numbers of engines and engine sizes that are favorable for AMLS type launch vehicles are dependent in part on the levels of vehicle technologies to be incorporated and the corresponding inert weight factors. We have examined inert weight factors within a range of

$\pm$25 % about a set selected as "nominal" for our analyses. These analyses indicate that AMLS vehicles using STME engines will be some 15-40 percent higher in gross weight than a corresponding vehicle equipped with SSME engine characteristics. There is no overpowering performance or gross weight difference between different versions of the STME engine in this application, except for an option using 20:1 area ratio engines in both stages.

With "nominal" vehicle sizing and provisions for engine-out capability during either booster of orbiter burns, it appears that a total of ten STME engines would be required (7 in booster plus 3 in orbiter). Sketches have been provided to show base area requirements in comparison with propellant tank/fuselage sizes. These indicate a preference for 20:1 area ratio nozzles in the booster stage.

We have recommended the combination of STME-20 (booster stage) and STME-62 (orbiter) as "best" for AMLS vehicles. However, use of lower area ratio engines in the orbiter stage should be considered further, if this turns out to be important for orbiter stage design. Parametric data indicate only a moderate performance penalty for use of 40:1 engines in the orbiter.

The orbiter application would prefer three engines of approximately 2/3 the size and thrust of the nominal 580K thrust for STME engines, when including considerations of engine-out capability. STME's of the full size can be utilized with no major performance penalty; however, capability to throttle down to approximately 44% thrust will be necessary in order to maintain a 3-g limit (or alternatively, to depend on shutting down 2 of the 3 engines). It might be noted that this "over-thrust" condition would become more pronounced if very advanced vehicle technologies are incorporated with resulting lower orbiter inert weights.

It seems likely that AMLS type vehicles will need more than $\pm$6 degrees gimbal capability, and will therefore need addition of "wrap-around" propellant feed ducts. The inert weight and space for these ducts have not been included in these early analyses. We have assumed that engine inlet locations, engine inlet pressures, and other STME interface requirements could likely be accommodated in the "design from scratch" for AMLS vehicles; however, additional trade studies of these specifics will be needed as the vehicle concept studies proceed.

An open-loop P. U. control system is currently planned for STME engines. The resulting propellant residuals could have a strong effect on performance-sensitive vehicles such as STS and AMLS. The "averaging" effect of the large number of engines will limit this effect somewhat in the booster stage. However, for the orbiter stage and until we better understand the levels of uncertainties in the vehicle feed system, we suggest active consideration of a closed-loop P. U. system option.

An engine life of 30-50 flights per engine will be preferred for highly reusable vehicles such as AMLS, compared with the currently planned value of 10 flights for STME engines. Hopefully the engine will have capability for a higher life inherent in its design; however, if that turns out not to be the case, trade data provided in this section illustrate that a fairly sizable investment might be warranted to achieve a longer life capability.

3.1.3.5 Summary, Requirements for STME Engine Applications

In this part of the study, we have examined STME applications for STS/Shuttle "C" vehicles, for LRB and PLS launch vehicles, and for AMLS fully reusable type launch vehicles. A summary of propulsion requirements for these vehicle applications, compiled in the "matrix" format adopted for this study, is provided in Figures 3-54A and 3-54B: In the case of PLS launch vehicles, requirements data are provided for several vehicle options, e.g., vehicles using LRB as the booster stage vs. vehicles of all-new design, and for both booster cases, options as to second stage propulsion.

Further and closely related discussion of engine options and applications can be found in Sections 3.2 and 3.3 of this report, "Analyses of Booster Propulsion Options" and "Engine Commonality Analyses", respectively.

Engine Reqmts/Objectives
Potential Future STME Applications

	Vehicle/Stage Application							
	ALS (REF)	STS 'C'	LRB	STS Evol.	AMLS (1) Booster	AMLS (1) ORB	AMLS (2) Booster	AMLS (2) ORB
• Fuel	LH_2 →							
• Engine Cycle	GG →							
• Vac Thrust - Nom - Abort/Engine Out	435 K 580 K	500 K 540 K	558 K TBD	500 K 540 K	522 K 580 K	464 K 580 K	470 K 550 K	265 K 395 K
• No. of Engines in Stg.	6-7 | 3-4	2-3	8	3	7	3	7	3
• Throttle Range - Nom - Abort/Engine Out	100% 100%	57-81% 93%	75-100% TBD	52-84% 93%	63-100% 80-100%	80-100% 80-100%	85% 100%	67% 100%
• Mixture Ratio	6	6	6	6	6	6	6	6
• Mixture Ratio Control	±3%	±1%	TBD	±1%	±1%	±1%	±1%	±1%
• Reliability - Confidence Level • Redundancy	.99 90 FO	.99 TBD FO	.99 TBD FO/FS	.99 TBD FO/FS	.99 TBD FO/FS	.99 TBD FO/FS	.99 TBD FO/FS	.99 TBD FO/FS
• Recovery Mode - Exp - P/A - Water - P/A - Land - Full Reus	 ✓ ✓ ✓ – – ✓ – –	 ✓ – –	 ✓ ✓ – –	 – – – ✓	 – – – ✓	 – – – ✓	 – – – ✓	 – – – ✓
• Load Factors - Axial - Lateral	 10 5	 4 4	 TBD TBD	 4 4-(10)	 TBD TBD	 TBD TBD	 TBD TBD	 TBD TBD
• Engine Life (Flights)	1 (10-15) Alt	1	1 15	30-50 (10-15)	30-50	30-50	30-50	30-50
• Inlet Press - Lox (psia) - Fuel	47 30	23.3 19.6	65 45	23.3 19.6	TBD TBD	TBD TBD	TBD TBD	TBD TBD
• Power Head Dia (m's) Exit Dia Engine Length Inlet L's	TBD 87 142 30	<73.7 <94 <167 30	TBD 61 103 30	<73.7 <94 <167 30	TBD 61 103 30	TBD 108 175 30	TBD 61 103 30	TBD 108 175 30
• Gimbal Limits - Pitch (D's) - Yaw	10 10	10.5 8.5	6 6	10.5 8.5	TBD TBD	TBD TBD	TBD TBD	TBD TBD
• Nozzle Expansion Ratio	40 | 40	50	~20	50	20	62	20	62
• Specific Impulse (secs)	429	433	414	433	414	438	414	438
• Engine Weight (lbs)	7245	7500	6615	7500	6615	7800	6300	5300

Notes: (1) Using full-sized STME engines (2) Using selected engine sizes

900326LS0900

FIGURE 3-54A REQUIREMENTS FOR STME ENGINE APPLICATIONS
NOTE: REQUIREMENTS MATRIX CONTINUED IN FIGURE 3-54B

Engine Reqmts/Objectives
Potential Future STME Engine Applications (Cont'd)

	PLS WITH STS/LRB BOOSTER			PLS-NEW DESIGN L/VEH		
	BOOSTER	SECOND STG (1XSTME)	SECOND STG (OTHER)	BOOSTER	SECOND STG (1XENG)	SECOND STG (4 ENG)
• FUEL	LH_2 →	→	→	→	→	→
• ENGINE CYCLE	G.G. →	→	→	→	→	→
• VAC. THRUST - NOM (LBS.) - ABORT/ENGINE-OUT	435K 580K	435K* 580K	(80-130K	345K 460K	345K* 460K	93K 123K
• NO. OF ENGINES IN STAGE - SPECIFIED - ASSUMED	4	1	4	4	1	4
• THROTTLE RANGE ~ % -g LIMITS -q LIMITS -ABORT/ENGINE-OUT	75% TBD 100%	50% N/A 100%*	100% N/A 100%	75% TBD 100%	37-50% N/A N/A	TBD N/A 100%
• MIXTURE RATIO • MIXTURE RATIO CONTROL	6 → TBD	→ TBD	→ TBD	→ TBD	→ TBD	→ TBD
• NOZZLE EXPANSION RATIO	20	20	50 - 100	40	40	40
• SPECIFIC IMPULSE (SECS.)	414	414	440-460	429	429	440-460
• ENGINE WEIGHT	6615	6615	TBD	5750	5750	TBD
• RELIABILITY - CONFIDENCE LEVEL • REDUNDANCY	.99 TBD FO/FS	.99 TBD FO/FS	.99 TBD FO/FS	.99 TBD FO/FS	.99 TBD FO/FS	.99 TBD FO/FS
• INLET PRESS - LOX (PSIA) - FUEL (PSIA)	65 45	65 45	TBD TBD	47 30	47 30	TBD TBD
• POWER HEAD DIA (IN) EXIT DIA (IN) ENGINE LENGTH (IN) INLET L'S (IN)	58.4 61 103 30	58.4 61 103 30	TBD TBD TBD TBD	TBD 87 142 30	TBD 87 142 30	TBD TBD TBD TBD
• GIMBAL CAPAB. - PITCH - YAW	± 6° ± 6°	± 6° ± 6°	TBD TBD	± 6° ± 6°	± 6° ± 6°	TBD TBD
• RECOVERY MODE - EXP - P/A - WATER - P/A - LAND - FULL REUS	✓ ✓ — —	✓ — ✓ —	✓ —	✓ ✓ — —	✓ — ✓ —	✓ — ✓
• INSTL LOAD FACTORS (g's) - AXIAL - LATERAL	TBD	TBD	TBD	TBD	TBD	TBD
• ENGINE LIFE (IF EXP) (IF RECOV)	1 10-15	1 10-15	1 10-15	1 10-15	1 10-15	1 10-15

* IF PARALLEL STG. OTHERWISE, NOMINAL = 100%

891018LS0800

FIGURE 3-54B REQUIREMENTS FOR STME ENGINE APPLICATIONS (CONT'D)

3.1.4 Propulsion and Vehicle Margins

3.1.4.1 Introduction

A number of efforts in recent years have recognized the potential to achieve improvements in operating characteristics, and to achieve reduced costs for development and operation of space transport systems, by incorporating larger margins into systems and sub-systems than has been the practice in the past. We want to examine this prospect briefly as a part of this study task, in the context of propulsion requirements and vehicle applications.

Some of the vehicles and systems in our experience to date may have been designed to operate too close to the limits of their capabilities, and may have contributed to the levels of analyses, testing, and support required for development and operations of these systems. It may be that operations characteristics and costs of the systems can be improved by judicious applications of increased margins. However, very close analyses of this process will be necessary, to avoid increases in vehicle sizes and weights to an extent that could more than off-set the benefits being sought. This will be particularly true for some types of manned reusable launch systems, which are more performance-sensitive than most cargo launch vehicles. This premise is illustrated schematically in Figure 3-55.

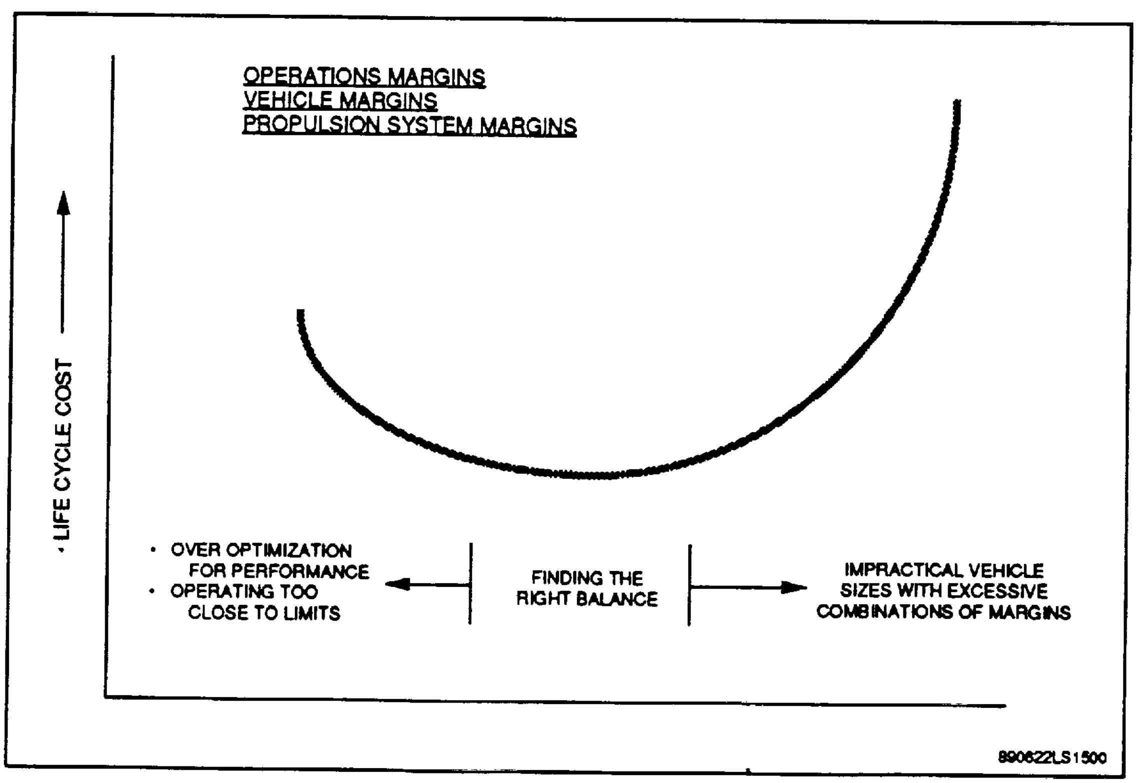


Figure 3- 55 Balance In Use Of Margin

Our purpose in these limited analyses is to try to help find that "balance" in the middle ground, where we can realize the benefits, but stop short of "going up the other side of the curve". In our analyses of variations in vehicle sensitivities to propulsion margins, it appeared necessary to examine variations in vehicle margins at the same time, and to look at interactions between propulsion and vehicle margins.

3.1.4.2 Categories of Margins

Let us first try to establish some terms of reference for a discussion of propulsion and vehicle margins. The sketch in Figure 3-56 indicates three different levels or categories of margins: (1) The first category represents steps to put in place larger operating margins, which would allow a system to operate with fewer constraints. The system would be less constrained by weather, for example; would have reduced constraints due to winds aloft; or other conditions that would otherwise impede its operations. In order to achieve these operating margins and reduced constraints, however, it is necessary to place greater demands upon the vehicle and ground system designs. Once these are established, these become the "floor" for the second category of margins. (2) These are the margins in the flight vehicle and ground systems, over and above the minimum capabilities necessary to meet the basic requirements, including the operations margins noted in the first category. These are margins in propulsive capability, in structural load capability, in vehicle control capability, etc., that will allow the vehicle to complete its mission successfully and safely even in the event of below-normal performance for some elements, or failures or partial failure of some elements. This is the level of capabilities desired in the vehicle and ground systems when the vehicle is on the pad, ready for launch. This leads then to the third category. (3) This is the level of margins that are included during the concept design and preliminary design phases, to allow for growth in inert weights and reductions in some performance factors that invariably occur as a system design matures. Note: it is recognized that some of the historical growth in weights during the definition phase are due in part to changes in requirements, that are actually of the nature of categories 1 and/or 2, noted above.

In this discussion, we want to focus on the second of the three categories noted above, e.g., the margins that will exist in the vehicle and ground system capabilities at the time of launch and throughout the missions. The sketch in Figure 3-56 indicates some examples of the second category of margins, of interest in this study task. These examples include provisions for engine-out capability during a part or all of the mission profile. They also include larger margins in engine performance and inert weight parameters. This latter type margins can provide not only for variations in engine performance parameters and weights directly - to a greater degree than in current practice-, but more importantly, can allow steps that would be expected to make the engine more dependable, less vulnerable to variations in its operating environments, and require less monitoring and support during its operations. This would include larger margins between normal operating conditions and the structural/ thermal/pressure limits in the engines, for example, that would allow reduced monitoring of "red-lines".

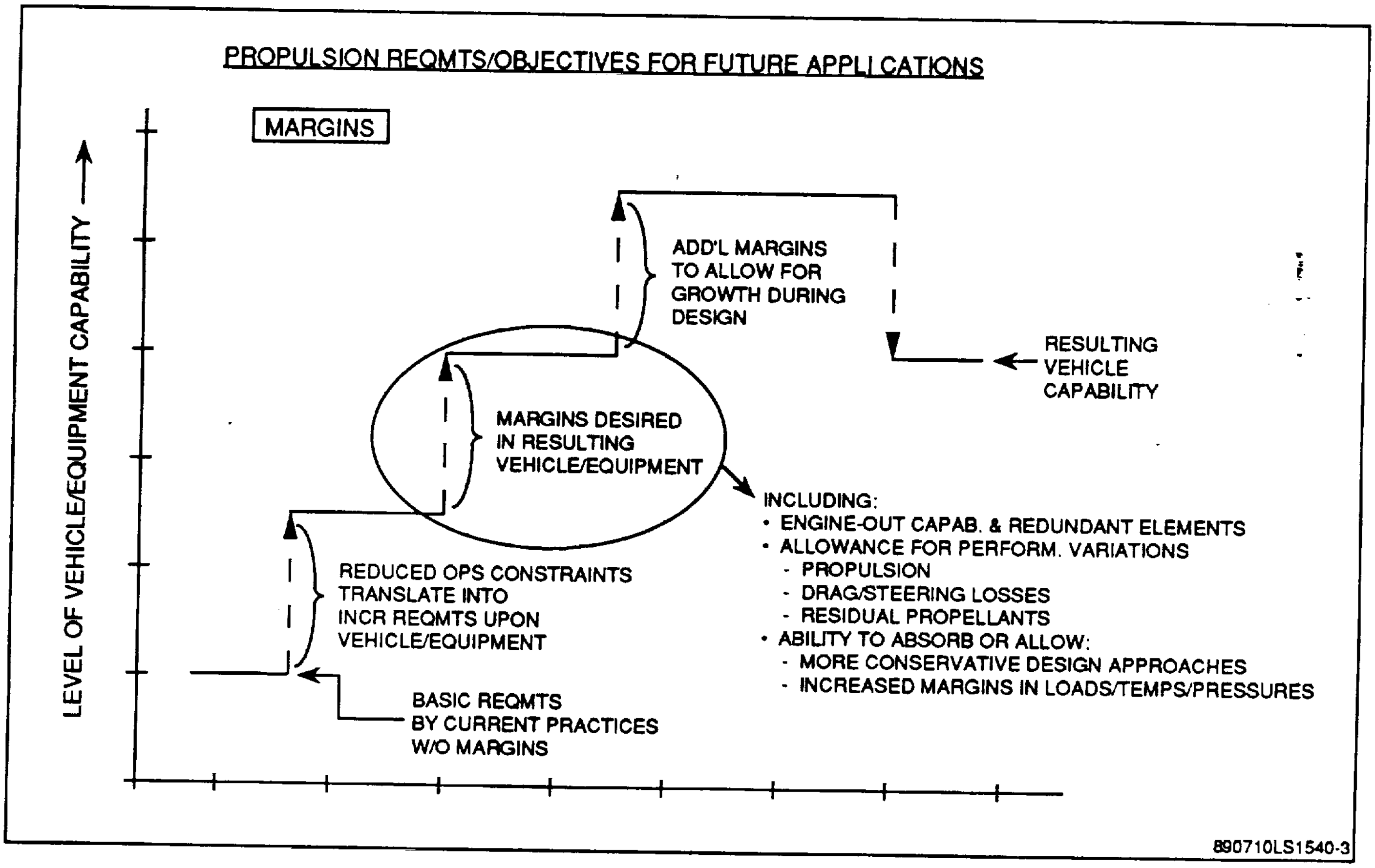


Figure 3-56 Types Of Margins

Including larger than normal margins in selected engine elements would result in reduced engine performance and/or increased engine weight, to a greater extent than the normal specification margins or tolerances. In this analysis, therefore, we will want to examine larger ranges for engine performance and inert weight margins than would normally be the case.

3.1.4.3 Candidate Engine Areas for Increased Margins

Candidate areas for application of increased margins within the engine assembly would have to be examined closely, and prioritized within whatever "ceiling" or budget in vehicle growth judged to be acceptable limit for absorbing higher margins. Turbopump assemblies are one of the hardest worked elements of pump-fed rocket engines, and would likely be one of the primary candidate areas. Pump size and weight can be minimized by designing to operate at rotational speeds as high as strength of materials will allow. Turbine size and weight can be minimized by designing to turbine operating temperatures as high as materials will allow. The question is: to what extent would it be profitable to back off further than in normal practice below the limiting temperatures for turbine operation? - and to back down further than in normal practice in pump rotational speeds? These specific design trades within the engines will obviously have to be worked, and are being worked, by the engine manufacturers. We claim no expertise in turbopump design, but do have an appreciation of the critical nature of turbopump bearings by virtue of SRS support to MSFC in analytical modeling and testing of SSME turbopump bearings and seals. We have therefore included a simplified analysis of increased-margins in turbopump bearings/life as an example or candidate area for increased margins. The focus and approach for this part of the analysis is shown schematically in Figure 3-57.

Cryogenically cooled turbopump bearings have several failure modes, which can independently or in combination cause the load support system to fail. Failure modes include fatigue, thermal excursion, and cage stability for example. Detailed analyses of bearing performance and operating life must investigate all of these factors. For purposes of this study, only bearing fatigue life was considered. Fatigue life is easily quantified, and it provides a good barometer of the magnitude of bearing wear, heat generation, and other factors which can contribute to bearing failure.

The effects of turbopump shaft speed and applied axial load on bearing B10 life are shown in Figure 3-58 (the number of hours a bearing is expected to operate with less than 10 percent failure rate). Reducing shaft speed significantly improves bearing fatigue life, with the effect being most pronounced for lighter loaded bearings. Reductions in axial loading has an even greater effect on fatigue life. For a typical turbopump ball bearing application, axial load on the bearing is induced to increase bearing stiffness, as required by rotor dynamics considerations. Pumps designed to operate at lower shaft speeds could have reduced stiffness requirements. In this case, the pump might experience a two-fold improvement in fatigue life margins; e.g., benefits from reduced shaft speed and also benefits from reduced loading.

