GENCORP AEROJET

MARTIN MARIETTA

HYBRID PROPULSION TECHNOLOGY PROGRAM

Phase I—Final Report

Volume I Executive Summary

Contract NAS8-37775

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George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

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FOREWORD

This is the final report for Contract NAS 8-37775, a research technology study entitled "Hybrid Propulsion Technology Program Phase I." The study was performed for NASA-MSFC by Aerojet with vehicle effects analysis provided by Martin Marietta.

This report has been assembled in two volumes for clarity. Volume I is an executive summary with an overview of the study program, methodology of trade studies, study results, and Phase II and III planning.

Volume II is a compilation of detailed study charts with facing page annotation added as required for explanation.

The NASA-MSFC Study Manager was Ben Shackelford. Bob Friedman was the Aerojet Program Manager, supported by Art Kobayashi, Technical Advisory Group Manager; Don Culver, Technical Manager; Bill Barnette and Larry Hoffman, Solid and Liquid Component Project Engineers, and Brian Strickfaden, Life Cycle Costing. Craig Hansen, of MMAG supported Aerojet with vehicle integration studies.

The contract period of performance was 6 March 1989 through 23 October 1989.

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1.0 INTRODUCTION

The study program described herein was contracted to evaluate concepts of hybrid propulsion, select the most optimum, and prepare a conceptual design package. Further, this study required preparation of a technology definition package to identify hybrid propulsion enabling technologies and planning to acquire that technology in Phase II and demonstrate that technology in Phase III.

1.1 PROGRAM PHILOSOPHY

Our program was orientated to perform a study aligned with NASA priorities. The selection criteria were therefore prioritized as :

- Flight safety and reliability
- Low life cycle cost
- Performance
- Other important criteria
  - Availability (development risk, etc.)
  - STS compatibility

We evaluated two design philosophies for Hybrid Rocket Booster (HRB) selection, Figure 1. The first is an ASRM modified hybrid wherein as many components/designs as possible were used from the present ASRM design. The second was an entirely new hybrid optimized booster using ASRM criteria as a point of departure, i.e., diameter, thrust time curve, launch facilities, and external tank attach points.

We selected the new design based on the logic of optimizing a hybrid booster to provide NASA with a next generation vehicle in lieu of an interim advancement over the ASRM. The enabling technologies for hybrid propulsion are applicable to either and vehicle design may be selected at a downstream point (Phase III) at NASA's discretion.

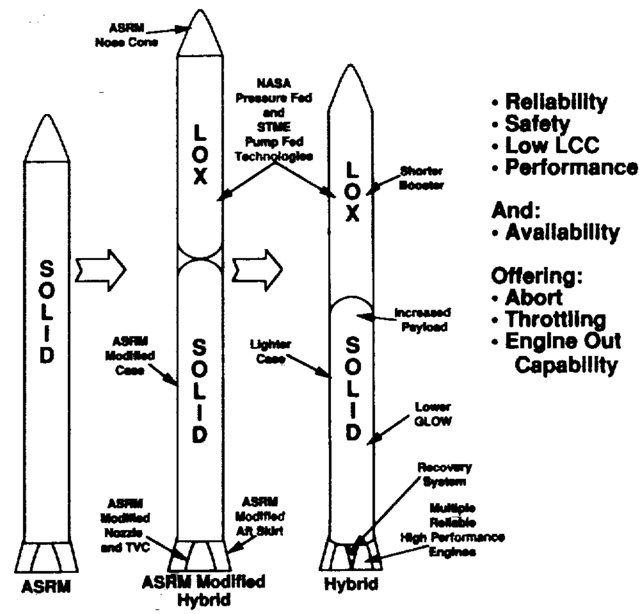


Figure 1. We Selected a New Optimized Hybrid Booster

1.2 RESULTS

The completion of these studies resulted in the chart shown in Figure 2, ranking the various concepts of boosters from the RSRM to a turbopump fed (TF) hybrid. The scoring resulting from our Figure of Merit (FOM) scoring system (see Section 2.1) clearly shows a natural growth path where the turbopump fed solid liquid staged combustion hybrid provides maximized payload, minimum GLOW, and the highest safety, reliability, and low life cycle costing.

2.0 STUDY PROGRAM METHODOLOGY

We performed the study program in five logical steps based on the proven methodology

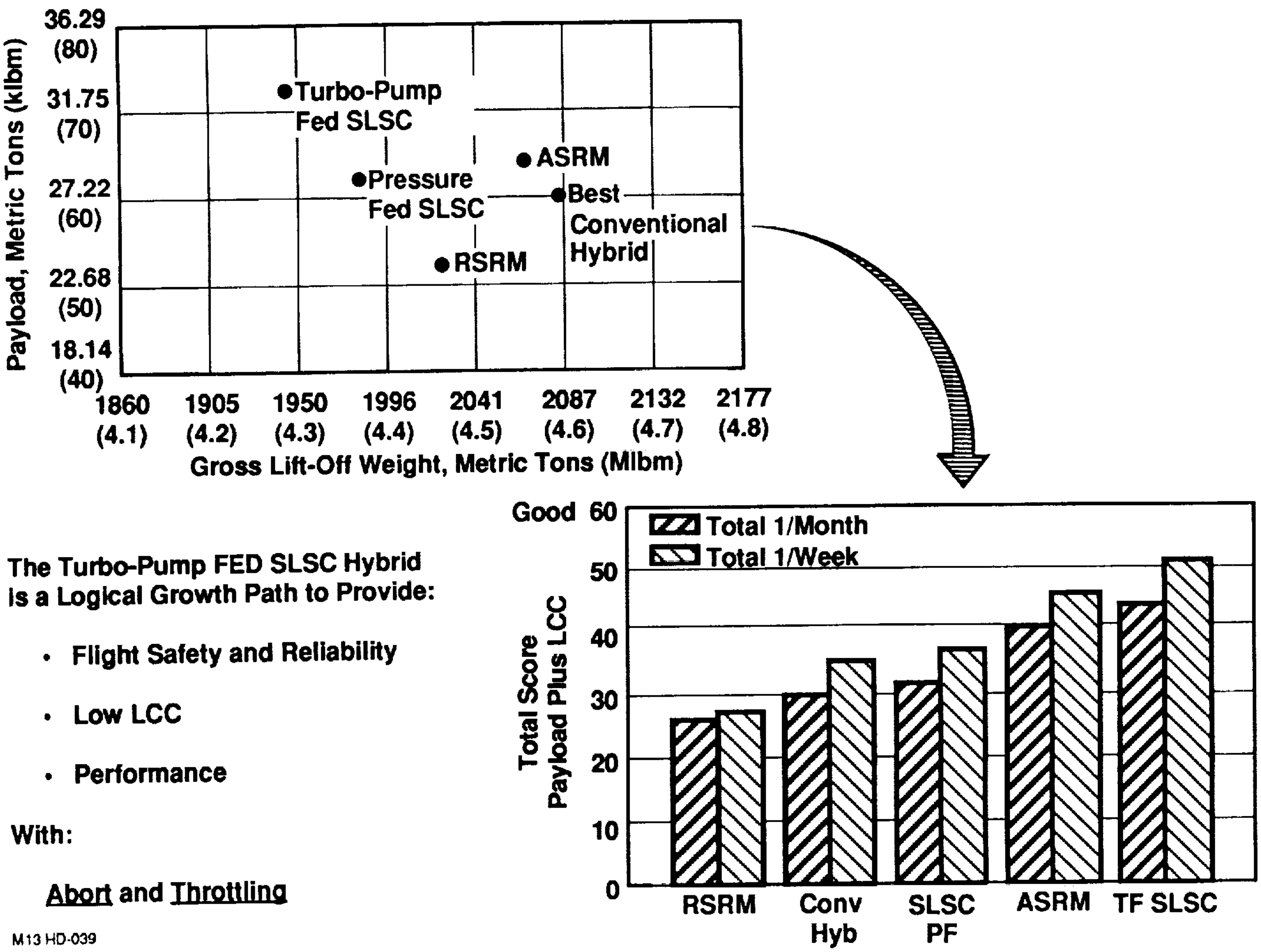


Figure 2. We Have Applied Our Scoring to Existing and Future STS Boosters

that was demonstrated during the Aerojet MSFC ALS engine program. The overall logic is shown in Figure 3. Beginning with the HRB requirements and using our liquid and solid rocket experience base we defined the screening criteria and the Figure of Merit (FOM) evaluation model. Then the HRB subsystem concepts were defined by logic matrices and concept lists. We were able to screen out unacceptable concepts and define acceptable candidates. Next we generated weights and cost data for these successful candidates. From this point the FOM provided data that allowed us to narrow down the concepts by selecting high scores. We then performed sensitivity and optimization studies and created a conceptual design incorporating the selected concepts. Finally, hybrid enabling technologies were identified and Technology Acquisition Plans (Phase II) and Demonstration Plans (Phase III) were defined.

