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FINAL REPORT

CR-123614

EXECUTIVE SUMMARY

STUDY OF SOLID ROCKET MOTORS FOR A SPACE SHUTTLE BOOSTER

CONTRACT NO. NAS8-28429
JANUARY 13, 1972 TO MARCH 15, 1972

MARCH 15, 1972

PREPARED FOR
THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

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Volume I

Data Requirement MA-02

FINAL REPORT

EXECUTIVE SUMMARY

STUDY OF SOLID ROCKET MOTORS FOR A SPACE SHUTTLE BOOSTER

Contract No. NAS8-28429

January 13, 1972 to March 15, 1972

A. H. Von Der Esch
Lockheed Propulsion Company
Vice President, Technical and Marketing

MARCH 15, 1972

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ABSTRACT

On 13 January 1972, Lockheed Propulsion Company was requested by NASA to perform a study of the applicability of solid rocket motors as the booster for the Space Shuttle Vehicle. This volume of the final report presents a review of the activities of the study effort, the major findings and conclusions, as well as significant substantiating data.

Lockheed Propulsion Company's approach to the study was to use (1) a design approach representative of Phase B system contractor design input and based on conservative design practice, and (2) conservative costs based on large solid rocket motor experience and firm subcontractor quotes. The 156-inch-diameter, parallel-burn solid rocket motor was selected as the baseline design. Five motors of this size have been tested by LPC with complete success. Lockheed Propulsion Company believes this design to be the best solid rocket motor for the Space Shuttle Booster because:

- It provides low booster vehicle cost.
- It is the largest proven transportable system.
- It is a demonstrated design.

The key issues related to the SRM booster -- recovery/reuse, abort, and ecological considerations -- were evaluated, with the following conclusions:

- Recovery/reuse is feasible, and would significantly reduce costs from the baseline costs.
- Abort can be accomplished successfully.
- Ecological effects are minor, and therefore considered to be acceptable.

The current (Revision 1) baseline total program cost is 3.14 billion dollars and the total cost per launch is 7.1 million dollars. (recurring cost per launch is 6.6 million.)

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FOREWORD

This document is Volume I, Executive Summary, of Lockheed Propulsion Company's final report for the Study of Solid Rocket Motors for a Space Shuttle Booster. The study was conducted for the National Aeronautics and Space Administration under Contract Number NAS8-28429. The report is submitted in response to Data Requirement MA-05.

This final report is organized as follows:

Volume I	Executive Summary
Volume II	Technical Report
Book 1	Analysis and Design
Book 2	Supporting Research and Technology
Book 3	Cost Estimating Data
Volume III	Program Acquisition Planning
Volume IV	Mass Properties Report

CONTENTS

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SUMMARY

Lockheed Propulsion Company's objective from the outset of the Space Shuttle Program has been to provide complete and conservative design and cost parameters for an expendable Solid Rocket Motor (SRM) Booster Vehicle for the Space Shuttle Program. With this approach, LPC has attempted to identify the maximum technical and cost risks that could be encountered by NASA in employing a solid rocket motor as the Space Shuttle Booster Vehicle. Therefore, LPC believes that the baseline vehicle costs presented in this report are distinctly conservative and will be reduced upon further definition and detailed estimating. Two items, which LPC has not included and which will affect a fixed-payload program cost, are escalation and profit, both of which were directed in the Study Contract to be deleted from consideration.

As directed by NASA, LPC also attempted to determine "hard" versus "soft" costs, and an upper band was established above the baseline for a "worst condition." As a result of Lockheed's solid rocket motor experience, the propulsion system costs are "hard" and, therefore, an upper limit of 2 percent on the SRM cost has been defined. LPC believes that the Stage costs are "soft" and a 30-percent upper limit on the Stage cost was established. With the SRM and Stage combined, a total of 10-percent upward variation has been identified in the Booster Vehicle (WBS 3.3) Program costs. A lower range has also been established, which identifies potential reductions for thrust vector control, thrust termination, and recovery.

The Booster Vehicle selected as the baseline configuration is a parallel-burn (two-motor) 156-inch-diameter SRM vehicle sized for the large (65,000-pound) Orbiter payload. The baseline program assumed for study purposes includes a 5-year (1973 - 1978) development/qualification program, a 13-year (1976 - 1988) production program, and an 11-year (1978 - 1988), 440 vehicle launch program.

The development program includes 25 SRMs; 5 development motor tests, 4 PFRT motor tests, 2 inert booster vehicles (2 SRMs per vehicle) and 6 launches (1 unmanned and 5 manned flights with 2 SRMs per vehicle). All 25 motors in the development program will be fabricated in LPC's existing, large-motor Potrero manufacturing facility. The development program schedule was established at 5 years to minimize annual funding and could be shortened by as much as 1 year without impacting the launch schedule.

The production program of 440 launches includes manufacture of 883 SRMs (880 for launches and 3 for production facility start-up demonstration) and 440 sets of Stage hardware. Due to the nature of the solid rocket motor, quality is ensured by the facility process controls in manufacturing. Thus a three-motor test program is planned to demonstrate that the production facilities will reproducibly deliver the SRMs qualified during development. As directed in the Study Contract, all launches were considered to be from Kennedy Space Center (KSC).

Lockheed Propulsion Company, as prime contractor for the Booster Vehicle, would utilize all of the industry production capability before additional facility expansion. LPC would subcontract to at least two other SRM manufacturers for a portion of the production motors. Additionally, all components would be considered for dual procurement to ensure a redundant capability for Booster Vehicle delivery. This LPC plan provides Booster Vehicle procurement at a very low risk to NASA in e event of a labor, facility, or material problem at any time during the program. This approach also results in a relatively low facility expansion cost ($25.7 million) for the production program and avoids the building of a brand new facility, which would cost approximately $70 million.

The three production facility start-up demonstration tests are considered adequate by LPC to qualify the three production facilities (LPC and two others) for the baseline costing effort. It was considered that NASA might desire additional testing to qualify the new subcontractors ("second sources") and, therefore, nine motor tests were included in establishing the upper limit 2-percent variation in SRM costing. However, LPC recommends only three tests and has used this in the baseline costing.