FEATURES TO ENHANCE OPERATIONS
-MARGINS-

MARGINS	STRUCT-LOADS	PRESSURE	TEMPERATURE	PUMP SPEED
• BOOST PUMPS				
• PRE-BURNER (OR EQUIV)		✓	✓	
• TURBO-PUMPS	✓	✓	✓	✓
• INJECTOR		✓	✓	
• MCC		✓	✓	
• NOZZLE	✓		✓	
• VALVES				
• CONTROLS				
• HEAT EXCH		✓	✓	
• ACCESS DRIVES	✓			

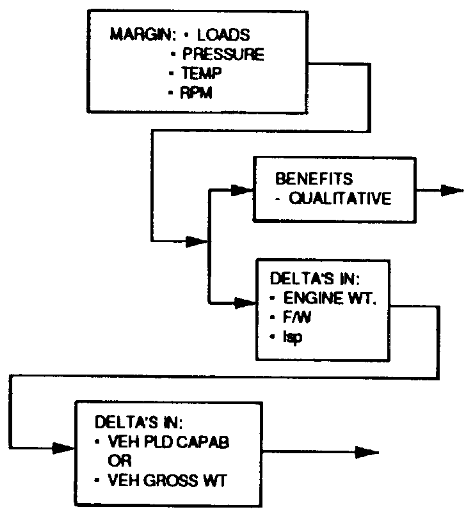


Figure 3-57 Candidate Areas for Increased Margins

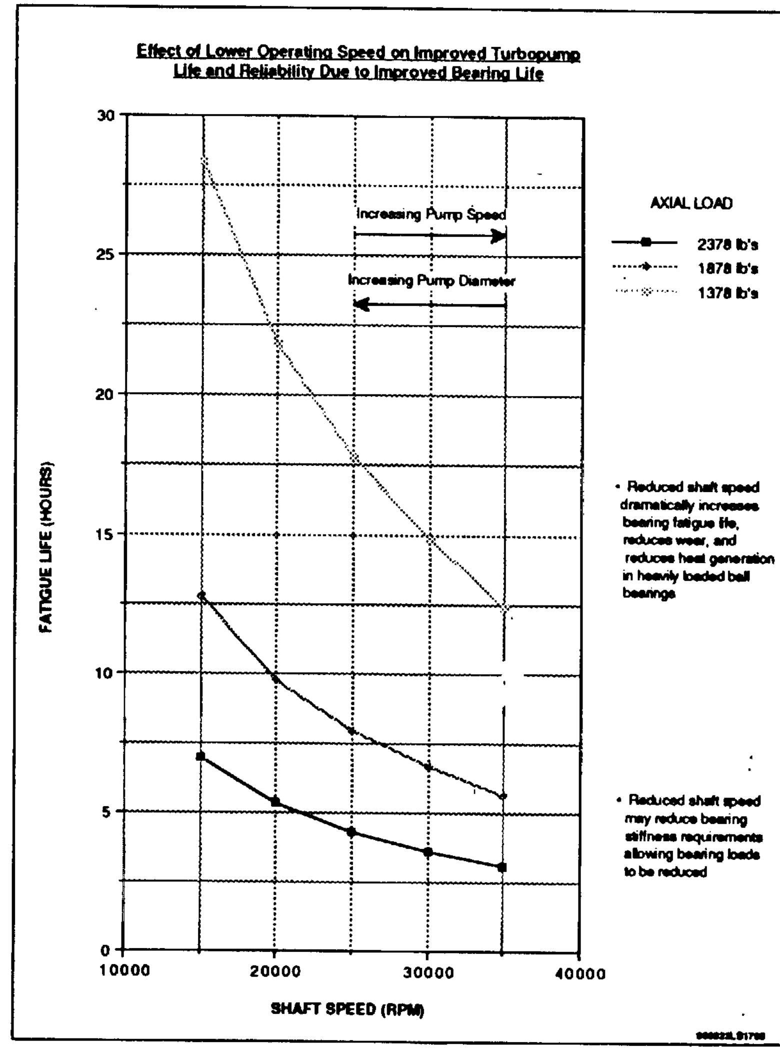


Figure 3-58 Effects of Operating Speed on Bearing Life

900329LS1300

Design of pumps for operation at lower shaft speed would require increases in diameter of the radial flow impeller. The relationship between shaft speed and pump diameter is shown in Figure 3-59, for pumps with constant discharge pressure. It can be seen for example that a 50 percent increase in impeller diameter could allow up to a 25 percent reduction in shaft speed. (This curve does not include viscous effects, which could influence the attainable reductions in shaft speed to some degree).

Estimates for weight increases in key elements of the pump assembly, corresponding to reductions in shaft speeds and increases in pump size, are shown in Figure 3-60.

Estimates of the effects of increases in engine inert weights upon over-all launch vehicle weights are shown for AMLS and PLS type vehicles in Sections 3.1.4.4 and 3.1.4.5, following. Estimates of increased margin in bearing fatigue life, combined with data on the corresponding increases in pump/engine inert weights and vehicle weights, can then allow a program manager to make judgments on the perceived benefits-vs-cost for each candidate application of increased margins, and to prioritize these candidates within his selected ceiling.

3.1.4.4 Margins in AMLS Vehicle Applications

We elected to use AMLS type (two-stage fully reusable) type vehicles for the first examinations of sensitivities of vehicle performance and sizing to different levels of propulsion margins. Sensitivities in terms of vehicle gross weight changes are discussed first; followed by discussion of corresponding changes in vehicle dry weights or hardware weights.

Sensitivities of AMLS type vehicles to engine inert weight margins and to engine specific impulse margins are shown individually and in combination in Figure 3-61. Not surprisingly, sensitivity to Isp margins is shown to be much stronger than to inert weight margins. Over this range of Isp margins, gross weight increases of 7-to-8 percent are indicated for each percent reduction in engine Isp. Since each percent Isp represents some 4 to 4.5 seconds, this means increases in vehicle gross weight of 1.75-to-2 percent for each second reduction in Isp. By comparison, the exchange factor for engine inert weight margins is more like 0.25 to 0.3 of one percent increase in vehicle gross weight per percent increase in engine inert weights.

Corresponding sensitivities in terms of vehicle dry weights are shown in Figure 3-62. This indicates a slightly lower sensitivity than that for vehicle gross weights, due no doubt to inert weight fractions getting a little better as the vehicle size increases in response to Isp reduction. Vehicle dry weight sensitivity to engine inert weight margins is shown to be slightly higher than that for vehicle gross weights, reflecting its more direct influence upon vehicle dry weights.

Re[illegible]onship Between Pump Size and Shaft Speed for P[illegible]ps of Constant Discharge Rate and Head Rise

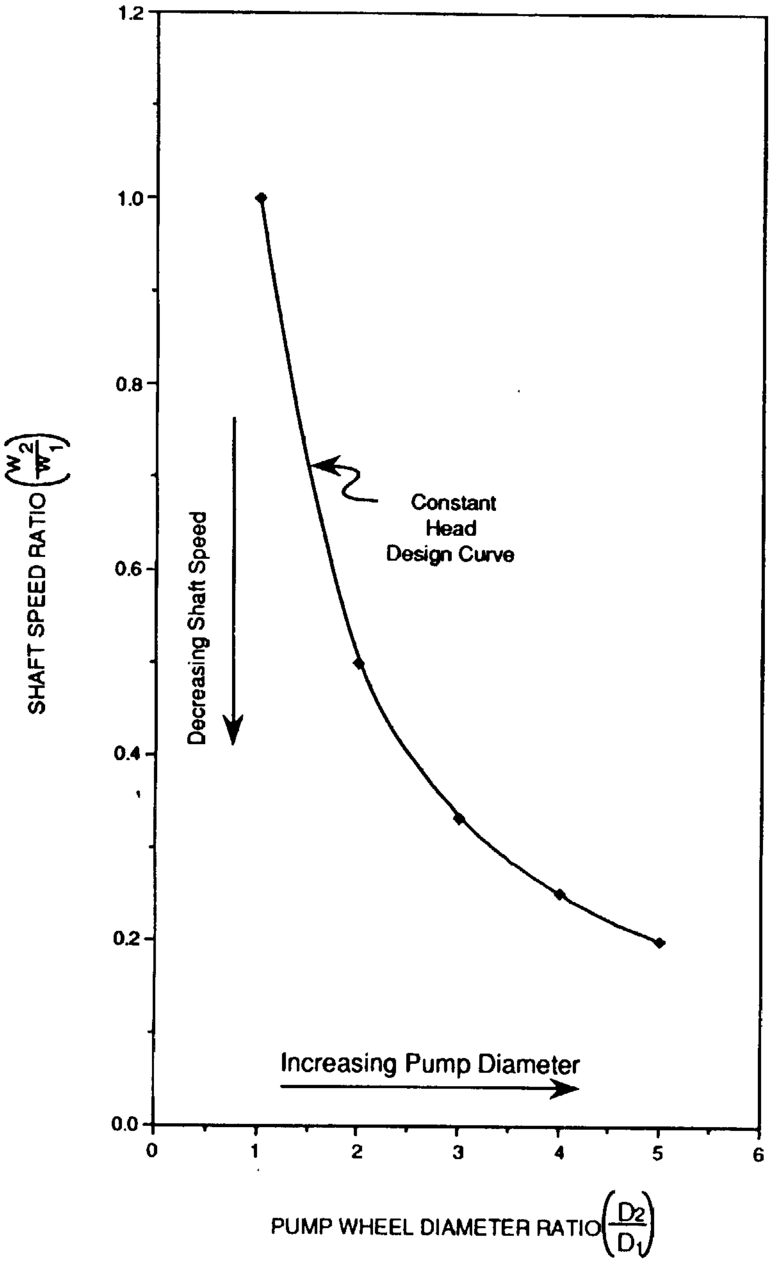
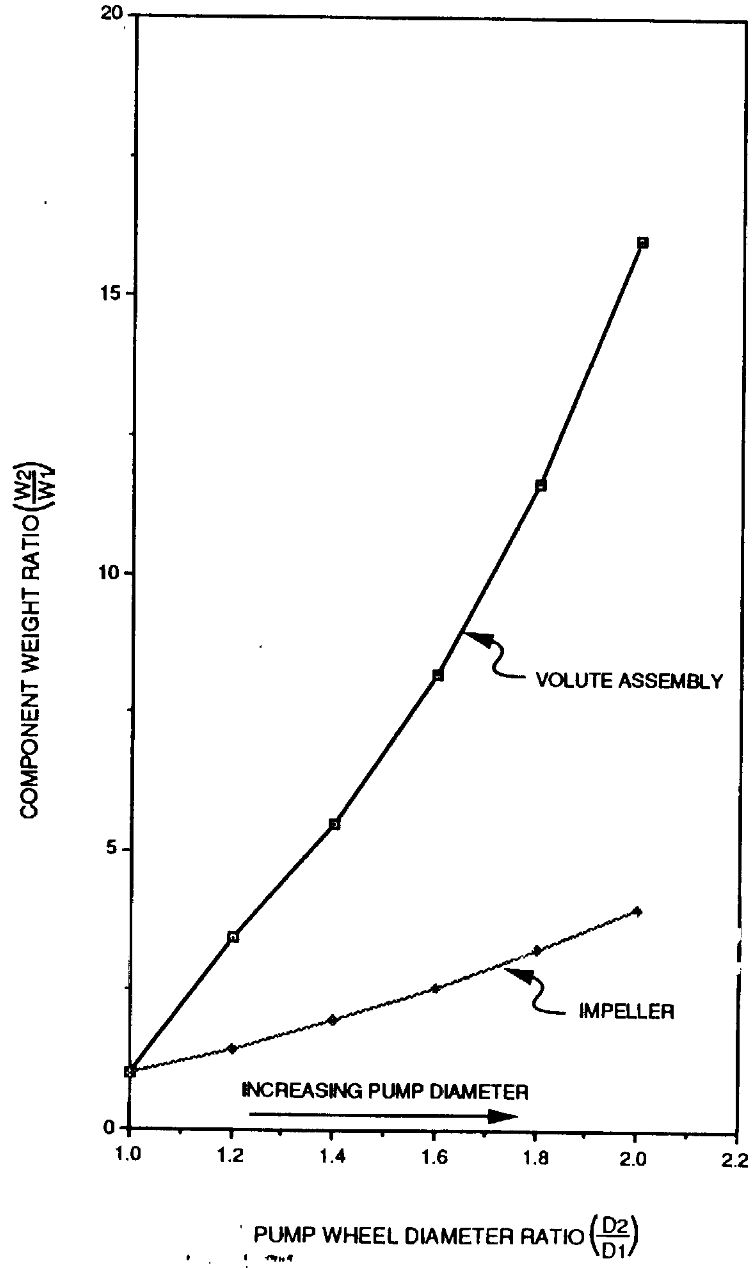


Figure 3-59 Relationship Between Pumpsize And Shaft Speed

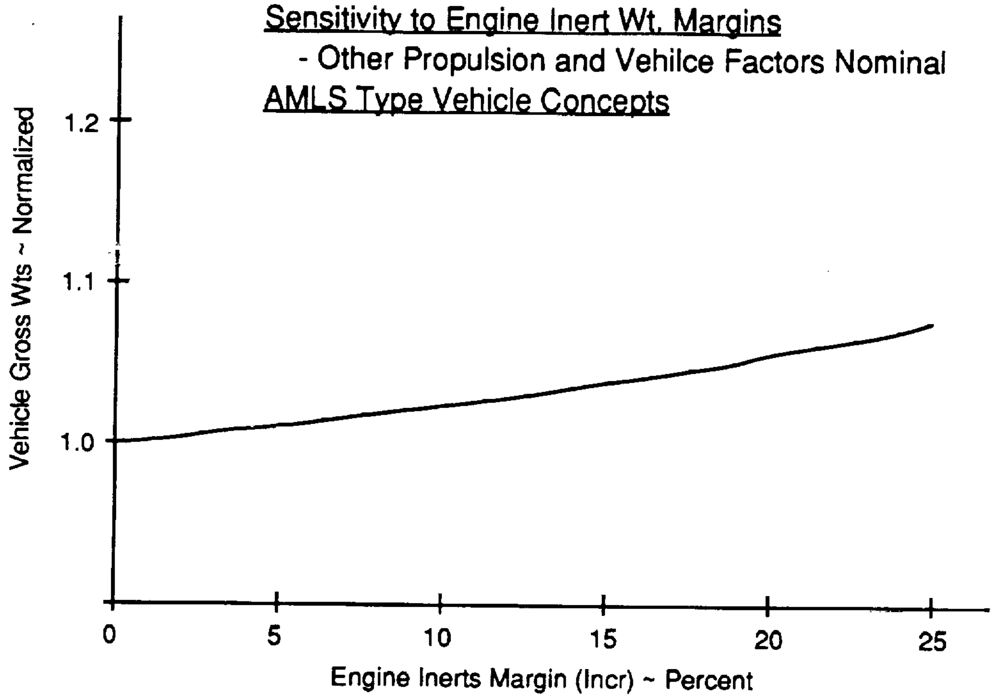
Estimated Weight Increase Penalty For Turbopump Components For Pump Designs With Increasing Pump Diameter



- Pumps designed for lower operating speeds result in geometrically increasing weights for components such as the volute and impeller.
- Pumps designed for lower operating speeds may also require increased turbine diameters to maintain efficiency

Figure 3-60 Weight Increases In Pump Elements

900329LS1400



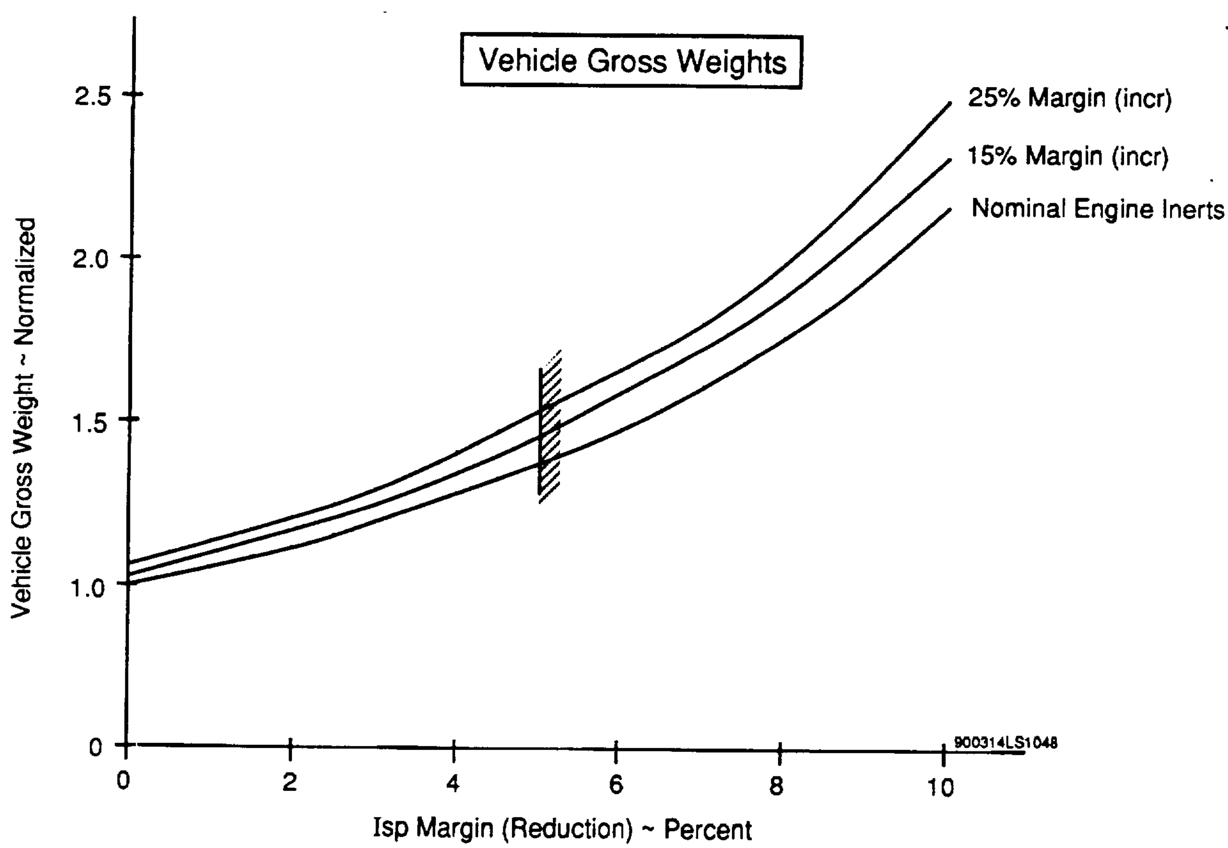


Figure 3-61 Sensitivity To Propulsion Margins

900329LS1315

These figures indicate that a 5 percent margins in engine Isp's in combination with a 15 percent margin on engine inert weights can be accommodated within a gross weight increase of approximately 46 percent and a dry weight increase of approximately 42 percent (compared with a baseline not including those margins). Secondly, this again indicates that, where there is a choice in design decisions, an improvement resulting in an increase in engine inert weight will have less impact upon vehicle size and weight than would a change resulting in a decrease in engine Isp.

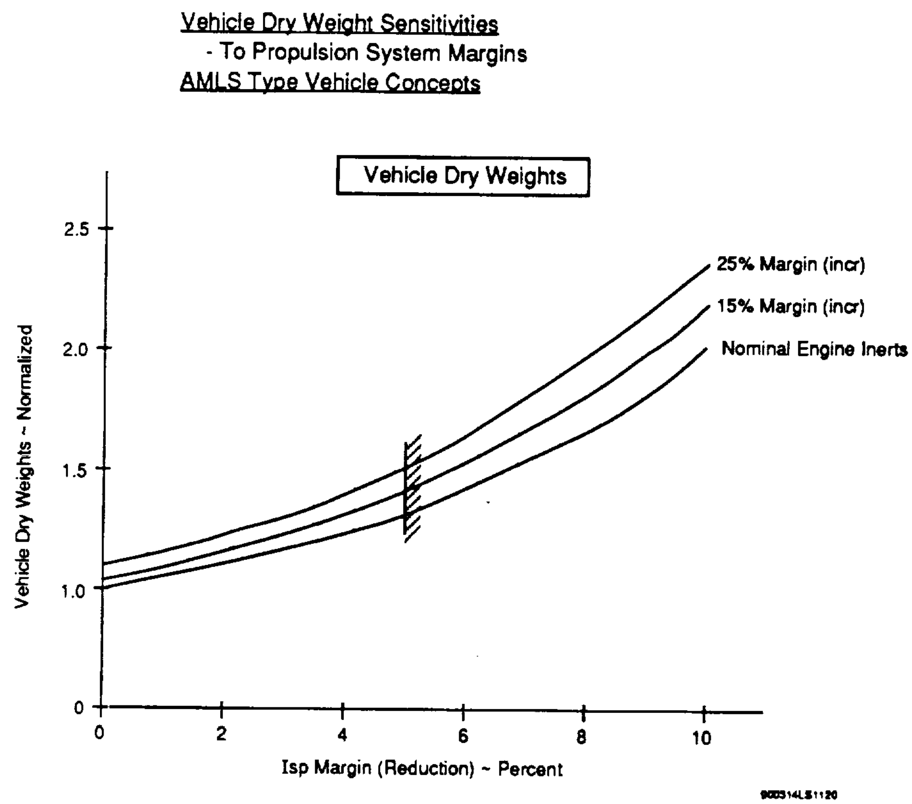


Figure 3-62 Vehicle Dry Weight Sensitivity To Propulsion Margins

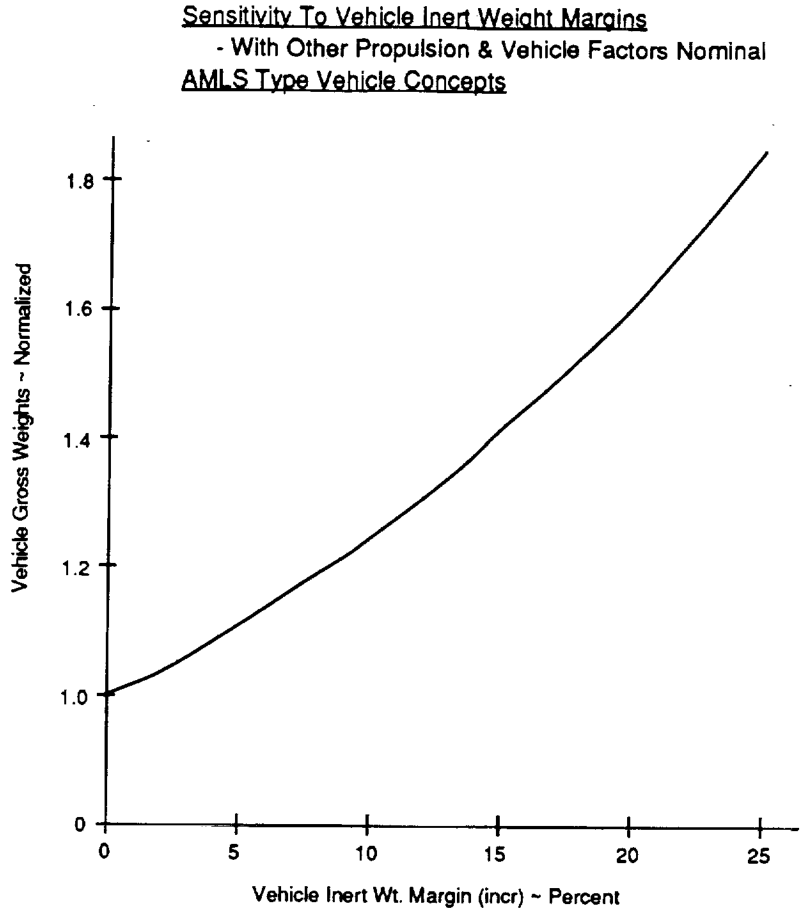
Interactions Between Propulsion and Vehicle Margins

Potential benefits of increased margins are being examined for other elements of vehicle systems, just as we are here for propulsion systems. Unfortunately, sensitivities to increased propulsion margins will be strongly influenced by the extent of margins in the rest of the vehicle system, and vice versa. We will first look briefly at some candidate vehicle system margins, and sensitivities to those margins separately, before looking at them in combination. One is a margin in vehicle inert weights (other than engine weights). The second is a margin or variation in the equivalent delta-v that the vehicle is required to deliver. A margin of the latter type in current practice recognizes uncertainties in drag losses and steering losses, for example, and would presumably include uncertainties in residual propellant quantities. There is considerable interest at present in possibilities, through larger performance margins and/or improved guidance and control system flexibilities, to allow less specific and precise tailoring of flight plans for individual flights, and the costs involved. We have examined values ranging up to 5 percent for this parameter. Sensitivities to these two margins individually and in combination are shown in Figure 3-63. It can be seen that both of these margins are "heavy hitters". A gross weight increase of approximately 40% is indicated for a 15% margin on vehicle inert weights, with other factors at their nominal values. A gross weight increase of approximately 36 percent is indicated for a 5% margin on vehicle delta-v requirements, with other factors nominal. Applying the two in combination go clearly beyond practical limits (tripling vehicle gross weights), and show the necessity to look into less ambitious ranges for margin increases. Perhaps the example shown for 15% inert weight margin in combination with 2% margin on vehicle delta-v requirements would be a more practical combination to consider.