2.1 FIGURE OF MERIT (FOM)

The FOM is the heart of the selection process, and we selected a well defined method in use at Aerojet. Our assignment of a numerical rating system prior to concept/component selection precludes bias and provides selection

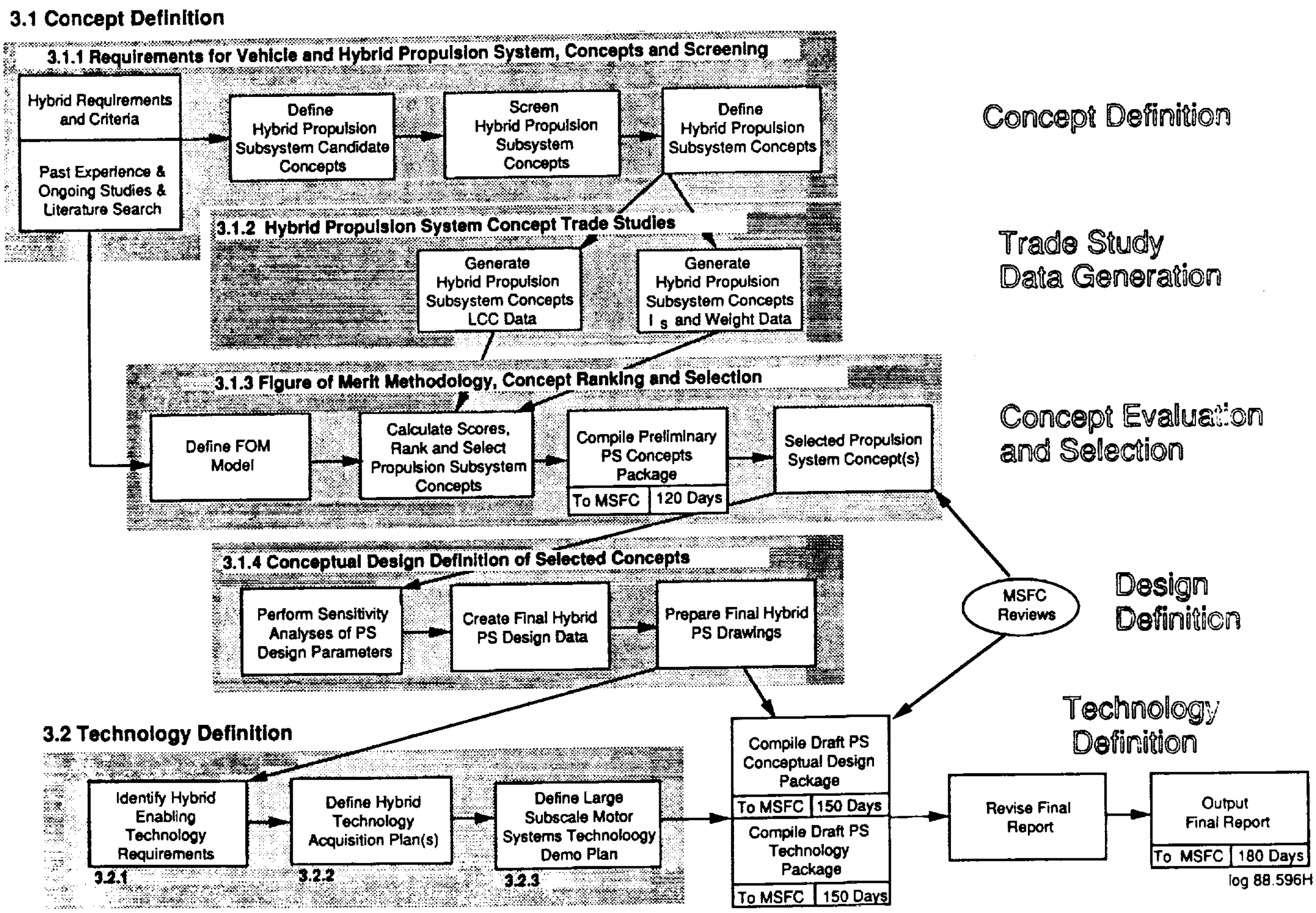


Figure 3. Our Technical Approach Is Powerful and Logical

data automatically. By this use of the FOM system, Aerojet was able to make selections without influence of personal preference.

Using the baseline of the existing SRM program, five categories influencing the program were selected (Figure 4). The percentage each contributes to the whole is based on ALS data and becomes the maximum score points available in each category. Minimum (zero) points are the SRM baseline, and maximum are the ultimate to be expected. As an example, if the SRM has a payload capability of 24,950 kg (55,000 lb) then any booster with the same capability will get zero points. Conversely, if 38,550 kg (85,000 lb) lift is the ultimate then that unit will receive 14 points (the maximum in that category). Therefore, the FOM model contains LCC relative weighting factors that determine the maximum score a candidate may achieve in each cost category. It also contains weighting factor design parameter sensitivities. These two are functionally related to create the model that ties the concept parameter to the cost impact. A scoring format is included to sum the results of each category for each evaluated concept. The bases for the relative weighting factors and their design parameter sensitivities are the baseline system scenarios or requirements selected; that is, mission models, launch vehicle, and facilities. The result is an automated selection process that numerically rates the concept under study and provides numerical scoring for selection.

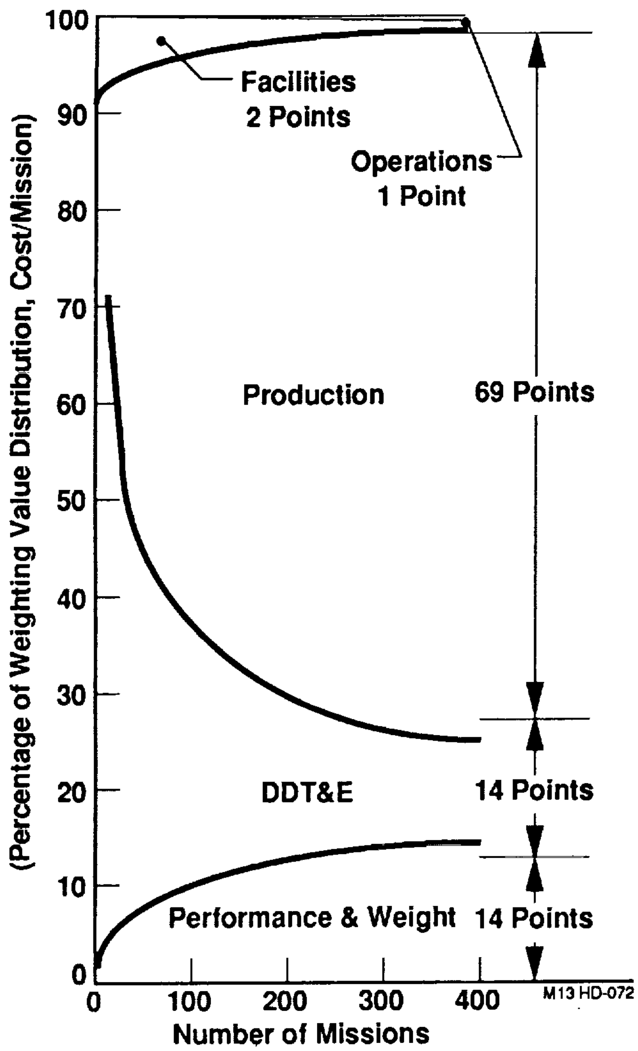


Figure 4. We Established the Category Cost Relationships vs Number of Missions From the Baseline Life Cycle Cost

2.2 EVALUATION PROCESS

The evaluation process screened from coarse to fine with immediate elimination of elements that did not pass (e.g., toxic propellants).

We considered propellants, combustion schemes, and propulsion subsystems to be three fundamental aspects of the rocket booster. We studied them in series in the order shown in Figure 5 (most to least fundamental) during the first three concept tasks in order to geometrically reduce the amount of work to be done. During design and technology tasks these distinctions collapsed and all work was done in parallel.

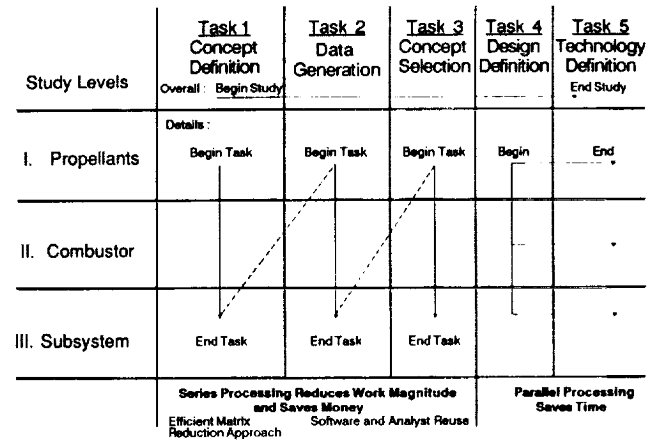


Figure 5. Our Five Step Methodology Uses Series and Parallel Processing as Appropriate

Our approach included an early yes/no type qualitative screening of developed concepts and a subsequent quantative selection, based on scores computed with life cycle cost and payload to LEO data (see Figure 6). Your

NASA Priorities for HRB (ranked)	Task 1 Qualitative (yes/no) Screening (not ranked)	Task 3 Quantitative Selection
1. Flight Safety and Reliability 2. Life Cycle Cost 3. Performance (PAYLOAD) 4. Other	I. Safety a. Explosive Hazard b. Auto-Ignition Hazard c. Toxicity d. FMEA - Loss of STS e. Physical II. Availability a. Tech Demo Date b. Development Risk c. Producability d. Maintainability e. Reliability - Loss of Mission III. Design and Operational STS Compatibility Requirements a. Geometric b. Operational	Loss of Mission Reliability = LCC Input LCC = Selection Fig. Of Merit STS Payload = a FOM element

Figure 6. Aerojet Study Criteria Concur With NASA MSFC HRB Priorities

priorities were considered in the screening process and some during selection.

We performed eleven selection studies to identify the best HRB concept for eight scenarios. Nine of the studies results are shown in Figure 7. Two additional ones showed that small HRBs and resuable HRBs score more poorly than large expendable ones, whereas a recoverable engine module scenario scored better. The chart shows that all scenarios need the same design for best scores, except small HRBs will be cylindrical their entire length, whereas our large HRBs have a short tapered section just ahead of the aft skirt. All scenarios use eight turbopumps and thrust chambers to maximize the score of our solid liquid staged combustion concept, which burn LO_2 and a solid hydrocarbon fuel rich solid propellant in the aft-mounted TCAs.

The results of the studies are shown in the nine charts of Figure 8.