Previously, it has been stated that the baseline design is conservative. As evidence of this, all metal structures have a minimum safety factor of 1.4. This has naturally imposed an additional cost on materials, but LPC believes that this should be maintained, thus guaranteeing the high reliability required for a man-rated system. As a bonus feature, analysis indicates that the motor chamber with this safety factor (wall thickness 0.460 inch) will withstand water impact loads at 100 feet per second and at entrance angles up to 45 degrees. Although recovery/reuse is not considered in the baseline costing, Lockheed's SRM design should therefore not require additional strengthening (higher material costs) should recovery/reuse prove cost-effective for the Booster Vehicle.

As further evidence of a conservative design, the safety factor for all ablative insulation materials was established at 2.0. Once again, it is felt that this should be maintained for man-rated reliability. In the areas of thrust termination (TT) and thrust vector control (TVC), no firm requirement was established by either the Phase B contractors or by the customer. LPC assumed that the Booster Vehicle would require both TT and TVC, plus a strenuous TVC duty cycle, which sized the system conservatively.

The baseline costs are backed by firm vendor quotes on procured components and conservative labor estimates. Lockheed's labor estimates were prepared from a task definition or "ground-up" standpoint, based on previous LPC large-motor experience, other LPC rocket motor programs, and also on related industry experience on solid propellant rocket motors. Nine full-scale, 156-inch-diameter demonstration motors have been test-fired to date, five by Lockheed Propulsion Company. These tests are summarized in the following table.

SUMMARY OF 156-INCH LARGE SOLID ROCKET MOTOR TESTS

		Motor Description		Test Data	
No.	Date	Designation	Fabrication	Maximum Thrust (lb)	Average Thrust (lb)
1.	1964 May	156-3	LPC	0.95M	0.88M
2.	Sep	156-4	LPC	1.09M	1.00M
3.	1965 Feb	156-2C-1	TCC	3.25M	2.97M
4.	Dec	156-1	TCC	1.47M	1.29M
5.	Dec	156-5	LPC	3.11M	2.84M
6.	1966 Jan	156-6	LPC	1.03M	0.94M
7.	Apr	L-73	LPC	0.66M	0.60M
8.	May	156-7	TCC	0.39M	0.32M
9.	May	156-9	TCC	0.98M	0.88M

All of these motors, with thrust levels up to three million pounds, performed within 2 percent of their calculated parameters, and only one incident (involving the loss of an exit cone in a moveable nozzle test by another contractor) was experienced. This is a significant feat in that each of the nine motors was a "one-of-a-kind" configuration and involved reuse of LPC-designed case hardware as many as four times. Lockheed is proud of this 100-percent successful completion of its five 156-inch motor tests, which were accomplished under-budget on firm fixed price contracts (see USAF Testimonials in Appendix A of the Cost Book).

As previously stated, the experience gained in these programs was applied by all LPC branches in estimating the labor for the Booster Vehicle. In the area of motor processing, the hands-on-hardware "first-unit" labor hours for the baseline were estimated, and then a 90-percent labor improvement or learning curve was applied. Comparison with both LPC experience and other SRM industry experience indicates that this is conservative; in the majority of previous programs, improvement curves in the middle to low eighties have been experienced. For example, on the basis of two large weapon systems, Minuteman and Poseidon, an improvement curve in the 80- to 85-percent range should be achievable in the Booster Vehicle. For this additional reason, LPC, employing a 90-percent curve, has estimated the baseline configuration production costs in a conservative manner.

As another consideration in development of the costs, LPC began this study on 13 January 1972 assuming that the Booster System (WBS 3.0) was to be costed. On 2 February, LPC was notified that the SRM contractors were to price at the Booster Vehicle level (WBS 3.3). While this was intended by NASA to alleviate the SRM contractors' efforts in the short study time available, it did turn out to add another variable, which is reflected as additional conservatism in the LPC costs. Included in LPC's costs are some items that could be interpreted as belonging under Booster Management (WBS 3.1), System Engineering (WBS 3.2), or Booster System Support (WBS 3.5), which may not be included in the cost estimates of the other study contractors.

The Booster Vehicle program costs (WBS 3.3) presented by LPC on 14 and 23 February 1972 were based on the previously defined configuration and costing assumptions. The LPC baseline Booster Vehicle cost estimate presented on these dates is summarized below.

	SRM	Stage	Total Booster Vehicle
Development	$ 141.6M	$ 48.2M	$ 189.8M
Production	2,545.7M	929.0M	3,474.7M
	$2,687.3M	$977.2M	$3,664.5M
Total Program Cost/Launch	$ 6.0M	$ 2.2M	$ 8.2M
Recurring Cost/Launch	$ 5.8M	$ 2.0M	$ 7.8M

The total program cost per launch is developed by dividing the total program cost (3,664.5 million) by the total number of manned launches (445). Although cost per launch does not normally include amortization of DDT&E or non-recurring production items, LPC chose to attempt to display the total program liability that NASA could encounter in employing a solid rocket motor Booster Vehicle. The standard way of displaying cost per launch is by using the recurring unit cost, which, for LPC's baseline, is $7.8M. Once again, these program costs were developed early in the Study Program with the objective of identifying the maximum technical and cost risk that could be encountered by NASA.

On 12 February, after the cut-off date for the 14 and 23 February presentations, Lockheed began a second iteration of the program baseline configuration and cost. Labor and material were analyzed in more depth, more definition was prepared to separate recurring from nonrecurring costs, and the Operations portions of the SRM and Stage were separated into more identifiable activities. This resulted in a redistribution of the baseline costs as shown in the following two tables:

	SRM	Stage	Operations	Total
Development	$ 131.0M	$ 31.0M	$ 27.8M	$ 189.8M
Production	2,303.9M	626.5M	544.3M	3,474.7M
	$2,434.9M	$657.5M	$572.1M	$3,664.5M

Note that in both tables the previously shown total program costs have remained unchanged but are redistributed by LPC for better understanding.