Combining Propulsion and Vehicle Margins

We can now re-examine sensitivities to propulsion margins, in combination with selected vehicle-related margins. The plots in Figure 3-64 show sensitivities to engine inert weight margins, with and without vehicle margins included. The sensitivity to engine inert weight margins with vehicle margins included is approximately double that indicated earlier without vehicle margins, e.g., approximately 0.6 percent increase in vehicle gross weight per percent increase in engine inert weights, compared with the 0.25-0.30 value quoted earlier. In either event, the curves are both fairly flat, indicating still a low level of sensitivities to engine inert weight margins. The curves in Figure 3-65 show a strongly different level of sensitivities to engine Isp margins. The slope of the top curve indicates is a average of approximately 24 percent increase in vehicle gross weight per percent Isp margin over the range shown; and when added on top of the influence of the other margins, results in gross weight increases to an impractical extent. We have therefore indicated on the figure a region that might be of more practical interest here, including Isp margins up to 2 percent (8 t0 9 seconds).

C-2



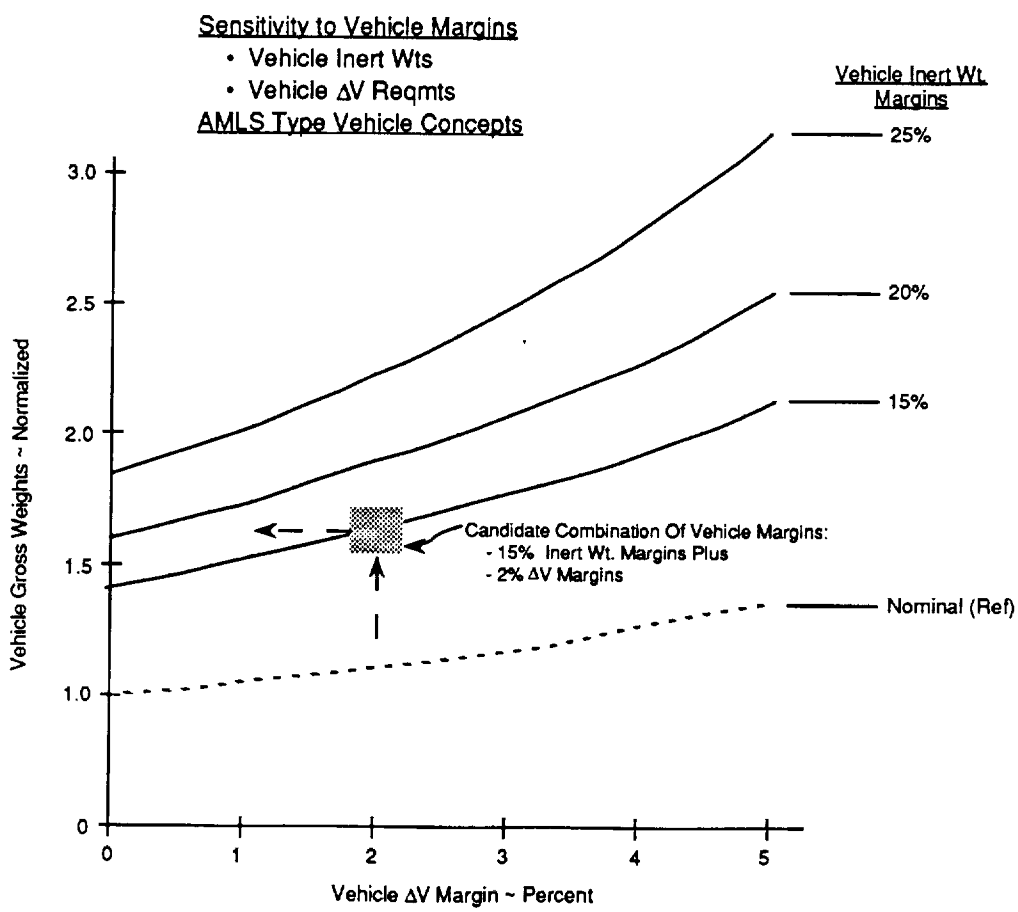


Figure 3-63 Sensitivity To Vehicle Margins

900314LS1337

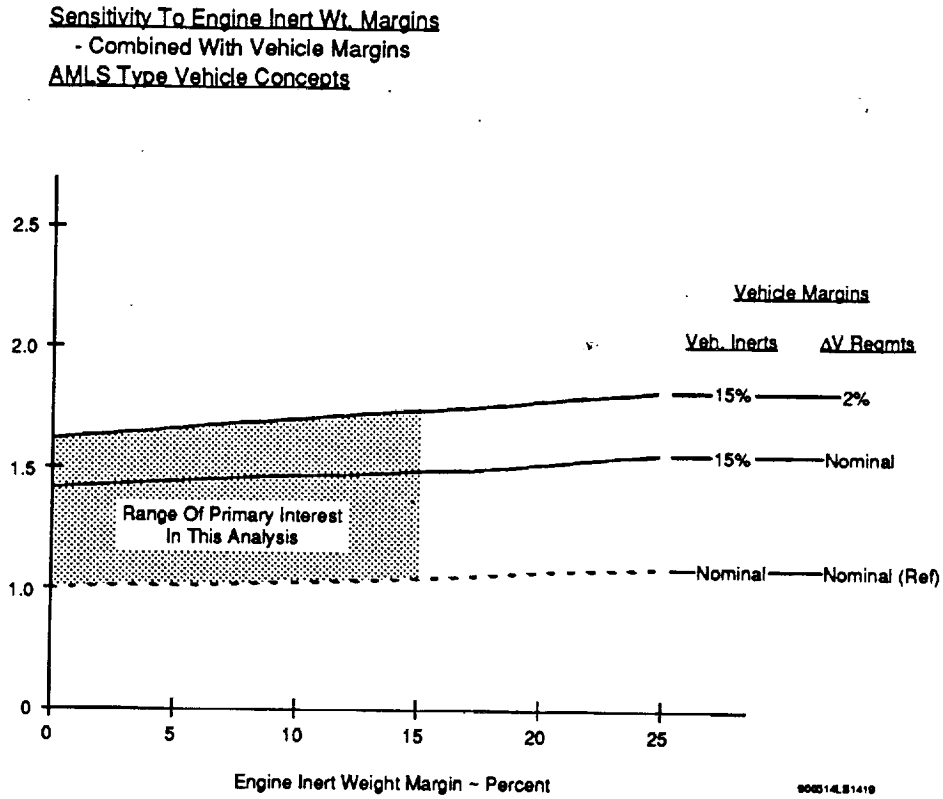


Figure 3-64 Propulsion and Vehicle Margins

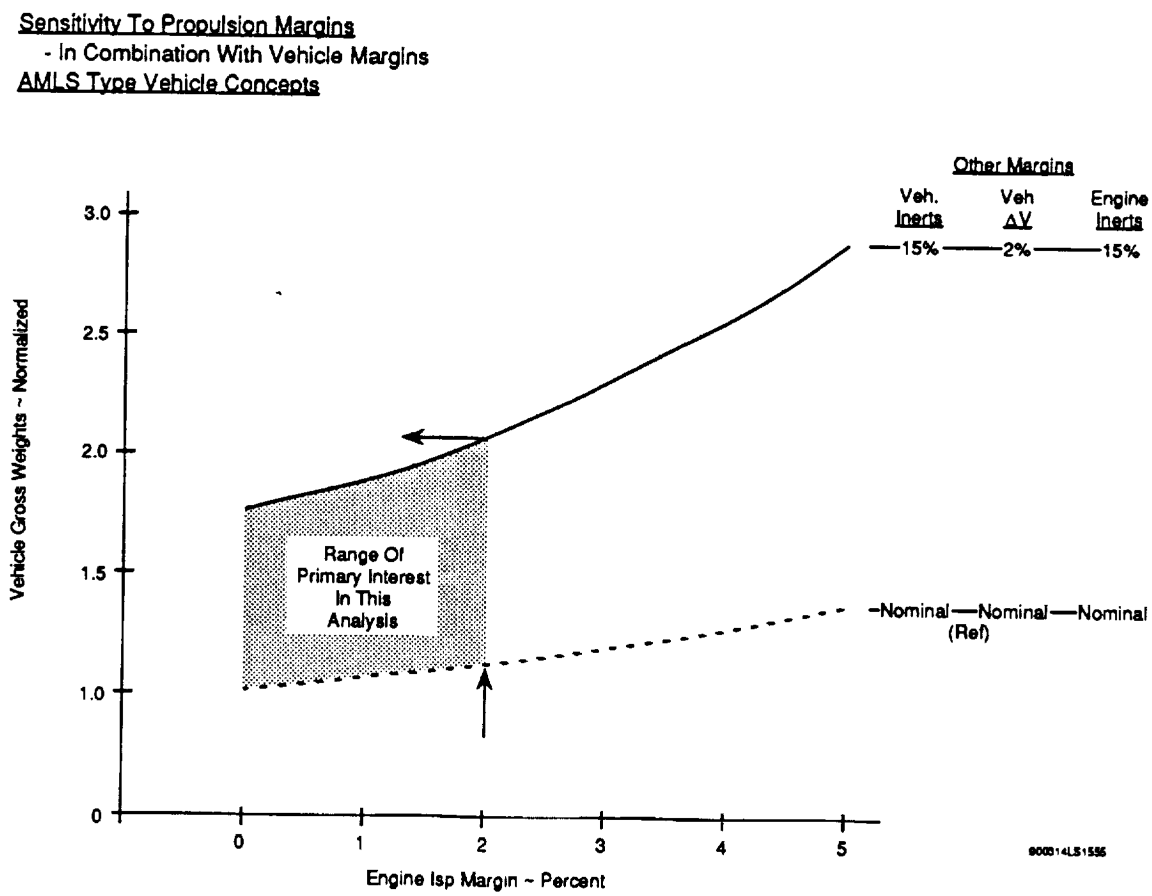


Figure 3-65 Propulsion and Vehicle Margins

Analyses of sensitivities for AMLS type vehicles using STME engines and the vehicle inert weight characteristics that we have used as nominal lead to suggestion of the following ranges of margins as a starting point for further analyses of propulsion and vehicle margins. Critical analyses and prioritizing of candidate applications of margins within these ranges will be necessary. The effects of different propulsion and vehicle characteristics in the baseline vehicle (before application of increased margins) will be discussed in the following section.

* Engine Inert Weight Margin......15%
* Engine Isp Margin..............2%
* Vehicle Inert Weight Margin 15%
* Vehicle Delta-v Margin 2%

Effects of Higher Performance Options in Nominal Vehicle

Hopefully design studies will show that the vehicles can be built to lower inert weight fractions than used as nominal values in these analyses. Secondly, when sensitivities to increased margins are taken into consideration, the motivation for higher performance propulsion options and more advanced vehicle technologies will be more evident than in the vehicle performance and sizing studies discussed in other sections of this report (Sections 3.1.3.4, 3.2, and 3.3). We can see this effect, for example, by using as baseline a vehicle with SSME engine characteristics (in lieu of lower performance STME engine characteristics) and with vehicle inert weight factors reduced by 15% (representing use of advanced vehicle technologies or other equivalent). Summary results from this analysis are shown in Figure 3-66. A vehicle with these characteristics (the bottom two of the three curves shown here) shows a much reduced sensitivity to increases in propulsion margins, even when combined with increased vehicle margins (the middle curve). This vehicle indicates a sensitivity of less than 10 percent increase in gross weight per percent Isp margin, compared with the 20-plus percent for the vehicle using STME engines and nominal inert weight characteristics (shown in the top curve for reference).

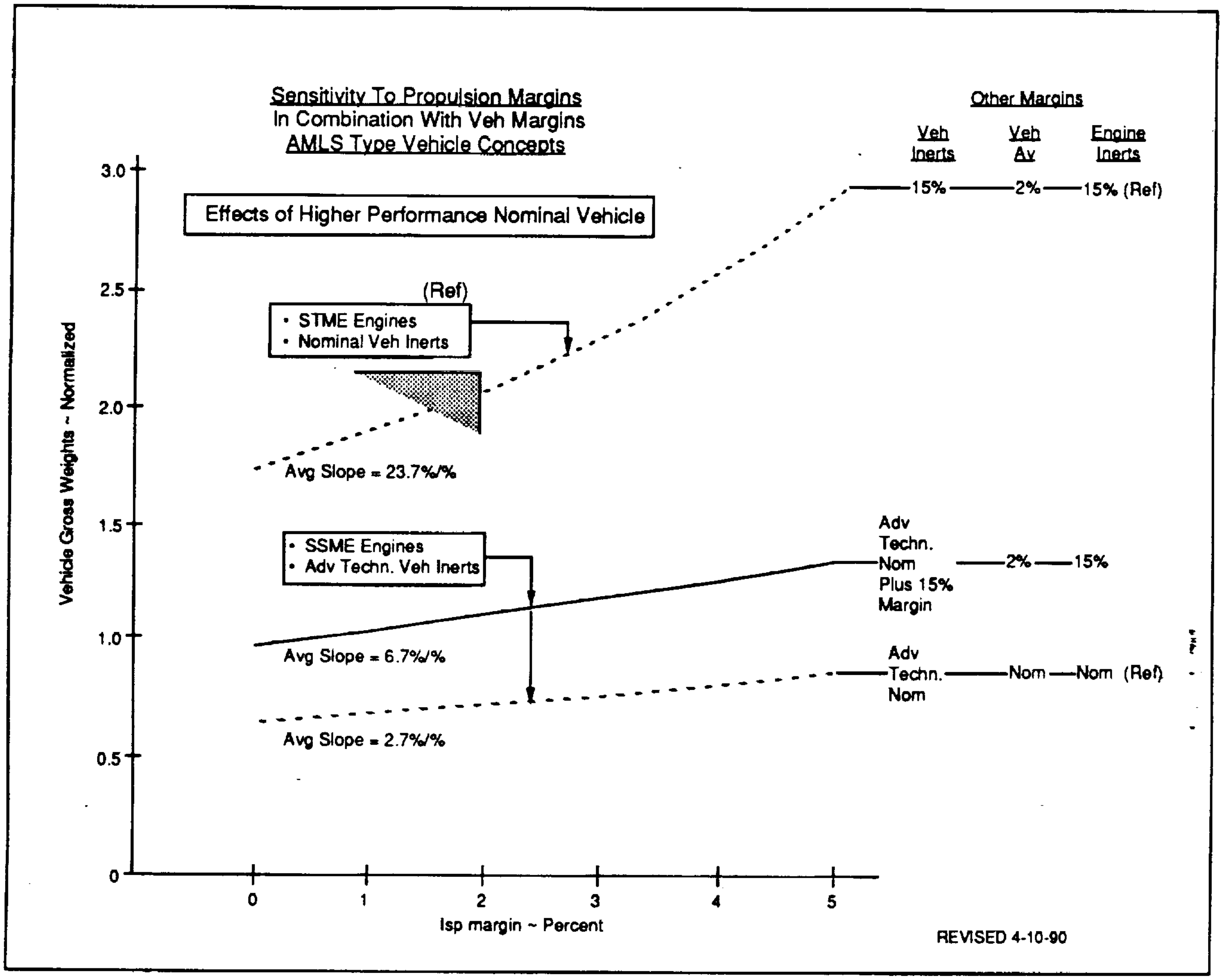


FIGURE 3-66 EFFECTS OF HIGHER PERFORMANCE NOMINAL VEHICLE

3.1.4.5 Margins in PLS Launch Vehicle Applications

We want to get some indications of sensitivities to propulsion and vehicle margins in classes of launch vehicles of simpler design and lower inert weights, such as PLS or ALS launch vehicles, for comparisons with the AMLS sensitivities discussed in the preceding paragraphs. PLS launch vehicle sensitivity to engine Isp margins, in combination with other propulsion and vehicle margins, are shown in Figure 3-67. The corresponding sensitivity curve for AMLS vehicles (from Figure 3-65) is also shown here in order to see this strong comparison. As might be expected, the PLS launch vehicle is much less sensitive to this combination of margins. For example, the vehicle weight growth over this range is a little over 4 percent per percent Isp margin, compared with the AMLS value of about 24 percent per percent. This obviously leaves room to consider a much wider range of margins within weight growth constraints, where there is benefit to do so in PLS launch vehicles.

It has been suggested at times that vehicles such as PLS launch vehicles, designed specifically for people transport, might incorporate margins and safety features to a much greater degree than in vehicles designed for cargo transport. The above data suggest that this could be done in PLS launch vehicles with minimum weight growth.

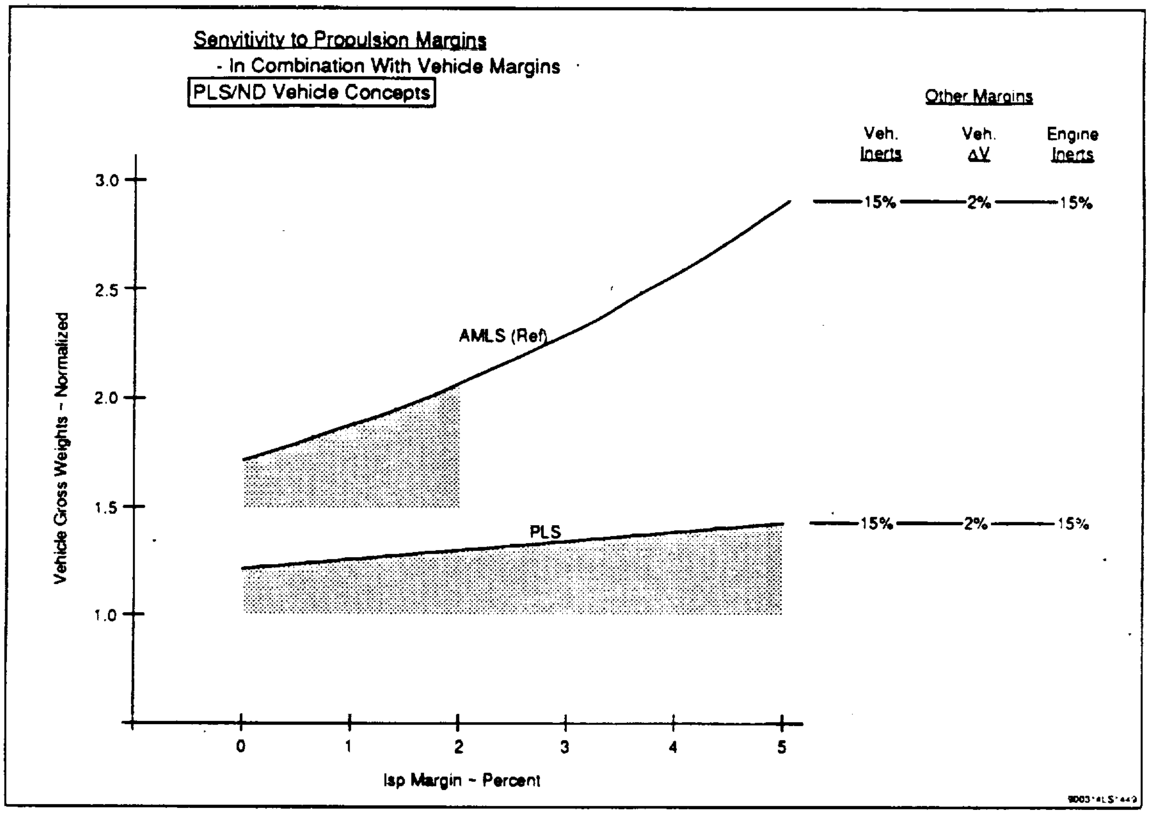


FIGURE 3-67 PLS VEHICLE SENSITIVITY TO PROPULSION MARGINS

3.1.4.6 Summary - Propulsion and Vehicle Margins

Judicious use of increased propulsion and vehicle margins represents a potential means to achieve improved operations, safety and cost characteristics in future manned launch vehicles. Careful analyses and prioritizing of candidate applications of increased margins will be necessary, in order to get the most important margins incorporated within vehicle weight growth constraints that could otherwise more than off-set the benefits being sought. The sensitivity data provided here shows this to be particularly true when propulsion and vehicle margins are considered in combination, and is true to a much greater degree for performance-sensitive AMLS type launch vehicles, than for PLS or ALS type launch vehicles.

These data again indicate that there is more "elbow room" for changes that would increase engine inert weights, rather than those that would reduce engine performance. The sensitivity to engine performance changes is more pronounced in these analyses than in comparisons in Section 3.1.3 comparing different versions of STME engines, because in those cases a decrease in vacuum specific impulse was a least in part off-set by a corresponding increase in sea level Isp.

We have presented most of the sensitivity data in terms of growth in vehicle gross weights, with an example in Figure 3-62 showing the corresponding dry weight sensitivities. As these analyses proceed, there would be increasing attention to dry weight sensitivities, as perhaps a better indicator of vehicle costs.

Based on these analyses and the stated assumptions, we have suggested values for propulsion margins, as starting point target or ceiling values within which to prioritize candidate applications for increased margins. The numerical values of these sensitivities are dependent upon the propulsion characteristics (STME) and the vehicle inert weight characteristics that we have used as nominal in these sensitivity studies.

Hopefully, further vehicle design studies will show lower inert weight options for use as nominal values. Secondly, this degree of sensitivity to margins for AMLS vehicles represents an additional motivation to consider higher performance propulsion options and higher technology/lower inert weight options, in further vehicle and propulsion studies.

3.2 Analysis of Booster Propulsion Options -

3.2.1 Introduction

This "Propulsion Evolution Study" is devoted almost completely to vehicle applications and requirements for hydrogen-fueled rocket engines. At the time this study was initiated, however, there was stronger consideration than at present for possible development of a hydrocarbon-fueled engine for booster stage applications. A task was included in this study (limited to approximately 5% of the study effort), therefore, for a limited look at hydrocarbon engine booster applications, in comparison with hydrogen-fueled engine options. This question is applicable for STS and Shuttle "C" applications only in the possible development of liquid rocket boosters (LRB) for use with STS. Both hydrogen and hydrocarbon engine options were examined as a part of the LRB Phase-A studies, leading to recommendation for the hydrogen -fueled engine option. In this study, we have attempted to add to this data base by a quick look and comparisons of hydrocarbon engines and "booster versions" of hydrogen engines in PLS and AMLS launch vehicle applications.

As one comparison, we will examine a vehicle in each class using a "booster version" of hydrogen engines in the booster stage of each vehicle, compared with vehicles using the "Orbiter/Core" version of the engine in both stages: (1) We will compare vehicles using SSME-35 engines in the booster stage with vehicles using standard SSME's in both stages. And, (2) we will compare vehicles using STME engines with 20:1 area ratio (STME-20) in the booster stage vs. the reference vehicle using STME-62 engines in both stages.

Secondly, we will make comparisons in each vehicle class with vehicles using Lox-hydrocarbon (STBE) engines in the booster stage, in comparison with all-hydrogen vehicles. Candidate hydrocarbon propellant combinations include Lox-kerosene, Lox-propane, and Lox-methane. Trade studies in recent years have resulted in primary attention on Lox-methane, and that combination is used as representative in these booster propulsion trades. Lox/methane booster engine characteristics used for the purpose of these trade studies are as follows:

* Specific Impulse (vac) .... 332 secs.
* Specific Impulse (s/l) .... 299 sec.
* Mixture Ratio 2.7
* F/W (vac) 100
* F/W (s/l) 90

Since engine sizes have not been fixed, particularly for Lox-hydrocarbon booster engines, our comparisons of vehicle sizes and weights in this part of the study were done with "rubber" engine sizes, e.g., using engine sizes and thrust levels as needed for the particular vehicle being studied.