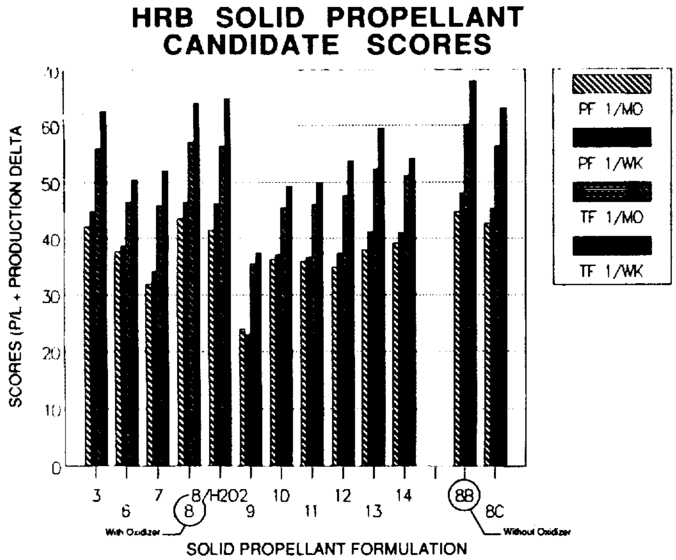
Best Scores (Scenarios 1 and 2)

Scenarios	1	2	3	4	5	6	7	8
Reusable	No	No	No	No	Yes	Yes	Yes	Yes
No. HRB Flights	2	2	8	8	2	2	8	8
Flight Rate	1/wk	1/mo	1/wk	1/mo	1/wk	1/mo	1/wk	1/mo
Concept Selections								
Level 1 Propellants	LO_2 + #8	→						
Level 2 Combustor	SLSC (D)	→						
Level 3 Feed System	TF/EBBC	→						
Nozzle Exit Pressure	41.37 kPa (6 psi)	→						
No. TCAs, 0 "Out", HRB	4	4	1	1	4	4	1	1
No. TPAs/HRB	4	4	1	1	4	4	1	1
No. Solid Cases/HRB	1	1	1	1	1	1	1	1
Solid Case Shape	Coni-Cyl	Coni-Cyl	Cyl	Cyl	Coni-Cyl	Coni-Cyl	Cyl	Cyl
and Tank Shape	Cone/Cyl Rev. Hd.	→						
TCA Cooling (Throat)	LO_2 Regen	→						
Tank Pressure	Autog.*	→						

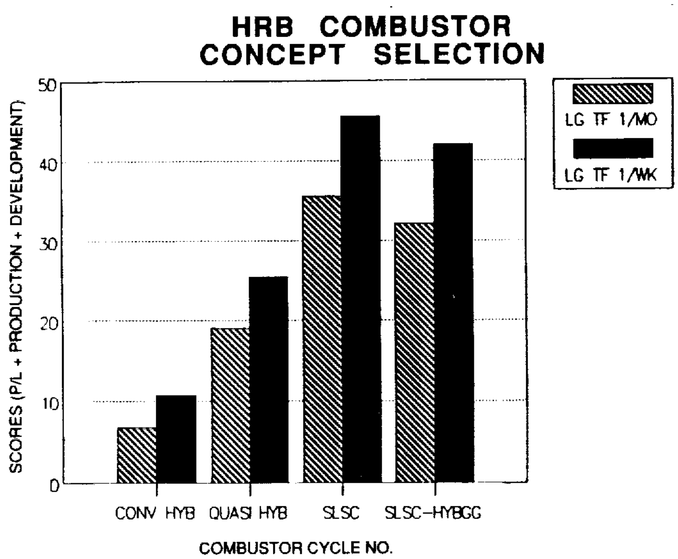
M4D10/Hybrid/PI 1

*Turbine Exhaust Bleed - No Heat Exchanger or Regulator Required

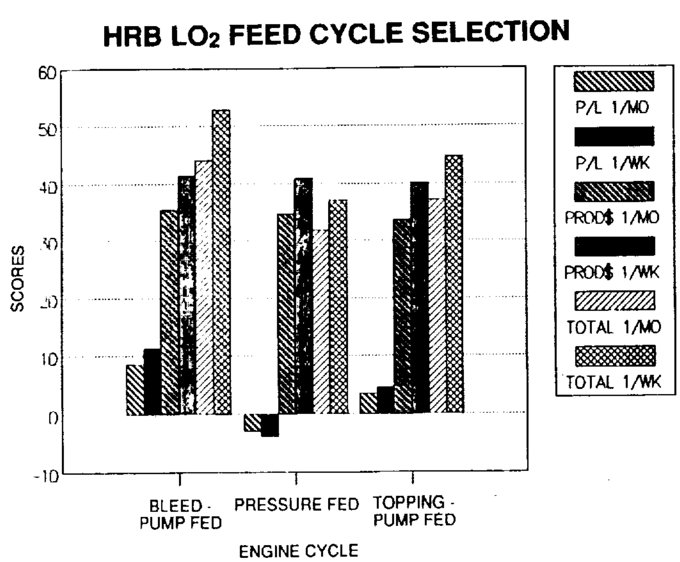
Figure 7. Task 3 Concept Selection Summary



We evaluated solid propellants for use with LO_2 and LO_2 densified with solidified H_2O_4 and H_2O_2 particulates. One is pure fuel, and others are fuel with a small amount of solid oxidizers. We selected pure fuel 8B, a PEBC hydrocarbon and a fuel-rich selection No. 8,both with LO_2. It is the same as No. 8B with solid oxidizers and HCl scavengers added to the PEBC hydrocarbon. H_2O_2 had been screened out on the basis of safety.



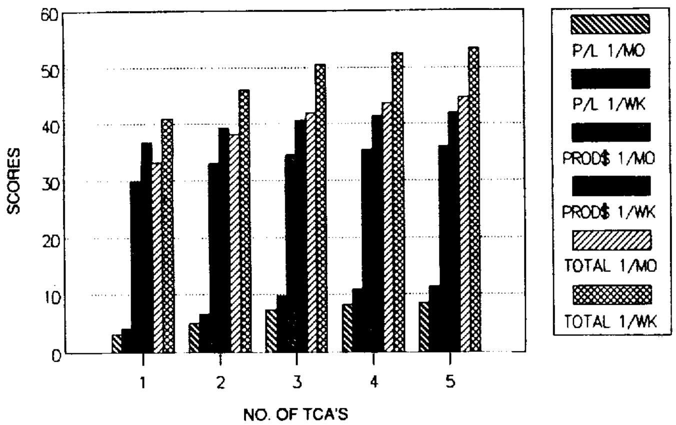
We selected the solid/liquid staged combustion scheme, because it had nearly twice the score of the best "single stage combustion" hybrid. The SLSC version with the hybrid gas generator did not score as well as the simpler one with the fuel-rich solid gas generator (solid case). All candidates used LO_2 with either No. 8 or No. 8B solid propellants.



Turbopump fed HRBs scored much better than pressure fed designs when the turbine is driven with bleed gases (not by gases to pass through the injector). Pressure fed variants suffered from low payload delivery to LEO, because of heavy tankage and pressurization weights. The topping cycle score was lower than the bleed cycle because its low specific impulse hurt its payload capability. The low I_{sp} is caused by the relatively poor combustion efficiency of a gas/gas injector when used with O_2/hydrocarbon systems.

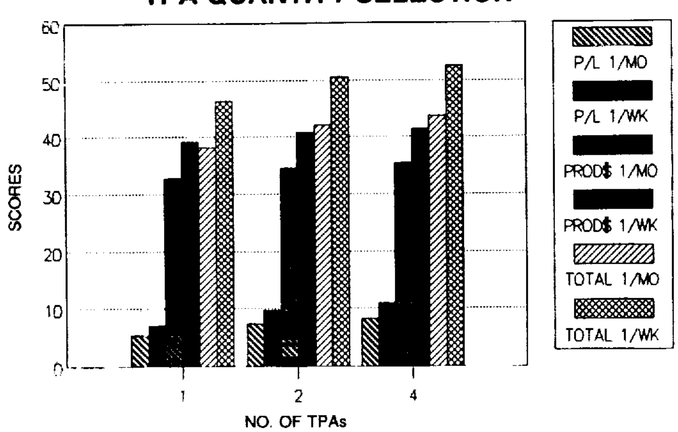
Figure 8. HRB Concept Scoring, Sheet 1 of 3

TCA QUANTITY SELECTION
NO TCA OUT, TURBOPUMP FED



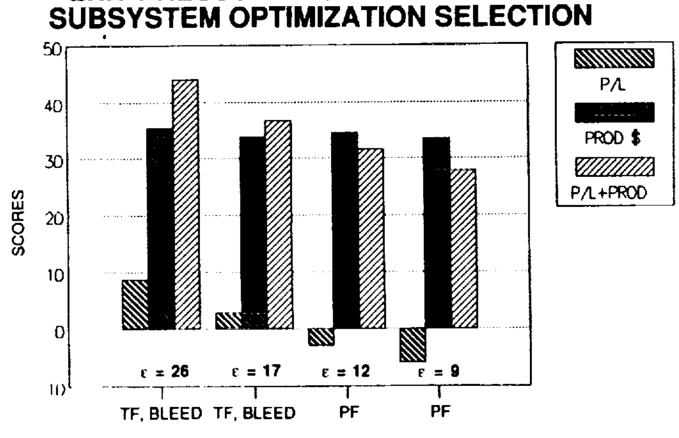
We selected four thrust chamber assemblies per large HRB, because the only numbers that package well at the vehicle base are 1, 3, 4, and 7. Four has the highest score of these candidates and is within ~2% of the score of the unworkable five TCA options. Total TCA weight drops as the number increases, minimizing at about 4 or 5/HRB. Learning curve effects also favor use of a greater number of identical TCAs. Use of multiple TCAs also allows operation with failed TCAs if the system concept properly accounts for this factor.