	Total Costs	Recurring Cost/Launch	Total Cost/Launch
Recurring SRM production	$2,242.8M	$5.1M	$5.1M
Recurring Stage production	626.5M	1.4M	1.4M
Recurring operations	544.3M	1.2M	1.2M
Nonrecurring production	61.1M	0	0.1M
Development	189.8M	0	0.4M
Total	$3,664.5M	$7.7M[a]	$8.2M

The next step in the second iteration of the baseline configuration and cost was to review areas where cost might be overly conservative and could thus be reduced. Since the hardware is a major portion of the SRM cost, additional definition and breakdown of vendor component and material costs were requested from the subcontract suppliers. In vehicle configuration, better design definition was developed and rebids were prepared in some areas. As an example, in January, prior to completion of the TVC system sizing, quotes had to be obtained on the actuator. LPC requested bids on the actuator used on the S1-C Vehicle, knowing that it would be more than adequate for the job. The actuator requirement was found to be far less and was rebid at a significantly lower cost. Safety factors of all hardware were maintained and the material costs still reflect safety factors of 1.4 on structures and 2.0 on ablative insulations.

The motor processing tasks and the improvement/learning curve were reviewed in considerable depth. A steeper curve (86 percent) was selected as realistic but still sufficiently conservative in comparison to other major solid rocket motor programs and LPC's 156-inch motor experience. Assembly and support labor were also analyzed and some areas of redundancy between WBS paragraphs were identified and deleted. The analysis of labor and material on the SRM has resulted in a lower unit cost position for the SRM baseline. These analyses have been time-consuming and, although some areas of the Stage attachment hardware and Operations have been reviewed and reduced, additional effort is being expended by Lockheed toward further definition, analysis, and reduction.

To support a final report date of 15 March, a cut-off was made on 8 March in the second costing iteration. The reduced program costs are shown in the following table as "Baseline, Revision 1" and are compared by item to the original baseline costs shown previously.

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[a] As a minor note, the redistribution identified additional nonrecurring production costs, resulting in a lower recurring cost per launch.

	Baseline Cost	Reduction	Baseline Revision 1
Recurring SRM Production	$2,242.8M	$266.8M	$1,976.0M
Recurring Stage Production	626.5M	155.7M	470.8M
Recurring Operations	544.3M	98.0M	446.3M
Nonrecurring Production	61.1M	0	61.1M
Development	189.8M	3.7M	186.1M
	$3,664.5M	$524.2M	$3,140.3M
Total Cost/Launch	$ 8.2M	$ 1.1M	$ 7.1M
Recurring Cost/Launch	$ 7.7M	$ 1.1M	$ 6.6M

Each of the reductions shown in this table is discussed in the Addendum to the cost book of the final report. The cost per launch, both recurring and total, has been reduced by over a million dollars. Further analysis will yield even more reductions in the areas of Stage and Operations. It is believed by Lockheed that the SRM, however, will not yield further major reductions without a change in either performance or hardware safety factors, which is not recommended by LPC.

Therefore, the Baseline Revision 1 costs ($3,140.3B) are submitted as Lockheed's formal position on the SRM Booster Vehicle (WBS 3.3).

The conclusions of the LPC study are:

(1) The LPC 156-inch-diameter baseline design meets all the technical requirements for the Booster Vehicle.

(2) The baseline design appears to have the structural capability to withstand recovery-load impacts should recovery/reuse prove cost-effective for the Booster Vehicle.

(3) The SRM Booster Vehicle, because of its demonstrated technology, can be developed to meet all NASA schedule requirements.

(4) The Baseline Revision 1 costs are realistic and achievable and are subject to further reduction.

(5) The cost for development ($186.1M) of an expendable SRM Booster Vehicle are less than 4.0 percent of the total Space Shuttle Development budget ($5.5B).

(6) The Baseline Revision 1 SRM Booster Vehicle cost per launch (recurring $6.6M, total $7.1M) is less expensive than that of a liquid booster.

In summary, Lockheed believes that an SRM propulsion system can perform the mission, can be easily developed in the time available, and will prove to be a cost-effective booster vehicle for the Space Shuttle Program.

Section 1

GROUNDRULES AND APPROACH

The study requirements specified by NASA are summarized as follows:

NASA STUDY REQUIREMENTS

TECHNICAL

- ORBITER PAYLOAD - 45 AND 65 K POUNDS
- PARALLEL AND SERIES BURN/120 AND 156-INCH SRM/EXPENDABLE AND REUSABLE/WITH AND WITHOUT TVC/WITH AND WITHOUT THRUST TERMINATION
- PERFORMANCE REQUIREMENTS FROM PHASE B CONTRACTORS

SCHEDULE

- DEVELOPMENT - 5 YEARS (1973 - 1978)
- PRODUCTION - 13 YEARS (1976 - 1988)
- LAUNCH TRAFFIC - 11 YEARS (1978 - 1988)
- LAUNCH SITE - KSC ONLY
- MAXIMUM YEARLY LAUNCH RATES AND TOTAL PROGRAM QUANTITIES
  - 10/106
  - 20/201
  - 40/357
  - 60/445

COST

- COST DATA - 1970 DOLLARS (NO ESCALATION)

In addition to the NASA-specified study requirements, LPC imposed additional groundrules on itself for the conduct of the study.

LPC STUDY GROUNDRULES

BASELINE DESIGN MUST:

- REFLECT TYPICAL PHASE B STUDY RESULTS
- USE DEMONSTRATED TECHNOLOGY
- EMPHASIZE HIGH RELIABILITY

BASELINE COST MUST:

- USE SUPPORTABLE COST ESTIMATING
- REFLECT PAST MANUFACTURING EXPERIENCE

Section 2

CONCLUSIONS

Technical

(1) The 156-inch-diameter baseline design presented meets all the technical requirements for the Booster Vehicle.

(2) The baseline design appears to have the structural capability to withstand recovery load impacts should recovery/reuse prove cost-effective for the Booster Vehicle.

(3) Abort can be accomplished successfully.

(4) Ecological effects are acceptable.