3.2.2 PLS Launch Vehicle Applications

In order to get some comparisons of vehicle sizes and weights for these propulsion options, PLS launch vehicles were sized with each of six propulsion combinations, e.g.: (1a) - STME-62/STME-62 (the reference case), (1b) - STME-20/STME-62, (1c) -STBE/STME-62, (2a) -SSME/SSME, (2b) - SSME-35/SSME, and (2c) - STBE/SSME. A nominal payload requirement of 40K lbs. was used as basis for these comparisons. Results from sizing PLS vehicles using these engine combinations are summarized in Figures 3-68 and 3-69. Note: Data are included for PLS launch vehicle concepts using SSME engines; however, as noted elsewhere in this report, we assume that SSME engines will not be a primary candidate for LRB or PLS launch vehicle applications, unless effective stage/engine recovery provisions are developed which would allow several reuses of the SSME engines.

Booster Versions of Hydrogen Engines (PLS)

Booster base area requirements for PLS launch vehicles and three different versions of STME engines were shown earlier in Figure 3-42A (Figure repeated here for convenience). When compared with the large area requirements for use of STME-62 engines, the 20:1 (or 40:1) area ratio engines allow closer engine spacing, minimize or reduce need for skirt flare, facilitate integration with other vehicle elements and launch facilities, and would reduce vehicle metal/weight requirements for the engine(s) installation/base area. Particularly when used with tanks of limited diameter (as in LRB vehicles), low area ratio engines will be a strong advantage in these installations. As was noted in Section 3.1.3.3, the arrangement of pumps and plumbing around the thrust chamber of 20:1 area ratio engines may turn out to be the limiting factor for engine spacing, and if so, could suggest going to an area ratio slightly higher than 20:1.

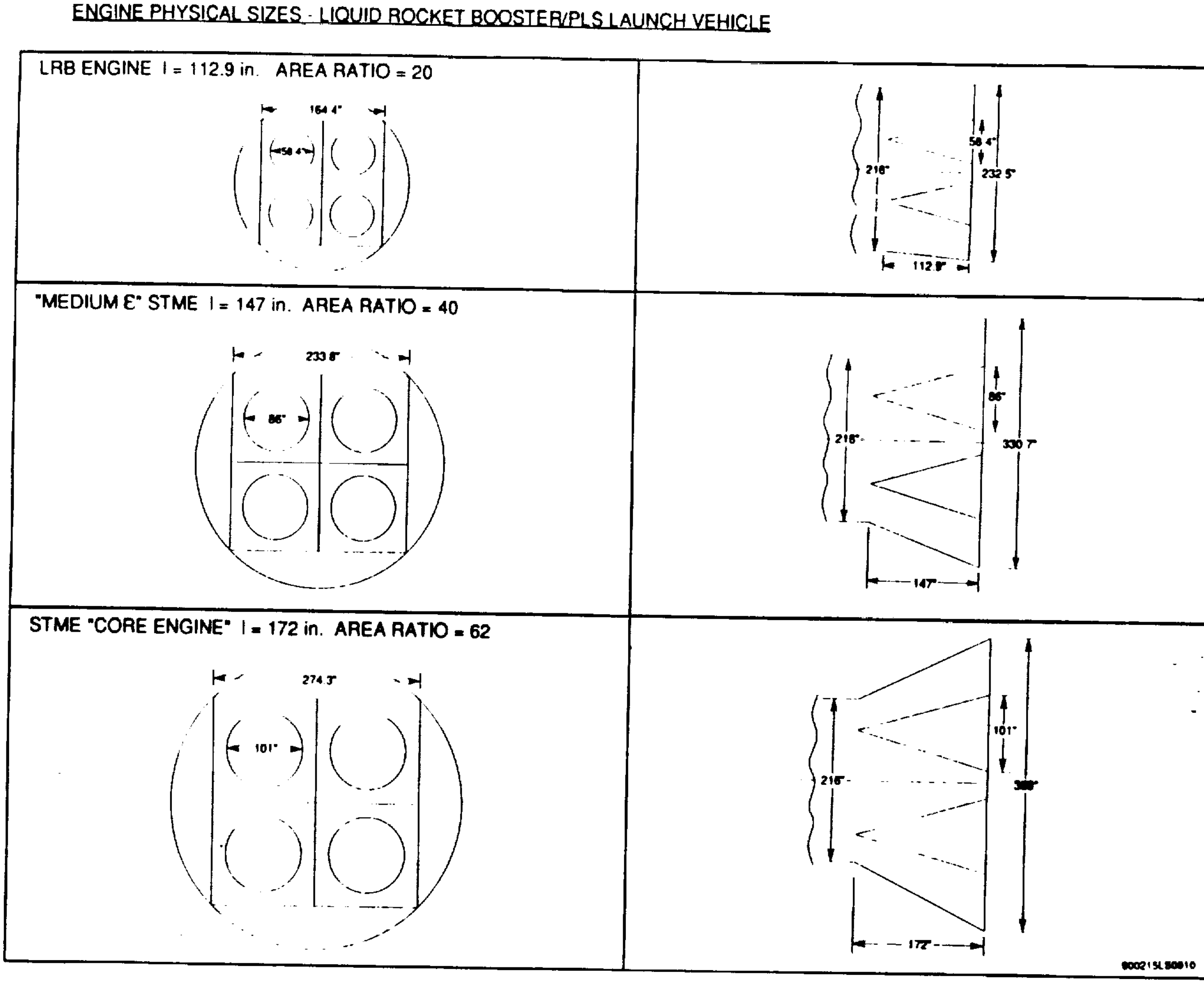


Figure 3-42A Base Area Requirements for PLS Launch Vehicles

With STME engines, use of the low area ratio engines in the booster stage results in moderate reductions in both vehicle gross weights and in vehicle dry/hardware weights (see Figure 3-68). (The similar effect with SSME engines is masked somewhat in this case, due to our use of discrete numbers of SSME engines at their established size and thrust levels). The reductions in dry/hardware weights are mostly in reductions in engine weights, because the booster versions produce more thrust per pound of engine weight (at sea level) than do the upper stage versions of these engines. It seems likely that considerations of vehicle/facility integration would weigh more heavily than these weight differences; the weight differences are not large, and might reduce or disappear when using discrete numbers of fixed engine sizes.

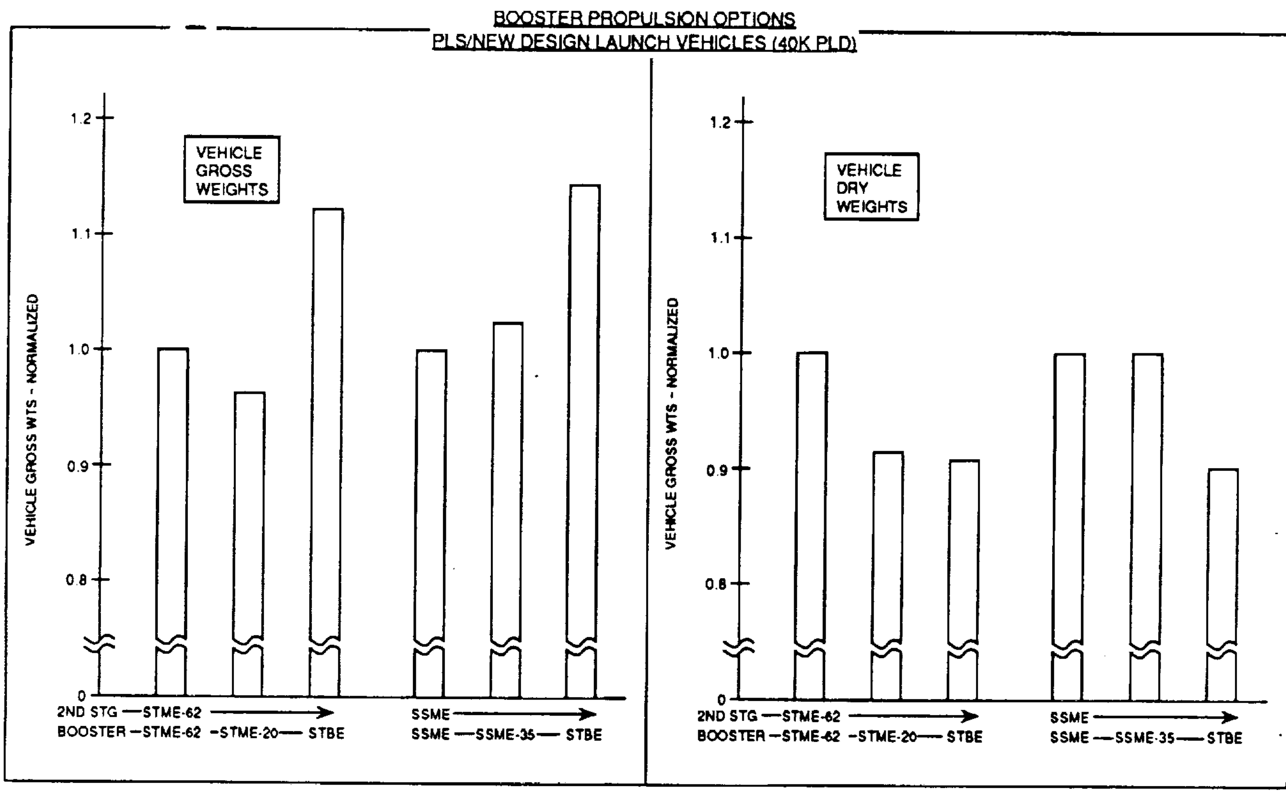


FIGURE 3-68 BOOSTER PROPULSION OPTIONS (PLS)

Hydrocarbon/Methane Booster Engines (PLS)

Use of Lox-Methane (STBE) booster engines in combination with either STME or SSME engines in the upper stages results in an increase in vehicle gross weights (due to lower engine performance), but lower dry/hardware weights (due to higher propellant density) (See Figure 3-68). The latter is generally believed to be a better indicator of vehicle costs, than vehicle gross weights.

Considerations of engine/nozzle physical sizes and base area requirements for Lox-Methane engines would be quite similar to that discussed earlier for booster versions of hydrogen engines, and shown in Figure 3-42A. With hydrocarbon booster engines, however, there is an additional consideration of propellant tank volumes and sizes. Propellant tank size comparisons are shown in Figure 3-69 for PLS vehicles using combinations of STME and STBE engines (vehicles using SSME/STBE combinations should follow a similar pattern). These tank heights are shown for 18 ft. propellant tank diameter, which is typical for PLS/LRB launch vehicles. Even though a higher propellant mass is required for Lox-Methane boosters, its higher propellant density still results in reduced physical size for the Methane booster tankage (the size of the hydrocarbon booster tankage is more than a third less than its hydrogen-fueled counterpart). This could become a significant consideration if a series-burn, vertical-stack configuration as shown here were selected. For information purposes only, a case is also shown in Figure 3-69 (in dashed lines) in which Lox-Methane propulsion is used in both stages of a PLS launch vehicle. Although much higher propellant mass is required, the over-all tank/vehicle size is still equal or lower than that of an all-hydrogen vehicle.

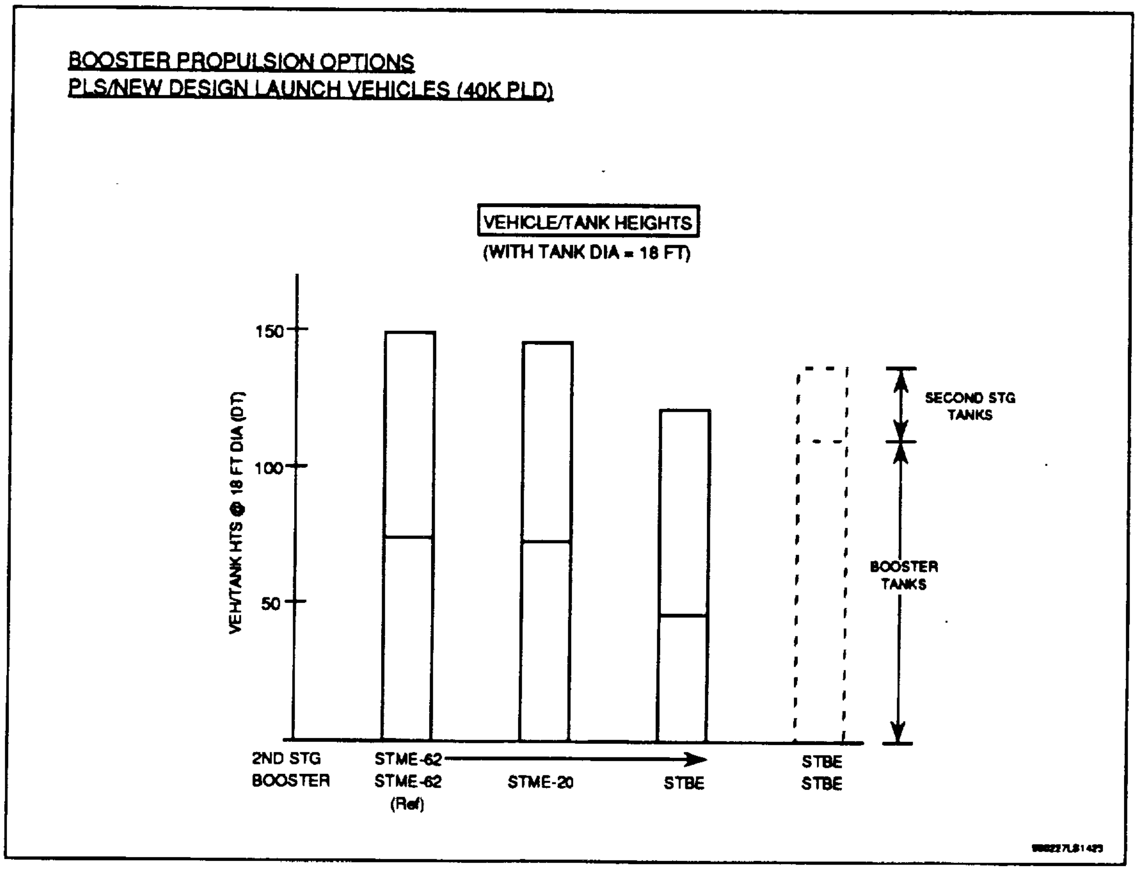


FIGURE 3-69 PROPELLANT TANK SIZES

3.2.3 AMLS Vehicle Applications

Booster Versions of Hydrogen Engines (AMLS)

We will again examine use of "booster versions" (low area ratio versions) of hydrogen-fueled engines, in comparison with use of the "upper stage" (high area ratio) versions in both stages. Considerations of engine physical sizes, engine spacing, and base area requirements were discussed earlier in Section 3.1.3.4, and Figure no. 3-50 from that Section is repeated here for convenience. Engine spacing for three different versions of STME engines is shown, including the 20:1 and 62:1 area ratio versions that are the subject of the comparisons in this part of the study. Booster base areas are shown in comparison with a booster propellant tank of typical size, which would comprise the major part of the booster fuselage. From these sizes, use of the high area ratio engine would be a strong disadvantage. It is assumed that a booster base area this large would add greatly to difficulties in developing the aerodynamic and flying characteristics of the fly-back or glide-back booster, in addition to the additional inert weight for this large area installation. The booster (STME-20) engines, by comparison, fit neatly within the projected area of the booster propellant tank. (The possibility for compromise use of a "medium area ratio" engine, such as the 40:1 case shown, is examined in an earlier section of the report, and is the reason for the options being shown in Figure 3-50 for engine and tank arrangements).

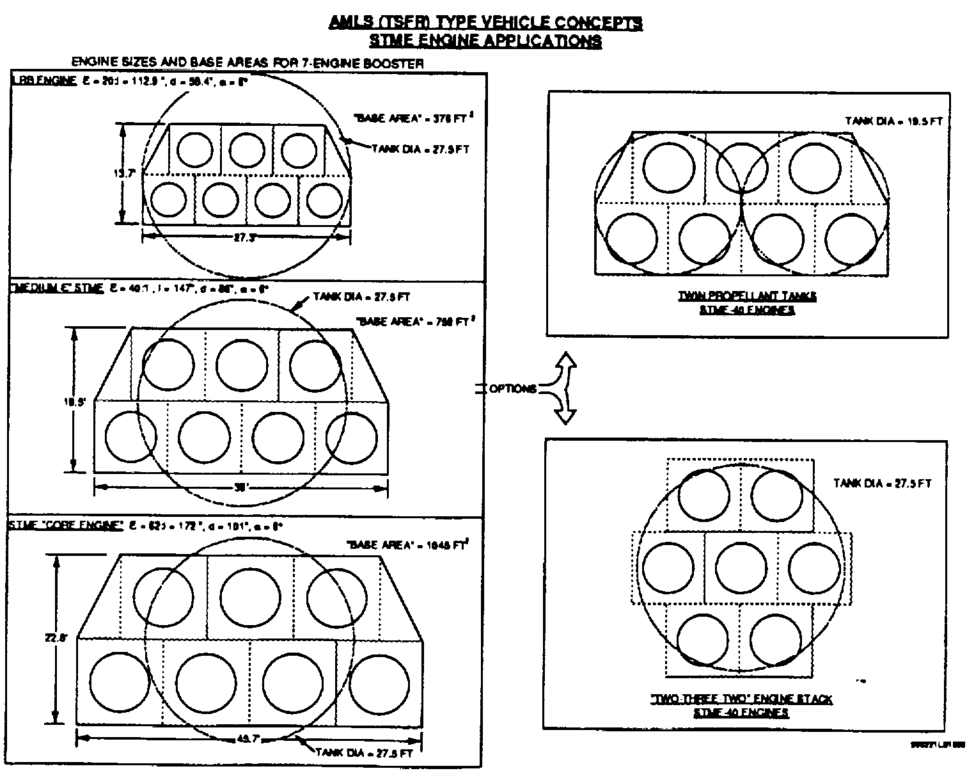


FIGURE 3-50 ENGINE SIZES AND BOOSTER BASE AREA

Gross weights and dry weights for AMLS vehicles sized with the six engine combinations under discussion are summarized in Figure 3-70. From these data, it can be seen that use of booster versions of STME or SSME engines would result in moderate reductions in both vehicle gross weights and dry/hardware weights. We suspect, however, that these weight reductions would not be as strong a consideration as the engine physical sizes and base area requirements noted earlier. Secondly, it is anticipated that vehicle conceptual designs and weights estimates for boosters configured with these two engine options would show additional weight differences (not reflected in these data), when properly accounting for the large surface areas and structures that would accompany the large base areas shown with STME-62 engines.

BOOSTER PROPULSION OPTIONS
AMLS (TSFR) TYPE VEHICLE CONCEPTS

Engines						
Orbiter	STME-62	→	→	SSME	→	SSME
Booster	STME-62	STME-20	STBE	SSME	SSME-35	STBE
• W_0 (K lbs.)	3141	3122	3903	2650	2562	3411
• W_0/W_0 (Nom)	1.00	0.994	1.243	1.00	0.966	1.287
• W_{d2} (K lbs.)	183	183	183	164	164	164
• W_{d1} (K lbs.)	354	340	373	306	284	331
• W_d (Veh) (K lbs.)	537	524	557	470	448	495
• $\frac{W_d\text{ (Veh)}}{W_d\text{ (Veh)(Nom)}}$	1.00	0.974	1.036	1.00	0.952	1.054

900222LS0884

FIGURE 3-70 BOOSTER PROPULSION OPTIONS FOR AMLS VEHICLES

Hydrocarbon/Methane Booster Options (AMLS)

Vehicle weights and sizing data for AMLS type vehicles using Lox-Methane engines in the booster stage are also shown in Figure 3-70. This indicates increases in vehicle gross weights on the order of 25%, when compared with use of STME or SSME engines. This rough-order analysis indicates, however, that the benefits of the higher propellant densities (reducing tankage and hardware weight requirements) just about off-sets the performance advantage of the hydrogen booster engines, with the net result that the dry/hardware weights for the two booster propulsion options are approximately equal. (Note: Some other analyses, including some of our own, indicate a net reduction in vehicle hardware weights, in favor of the hydrocarbon booster option). As will be noted later, it is assumed that development and operating costs, at equal or lower inert weights, would favor the hydrocarbon booster option.

Considerations of base area requirements with low-to-moderate area ratio versions of Lox-Methane engines would be expected to be essentially as shown in Figure 3-50 for Lox-Hydrogen engines. However, in this case we have the additional possibility of a distinct difference in propellant tank volumes and sizes, with resulting implications to over-all vehicle sizes. It was noted in an earlier section (Section 3.1.3 - Vehicle Applications for STME Engines) that propellant tankage for the booster stage of an all-hydrogen vehicle would be approximately 27 1/2 feet in diameter and approximately 137 feet in length. Although propellant mass for the methane-fueled booster is higher than that for the hydrogen booster, the higher bulk density for the Lox-Methane combination results in smaller propellant tankage. If we assume an l/d ratio of approximately 5:1 for both tanks, the comparison of tank sizes is as shown in Figure 3-71. This would be an obvious advantage, in that the booster wings and other elements could be proportionately smaller in size.

3.2.4 Observations

Although there are some vehicle and dry weight advantages for use of booster versions of hydrogen engines, the primary motivation for their use is likely to be the benefits of their smaller physical size, from the standpoints of base area requirements, stage sizes, and integration with vehicle stages and launch facilities. These consideration are particularly pronounced for the PLS/LRB class of launch vehicles (where the booster stage would be utilized as a Shuttle booster), and in AMLS type vehicles (where the booster must be configured for reentry, aerodynamic flight, and horizontal landing).