TPA QUANTITY SELECTION



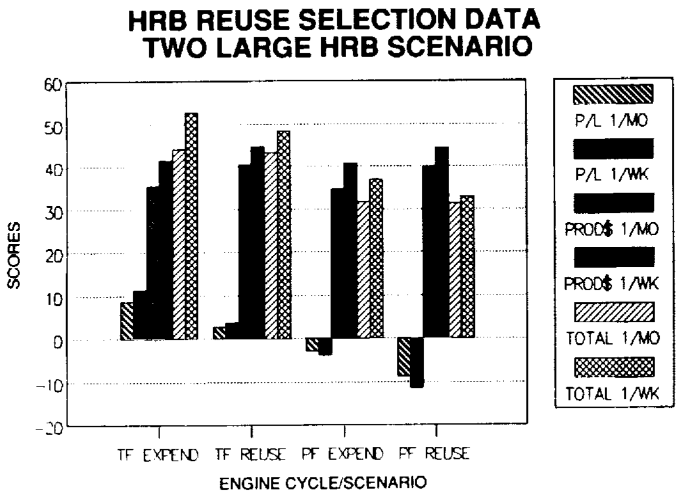
We selected four turbopump assemblies per large HRB, because they have the best score, and we get a one to one correspondence with four thrust chambers. Scores are higher for four TPAs, because their total weight minimizes at 4 or 5 and the learning curve reduces production costs of identical units.

EXIT PRESSURE/NOZZLE GEOMETRY
SUBSYSTEM OPTIMIZATION SELECTION

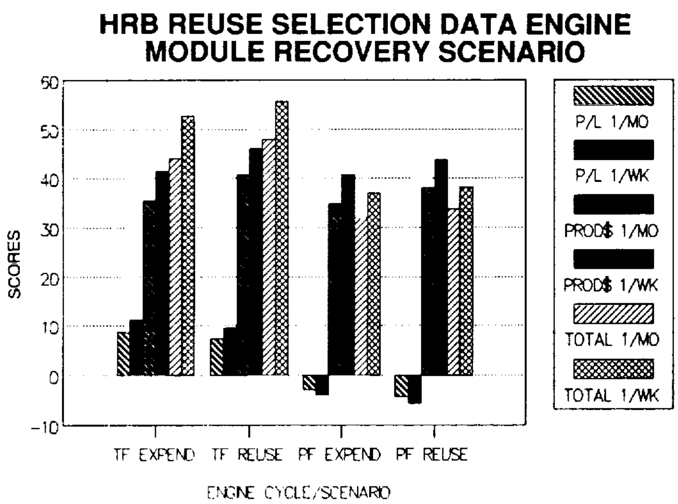


We selected large area ratio nozzles, because they score much better or a little better than small nozzles, depending upon the design and use scenario. For our selected design, turbopump fed, the large nozzle advantage can be as large as 15 to 20%. More frequent flights accentuate the payload carrying advantage of large nozzled boosters. The smaller TF and PF nozzles fit the current mobile launch platform (for single nozzled HRBs), and the large ones expand exhaust gases to the generally accepted "best" value of 41.37 kPa (6 psia.)

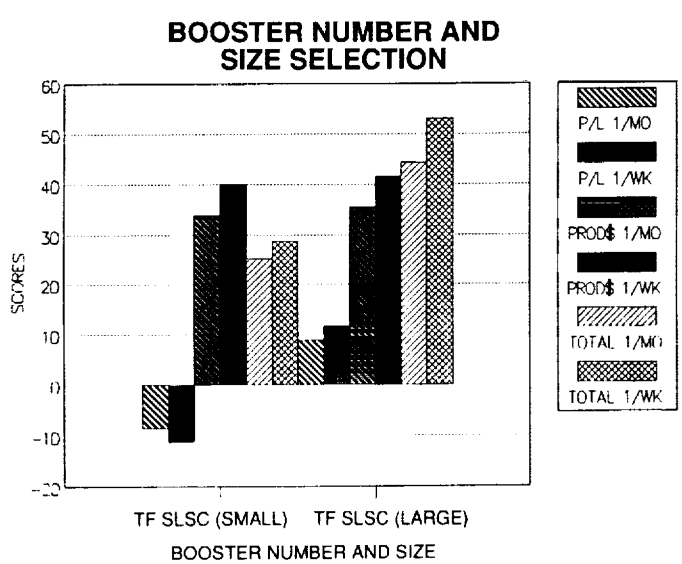
Figure 8. HRB Concept Scoring, Sheet 2 of 3



For high flight rates, expendable HRBs out score reusable ones, largely because of payload carrying differences. For lower flight rates the scores are equal. These results apply to both the selected turbopump fed and pressure fed HRBs. HRB reuse does not appear to offer many advantages, because refurbishment costs are high and learning curve production cost savings are not realized.



Reusable engine modules outscore expendable engines, because only relatively small, lightweight, and high valued HRB elements are recovered and refurbished. Thus, HRBs ought to be designed with recovery module integration in mind.



Use of two large HRBs per STS is favored over eight small ones by nearly 2 to 1 on the basis of scores. Small HRBs require more assembly hardware, add drag, and increase the amount of tankage and case hardware to be built along with their weights. Payload carrying losses reduce small HRB desirability considerably. Thrust chamber and turbopump development and production costs are not affected, because they are the same units in either scenario.

Figure 8. HRB Concept Scoring, Sheet 3 of 3

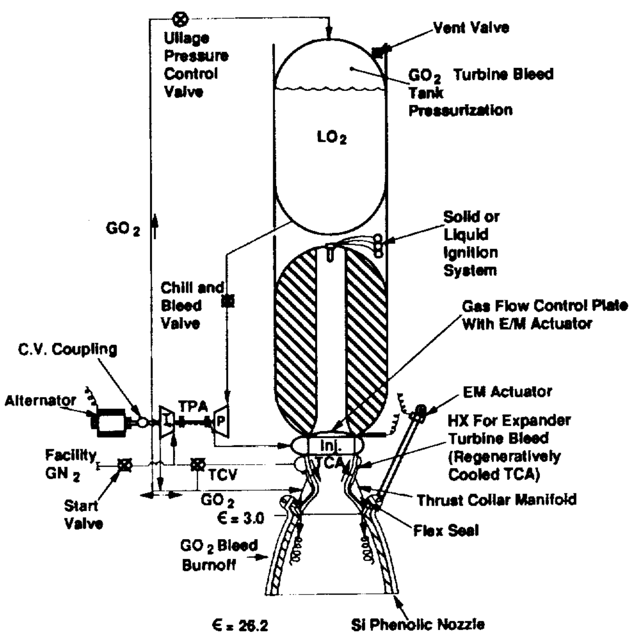
2.3 HRB CONCEPT SELECTION

The result of our selection system is a solid/liquid staged combustion cycle, pump fed, expander bleed burn-off cycle as shown in the flow schematic in Figure 9. The main features and benefits of this design are noted as is the operational sequence. Our concept design specification is summarized in Figure 10.

3.0 CONCEPT DESIGN

During the concept design phase of the study, we continued to prioritize the same criteria as we used in the scoring/selection process, i.e.

- Flight safety and reliability
- Low life cycle cost
- Performance
- Other important criteria
    - Availability (development risk, etc.)
    - STS compatibility



Main Features:	Main Benefits:
• No Throat Growth	Payload
• No Expensive Throat Material	Cost
• No Gas Generators or Diluent Systems	Cost and Payload
• No Seals in Turbopump - No Buffer Gas Systems	Safety, Cost and Payload
• Low Turbine Drive Temperature and I sp Losses	Payload and Cost
• Dump Cooled Large ϵ Low Cost Ablative Nozzles	Payload and Cost
• No Autogenous HX, Regulator, or Gas Bottles	Safety, Cost, and Payload
• No Flex Lines	Cost

HRB Operational Sequence is as Follows:

- Chill Down and Bleed in the LO_2 Pump and Injector With Bleed Valve
- Open Facility GN_2 Valve to Spin Turbo-pump With Turbine Bypass Valve Closed GN_2 Exhausts to Rocket Nozzle at $\epsilon = 3.0$
- Ignite Solid Propellant Grain
- Combustion in Thrust Chamber Begins when LO_2 and Solid Grain Fuel-rich Warm Gases Meet. LO_2 Bleed Flow in Regenerative Cooling Jacket Receives Heat
- Turbine Receives Heated O_2 and Flashes to GO_2 Drive Fluid in Nozzles. GO_2 Turbine Exhaust Follows N_2 into Burnoff Manifold at ϵ =3.0 in Rocket Nozzle and Forward to LO_2 Tank Ullage at 1.72 MPa (250 psia). Fuel-rich Boundry Layer Burns Off in Nozzle With GO_2 Turbine Exhaust
- LO_2 System Bootstraps as Solid Grain Fully Pressurizes. Remove Facility GN_2 Line
- Thrust is Controlled With Turbine Bypass Valve That Prevents Regenerative Coolant Flow Loss
- O / F Mixture Ratio is Controlled With Flow Control Plate Forward of Gas / Liquid Injector
- TPA Provides Alternator Power for Valve and TVC Actuators. Ablative Nozzle is Attached With a Flexseal
- Near End of Operation the LO_2 Ullage Pressure Control Valve is Closed to Let Ullage Pressure Drop to Reduce Tank Weight at Burn out and Tank Stiffness
- Shut Off LO_2 when Staging and Open Control Plate to Extinguish Solid Propellant

3.18.0.11

Figure 9. Our HRB Turbine Drive Cycle is Expander Bleed Burnoff Cycle (EBB)