Schedule

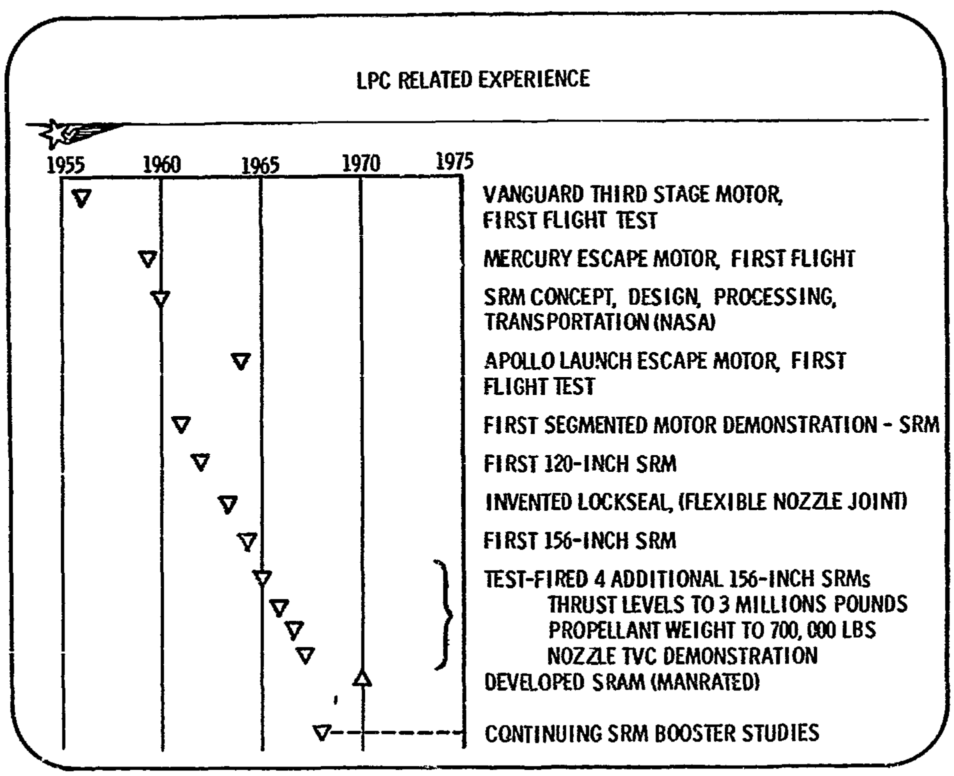
The SRM Booster Vehicle, because of its demonstrated technology, can be developed to meet all NASA schedule requirements.

Cost

(1) The Baseline Revision 1 costs are realistic and achievable and are subject to further reduction.

(2) The cost for development ($186.1M) of an expendable SRM Booster Vehicle is less than 4 percent of the total Space Shuttle Development budget ($5.50B).

(3) The Baseline Revision 1 SRM Booster Vehicle cost per launch (recurring $6.6M, Total $7.1M) is less expensive than that of a liquid booster.


LPC RELATED EXPERIENCE
1955
1960
1965
1970
1975
VANGUARD THIRD STAGE MOTOR, FIRST FLIGHT TEST
MERCURY ESCAPE MOTOR, FIRST FLIGHT
SRM CONCEPT, DESIGN, PROCESSING, TRANSPORTATION (NASA)
APOLLO LAUNCH ESCAPE MOTOR, FIRST FLIGHT TEST
FIRST SEGMENTED MOTOR DEMONSTRATION - SRM
FIRST 120-INCH SRM
INVENTED LOCKSEAL (FLEXIBLE NOZZLE JOINT)
FIRST 156-INCH SRM
TEST-FIRED 4 ADDITIONAL 156-INCH SRMs
THRUST LEVELS TO 3 MILLIONS POUNDS
PROPELLANT WEIGHT TO 700,000 LBS
NOZZLE TVC DEMONSTRATION
DEVELOPED SRAM (MANRATED)
CONTINUING SRM BOOSTER STUDIES