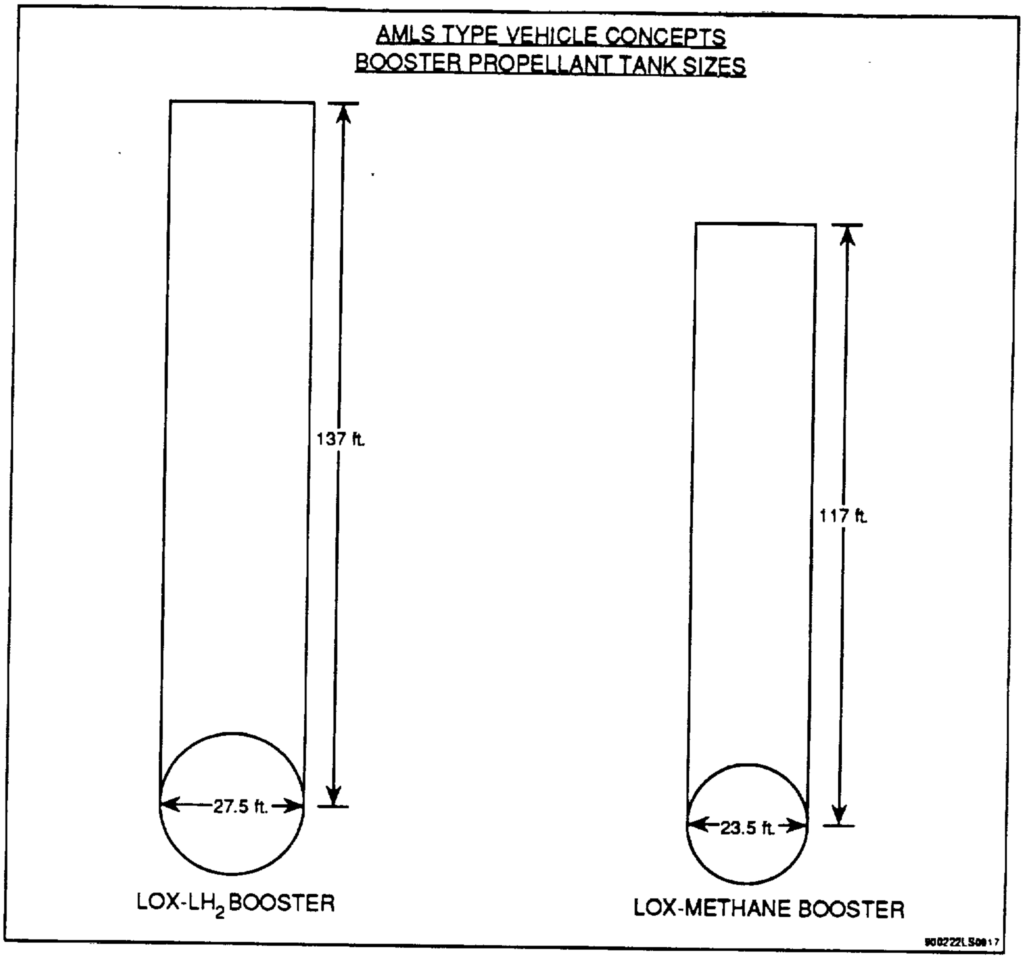


FIGURE 3-71 BOOSTER STAGE PROPELLANT TANKAGE (AMLS)

Use of methane/STBE booster propulsion shows a reduction in booster and vehicle dry weights for PLS type vehicles, in comparison with the hydrogen/reference vehicle, and equal or lower dry/vehicle weights for AMLS type vehicles. In both cases, the booster tankage and vehicles are shown to be distinctly smaller in physical size than their hydrogen booster counterparts. This smaller physical size should be a distinct advantage in itself, particularly for the large, winged boosters for AMLS type vehicles.

We have not done cost analyses as a part of these limited analyses; however, it seems likely that Lox-hydrocarbon stages at the same or lower weights than that of hydrogen stage counterparts should be lower in cost to develop and maintain, due to the absence of deep cryogenic requirements for the hydrogen propellant storage and feed systems, as well as the engines themselves. If a booster stage is to be expended, it seems likely that unit costs of the expendable hardware items for hydrogen-fueled stages would be higher (deep-cryogenic/hydrogen elements) than with Lox-hydrocarbon elements. If the booster stage is to be reusable, it seems likely that turn-around efforts and costs might be higher for hydrogen boosters, due to handling and inspection requirements for the critical insulation provisions for tanks, feed lines, etc. If a new engine development is required for upper stage applications, costs for the second/hydrocarbon engine development would likely off-set the cost benefits of hydrocarbon-fueled boosters. This consideration has no doubt figured heavily into the current National focus on development of a hydrogen engine for use in both booster and upper stages. If, however, an existing engine such as SSME were adaptable for orbiter/upper stage use, booster considerations, alone, could easily result in preference for a hydrocarbon booster engine development.

3.3 Engine Commonality Analyses

3.3.1 Introduction

In the preceding Sections 3.1 and 3.2, we have discussed potential vehicle applications for SSME and STME engines, normally addressing each vehicle category individually, e.g., STS/Shuttle "C", PLS and AMLS classes of vehicles. In this Section, we want to examine briefly a broader question: What are prospects for application of a single engine configuration (" a common engine") over a broad range of launch vehicles, including ALS, STS/Shuttle"C", PLS and AMLS?

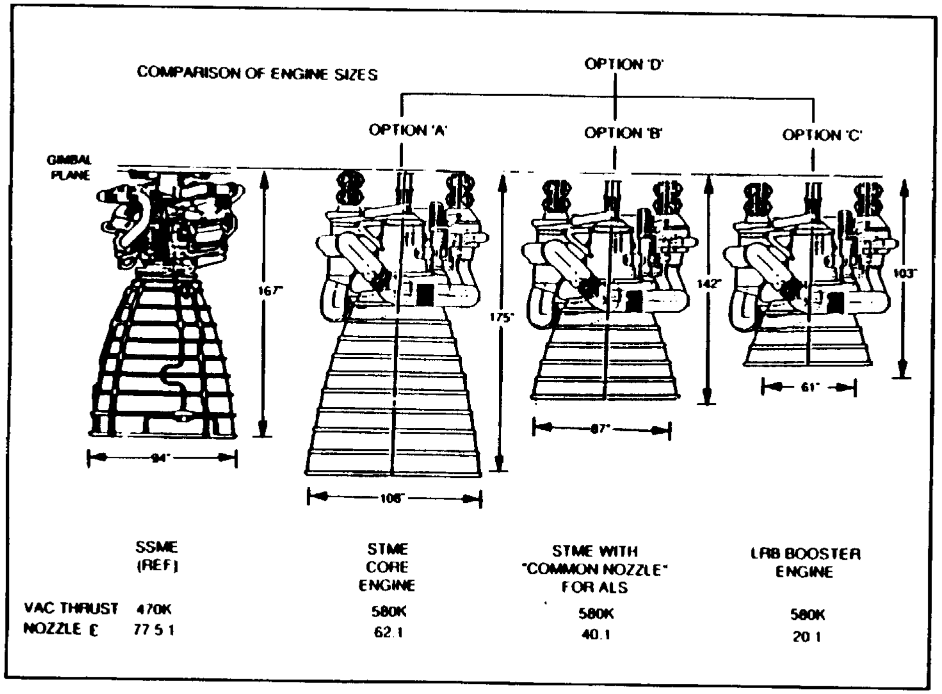
This initial set of engine commonality studies focused on prospects for use of STME engines in a wide range of vehicle applications, including the manned space launch vehicles under study here. Three different versions of the STME engine were selected as "straw-man engine options" for analysis in these vehicle applications. A hypothetical version of the STME engine having two different nozzle configurations (62:l and 20:l) was selected as the fourth "straw-man/option". There are obviously other engine candidates and other engine-vehicle combinations that warrant further study, with varying degrees of commonality between the booster and upper stage engines. We will note some of these in a later part of this section of the report, to suggest further studies of this nature.

In performing this "Engine Commonality" study task, it turned out to be necessary to do some additional studies of individual vehicle applications, beyond what had already been done under Task No. 1 (Vehicle Applications and Propulsion Requirements) and Task No. 4 (Booster Propulsion Options). In those cases, we have elected to"fold that material back" into Sections 3.1.3 and 3.2, in order to minimize over-lap and duplication of topics between this and the earlier sections. In this section, we will try to deal more directly with considerations of multiple vehicle applications for any candidate "common engine".

3.3.2 Candidate "Common Engine" Options

The four straw-man/options selected for these initial analyses are illustrated in Figure 3-72 in comparison with the Space Shuttle Main Engine, and will be referred to as options "A" thru "D". The STME engine with 62:1 area ratio nozzle, developed initially for ALS Core stage application, is included as "Option A". A "booster version" of the STME (20:1 area ratio) is included as "Option C", and is similar to engine concepts used in STS Liquid Rocket Booster studies, or for hydrogen-fueled boosters in ALS vehicle configurations. The ALS and STEP (Space Transportation Engine Program) programs have more recently concentrated on a

COMMON ENGINE STUDY
CANDIDATE COMMON ENGINE OPTIONS



• OPTION 'A' -	BASELINE STME ENGINES, AS CONFIGURED PRIMARILY FOR ALS CORE APPLICATION • 'CORE STME' • 'STME/62:1'
• OPTION 'B' -	STME WITH 'COMMON NOZZLE', AS COMPROMISE BETWEEN BOOSTER AND CORE APPLICATIONS • 'COMMON MOZZLE STME' • 'STME-40'
• OPTION 'C' -	STME TYPE ENGINE WITH LOW AREA RATIO, DESIGNED FOR BOOSTER APPLICATIONS (BUT USED IN BOTH STAGES). • 'STME/20:1' • 'STME BOOSTER ENGINE' • 'LRB ENGINE'
• OPTION 'D' -	STME TYPE ENGINE WITH DETACHABLE NOZZLE SKIRT, TO ALLOW OPERATION WITH TWO DIFFERENT AREA RATIO'S. • HIGH AREA RATIO ENGINE - SAME AS OPTION 'A' • LOW AREA RATIO ENGINE - SAME AS OPTION 'D'

FIGURE 3-72 CANDIDATE COMMON ENGINE OPTIONS

version with nozzle expansion ratio in the intermediate range (40:1), in order to use the same engine configuration on both booster and core stages of all-liquid ALS vehicles. This engine is included as "Option B". The fourth option ("Option E") departs slightly from the concept of a single configuration, assuming as a candidate a version of STME that could have two different nozzles (20:1 and 62:1). We have assumed that the latter option could be achieved by having a "bolt-on" nozzle section for the higher area ratio, with the basic engine being the same in both cases. We have not obtained or incorporated however the small difference in performance that would result from this approach vs. engines with nozzles optimized separately.

We have started in each case with the engine characteristics as established for the ALS or LRB application. These basic characteristics assumed as the starting point for the three engine versions are shown in Figure 3-74 (with the fourth option being a combination of two columns). Some changes to these initial characteristics are virtually necessary if an engine is to be utilized in other (manned) vehicle applications. As we have proceeded through this study task and as illustrated in Figure 3-73, we have attempted to identify and compile a listing of what these "necessary changes" would be, as one primary part of the study task output.

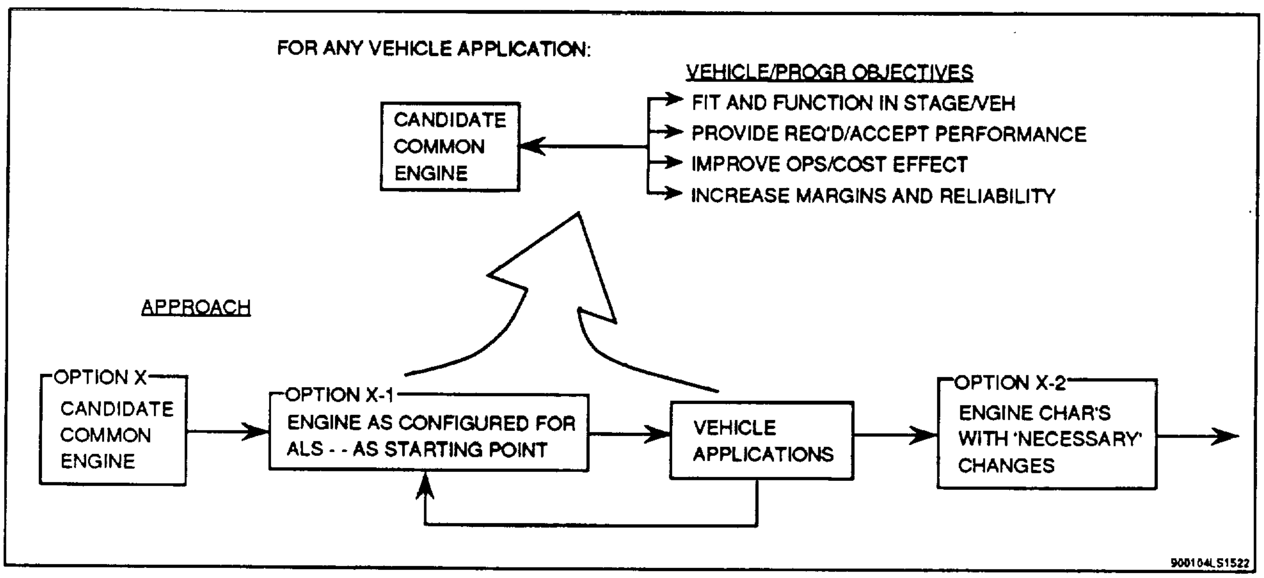


FIGURE 3-73 APPROACH FOR COMMON ENGINE STUDY TASK

3.3.3 Engine Changes for Manned Vehicle Applications

A top-level summary of engine changes indicated to be necessary for applications in this range of manned launch vehicle applications is shown in matrix form in Figure 3-75.

STRAW-MAN COMMON ENGINE CASES

	OPTION Ⓐ STME CORE ENGINE	OPTION Ⓑ STME 'COMMON NOZZLE' ENGINE	OPTION Ⓒ STME FOR BOOSTER APPL.
• FUEL	LH2	LH2	LH2
• ENGINE CYCLE	G.G.	G.G.	G.G.
• OPERATING THRUST LEVELS			
• NOMINAL	435K	435K	419K
• MAX (ENGINE-OUT)	580K	580K	558K
• THROTTLE CAPABILITY	100% AND 75% (DUAL-POSITION)	→	→
• SEA-LEVEL THRUST - NOM	346K	371K	389K
- MAX	461K	495K	519K
• NOZZLE EXP. RATIO	62	40	20
• VAC. SPECIFIC IMPULSE	438	429	414
• S/L SPECIFIC IMPULSE	344	368	387
• ENGINE WEIGHT	7800	7245	6615
• MIXTURE RATIO	6.0	→	→
• MIXTURE RATIO CONTROL	± 3%	→	→
• ENGINE RELIABILITY	0.99	→	→
- CONFIDENCE	0.90	→	→
- REDUNDANCY	FO	→	→
• ENGINE SIZE			
- POWER HEAD/MCC DIA(in)	TBD	→	→
- ENGINE LENGTH(in)	175	142	103
- NOZZLE EXIT DIA(in)	108	87	61
- INLET CENTER LINES(in)	30	30	30
• GIMBAL CAPABILITY - PITCH	± 6°*	→	→
- YAW	± 6°*	→	→
• INLET PRESS - LOX	47-285	→	→
- FUEL	24.5-125	→	→
• RECOVERY MODE: • EXPEND	√	√	√
• P/A-WATER	√	√	√
• P/A-LAND	√	√	-
• FULL RECOV	-	-	-
• LANDING ACCEL (g's) - VERTICAL	± 10 g's	→	→
- HORIZONTAL	± 5 g's	→	→
• ENGINE LIFE - WATER REC.	10	10	10
- LAND REC.	10	10	-
• ENGINE UNIT COST	TBD	TBD	TBD

NOTES: * ENTRY/VALUE TO BE VERIFIED
• OPTION Ⓓ = OPTION Ⓐ PLUS OPTION Ⓒ.

891214LS1500

FIGURE 3-74 CHARACTERISTICS FOR CANDIDATE COMMON ENGINE OPTIONS

A basic engine reliability as high as practical will be required, as it is for cargo launch vehicle applications, along with redundancy in key elements to allow mission completion in spite of component failures ("fail-ops"). For manned vehicle applications, however, we have the additional requirement for "benign" shut-down modes, that can allow safe and intact recovery in crew and craft in the event of critical system failures ("fail-ops/fail-safe"). This requirement naturally includes status monitoring provisions and controls to implement these crew safety provisions.

- OPTION 'A' - STME/62:1
- OPTION 'B' - STME/40:1
- OPTION 'C' - STME/20:1
- OPTION 'D' - STME/20:1+62:1 *

	STS/EVOL	SHUTTLE 'C'	LRB/STS	PLS/LRB/B	PLS/LRB/2	PLS/ND/B	PLS/ND/2	AMLS/B	AMLS/O	CRV/B	CRV/2
• OPERATE AT 490K F	✓	✓									
• OPERATE AT 512/540K (ENG-OUT)	✓	✓									
• THROTTLE DOWN TO 306K (qα)	✓	✓									
• FO/FS REDUNDANCY	✓	—	✓	✓	✓	✓	✓	✓	✓	—	—
• GIMBAL CAPAB OF ±10.5/8.5	✓	✓									
• ENGINE/VEH MODS. FOR INSTL	✓	✓									
• VERIFY CAPAB FOR HORIZ LDG	✓	—	—	—	—	—	—	✓	✓	—	—
• M.R. CONTROL ~ ±1%	✓	✓	—	—	—	—	—	✓	✓	—	—
• THROTTLE TO APPROX 50% (g)					✓	✓					
• THROTTLE TO APPROX 33% (g)							✓		✓		
• ENGINE LIFE OF 30-50 FLTS	✓							✓	✓		

* NOT ALL CHANGES IN BOTH ENGINES (MOST IN STME/62:1)

900103LS1213

FIGURE 3-75 MODS. NEEDED FOR MANNED VEHICLE APPLICATIONS

Probably the most basic change necessary would be in the operating thrust levels and throttling requirements. A single thrust setting is planned for the ALS application, or at most a dual thrust setting (75% and 100%). Assuming that the nominal 580K lbs. thrust level (100%) is required for the ALS application, normal operations at a point in between those two settings would be needed for STS and Shuttle "C", and the ability to throttle down to settings considerably lower than 75% would be needed for control of acceleration levels during ascent, and for control of "q-alpha" or structural load indicators during the atmospheric phase of ascent.

Use of STME engines in STS or Shuttle "C" would require operation at thrust levels equivalent to 104% of SSME thrust, which is approximately 84% of STME rated thrust. (As noted in an earlier section, if more detailed analyses of STS thrust structure should indicate significantly greater load capability than currently understood, operation in STS/Shuttle "C" at higher thrust levels could partially off-set payload reductions resulting from lower engine performance).

Assuming that STS thrust structure is limited by thrust level of individual engines rather than total thrust of all operating engines, operation of STME's at a thrust level equivalent of 109-115 % SSME thrust level would be necessary (88-93 percent of STME nominal thrust) under engine-out conditions.

If the STS Orbiter with STME engines were operated with SRB boost over current ascent profiles, the capability to throttle back to the equivalent of 65% SSME thrust would be needed (approx. 53% STME thrust).

Use of a single STME at full thrust level in the second stage of a PLS launch vehicle would require capability to throttle down to a 37-50% range, to limit accelerations during ascent to the 3-4 g level. Use of three STME engines in the orbiter stage of an AMLS launch vehicle would likewise require capability to throttle down to approximately 37%; however, with multiple engines in a stage, there is an alternative to shut down two of the three orbiter engines.

Gimbal capability of ±8.5 degrees (y) and ±10.5 degrees (p) is required for operation in STS. At the time this study task was performed, the baseline STME gimbal requirement was ±6 degrees, which meant that STME gimbal capability would require increase for operation in STS, and that flexible feed ducting would have to be added in some form to allow engine motion over that range. However, the baseline STME requirement has since been increased to ±10 degrees. Flexible propellant feed lines are provided as an integral part of SSME engines; we do not yet have information on the configuration or weights of provisions necessary with STME engines to accommodate these gimbal angles.

The present STME baseline requirements include "open loop" propellant utilization (p.u.) control, with engine mixture ratio variations in the ±3% range. Propellant residuals associated with engine mixture ratio uncertainties in the ±3% range, along with other mixture ratio uncertainties due to propellant feed system factors, would be of serious concern to performance-sensitive vehicles such as STS and AMLS. It seems that consideration would need to be given to closed-loop p.u. system for application in either of these two vehicles.

Current STME requirements are based on expending the engines, with an option of having engine reuse with an engine life of 10 flights. An engine life of 10-15 flights seems to be an appropriate range for LRB, PLS vehicles, and for joint operation of STS and Shuttle " C" (where engines are expended in Shuttle "C" flights). For operation in the STS (alone) or in AMLS, however, longer engine life would be very desirable, preferably into the range of 30-50 flights per engine. If life of this range is not inherent in the basic engine design, analyses will be needed to trade additional investments necessary vs. the cost benefits of longer engine life (Some examples of such trades are provided in earlier sections of this report).

Additional Changes for STS/Shuttle "C" Application

There are several additional areas where changes will be necessary in the engine and/or the vehicle in order for STME engines to be utilized in STS or Shuttle "C". As examples, some reduction in nozzle area ratio (below 62:1) would be necessary to achieve full 8.5/10.5 degree gimbal movement. And, engine inlet feed pressure requirements (minimum values) would have to be increased, or incorporate vehicle changes to provide higher inlet pressures. These changes for STS/Shuttle "C" applications are discussed in Section 3.1.3 of this report. Although there will be more flexibility in the cases of the other vehicle concepts (where they have not yet been designed or built), we can expect that additional engine changes will be indicated as designs for those vehicles and engine-vehicle trade studies mature.

Revised Sets of Engine Characteristics

A revised set of characteristics for each of the common engine candidates is summarized in Figure 3-76, shown in comparison with the baseline set of characteristics that were used as the starting point in each case.

3.3.4 Vehicle Applications of Candidate Common Engines

Assuming the changes identified as "necessary changes" in the preceding paragraphs are incorporated into the candidate engines, how well do they seem to fit and operate across this range of vehicle applications? This discussion becomes less subject to quantitative assessment, and becomes more nearly a subjective ranking of candidates, depending for example how much weight is placed upon one consideration in comparison with others, etc. The following comments are offered in this context regarding prospects for each of the common engine candidates in these vehicle applications; the summary graphic in Figure 3-77 will be used as a reference in the following subparagraphs.

COMMON ENGINE STUDY
CHARACTERISTICS FOR CANDIDATE COMMON ENGINES (STME)

	OPTION 'A'		OPTION 'B'		OPTION 'C'	
	A-1	A-2	B-1	B-2	C-1	C-2
• FUEL	LH2	LH2	LH2	LH2	LH2	LH2
• ENGINE CYCLE	G.G.	G.G.	G.G.	G.G.	G.G.	G.G.
• OPERATING THRUST LEVELS • NOMINAL • MAX (ENGINE-OUT)	 435K 580K 580K	 435K 490K 580K 580K 540K	 435K 580K 580K	 435K 490K 580K 580K 540K	 435K 580K 558K	 435K 580K 558K 540K
• THROTTLE CAPABILITY	75% 100%	37% 44% 53% 84% 93% 100%	100%	37% 44% 53% 84% 93% 100%	75% 100%	37% 55% 93% 100%
• SEA-LEVEL THRUST - NOM - MAX	346K 461K	346K 461K	371K 495K	371K 495K	389K 519K	389K 519K
• NOZZLE EXP. RATIO	62	62	40	40	20	20
• VAC. SPECIFIC IMPULSE	438	438	429	429	414	414
• S/L SPECIFIC IMPULSE	344	344	368	368	387	387
• ENGINE WEIGHT	7800	7800	7245	7245	6615	6615
• MIXTURE RATIO	6.0	6.0	6.0	6.0	6.0	6.0
• MIXTURE RATIO CONTROL	± 3%	1%	± 3%	1%	± 3%	±1%
• ENGINE RELIABILITY	0.99	0.99	0.99	0.99	0.99	0.99
- CONFIDENCE	0.90	0.90	0.90	0.90	0.90	0.99
- REDUNDANCY	FO	FO/FS	FO	FO/FS	FO	FO/FS
• ENGINE SIZE - POWER HEAD/MCC DIA - ENGINE LENGTH - NOZZLE EXIT DIA - INLET CENTER LINES	 - 175 108 30	 - 175 108 30	 - 142 87 TBD	 - 142 87 TBD	 - 103 61 30	 103 61 30
• GIMBAL CAPABILITY - PITCH - YAW	6° 6°	10.5° 8.5°	± 6° (TBV) ± 6° (TBV)	10.5° 8.5°	± 6° ± 6°	± 10.5° ± 8.5°
• INLET PRESS - LOX - FUEL	47 24.5	23.3 19.6	47 (MIN) 24.5 (MIN)	23.3 19.6	47 24.5	23.3 19.6
• RECOVERY MODE	EXPEND P/A WATER	EXPEND P/A WATER FULL RECOV	EXPEND P/A WATER	EXPEND P/A WATER FULL RECOV	EXPEND P/A WATER	EXPEND P/A WATER FULL RECOV
• LANDING ACCEL (g's) - AXIAL - HORIZONTAL	±10 ±5	±10 (TBV) ±10 (TBV)	± 10 ± 5	± 10 (TBV) ± 10 (TBV)	± 10 ± 5	± 10 (TBV) ± 10 (TBV)
• ENGINE LIFE	10-15 (WATER REC)	10-15 (WATER) 30-50 (LAND)	10-15 (WATER REC)	10-15 (WATER) 30-50 (LAND)	10-15 (WATER)	10-15 (WATER) 30-50 (LAND
• ENGINE UNIT COST	TBD	TBD	TBD	TBD	TBD	

NOTES: • A-1, B-1, C-1: STARTING POINT ENGINE CHAR'S FOR EACH OPTION
• A-2, B-2, C-2: ENGINE WITH CHANGES FOR MANNED VEHICLE APPLICATIONS.
• OPTION 'D' = COMBINATION OF OPTION 'C' (STME/20:1) PLUS OPTION 'A' (STME/62:1)

900103LS1558

FIGURE 3-76 REVISED CHARACTERISTICS FOR COMMON ENGINE CANDIDATES

SUBJECTIVE RANKINGS

			STS/SRB	STS/LRB	SHUTTLE 'C'	PLS/LRB	PLS/ND	AMLS	CRV
A	STME/62:1	0/2	(1)	(2)(5)		(4)	(4)	(4)	
		B	X	(2)	X	(2)	(2)	(2)	(2)
B	STME/40:1	0/2	(3)	(3)		(4)	(4)	(4)	
		B	X	(2)	X	(2)			
C	STME/20:1	0/2	(3)	(3)	(3)	(4)	(4)	(3)	(3)
		B	X		X				
D	STME/62:1 + 20:1	0/2	(1)	(2)(5)		(4)	(4)	(4)	
		B	X		X				

900103LS0440

NOTES: (1) PERFORMANCE DECREMENT AND INSTL. PROBLEMS
(2) INSTL. PROBLEMS
(3) PERFORMANCE DECREMENT
(4) COULD BE MADE TO WORK, BUT WOULD PREFER SMALLER ENGINES
(5) ASSUME PERF. DECREMENT COULD BE OFF-SET BY LRB INCR.