- General Data
  - Propellants: Fuel Grain No. 8, Sat. HC [PEBC] and LO_2
  - Total [4 TCAs] MPL Thrust at Sea Level, 12.24 MN (2.75247 Mlbf)
    MPL Thrust at Vacuum, 14.01 MN (3.14874 Mlbf)
  - Combustion Scheme: Solid/Liquid Staged Combustion (SLSC)
  - Turbopump Drive Cycle: Expander Bleed Burnoff Cycle (EBB)
  - Gaseous O_2 Autogenous LO_2 Tank Pressurization From Turbine Exhaust
    — LO_2-Cooled Thrust Chamber
  - Dual Ignition System—Oxidizer Rich Liquid or Solid at Forward End of Grain
  - Electromechanical-Actuated TVC System With FlexSeal Mounted Nozzle
  - Turbopump Driven Alternator
  - All Hard Feed and Pressurization Lines and Engine Mounts
  - Solid Case Aft Head Is Engine Recovery Module Structure
- Design Point Data:
  - MPL TCA Pc, 11.72 MPa (1,700 psia)
  - Nozzle Area Ratio, 26.2 - Rao Contour
  - MPL Exit Pressure, 41.37 kPa (6 psia)
  - Throat Diameter, 45.7 cm (18 in.)
  - Exit Diameter, 233.7 cm (92 in.)
  - Combustion Mixture Ratio (CMR), 2.60
  - Liquid/Solid Mixture Ratio (LSMR), 1.90
  - MPL I_{sp} VAC and I_{sp} SL, 303 and 265 sec
  - 4 TCAs/TPAs Total Design Weight, 8346 kg (18,400 lbm)
  - Silica Phenolic/Nonmetallic Honeycomb Nozzle, GO_2 Cooled at $\varepsilon = 3$
  - Turbine Inlet Pressure and Temperature, 11.31 MPa (1,640 psia) and 478°K (860°R)
  - LO_2 Pump Outlet Pressure, 14.06 MPa (2,040 psia)
  - Solid Grain MPL Pressure, 12.89 MPa (1,870 psia)

Figure 10. Aerojet HRB TF Engine Concept Design Specification Summary

Figures 11 through 14 show our HRB concept with the design features that fulfill the criteria outlined above.

Figure 15 is an overview of the conceptual booster with the design features that we have incorporated to create an optimized booster. Details of the design, including engine layout, are included in the technical volume of this report.

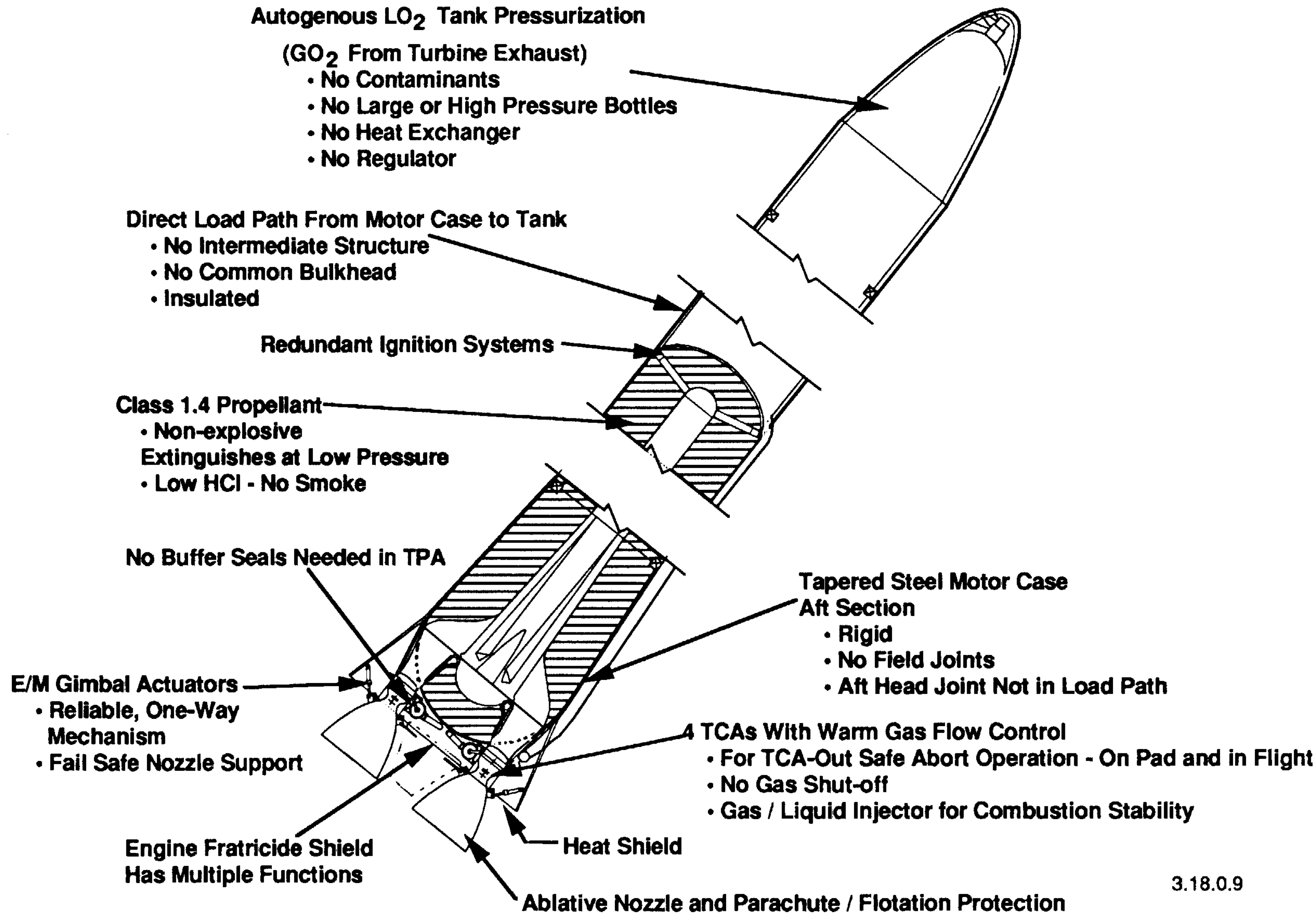


Figure 11. Our Design Provides Many Safety and Reliability Benefits – Safer Concept and Engine Out Operation

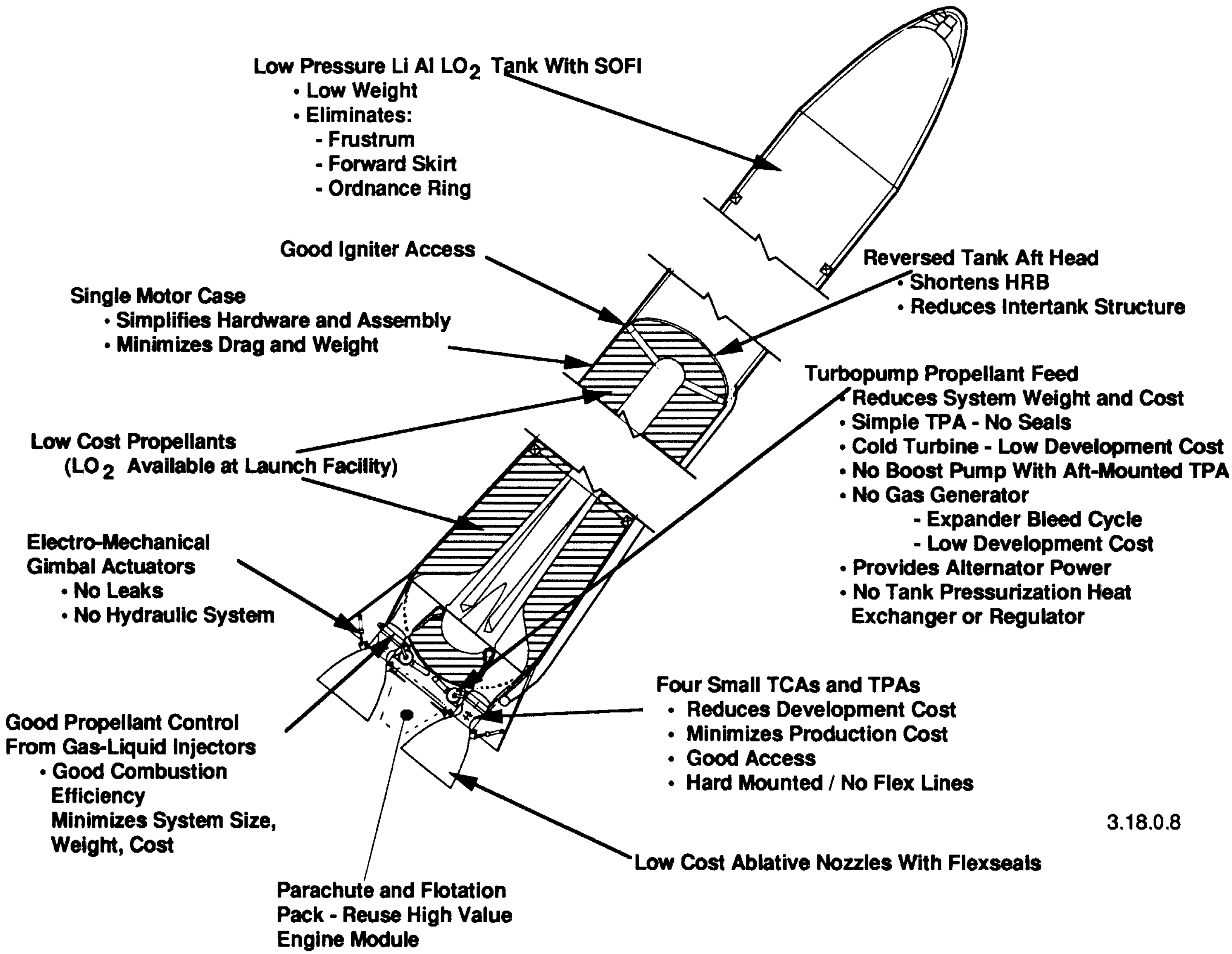


Figure 12. We Have Provided Life Cycle Cost Benefits – Lowest Weight and Simplest Concept