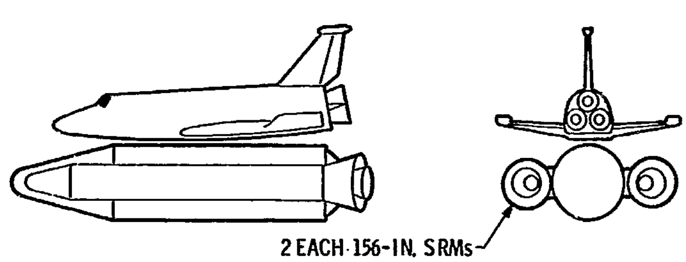
Section 3

SUMMARY

3.1 DESIGN AND PERFORMANCE

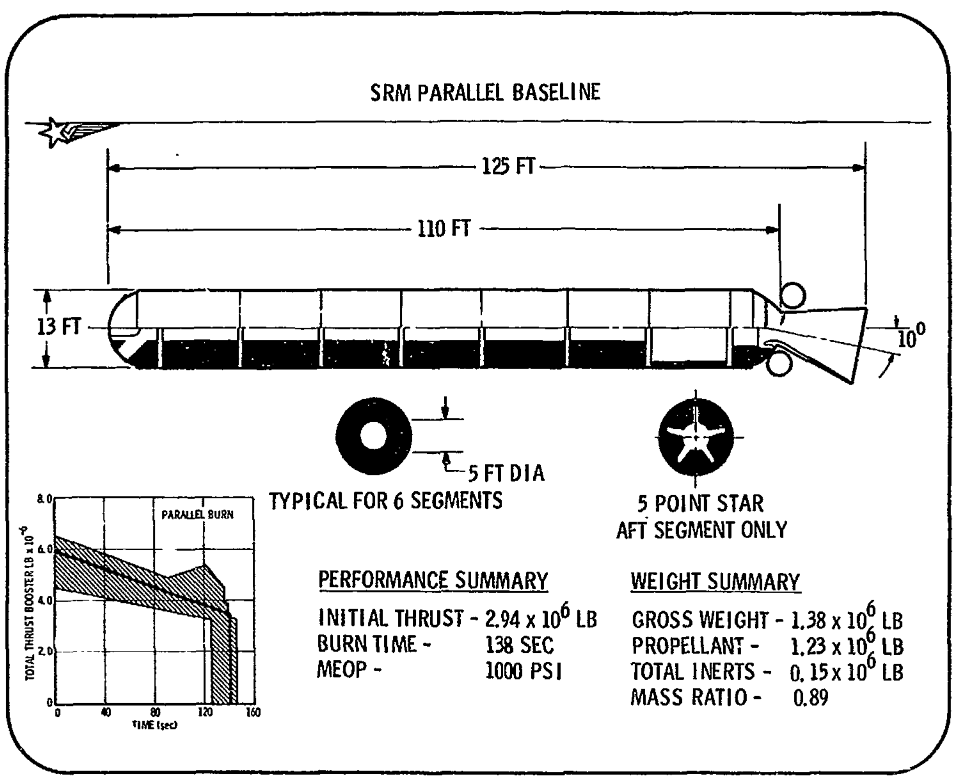
The baseline parallel burn vehicle configuration is shown below. It is representative of the most conservative configurations and vehicle weights received from the Phase B systems contractors. The booster lift-off weight of 2.835 million pounds is compatible with the 65,000-pound payload.

156-INCH VEHICLE BASELINE
PARALLEL BURN



WEIGHTS LB x 10^{-6}	
ORBITER LIFT-OFF WEIGHT	1.800
BOOSTER LIFT-OFF WEIGHT	2.835
GROSS LIFT-OFF WEIGHT	4.635

The illustration below shows the general configuration, performance, and weight information for the selected baseline motor, a 156-inch, parallel-burn, 7-segment SRM. The inert weights and mass fraction are conservative. They include the effects of thrust termination and a thrust vector control system designed to meet a most severe set of requirements. The baseline thrust-time curve is shown in the middle of the cross-hatched area. This band represents the extremes of Phase B prime contractor inputs. Motor performance can be tailored to match any of the specific prime requirements.



BASELINE SRM COMPONENTS

	WHAT	WHY
MOTOR CASE	D6AC, 225 KSI ULTIMATE	EXTENSIVE PRODUCTION EXPERIENCE - MINUTEMAN
NOZZLE	ABLATIVE PLASTIC THROAT	LOW RISK; MATERIALS PROVEN
IGNITER	HEAD END PYROGEN	CONVENTIONAL SRM APPROACH
INTERNAL INSULATION	FILLED NBR SHEET STOCK, AUTOCLAVE CURE	PROVEN RELIABILITY
PROPELLANT	PBAN, LPC-580, CLASS II	DEMONSTRATED ON 156-INCH SRM's
THRUST TERMINATION	DUAL HEAD END PORTS	POSEIDON, MINUTEMAN, AND TITAN III
THRUST VECTOR CONTROL	LOCKSEAL FLEXIBLE JOINT	100 SUCCESSFUL FLIGHTS - USED ON POSEIDON

The basis for selection of the components for the baseline SRM is demonstrated experience. This approach provides for minimum-risk booster development and the availability of cost information based on actual experience. Each of the components has an extensive production history. The propellant, polybutadiene acrylonitrile (PBAN), was used in previous 156-inch motors fired at Lockheed Propulsion Company. This propellant has been classified by the ICC as Class II, fully safe to handle, ship, and store without danger of detonation.

The key stage features are shown below. Conventional attachment and separation methods are incorporated in the design. The electrical characteristics are also straightforward, with emphasis on safety and high reliability.

BASELINE STAGE FEATURES

	WHAT	WHY
MECHANICAL	THRUST TAKE-OUT FORWARD ON CENTERLINE	DISTRIBUTION OF LOADS
	FLARED AFT SKIRT	REDUCED NOZZLE TORQUE
	SMALL SOLID MOTORS FOR SRM SEPARATION	RELIABLE, POSITIVE SEPARATION FORCE
ELECTRICAL	NO RACEWAY; UMBILICAL TO ORBITER	SIMPLICITY, COST
	EBW HIGH VOLTAGE INITIATION	SAFETY, RELIABILITY
	REDUNDANT CIRCUITRY AND POWER	RELIABILITY

3.2 KEY ISSUES

Lockheed Propulsion Company has evaluated the key issues related to the SRM booster: recovery/reuse, abort, and ecological considerations. The results of this evaluation are summarized below, with additional detail on the following pages.

SUMMARY - KEY ISSUES

RECOVERY / REUSE

- RECOVERY FEASIBLE, REQUIRES DEVELOPMENT
- MINIMUM RECOVERY WEIGHT (175K) EASES DEVELOPMENT
- REUSE SAVES $868 MILLION PROGRAM COSTS (10 REUSES)

ABORT

- SAFE ABORT PRACTICAL
- INDEPENDENT ESCAPE SYSTEM REQUIRED

ECOLOGY

- WASTE DISPOSAL NO PROBLEM
- NOISE NO PROBLEM
- $HC\ell$ IN LAUNCH PLUME - POSSIBLE MINOR PLANT EFFECTS

3.2.1 Recovery and Reuse of SRM Booster

The following chart shows the effect of the number of reuses on total program cost and cost per launch. Two items are particularly significant:

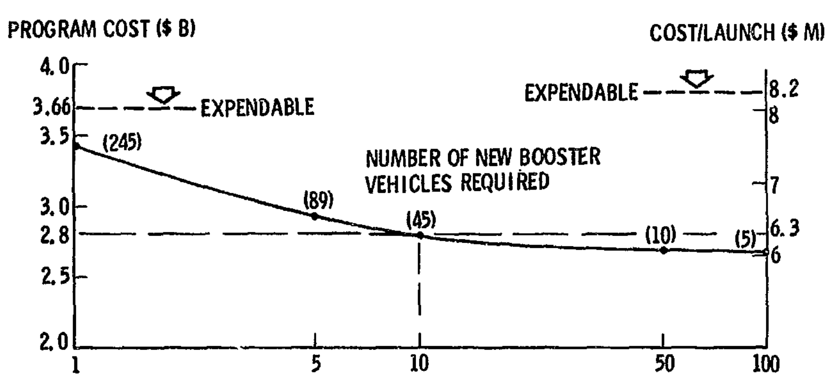
(1) The total program cost and cost per launch are reduced by approximately 25 percent with recoverability.