Figure 3-77 Subjective Assessment Of Common Engine Candidates

STME-62 Engine (Option "A")

Since the STME with 62:1 area ratio was initiated for core/upper stage applications, it is not surprising that this engine is not a good candidate for a range of applications including both boosters and upper stages. Phase A studies of Liquid Rocket Boosters for STS have indicated that lower area ratio nozzles are required to allow integration with the vehicle stack and with launch facilities. There would be no performance advantage of the higher area ratio nozzle in the other booster applications, and its larger physical size would be a distinct detriment. The information on AMLS booster sizes in Section 3.I.3.4. shows that it would be very difficult to make a workable flight vehicle with the large base area necessary to accommodate engines with 62:1 area ratio nozzles. As indicated in the chart, this engine could be utilized quite well in upper stage applications, except in the case of STS/SRB. Even if the full 62:1 area ratio nozzles could fit into the vehicle application, the performance decrement (compared with use of SSME engines) represents a large fraction of STS payload capability. If it becomes necessary to reduce area ratio to something lower than 62:1 (to allow full gimbal capability), this performance decrement would be even larger. If incorporated however in conjunction with Liquid Rocket Boosters, this performance decrement could be off-set by sizing of the LRB's.

In summary, this version of STME is a good candidate for upper stage applications other than STS, but unworkable in some of the booster applications, and its physical size would be a strong detriment in other booster applications. Although not a direct part of this study task, it might be noted that SSME engines would rank higher than this version of STME against some criteria for upper stage applications. Engine performance and physical size would both favor SSME engines; projected engine costs would favor STME engines, particularly in those cases where upper stage engines are expended.

STME-20 Engine ("Option C")

As expected, the reverse trend is indicated for the 20:l area ratio version of STME (option "C"), e.g., it is favorable for booster applications, but not for some of the upper stage applications. Although not performance-optimum, this engine could be used satisfactorily in both stages of PLS or CRV launch vehicles where payload performance requirements are not overly demanding (See Section 3.1.3.3). Performance penalties for use of 20:1 area ratio engines in both stages of AMLS launch vehicles, although sizable, might be partially off-set by lower inert weight and other benefits from the smaller physical size for the orbiter base installation. The performance decrement for use of this engine in STS or Shuttle "C" would seem to exclude its consideration for this application.

In summary, the 20:1 area ratio version of STME seems workable in both stages of PLS launch vehicles, could possibly be made workable in both stages of AMLS vehicles, but does not seem adaptable for use in STS or Shuttle "C" applications.

This leads us to the intuitive position that the two contending candidates for applications in both booster and upper stage applications are Option "B" (with intermediate 40:1 area ratio nozzle), or Option "D" (one basic engine configuration with two different nozzle configurations).

STME-40 Engine ("Option B")

Use of 40:1 area ratio engines in both stages has shown to be favorable for ALS vehicles. Analyses in this study have indicated that use of this engine in both stages of PLS/New Design launch vehicles and in AMLS vehicles would be workable and could be favorable. There are two vehicle applications, however, where this does not seem to be the case. We understand that LRB studies have shown that lower area ratio nozzles are necessary for integration with vehicle and launch facilities. And secondly, performance decrements from use of this engine would seem to preclude consideration of its use in STS (STS payload reduction of approximately 50% of its capability - See Figure 3-30).

In summary, use of an engine of intermediate area ratio seems workable where vehicles are to be of all new design; however, constraints from already existing vehicles and equipment would seem to preclude use of this approach in the Space Shuttle or in Liquid Rocket Boosters for use with STS.

STME-20 and -62 ("Option D")

This leads us to an indication that more than one engine configuration would be needed for applications over this range of vehicles. This could hopefully be accomplished with a singe basic engine configuration, with two different nozzle options. The "Option D" included here is one example of a program with two different nozzle sizes (62:1 and 20:1). With further study, the larger nozzle size might turn out to be somewhat lower than 62:1. Data were shown in an earlier section indicating that full gimbal capability could be achieved without interference in the STS installation if the nozzle area ratio were reduced from 62:1 to approximately 50:1. It is quite possible that a compromise would indicate an area ratio somewhere between 50:1 and 62:1. It also seems likely that this reduced area ratio could be workable in upper stages for PLS and AMLS vehicles.

Engine Thrust Levels and Throttle Requirements

Assuming that the basic engine thrust level is fixed at the ALS/STEP nominal value of 580K lbs., a composite picture of operating thrust levels and throttling requirements for the other vehicles are shown in Figure 3-78. As noted earlier, the very deep throttle requirements result from use of a full-size STME engine in the upper stage of a PLS launch vehicle sized for 40K lbs. payload capability, and from use of three STME engines in the orbiter stage of AMLS launch vehicles (in the latter case, there is an option to shut down two of the three engines in lieu of deep throttling). The chart in Figure 3-79 shows a composite of "where the vehicles would like the engines to be", in comparison with SSME characteristics and current nominal values for STME engines. This picture indicates that SSME size and thrust level may be a better fit for these vehicles than the current nominal thrust for STME engines. This is obviously due in part to the fact that the Space Shuttle has been designed and built to that value. However, with PLS and AMLS orbiter preferring engines in the 400-450K thrust range and ALS, CRV and AMLS boosters preferring higher thrust levels, it seems that the SSME thrust level of 490-500K lbs. might be a good compromise value across this range of vehicle applications.

Some other prospects for engine commonality, beyond the SSME/STME class, are also evident from Figure 3-79. A single engine for use in the upper stage of a PLS/LRB launch

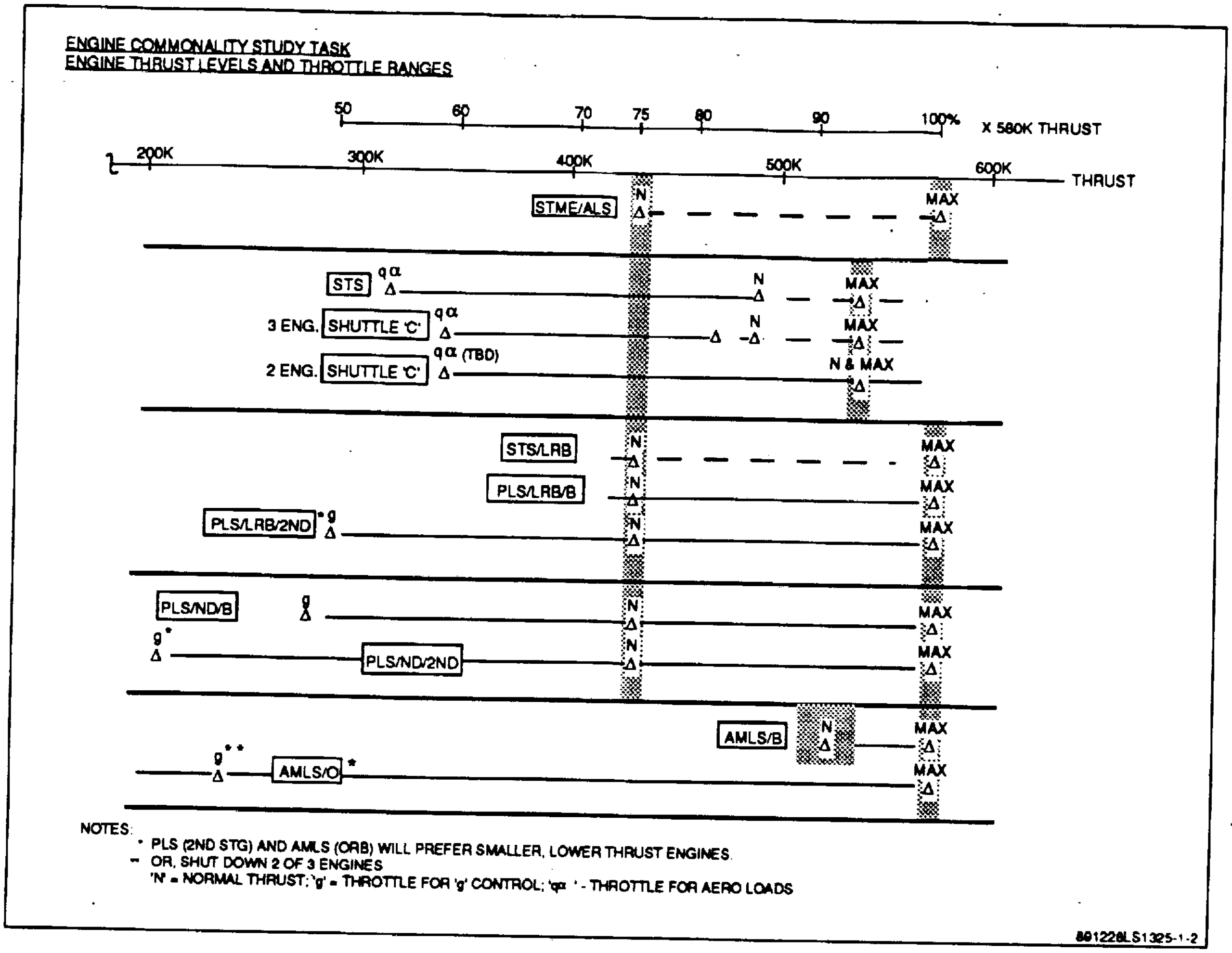


FIGURE 3-78 OPERATING THRUST LEVELS AND THROTTLE REQM'TS

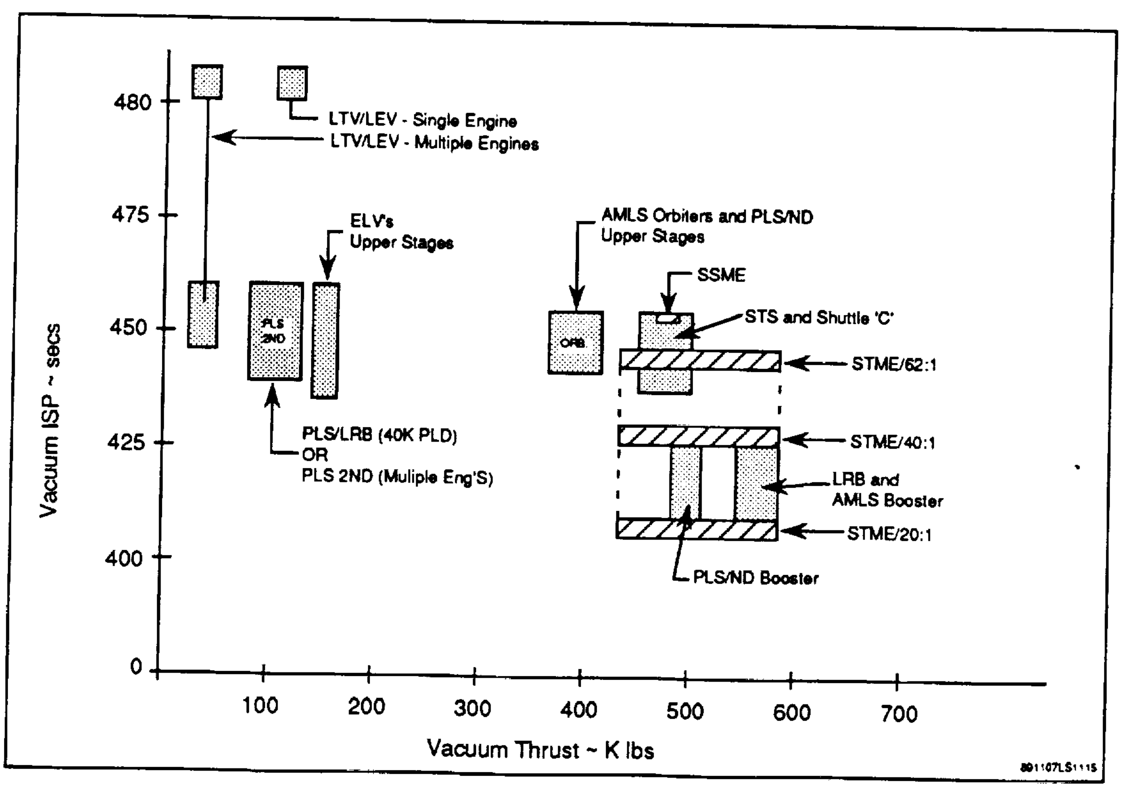


FIGURE 3-79 ENGINE THRUST LEVELS FOR VEHICLE APPLICATIONS

vehicle, or multiple engines for use in a bigger PLS upper stage, fall into the same engine size class as that of interest for possible development for ELV upper stages. Secondly, these PLS/LRB upper stage engines might be in the same size class as engines of interest for lunar transfer stages in Human Exploration Initiatives. These possibilities are suggested for examination in further studies of prospects for common engine applications.

3.3.5 Broader Observations

The preceding discussions have traced through each engine-vehicle combination to indicate the ones that appear could be made workable, leading to the indication of a two-nozzle version. From a broader perspective, however, it seems that it will be very difficult in practice to adapt a single engine configuration and program over this wide a range of vehicle applications. We believe that an engine can be configured for both cargo and manned launch vehicle applications, if adequate safety provisions are included. However, design and development considerations for booster stage vs. upper stage applications, and for expendable vs. water recovery vs. highly reusable vehicles, would pull in different directions to the extent that appropriate compromises would become very difficult if not impractical to establish. It seems that this new engine development could have a better prospect if geared to booster applications, in combination with upper stage applications for vehicles that are not performance sensitive and will likely have emphasis on low engine unit costs (such as ALS and PLS launch vehicles). Upper stages of performance-sensitive and highly reusable vehicles such as STS and AMLS could continue to use SSME engines, or possibly a next-generation successor to SSME. The AMLS booster application would then have a choice between the more rugged and lower cost new engine vs. the higher performance and smaller physical size of the SSME or its successor. This grouping of characteristics by vehicle applications is noted in Figure 3-80.

3.3.6 Summary - Common Engine Study Task

Observations from common engine studies under this task are summarized in bullet form in Figure 3-81. Several changes would be required in either of the candidate common engines to allow operation in the manned launch vehicles studied here, ranging from incorporation of safety provisions, to provisions for operation at the required thrust levels, and others as summarized in Figure 3-75. Several additional changes would be required in the engines and/or vehicles to allow operation in STS/Shuttle "C" vehicles, due to fact that STS elements have already been designed and built. It seems that, as a minimum, an engine with two different nozzle configurations/sizes would be necessary for adaptation over this range of launch vehicles.

Even with the engine changes noted here, it seems that it would be extremely difficult in practice to find workable compromises between the needs and pressures of the widely differents operating modes in this full set of vehicle applications. One option that might be more easily attainable would be to focus the new engine development on booster stage and selected upper stage applications, in combination with SSME or its successor in performance-sensitive and highly reusable vehicle applications.

Vehicle Applications and Engine Characteristics

	ALS	LRB/STS and PLS/LRB	PLS/ND	Shuttle 'C'	STS Evol.	AMLS	
• High Reliability	√	√	√	√	√	√	Common
• Low Maint. Support	√	√	√	√	√	√	
• Large Margins/Ops. Flex	√	√	√	√	√	√	
• Low Costs	√	√	√	√	√	√	
• Rugged, Adapt for Water Recovery	√√	√√	√√	-	√√	√√	Booster/ Cargo Veh Appls
• Low Unit Costs	√√	√√	√√	√√	√√	√√	
• Long Engine Life	-	-	-	-	√√√	√√√	Manned Reusable Veh Appls
• High Engine Perf.	-	-	-	√√√	√√√	√√√	
• Small Engine Size	-	√√√	-	√√√	√√√	√√√	

900323LS0815

Figure 3-80 Vehicle Applications And Engine Characteristics

Common Engine Study Task

Observations

- Changes needed for any of engines (chart)
- Additional engine or vehicle changes necessary, to adapt STME for use in STS/Shuttle 'C'
- Use of single engine configuration/size unlikely:
  - Need two nozzle sizes as minimum
- Very difficult in practice to adapt single engine program over this range of vehicle applications:
  - Cargo vs manned
  - Boosters vs upper stages
  - Expendable vs water recovery vs highly reusable
  - Low unit costs vs long engine life
  - Low engine cost vs high performance/small size

900323LS1100

Figure 3-81 Summary Observations - Common Engine Study Task

3.4 Evolution Requirements for the SSME Engine

The applicability of the SSME for meeting the propulsion requirements of evolving NMTS vehicle concepts would be significantly enhanced by changes and improvements to the engine in the post-1995 time frame. These changes and improvements would be made in addition to those that are currently programmed for the engine (i.e., external heat exchanger, Phase II + powerhead, Block II controller, alternate turbopumps, etc.) prior to 1995.

3.4.1 STS Evolution/Shuttle "C"

SSME evolution planning has been on implementing several upgrade initiatives:

- External Heat Exchanger
- Alternate Turbopump
- Block II Controller
- Phase II + Powerhead

Current evolution plans are focusing on design changes that will provide: lower annual cost by reducing fabrication costs and schedules, reducing post acceptance check-out time, and minimizing required refurbishments; increased safety margins; and increased launch capability. The major goal of the program is cost reduction to increase the viability of the SSME for STS applications. As shown in Figure 3-82, the SSME evolution for the post-1995 period will consist of follow-on upgrades, producibility/productivity improvements, and revolutionary changes, whereas the pre-1995 SSME evolution is characterized by evolutionary changes.

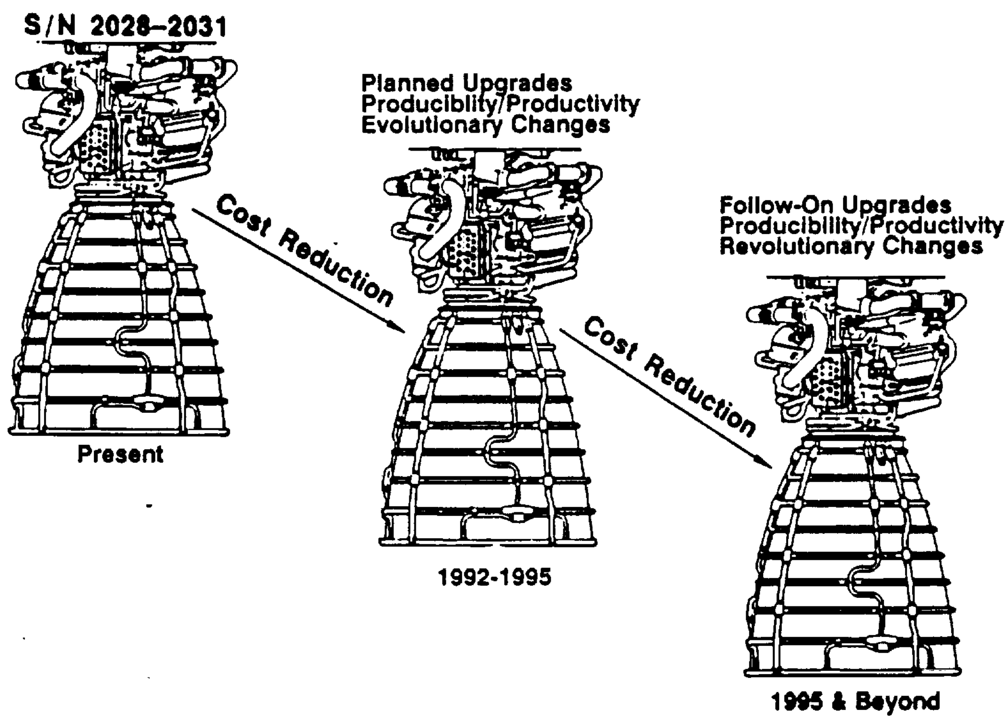


FIGURE 3-82 SSME EVOLUTION PROCESS

Cost reduction goals to be potentially realized would be in a reduction of SSME per engine costs from the current $37.9M (FY87 $) to $24.8M (FY87 $) by 1995. Realization of further cost reduction goals with the advent of revolutionary engine changes could lead to per engine costs of $15M (FY87 $) in the 1995 + time period.

Revolutionary changes in producibility could be accomplished by redesigning subsystem components to reduce life cycle costs and incorporating current/near term 1995 + manufacturing technologies, e.g., reduction in the number of welds. The advent of the Shuttle "C" would further increase the appetite for a lower cost SSME, because of the reduced life goals associated with expending SSME engines on an expendable Shuttle "C" core. The SSME Program schedule through 1995 is shown in Figure 3-83.