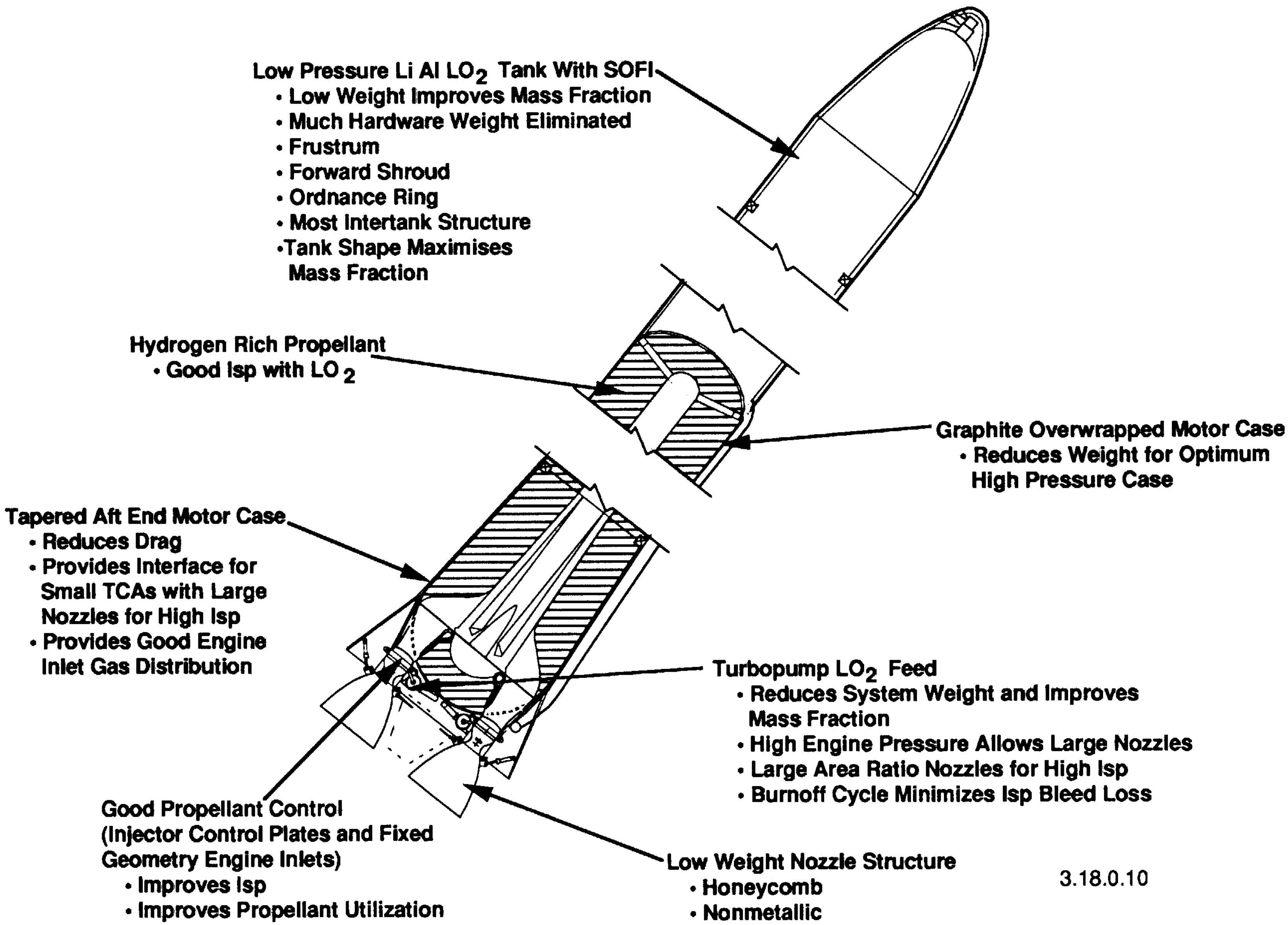


Figure 13. Payload Performance Benefits Are Derived From Our Design – Lowest Weight and Highest Isp

- **Retains Basic Launch Facility Configuration**
- **Maintains ET Attach Points**
- **Reduces Aerodynamic Drag**
- **Provides Increased Payload Capability**

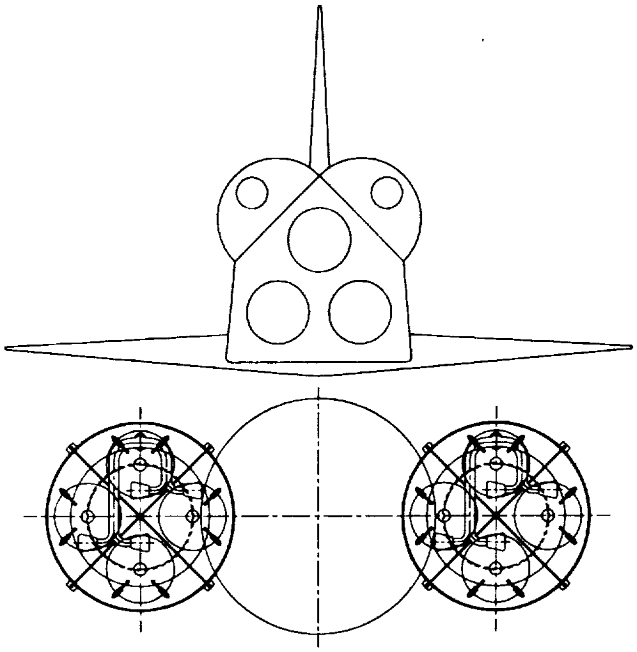


Figure 14. The Design is Compatible With the Space Transportation System

4.0 PLANNING: PHASE II - TECHNOLOGY ACQUISITION AND PHASE III - TECHNOLOGY DEMONSTRATION

In conjunction with our conceptual design, we have identified enabling technologies to bring an HRB to fruition. These are outlined in Figure 16.

Further, we evaluated schedules, costs, and test requirements for Phases II and III. The details of these studies may be found in the last section of the technical volume. In addition, we surveyed our in-house test capabilities and the test capabilities of government owned facilities.

The test planning for Phases II and III is summarized in Figure 17. We have selected thrust scaleup ratios that decrease as size increases. This reduces scaleup risk and provides a logical pattern of data throughout the range of potential application of the hybrid booster.

The test program for the Phase II 31 to 356 kN (7 to 80 klbf) units will be performed at the Aerojet Sacramento, CA facility where we have in-house capability requiring minimum modification.

The 1.8 MN (400 klbf) large-subscale demonstration will best fit the NASA MSFC Test Stand 116 capability which will be completely modified and will be available during Phase III.

Testing of the full sized 3.6 MN (800 klbf) HRB should be planned at MSFC on the planned/ modified FI stand.

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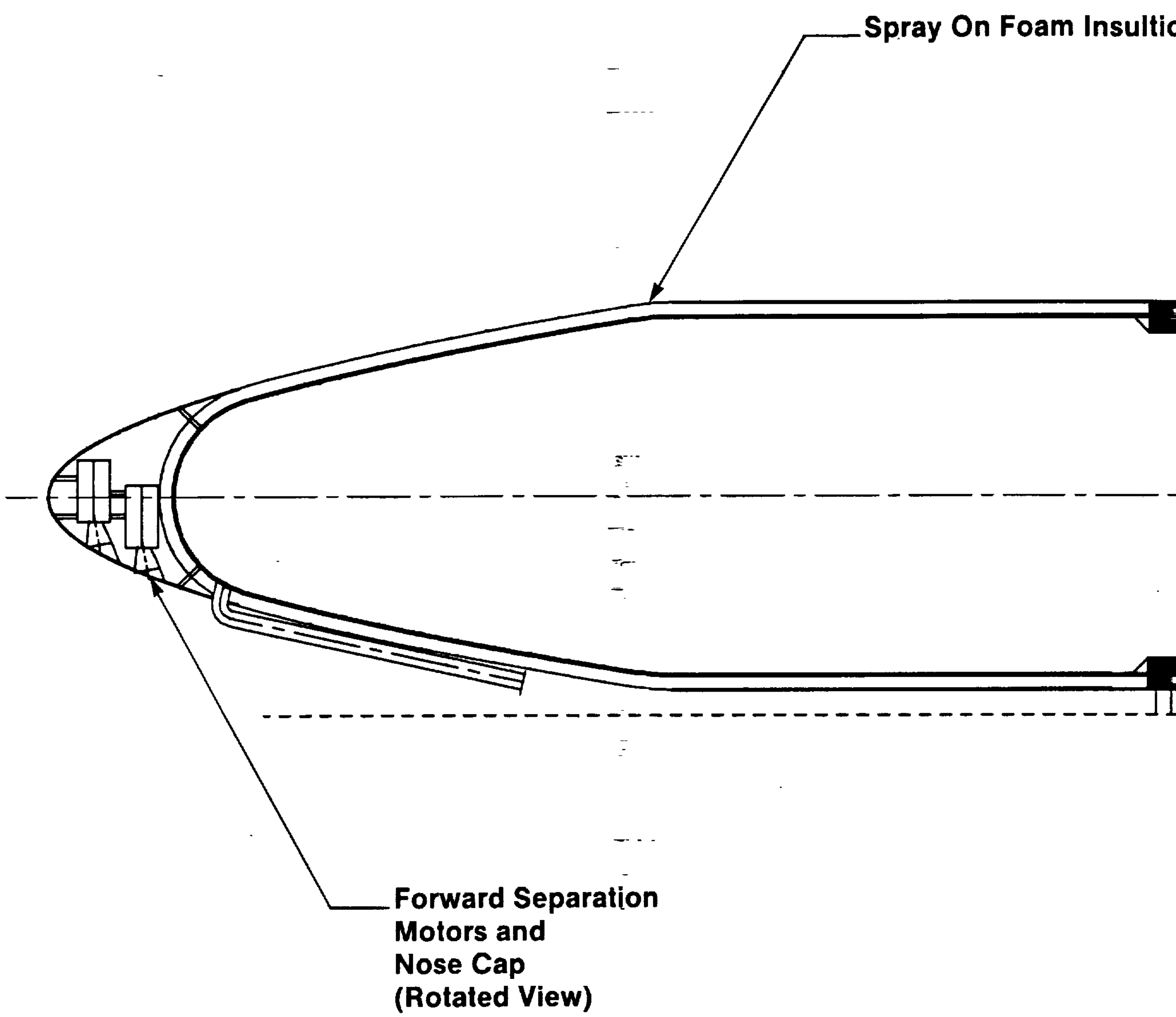