(2) Most of the savings from recoverability are achieved with only 10 reuses.

Although much additional study and development remain to be accomplished, SRM recovery and reuse is feasible and cost effective.

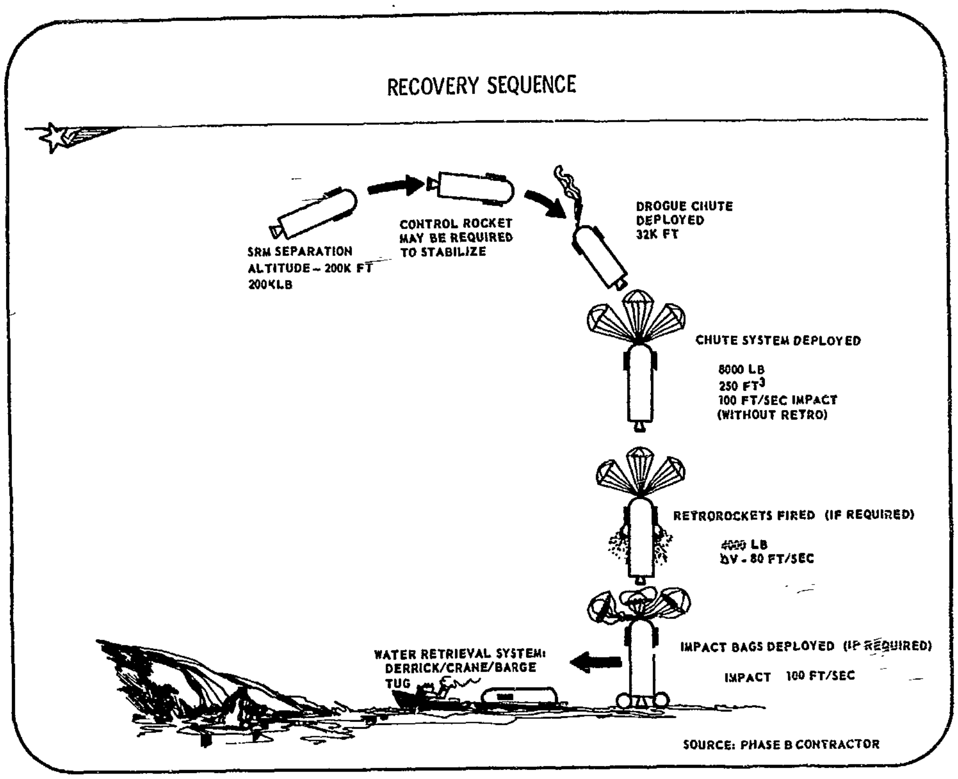
The effect of the program development/facilities cost on reuse savings can be considered minimal. An increase from the baseline development/facility estimate of $25 million to $100 million would reduce the potential savings per launch by less than 10 percent.

EFFECT OF RECOVERY/REUSE
TOTAL PROGRAM COSTS & LAUNCH COSTS
(ALL COSTS TO WBS 3.3)



NUMBER OF REUSES, 445 LAUNCHES
(DEVELOPMENT COST $25M)

NOTE: MOST OF THE SAVINGS AVAILABLE BY RECOVERY/REUSE ARE ACHIEVED WITH 10 REUSES - ALL REPORTED COSTS FOR RECOVERY BASED ON 10 REUSES. LOWER COSTS ACHIEVABLE WITH REVISION I TO BASELINE COSTS

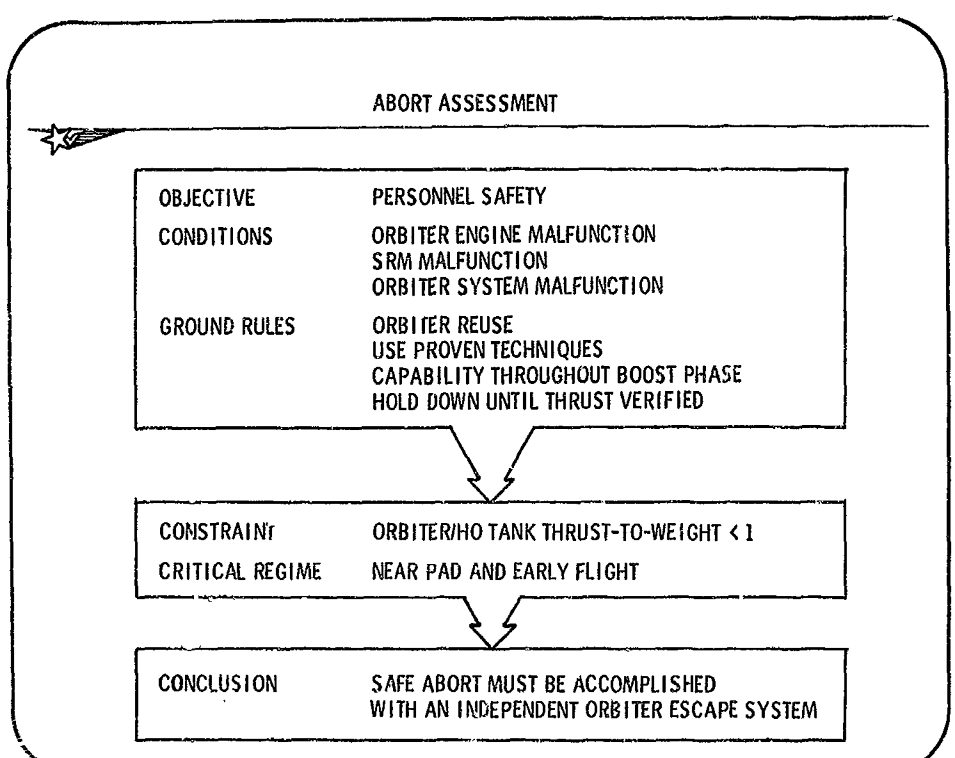


The baseline recovery sequence is shown above. The approach is based on information generated by Phase B prime contractor studies and information generated from this study. The primary deceleration device is a series of staged parachutes deployed to limit the velocity to 100 feet per second at impact. If a more detailed structural evaluation indicates the necessity, additional devices (retrorockets and impact bags) may be used to reduce the impact velocity below the baseline. After impact, the SRM hardware is lifted aboard a barge and returned to shore for refurbishment and recycling.