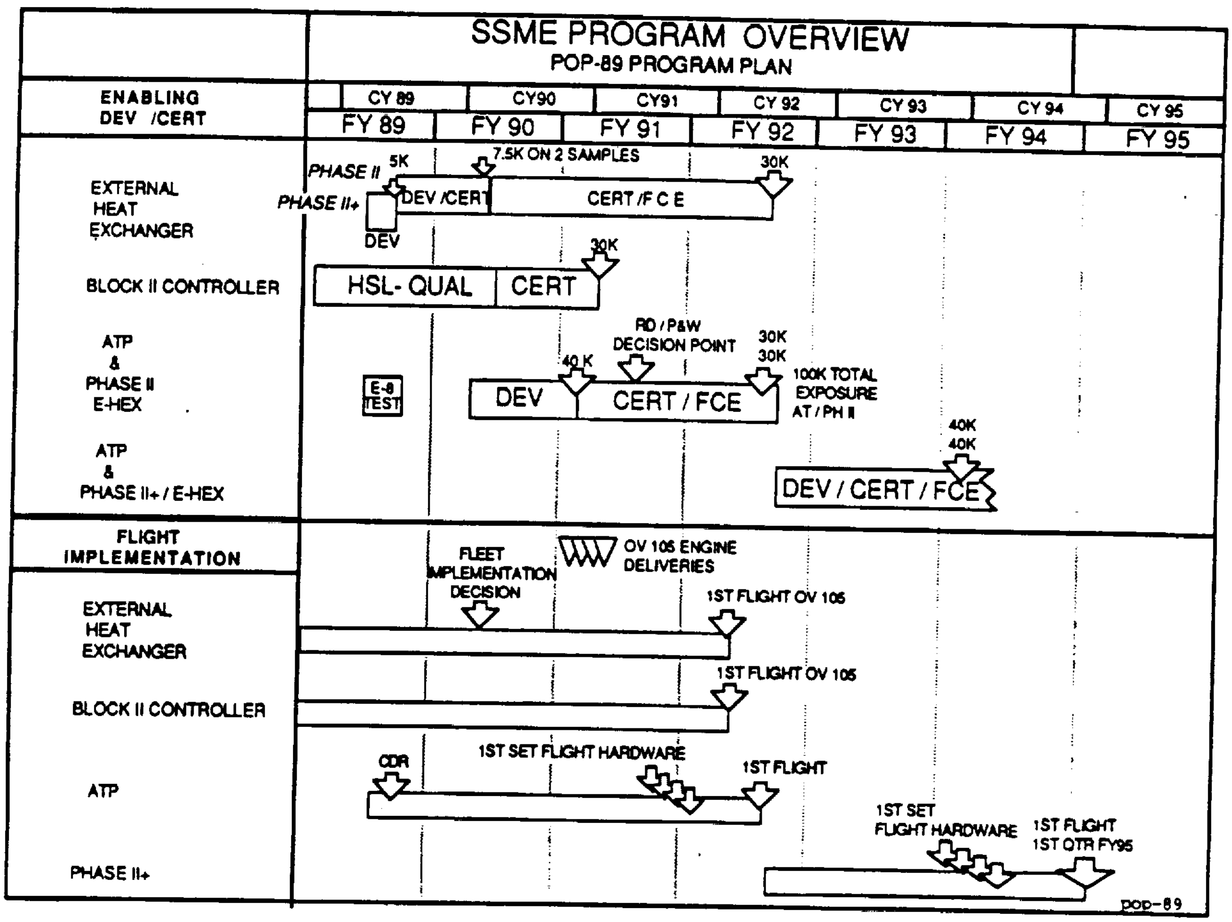


FIGURE 3-83 PLANNED SSME EVOLUTION PROGRAM SCHEDULE THROUGH 1995

3.4.2 PLS/LRB

The SSME is not considered a prime candidate for LRB or PLS applications unless the engines can be returned to land/recovered, or cost reduction programs yield SSME engines competitive with the SSME or another similar engine development.

3.4.3 AMLS

The SSME performance and weight characteristics are favorable for use on a high technology, future vehicle concept such as the AMLS. For booster applications, a 35:1 expansion ratio "flight weight" nozzle would need to be developed. Improvements in engine life capability, in addition to reliability and operations improvements would be required to reduce overall life cycle costs, which would be a major factor in the rationale for moving to a second-generation Shuttle vehicle. Throttle capability appears to be adequate, as does thrust level, for the depth of detail of AMLS vehicle requirements and definition that currently exist.

3.4.4 SSME Evolution for NMTS Applications

Because of the far-term nature of advanced/future vehicles such as the PLS, AMLS, etc., the focus for SSME Evolution will be the evolving STS. However, improvements made in SSME for STS Evolution will only enhance its viability for application to advanced manned reusable/recoverable vehicle concepts such as AMLS. Further development of low-cost versions of the SSME for Shuttle "C" would lead to improved applicability to the expendable stages of PLS/CRV concepts.

There are numerous technology gaps which must be filled over the decade if we are to evolve the SSME to increase (or at least not degrade) performance, maintainability, reliability, and decrease costs, including:

- Computation of coupled combustion and gas-dynamic processes
- Dynamic and steady loading/stress on high energy turbomachinery
- Solution methods for flow-structure coupling
- Modeling of flow-associated physics (e.g., turbulence)
- Thermal and dynamic modeling of bearings and seals
- Combustion stability prediction limited by understanding of combustion physics
- Material compatibility with propellants in the engine internal operating environment
- High strength, high temperature materials possessing high thermal conductivity
- Materials structural characterization
- Long-life propellant-cooled and lubricated bearings
- Fabrication processes, particularly material joining
- Use of reliability techniques in the development process

Currently, numerous SSME component technology projects are scheduled for integration and testing in the Technology Test Bed at MSFC, as shown in Figure 3-84.

Technology Project	Test Date (FY)	Component
Low Cost Controller	89	Controller
Plume Seeded Devices	89	Powerhead
Vortex Shedding Flowmeter	90	LOX Duct
Optical Pyrometer	90	Main LH_2 Turbopump
Non-Intrusive (IR) Gas Temp Sensor	90	Powerhead
Bearing Deflectometer	90	Main LOX Turbopump
Improved MAR-M-246(HT) Turbine Blades	91	Main LOX & LH_2 Turbopumps
Powder Metallurgy Disk Alloy	91	Main LOX & LH_2 Turbopumps
Turbine Nozzle Thermal Barrier Coatings	91	Main LH_2 Turbopump
Thin Film Sensors	91	Main LOX & LH_2 Turbopumps
Turbine Blade Thermal Barrier Coatings	91	Main LH_2 Turbopump
Powder Metallurgy Bearings	91	Main LOX & LH_2 Turbopumps
Cryogenic Roller Bearings	91	Main LOX Turbopump
Real-Time Safety Monitor	91	Engine
Raman Window for Preburner Temp Meas.	91	Powerhead
HPOTP Jet Coolant Ring	91	Main LOX Turbopump
Improved Bearing Cage Material	91	Main LOX Turbopump
Improved Bearing Coolant Path	91	Main LOX Turbopump
Long Life SSME LOX Pump Bearing	92	Main LOX Turbopump
Modified SSME Fuel Pump Labyrinth Seal	92	Main LH_2 Turbopump
Capacitive Pressure Transducer	92	Powerhead
Tribo Electric Flowmeter	92	Ducting
Smart Logistics Manager	93	Engine
Optical Plume Anomaly Detector	93	Nozzle
HPOTP Blade Tip Damper	93	Main LOX Turbopump
Optimized HPOTP Turbine Interstage Seal	93	Main LOX Turbopump
Improved Structural Alloy	93	H_2 Duct
Improved Bearing Cage Material	93	Main LOX & LH_2 Turbopumps
High Temperature Heat Flux Sensor	93	Main LOX & LH_2 Turbopumps
Improved Single Crystal Turbine Blades	93	Main LOX & LH_2 Turbopumps
Non-Intrusive Flowmeter	93	LOX Duct
Probe Wear Detector	93	Engine
Life Extending Control	93	Controller
Reusable Engine Condition Monitor	93	Engine
Sensor Failure Detection/Auto Cal	93	Engine
Brushless Torquemeter	93	LH_2 Boost Pump
Advanced Turbine disk Processing	93	Main LH_2 Turbopump
Electro Mech Actuators/Valves	94	Actuators
Expert Systems	94	Engine
Improved HPOTP Preburner Impeller	94	Main LOX Turbopump
Adv. Single Crystal Turbine Blades	94	Main LOX & LH_2 Turbopumps
Injector Diagnostics	95	Controller
Modular Software	95	Powerhead

FIGURE 3-84 ON-GOING/PLANNED MSFC TECHNOLOGY TEST BED PROJECTS

The goal of obtaining a reduction in space transportation costs is a direct function of lower life cycle costs in the SSME program which is in turn geared to improvements/advancements in specific technologies as depicted in Figure 3-85.

Benefit/Technology Improvement	CFD/ Modeling	Combustion Dynamics	Materials Technology	Seals & Bearings	Health Monitoring	Fabrication Processes
Reduced Maintenance			✓	✓	✓	
Eliminating Operational Failures				✓	✓	
Extended Operational Life	✓		✓	✓	✓	
Reduced Development Cost/Schedule	✓	✓	✓			✓
Improved Performance	✓	✓	✓			

FIGURE 3-85 BENEFITS OF TECHNOLOGY IMPROVEMENTS

Better analytical tools and codes can help strength and life predictions which can result in longer operating life and greater reliability at reduced costs because of a reduction in the need for costly and potentially destructive testing. Higher fidelity turbine and pump flow models will aid in development of improved performance, lower-life cycle cost, reduced development risk and schedule, and increased reliability turbopumps. Improved combustion dynamics models are needed to perform combustion stability and performance prediction analyses in order to reduce development risk, schedule, and cost and to increase performance, since current combustion stability analysis and demonstration methodologies involve techniques with unreliable analytical results and high cost testing.

Another area for technology improvements is in materials for liquid rocket engines, in particular, high strength, high heat transfer materials which facilitate thrust chamber cooling, lightweight high strength (high temperature in some cases) turbopump component materials for housings, rotors, discs, shafts and blades, and the development of lightweight, high strength, high temperature resistant composite thrust chamber materials. The development of these improved materials would result in longer engine operating life, and overall increases in performance due to higher pressure/higher temperature capabilities with lower engine weights. Bearings and seals technology is one of the critical technology areas for the SSME in extending turbopump and engine operating life with increased reliability and performance.

Engine diagnostics, health monitoring and control are new engine technology areas that are being developed to lower life-cycle costs, and improve reliability, safety and maintainability for reusable, long-life engines such as the SSME. The development of components and systems to perform these functions is vital to reducing space transportation costs.

A final technology area that needs to be developed is in fabrication processes, both component fabrication and in overall engine assembly. These improvements in fabrication processes should lead to reduced production and operation costs, and increased reliability.

Figure 3-86 shows time points when technology programs should be completed in an integrated technology program phased for maximum synergism and low-cost for modeling and for fabrication processes.

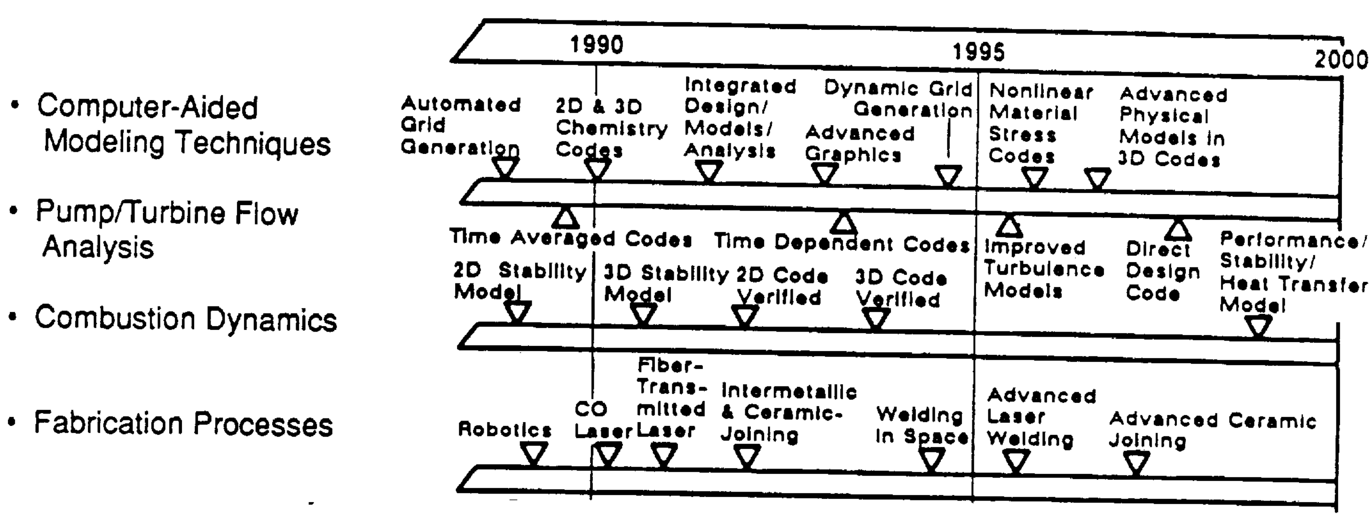


FIGURE 3-86 SSME ADVANCED TECHNOLOGY MILESTONE REQUIREMENTS

Figure 3-87 shows potential SSME component evolution requirements to support an "Early" AMLS.

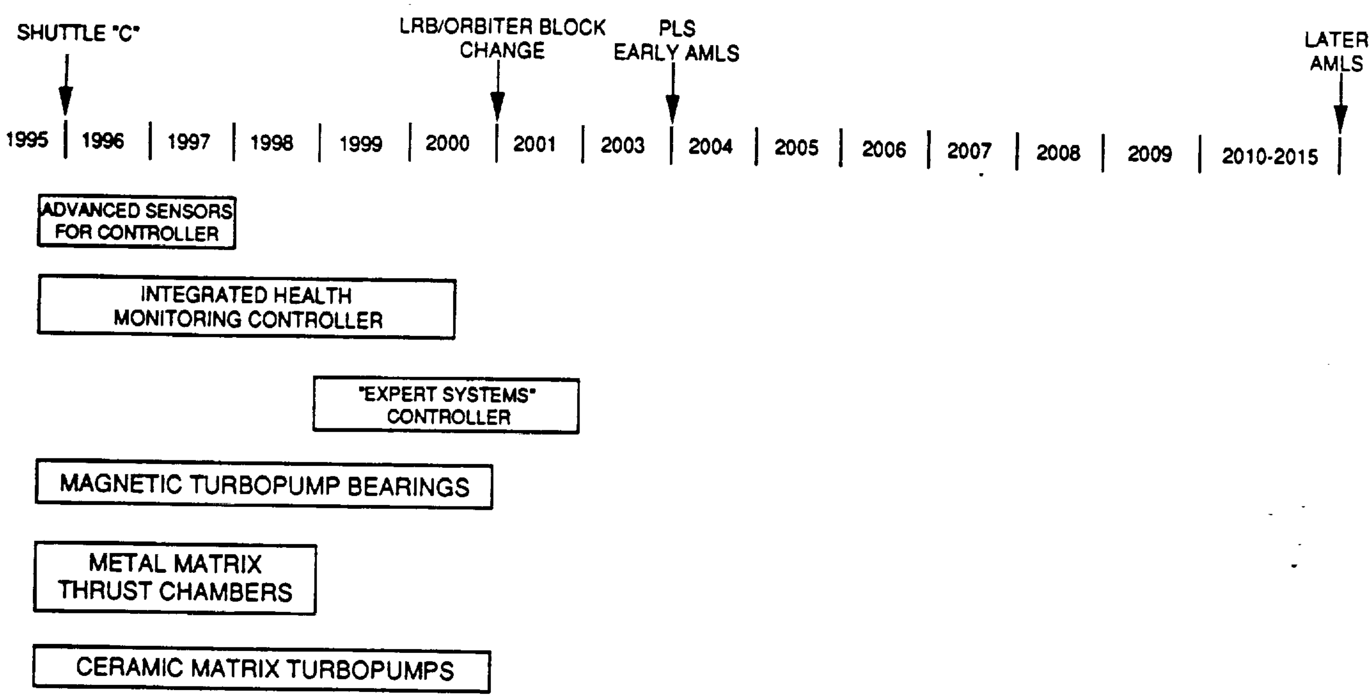


FIGURE 3-87 POTENTIAL SSME EVOLUTION FOR "EARLY" AMLS

3.5 Evolution Requirements for STME Engines

The first modification to be addressed for the STME to be employed in an NMTS, i.e., manned application are those necessary to provide a "man-rated" propulsion capability. Much of the man-rating of an engine has to do with "Fail Operational" and "Fail Safe" criteria.

The STME is currently being designed for booster and core engine applications for the ALS (Advanced Launch System), a joint NASA/DoD venture to develop low-cost, unmanned launch vehicles, to carry cargo, at times very expensive and strategically critical payloads, to low earth orbit. Overall ALS engine reliability, maintainability, and safety (RMS) requirements are shown in Figure 3-88.

<u>RELIABILITY REQUIREMENTS</u>

- Demonstrate Reliability of 0.99 at 90% Confidence
- Design Reliability of 0.999
- No Single Point Engine Functional Failure will Cause a Catastrophic Failure (i.e., loss vehicle) - Fail Safe
- Engine Must Shut Down Safely at Normal Operating Power

<u>MAINTAINABILITY REQUIREMENTS</u>

- Removal/Replacement of Engine within 16 Hours
- Visual Access of 360° Around Engine Powerhead
- Engine Removal/Replacement in Horizontal/Vertical Positions
- Installation of Components
  * No Awkward Positions
  * No Special Tooling
  * Minimized/Standardized GSE
  * No Mounting Hardware < 0.25 in. Diameter
  * Minimized No. of Types/Sizes of Fasteners/Washers/Etc.
  * Easy Seal Changes

<u>SAFETY REQUIREMENTS</u>

- LOX Compatible
- Contamination Control & Cleaning
- Containment & Leakage
- Control and/or Eliminate Predicted Failure Modes

FIGURE 3-88 ALS ENGINE RMS REQUIREMENTS

The major top-level change in reliability to provide for man-rating the STME would involve changing the "Fail Safe" criteria for a single point engine component functional failure to "Fail-Operational", with a second component failure resulting in a "Fail Safe" condition. "Fail-Operational" meaning no loss of vehicle, crew, or mission, while "Fail Safe" meaning no loss of vehicle or crew, but the mission may not be completed e.g., in a return to launch site abort, vehicle and crew are safe, but mission is lost.

The elimination of criticality-1 failure modes, coupled with the proper engine control logic and engine capabilities, will enable Fail-Operational-Fail Safe engine criteria to be in effect.

3.5.1 STS Evolution/Shuttle "C" Applications of STME

The STME has potential applications to all of the NMTS vehicles, as was discussed in previous subsections. As shown on Figure 3-33, for STME to be used in the STS orbiter, substantial vehicle and/or engine changes would need to be made. In order to meet the 8.5/10.5° gimbal requirement in the orbiter, the nozzle expansion ratio must be less than 50:1, and wrap-around ducting to allow 8.5/10.5° gimballing must be configured instead of "scissors" ducting, which would limit gimbal capability to about 6°.

Inlet pressure requirements as set for the STME would also not be compatible with STS requirements, necessitating STS ET tank pressure and feed line increases, or more probably, the addition of boost pump to the STME for STS applications.

It appears that payload losses using STME engines as opposed to the current SSME for orbiter propulsion would lead to substantial payload losses (approximately 10-25K lbs, depending upon thrust and nozzle expansion ratio). Vehicle thrust load limits, manned vehicle acceleration limits (3 g's), and the necessity for $q\alpha$ control make variable throttling a requirement. Currently, the STME has a one-step throttle (75%). STS/Shuttle "C" applications may necessitate variable throttling to as low as 50% (290K).

Propellant utilization is another area where the current STME operations capability on the ALS would require changing to operate on the STS. A mixture ratio control of $\pm 1\%$ is necessary to avoid large propellant residuals in STS/Shuttle "C" applications, which is beyond the capabilities of open loop control methodology ($\pm 3\%$ for ALS), which would therefore dictate a closed loop control system. There are several other fluid system requirement areas which are peculiar to STS/reusable vehicle/engine applications, as shown on Figure 3-27, which are different than those for the STME-ALS expendable application, but should not present any technology or compatibility problems.

The final area to be addressed is engine life/cost. As was shown in Figure 3-32 and the accompanying discussion, utilization of the STME in STS Evolution/Shuttle "C" applications, given the expendable engines for the Shuttle "C" core, and STS Evolution LRBs, is compatible with an engine life of 10-15 flights per engine, which is within the range of engine life requirements for the STME for ALS apr:i^ations.

A compilation of STME change/modification requirements for Shuttle "C" and STS Evolution applications is shown in Figure 3-89.

SHUTTLE "C" STME

- Nozzle Area Ratio: 50-62:1
- Modifications Required
  * Wrap-around Ducts for Increase Gimbal Capability
  * Boost Pumps for Increasing Main Pump Inlet Pressures
  * Active, Closed Loop Mixture Ration Control (±1%)

* 3 Engine Version	* 2 Engine Version
- Nominal Thrust: 540K (93%)[1]	- Thrust: 580K
- Throttling to 50% (290K)	- Throttling to 75% (435K)

  * LOX/LH2 Heat Exchangers for Autogeneous Main Tank Pressurization
  * GN2/On-ground Purge Capability

1 Requires thrust structure redesign to accommodate equivalent of 115% SSME

STS EVOLUTION STME[2]

- Modifications Required
  * Wrap-around Ducts for Increased Gimbal Capability
  * Boost Pumps for Increased Main Pump Inlet Pressures
  * Active, Closed Loop Mixture Ratio Control (±1%)
  * Fail-Operational/Fail-Safe Subsystem Redundancy
  * Nominal Thrust: 489K (84%)
  * Throttling to 50% (290K)
  * Orbiter Engine: ε=50/Booster Engine: ε=20
  * LOX and LH2 Heat Exchangers for Autogenous Main Tank Pressurization
  * Propellant Dump (Normal and Abort) Capability
  * GN2/On-ground Purge Capability

2 Recommend STME in STS concurrent with block change such as LRB replacement of SRBs. STME utilization in orbiter with SRBs is not a viable alternative.

FIGURE 3-89 SHUTTLE 'C'/STS EVOLUTION STME REQUIREMENTS

3.5.2 PLS Applications of STME

Another NMTS vehicle applications for STME is in the PLS. Several PLS candidate approaches are currently under consideration as discussed in Section 3.1.3.3. We have limited our analyses to PLS vehicles using LRBs as designed for use with the STS, and new PLS vehicle designs. In addition to "man-rating" the STME for PLS applications as previously discussed, involving Fail-Operational/Fail-Safe redundancies, etc., and vehicle pressurization, purge, and dump requirements as previously discussed for reusable vehicle/engine applications, several major STME engine requirements for PLS applications were investigated.

As was the case with Shuttle "C"/STS Evolution applications of the STME, the 75%, step throttle capability of the STME is inadequate for PLS applications, since throttling of the second stage of single STME to about 50% would be necessary for maintenance of a 3 g acceleration limit. A single STME engine in the second stage also does not permit an "engine out" capability, which could be accomplished by using multiple engines in the 80-130K thrust class. Engines of this thrust class would be potentially obtainable from other vehicles including the upper stages of expendable launch vehicles and STV or lunar vehicles.

Base area and engine installation analyses of PLS vehicles indicate that if the PLS is based on an LRB configuration, a nozzle expansion ratio of 20:1 is probably the largest that can be accommodated, while for a new PLS design, a nozzle expansion ratio of 40:1 would be possible if tank diameters larger than 15-18 feet were used. Previous studies have indicated that in parallel-staged PLS vehicles, $\pm 6°$ gimballing is adequate (with some engine cant), which means that "wrap-around" ducts would probably not be required. Specifics on engine inlet/feed pressure requirements are not fixed as on STS applications and these engine requirements would still be the subject of stage/engine trade studies. Engine life values of 10-15 flights per engine would also be compatible with recovery of booster engines for expendable second stage applications. A compilation of STME change/modification requirements for PLS applications is shown in Figure 3-90.

3.5.3 AMLS Applications of STME

The third category of NMTS applications is the AMLS (previously called Shuttle II) a vehicle concept that is more advanced and a next generation of manned vehicle that will at sometime replace the current STS. It is characterized as a vehicle having a high degree of recovery and reusability. As such, it will most likely have reusable engines on both a recoverable booster and orbiter.