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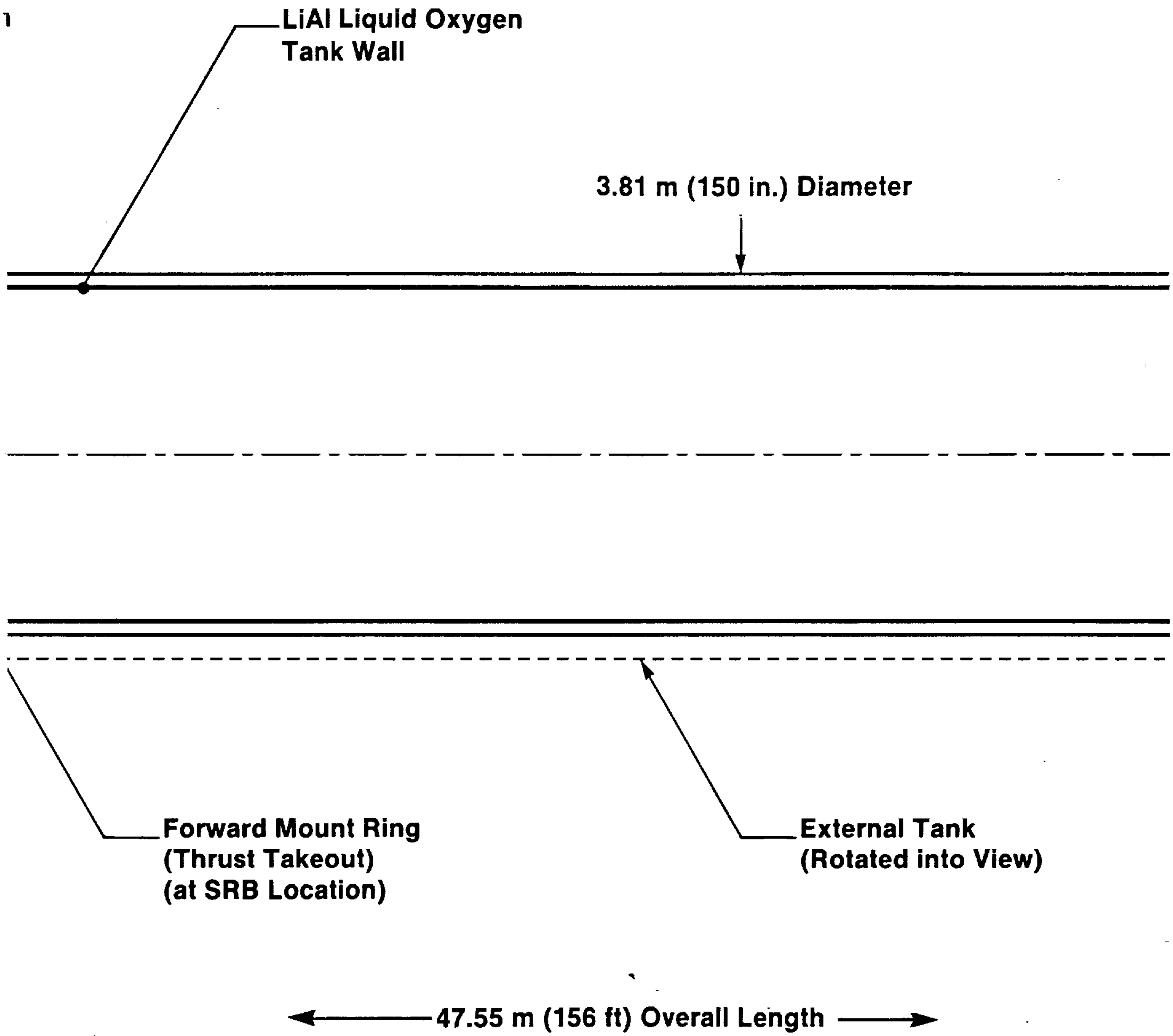
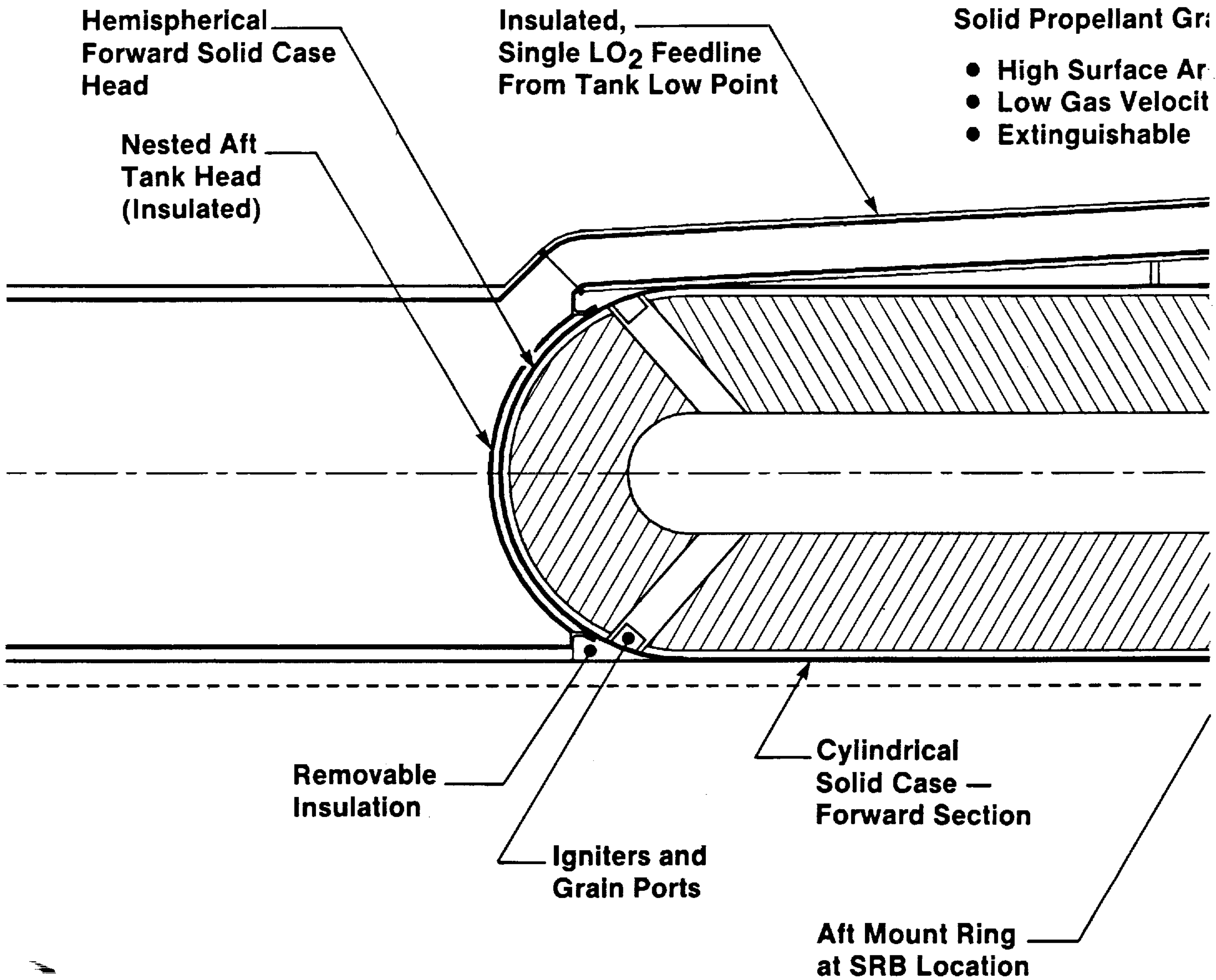
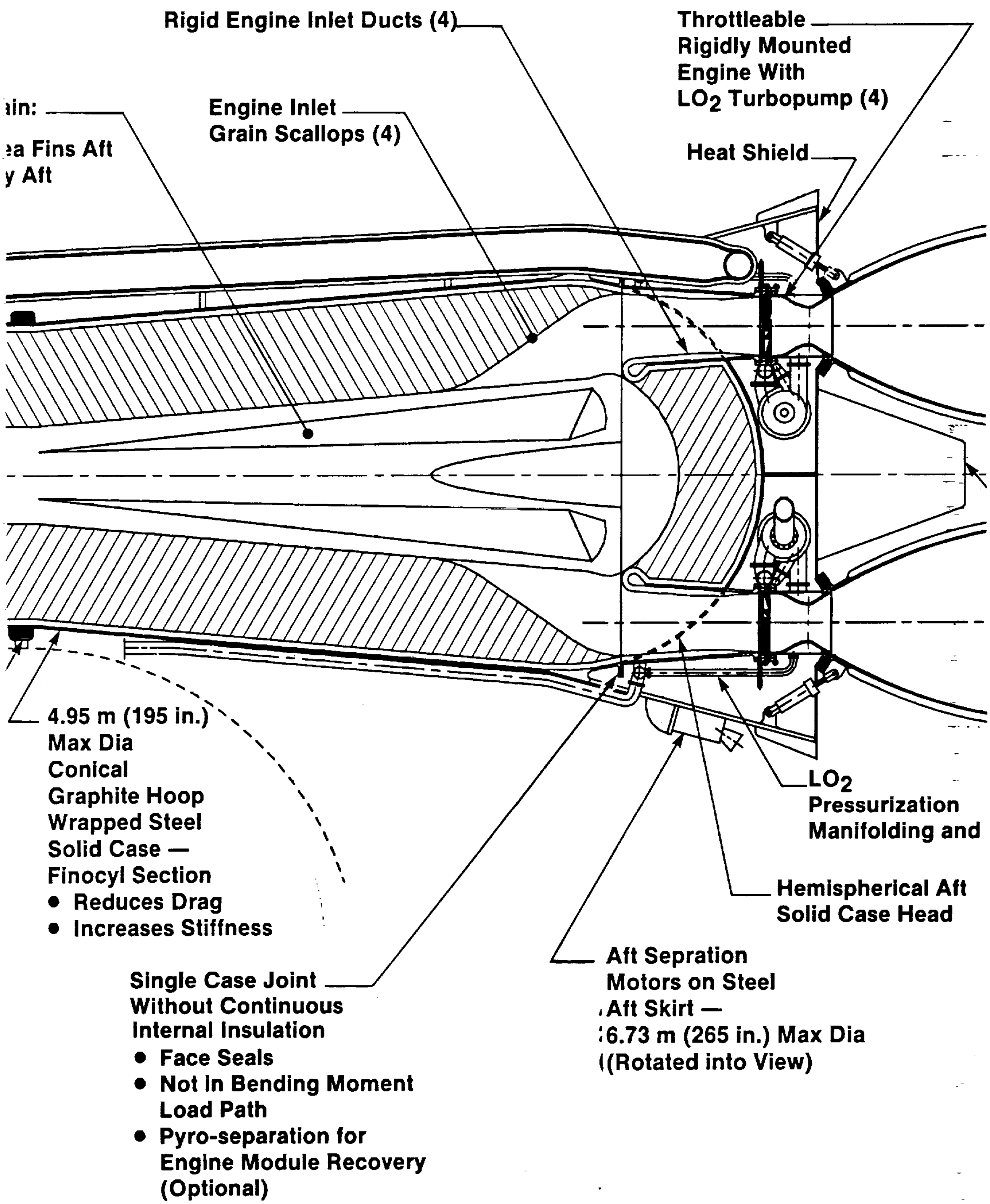