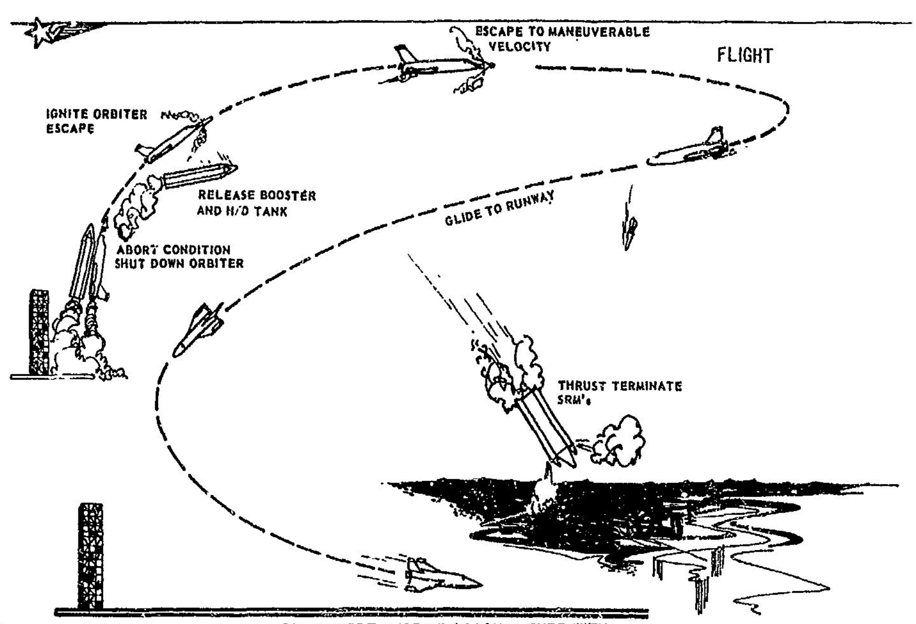
3.2.2 Abort

Abort conditions can be brought about by (1) orbiter engine failure, (2) SRM malfunction, or (3) critical orbiter system malfunction. Regardless of the cause, the critical regime occurs during early flight (0.5 to 40 seconds after launch) because the orbiter thrust-to-weight ratio is less than one, and the orbiter has not achieved a sufficient energy state to maneuver itself back to an emergency landing strip. In order to achieve safe abort during this regime, an independent orbiter emergency escape system is required. This emergency escape system, similar in concept to the Mercury and Apollo approaches, and capable of boosting the entire orbiter to safety, could be used when an abort is required at any time during booster operation.

This abort assessment is summarized below.