- PLS Based on LRB or New Design
- Modifications Required
  - Active, Closed Loop Mixture Ratio Control ($\pm$1%)
  - Fail-Operational/Fail-Safe Subsystem Redundancy
  - Nominal Thrust: 580K
  - Throttling to 50% (2nd Stage Applications - 290K)
  - LRB PLS Engine: ε=20/New Design PLS: ε=40
  - LOX & LH_2 Heat Exchangers for Autogenous Main Tank Pressurization
  - GN_2/On-ground Purge Capability
- Subject to Further Trade Studies
  - Need for Wrap-around Ducts
  - Need for Boost Pumps
  - Smaller Thrust Level 2nd Stage Engine
  - Depending Upon Recovery: Propellant Dump & On-orbit Purges

FIGURE 3-90 PLS STME REQUIREMENTS

It appears that performance, throttling, engine-out, gimbal, man-rating, engine life, and thrust level requirements for an AMLS are probably compatible with evolutionary modifications to the basic STME. This long-term evolution could build on the STME cycle (i.e., gas generator) and robustness, but would involve a new engine which would incorporate the latest in materials technologies for lightweight, but robust designs. The desire for high performance (ISP) and smaller powerhead diameters and nozzle exit areas for installation in aerodynamic lifting body shapes, would tend to move the chamber pressure more towards 3000 psia, as compared to the STME's 2250 psia chamber pressure. For engine out, throttling for g level and qα control, and basic installation geometries for enforcing gimbal requirements, an engine thrust on the order of 400K lb is what the vehicle would prefer. Since, at the earliest, AMLS would be envisioned for the past 2005 time period (which would be coincident with a Block II Shuttle), and more likely be operational for the post 2015 time period, we have chosen to consider the AMLS application of STME in two distinct phases. The early AMLS would be similar to a Block II Shuttle, which we have defined as incorporating STME in an orbiter stage concurrently with incorporation in a liquid booster stage. A later AMLS would likely see an STME having a lower thrust, higher chamber pressure, etc. A compilation of these changes/modifications and characteristics for AMLS application is shown in Figure 3-91.

EARLY AMLS

- Similar to STS Block Change
- Post 2003-2005 Time Period.
- Modifications Required
  * Wrap-around Ducts for Increased Gimbal Capability
  * Boost Pumps for Increased Main Pump Inlet Pressures
  * Active, Closed Loop Mixture Ratio Control ($\pm$1%)
  * Fail-Operational/Fail-Safe Subsystem Redundancy
  * Nominal Thrust: 580K
  * Throttling to 44% (255K)
  * Orbiter Engine: ε=40/Booster Engine: ε=20
  * LOX & LH_2 Heat Exchangers for Autogenous Main Tank Pressurization
  * Propellant Dump (Normal & Abort) Capability
  * Helium Purge/Pressurization Capability On-orbit
  * GN_2/On-ground Purge Capability

LATER AMLS

- New Engine Based on STME/Cycle
- Post 2015 Time Period
- Characteristics/Features
  * Wrap-around Ducts
  * Boost Pumps
  * Active, Closed Loop Mixture Ratio Control
  * Fail-Operational/Fail-Safe Subsystem Redundancy
  * Autogeneous Tank Pressurization
  * On-orbit/On-ground Inert Gas Purges
  * Propellant Dump Capability
  * Nominal Thrust: 400K
  * Throttling to 64% (255K)
  * Chamber Pressure: 2500-3000 psia
  * Altitude Compensating Nozzles for High Performance (I_{SP})

FIGURE 3-91 AMLS STME REQUIREMENTS

3.5.4 STME Evolution for NMTS Applications

A potential evolutionary path for STME to meet NMTS vehicle application is shown in Figure 3-92. This evolutionary path is not present as the only evolutionary path or as an optimum evolutionary path, but as an evolution consistent with the analyses performed in this study. Further, more detailed analyses, for each of the NMTS vehicles, should be performed as the different vehicle concepts are defined and mission requirements mature.

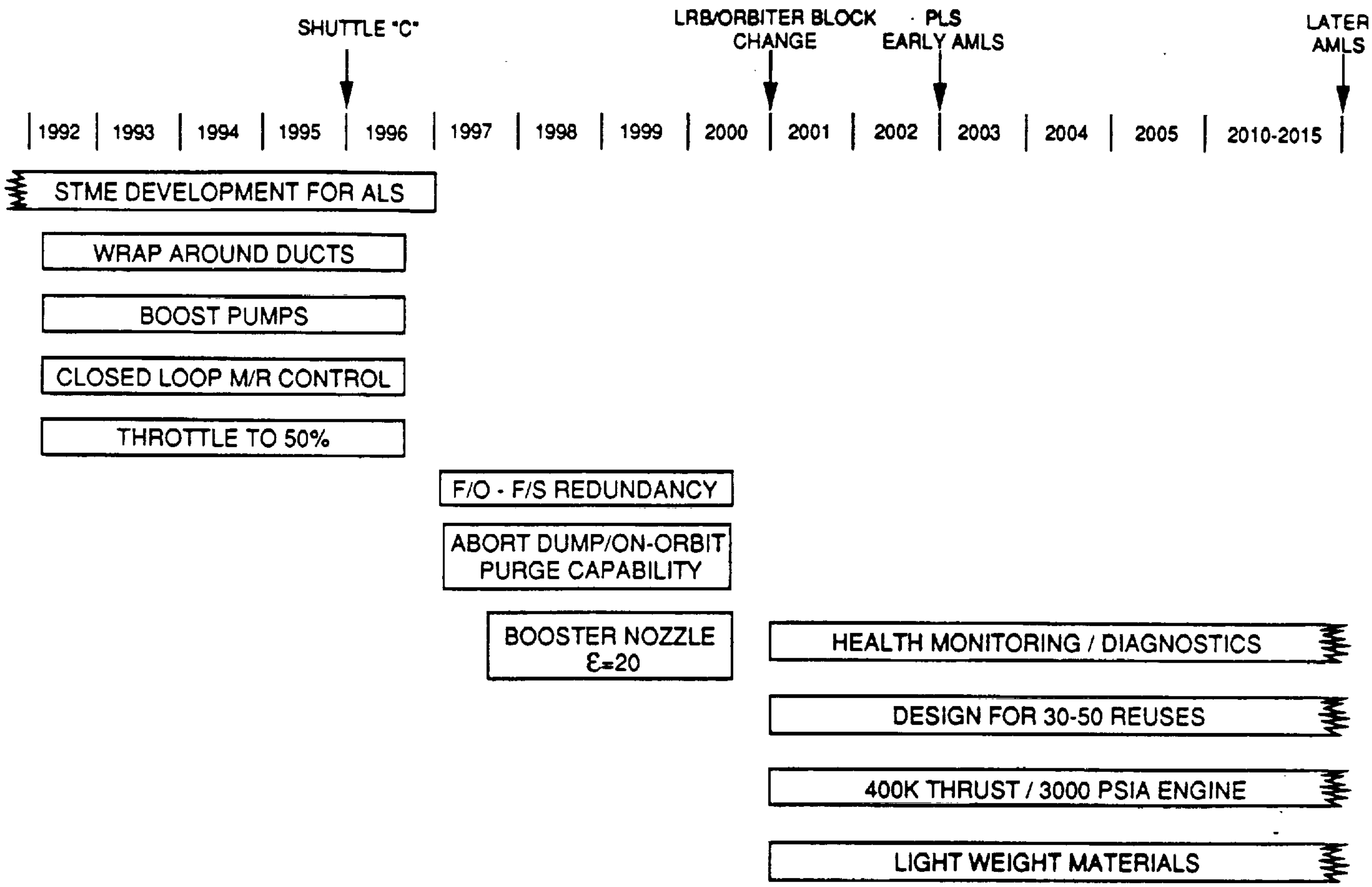


FIGURE 3-92 POTENTIAL STME EVOLUTION

3.6 Review of LOX/LH2 Technology Activities

3.6.1 NASA OAST Programs

The advanced propulsion research and technology (R&T) plan has been designed to extend and further develop the technology data base for earth-to-orbit, reusable, high pressure liquid propellant rocket engines in support of this nation's next generation space transportation needs. It was established in 1980 and funding began with the FY81 budget year. The program is sponsored and directed by the NASA Office of Aeronautics and Space Technology (OAST).

Initially the program focused on oxygen/hydrogen propulsion (O_2/H_2) and concentrated on addressing technology needs that surfaced during the development of the Space Shuttle Main Engine (SSME). The intent was, and remains today, to fill those technology gaps for use in the development of the next generation of reusable, O_2/H_2 rocket engine and for product improvements where feasible to the SSME. In 1985 an engine systems test bed program was established using a SSME as the test system. The purpose of this program was to provide a means for validating products of the R&T program in an engine system environment and for exploring advanced SSME subcomponent and component concepts outside the mainstream development program. Initially this was a separate program managed in parallel with the R&T program.

By 1986, studies of advanced launch vehicles then in progress began to show a clear need for reusable, oxygen/hydrocarbon (O_2/HC) rocket propulsion. As a result the R&T program was expanded to include technology needs for advanced, reusable, high pressure, O_2/HC propulsion. The hydrocarbon fuels of interest are RP-1, liquid methane and liquid propane. Prior to 1986 O_2/HC propulsion R&T was carried out in a separate program.

In 1988 with the establishment of the Civilian Space Technology Initiative (CSTI) the program was further expanded and restructured. The R&T program which consisted of O_2/H_2 and O_2/HC propulsion was combined with the O_2/H_2 systems test bed program. A third element, large scale subsystems technology validation, was added to provide a means for validating the O_2/HC technology emanating from the R&T acquisition portion of the program. The CSTI propulsion program as it is now structured began in FY88 and will end in FY93. The CSTI propulsion program consists of a technology acquisition phase and a validation phase leading to specific deliverable products by the termination date. The acquisition and validation phases are concurrent. Figure 3-93 summaries the program.

PURPOSE
- Contribute to the Maintenance of U.S. Leadership in Space Transportation

OBJECTIVE
- Continue Enhancement of Knowledge, Understanding, and Design Methodology Applicable to the Development of Advanced Oxygen/Hydrogen and Oxygen/Hydrocarbon ETO Propulsion Systems

JUSTIFICATION
- Space Transportation Systems can Benefit from Advancements in Propulsion System Performance, Service Life and Automated Operations and Diagnostics

CONTENTS
- Analytical Models for Defining Engine Environments and for Predicting Hardware Life (Flow Codes, Loads Definition, Material Behavior, Structural Response, Fracture Mechanics, Combustion Performance and Stability, Heat Transfer)
- Advanced Component Technology (Bearings, Seals, Turbine Blades, Active Dampers, Materials, Processes, Coatings, Advanced Manufacturing)
- Instrumentation for Empirically Defining Engine Environments, for Performance Analysis, and for Health Monitoring (Flow Meters, Pressure Transducers, Bearing Wear Detectors, Optical Temperature Sensors)
- Engineering Testing at Subcomponent Level to Validate Analytical Models, Verify Advanced Materials, and to Verify Advanced Sensor Life and Performance
- Component/Test Bed Engine for Validation/Verification Testing in True Operating Environments

WORK BREAKDOWN
- Technology Acquisition Phase
  - Seeks Improved Understanding of the Basic Chemical and Physical Processes of Propulsion
  - Develops Analysis and Design Models and Codes Using Analytical Techniques Supported by Empirical Laboratory Data as Required
  - Results are Obtained Through Ten Discipline Working Groups
    - Bearings
    - Structural Dynamics
    - Turbomachinery
    - Fatigue/Fracture/Life
    - Ignition/Combustion
    - Fluid & Gas Dynamics
    - Instrumentation
    - Controls
    - Manufact./Prod./Inspection
    - Materials

- Large Scale Subsystem Technology Validation
  - Validates Technology Emanating from the Acquisition Phase at the Large Scale Component or Subsystem Level
  - Three Categories of Effort
    - Large Scale Combustors
    - Large Scale Turbomachinery
    - Controls and Health Monitoring

- Technology Test Bed Validation
  - Validates Technology Emanating from the Acquisition Phase at the Engine System Level
  - Three Categories of Effort
    - Combustors
    - Turbomachinery
    - Controls and Health Monitoring

Figure 3-93 NASA CSTI Earth-To-Orbit Propulsion Technology Program

The program has ten discipline working groups co-chaired by MSFC and LeRC. These working group disciplines currently include bearings, structural dynamics, turbomachinery, fracture and fatigue, combustion and ignition processes, fluid and gas dynamics, instrumentation, controls, manufacturing, and material. To facilitate the validation phase of the program three subsystem thrusts; combustors, turbomachinery, and health monitoring and control, each co-managed by MSFC and LeRC, have been established.

CSTI's contribution to Earth-to-Orbit LOX/LH2 engines is to reduce risk by testing larger components, and improve health monitoring. To assist in booster technology, CSTI will also evaluate pressure-fed liquid bipropellant engines (including LOX/LH2) for future transportation; investigate increasing booster thrust to relieve SSME requirements (109%); and consider hybrid booster technology including LOX delivery techniques, performance prediction and start/shutdown characteristics verified by scale model firings, combustion stability, pressurization systems, and materials compatibility.

3.6.2 ALS

The Space Transportation Main Engine (STME) program objective was to provide conceptual definition of a high reliability, low cost LOX/Hydrogen engine to meet ALS propulsion requirements. The program was structured to (1) establish engine design concepts, cost and performance characteristics, trade data and programmatics necessary for the ALS vehicle studies and (2) provide analytical verification that ALS engine requirements can be met. The Space Transportation Booster Engine (STBE) program was structured likewise for LOX/Hydrocarbon booster engines for ALS. The follow-on Space Transportation Engine Program (STEP) objectives are to provide preliminary designs and program plans for high reliability low cost engines: (1) LOX/Hydrogen STME for ALS core and booster, and (2) LOX/Methane STBE derived from STME hardware for ALS boosters. The results from the STEP effort will be (1) establishment of engine parametrics necessary for Phase II studies in preliminary design, cost and performance characteristics, interfaces, and programmatics and (2) providing analytical verification of these requirements.

In addition to the main-stream gas generator cycle, the ALS progrm is also addressing the split expander cycle engine option. Some potential advantages of the split expander cycle over the gas generator cycle are (1) the elimination of the gas generator combustion chamber and the GG exhaust dump and (2) a much more benign turbine environment. However, the expander cycle is limited by the requirement to maintain the combustion chamber wall temperature below a maximum value while obtaining the maximum available power to drive the turbopumps. The major technological issues with the cycle are: (1) the "power margin" or heat transfer to the coolant (turbine drive) versus the chamber wall temperature and chamber pressure requirements, (2) combustion stability margin for large, low pressure chambers, and (3) start transient characteristics. Design concepts to enhance coolant heat transfer and/or increase the allowable chamber wall temperature and provide for a stable transient through start, must be demonstrated to enable advanced development of the split expander engine system.

3.6.3 Summary

As discussed in Section 3.4, numerous technology efforts are planned for the Technology Test Bed at MSFC to support SSME development. In addition to these technology efforts, we have offered potential SSME and STME evolution plans to support advanced NMTS vehicle systems.

Current STEP rocket propulsion program has identified candidate rocket engines for the next generation of launch vehicles. This engine program is considering one developed cycle, the gas generator, and undeveloped cycles, including the split expander cycle. NASA inhouse efforts along with contracted efforts are planned to develop the needed technology for each of these engines. Long term technology requirements are still being developed. Other possibilities for undeveloped LOX/LH2 cycles requiring technology development include the open expander (bleed cycle) and a full flow staged combustion cycle, which is examined in the companion SRS study of undeveloped rocket engine cycles (SRS TR89-90). An analysis that considers using undeveloped cycle engines for liquid rocket booster (LRB) propulsion is also warranted. Trade studies and planning should continue to more closely examine various advanced/undeveloped LOX/LH2 propulsion options.

Note: The summary from Section 2.0 is repeated here, for convenience of the reader.

2.0 SUMMARY

The Space Shuttle Main Engine (SSME) is currently flying in the Space Shuttle (STS), and changes are planned into the mid-1990's to improve its operations and to reduce costs. Work is in progress toward potential development of one or more new liquid rocket engines for launch vehicle applications (The joint NASA-DoD program - Space Transportation Engine Program, or STEP). This latter effort is currently focusing on a new hydrogen-oxygen engine for use in both booster and upper stages, with the potential for application in the Advanced Launch System (ALS) around the turn of the Century.

The objectives of this Propulsion Evolution study were to examine potential engine applications in manned launch systems beyond the l995-2000 time period, to determine propulsion requirements for such applications, and to suggest evolution paths for SSME and STME engines as candidates for use in these manned launch systems.

The classes of vehicle concepts currently under study by NASA for future manned space transportation, e.g., the "Next Manned Transportation System" were the basis for these studies. These include: (l) STS Evolution, (2) Personnel Launch System (PLS)", and (3) Advanced Manned Launch System (AMLS). And, because of its interaction with STS Evolution planning, we have included some discussion of Shuttle "C" engine applications and requirements. In examining these vehicle applications, we have used as guidance the NMTS objectives including: adaptability for physical integration into the vehicle under discussion; improved system reliability, safety and margins; an acceptable level of performance or improvement; enhanced operations; and reduced costs.

Through the use of available data on manned vehicle concepts in combination with top-level trade studies performed as a part of this study, we have compiled a summary set of suggested propulsion requirements for each of these classes of vehicle concepts. These data are provided in summary matrix form in Figure 3-7 (SSME applications) and in Figures 3-54A and 3-54B (STME engine applications). Summary information from the trade studies in this report, is provided to indicate rationale for these requirements, and to aid in further vehicle and propulsion studies.

A low level of effort task was included in this study to examine propulsion options for booster applications, including Lox-Hydrocarbon engines as well as booster (low area ratio) versions of Hydrogen-Oxygen engines. Use of one of these versions would be highly preferable and possibly mandatory (in lieu of an upper stage version of a hydrogen engine) for Liquid Rocket Booster and AMLS booster applications. The choice between the two will be highly dependent upon the approach selected for orbiter or core stage propulsion.

As one of the major tasks in this study (Common Engine study task), we have examined prospects for use of a single engine configuration over this full range of vehicle applications, including ALS. A program of this type is illustrated as "Scenario no. 2 in Figure 2-1. Studies under this and other tasks indicated that a number of changes from the basic STEP/STME engine requirements would be necessary to adapt it for use in any of the manned vehicles, and that additional engine or vehicle changes would be necessary for its use in STS/Shuttle "C". It would be very difficult if not impossible to utilize a singe engine/nozzle configuration over this full range of boosters and upper stages, as is currently planned in ALS; it appears that two nozzle configurations would be required as a minimum.

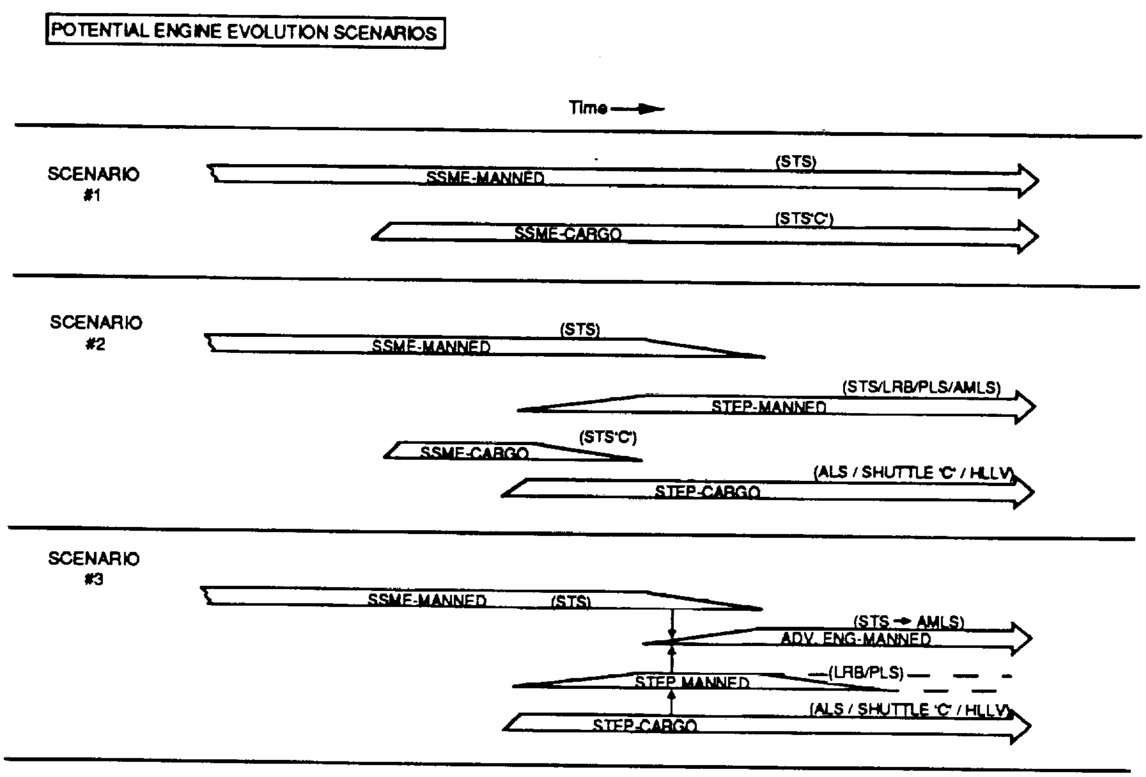


Figure 2-1 Potential Engine Evolution Scenarios

900328LS1010-2

All engines and vehicle applications naturally will want high reliability, high performance, low weight, and low costs. However, the relative importance of some of these characteristics suggests two companion categories of engine applications out of the range studied here. The category including emphasis on more rugged design, adaptability for water recovery, and lower unit costs would best fit the ALS, the Liquid Rocket Booster, and PLS launch vehicle applications. The group with more emphasis on higher performance, smaller engine sizes, and longer engine life would best fit STS orbiters and AMLS vehicle applications. Shuttle "C" in an expendable engine mode would likely prefer the former category, for lower unit costs. The new engine development under STEP/STME is geared more strongly to the characteristics of the first category, while the SSME is already established in the latter.

The alternative shown as "scenario no. 3" in Figure 2-1 suggests continued use of SSME engines in manned, reusable vehicles, to be followed (later) by a successor to the SSME engine that can incorporate some of the characteristics from the STEP engine experience without changing its character completely. The extent to which the current SSME engine can attain the objectives of longer life, improved operations and lower costs, and therefore the timing that would be desirable for conversion to a successor engine, remain yet to be established (as are all the target objectives for a new engine development).

We believe it is important to implement increased levels of margins in vehicles and systems, as a means to improve safety/reliability, to improve operations and maintenance, and to reduce costs. The brief study of margins in propulsion and vehicle systems in this study again points up the higher levels of performance sensitivities for manned, reusable vehicle systems, and the greater degree of care and prioritizing necessary in the selection and application of margins. Secondly, the level of sensitivity to increased margins should be a more prominent factor in future trade studies and selections of baseline approaches for propulsion and other vehicle systems.

Based on these studies of future manned vehicle applications, we have outlined suggestions for SSME evolution beyond that currently scheduled in the STS program (Section 3.4 of the report) and for STME engine evolution beyond its initial application in ALS launch vehicles (Section 3.5 of report). As the final task in this study, we have summarized and reviewed the Lox-Hydrogen technology efforts that are currently in progress or planned under NASA propulsion technology programs and the ALS advanced development program, in comparison with the evolution trends suggested here.