Hemispherical Forward Solid Case Head
Insulated, Single LO_2 Feedline From Tank Low Point
Solid Propellant Gr
● High Surface Ar
● Low Gas Velocit
● Extinguishable
Nested Aft Tank Head (Insulated)
Removable Insulation
Igniters and Grain Ports
Cylindrical Solid Case — Forward Section
Aft Mount Ring at SRB Location


Rigid Engine Inlet Ducts (4)
Throttleable Rigidly Mounted Engine With LO_2 Turbopump (4)
ain:
ea Fins Aft
y Aft
Engine Inlet Grain Scallops (4)
Heat Shield
4.95 m (195 in.) Max Dia Conical Graphite Hoop Wrapped Steel Solid Case — Finocyl Section
• Reduces Drag
• Increases Stiffness
LO_2 Pressurization Manifolding and
Hemispherical Aft Solid Case Head
Aft Sepration Motors on Steel Aft Skirt — 6.73 m (265 in.) Max Dia (Rotated into View)
Single Case Joint Without Continuous Internal Insulation
• Face Seals
• Not in Bending Moment Load Path
• Pyro-separation for Engine Module Recovery (Optional)

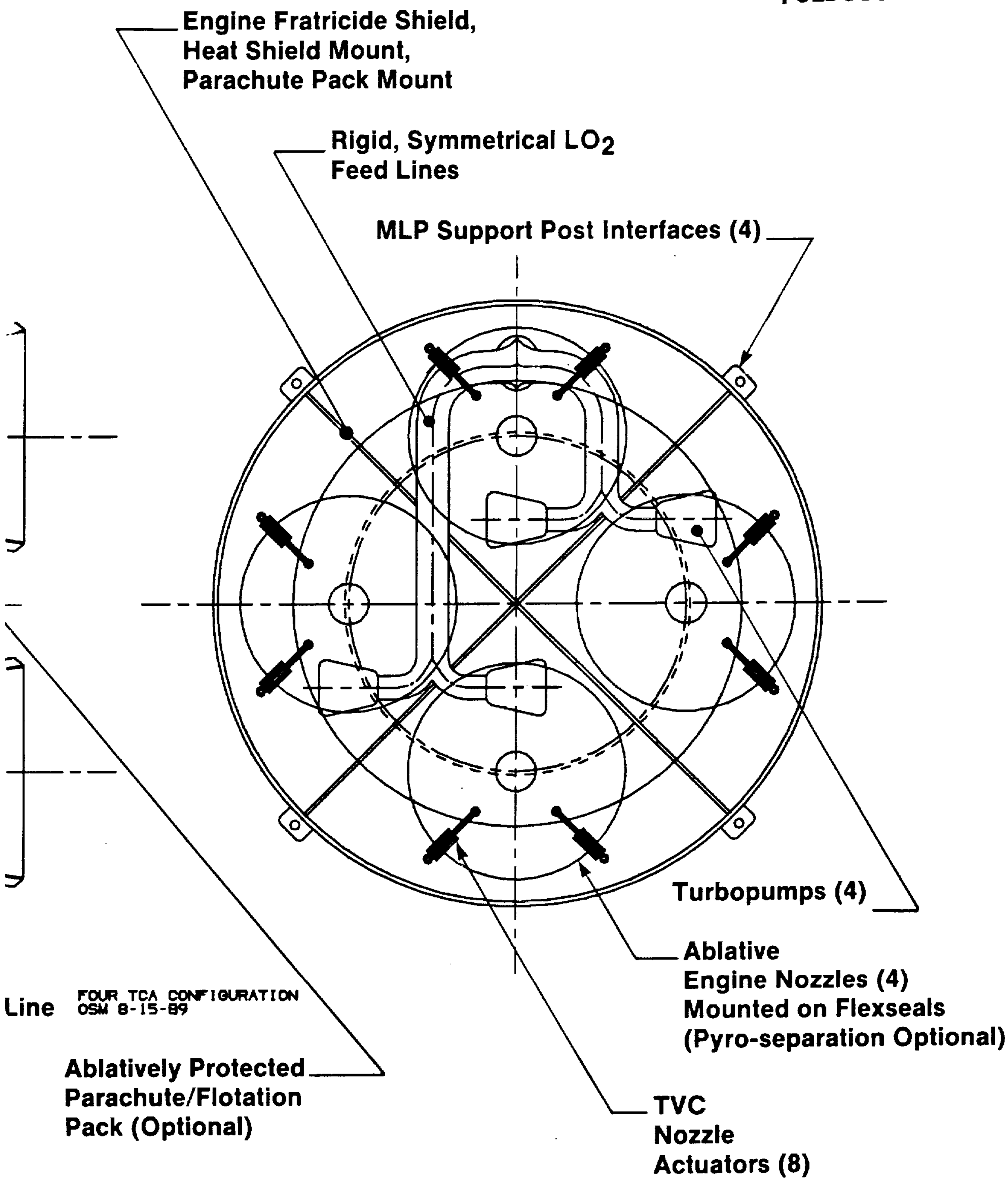


Figure 15. SLSC HRB Features

Priority	Technology	Benefit
1.	Solid Propellant Gas/Liquid Injector (Gas/Liquid Injectors Successfully Tested)	> 15% Higher Combustion Efficiency vs Forward Injection; Improves I_{sp}, Weight, Cost, and Payload
1.	Fuel-Rich Propellant and Ignition (Similar Propellant Successfully Tested)	Provides for Reduced LCC and ~20% P/L Advantage of SLSC Concept
2.	Fuel Rich Gas Control Plates (Routine With Fixed Plates)	Improved Both P/L and Cost: • Allows Safe Aborts With TCA Out • Provides Independent MR Control for Improved Propellant Utilization • Increases I_{sp} by Providing Uniform Gas Flow to Injectors • Protects Injector • Reduces Development Cost (Ignition and Stability)
3.	GO_2 Bleed Burnoff in Nozzle (Routine Without Combustion)	Improves Both P/L and Cost • Renders Low Cost Cycle Feasible • Reduces Turbine Bleed I_{sp} Loss • Protects Flex Seal and Cools Nozzle

Figure 16. We Have Selected and Prioritized Our HRB Technology

HRB Project Phase	Engine Vacuum Thrust Level	Thrust Scale-Up Ratio	Test Duration	Duration Scale-Up Ratio	Solid Case	Purpose
II.a.	31 kN (10 klbf)	—	4 sec		BATES Motor 0.305 m (12 in.) dia	• Solid Propellant • Injector (Performance)
		12.0		3.0		
II.b.	356 kN (80 klbf)	—	12 sec		Super BATES 0.711 m (28 in.) dia)	• Solid Propellant • Gas Control Plate • Bleed Burnoff (Performance)
		5.0		3.0		
III.	1.8 MN (400 klbf)	—	36 sec		Stage 2 Peacekeeper 2.34 m (92 in.) dia	• Cold GO_2 Turbine • LO_2 Cooled TCA • SS Splitline TVC
		2.0		3.5		• Hoop Wrapped • Coni-Cyl Case
Development and Production (Large HRB for STS)	3.6 MN (800 klbf)	—	128 sec		Production 3.71 m (146 in.) dia	• Flight

Risk Is Reduced With Decreasing Scale Up Ratios

Figure 17. A Logical Scale-Up, Low Risk Approach to HRB Technology Demonstration