ABORT APPROACH

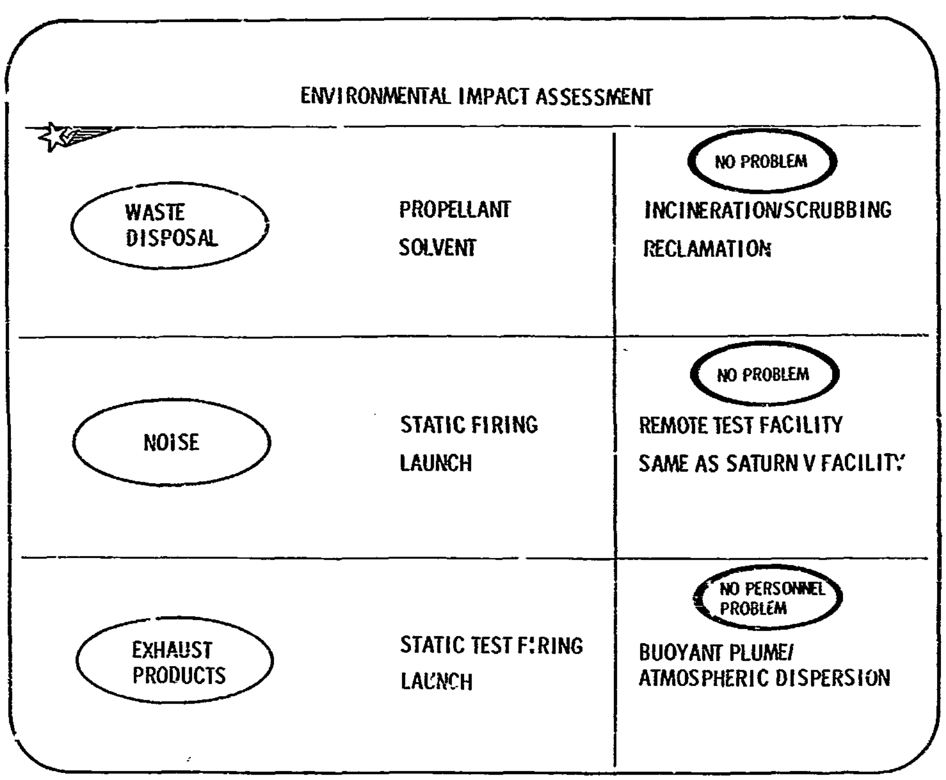


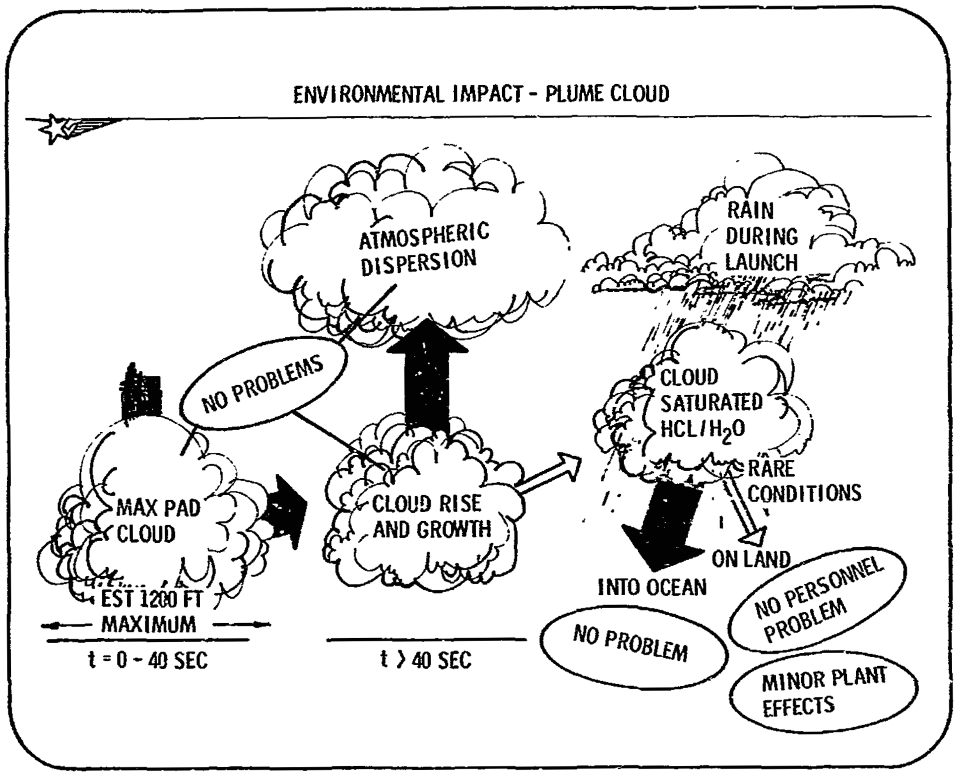
SAFE ABORT MUST BE ACCOMPLISHED WITH
AN INDEPENDENT ORBITER ESCAPE SYSTEM

A typical abort sequence is shown on the figure above. After verification of an abort requirement, the orbiter engine will be shut down and the orbiter separated from the vehicle. The orbiter escape rocket system will then be activated to propel the orbiter to a sufficient altitude and velocity to allow a safe glide back to an emergency landing strip. For abort, the boosters will be thrust-terminated to render the booster/tank assembly nonpropulsive for a controlled descent to the ocean.

3.2.3 Environmental Impact

During the course of the study, LPC evaluated the potential sources of environmental impact: manufacturing waste disposal, noise, and plume exhaust products. No problems or operational limitations caused by the SRM booster have been identified. The effect of plume exhaust products on the environment is the most complex of the potential sources, and is discussed in more detail.





The results of LPC's findings on rocket exhaust products are summarized above. Shortly after launch, and until 40 seconds afterwards, the plume cloud is in contact with the launch pad. The concentration of hydrochloric acid (HCl) in the plume during this period is high (>3,000 ppm). After 40 seconds (based on Titan III data), the plume rises above the pad as a result of convective forces of the hot exhaust gases, and the HCl concentration at the launch pad drops below 3 ppm. The cloud then rises rapidly and disperses into the atmosphere. The concentration of HCl is of concern only during extreme humidity conditions, such as a rain storm. Even then, if the wind is off-shore, there is no problem since the dilute HCl is dissipated over the ocean. Only if rain and on-shore wind conditions prevail simultaneously will dilute HCl fall in the launch area. There will be no personnel problem, but minor cosmetic damage to plant life in the immediate area may occur.

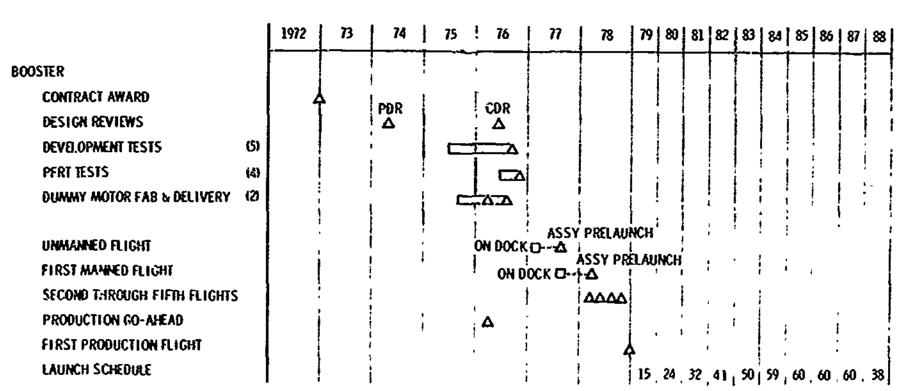
3.3 BASELINE PROGRAM AND SCHEDULE

The proposed baseline program and an assumed typical schedule are presented below. The total program includes 908 SRMs.

SRM BOOSTER SUMMARY
BASELINE PROGRAM

	SRM'S
DEVELOPMENT - LPC POTRERO FACILITY	
DEVELOPMENT TESTS - POTRERO	5
PFRT MOTOR TESTS - POTRERO	4
TWO INERT SRM STAGES - KSC	4
ONE UNMANNED FLIGHT - KSC	2
FIRST FIVE MANNED LAUNCHES - KSC	10
TOTAL DEVELOPMENT	25
PRODUCTION	
PRODUCTION FLIGHTS (440) POTRERO OR NEW FACILITY	880
FACILITY START-UP TESTS - POTRERO	3
TOTAL PRODUCTION	883
TOTAL SRM'S	908

156-INCH BASELINE PROGRAM SCHEDULE



3.4 COSTS

The LPC groundrules to use proven technology has resulted in motor designs and costs that are conservative. The costs include all the known, identifiable cost items. The table below summarizes LPC's approach to the costing effort.

SUMMARY - COST

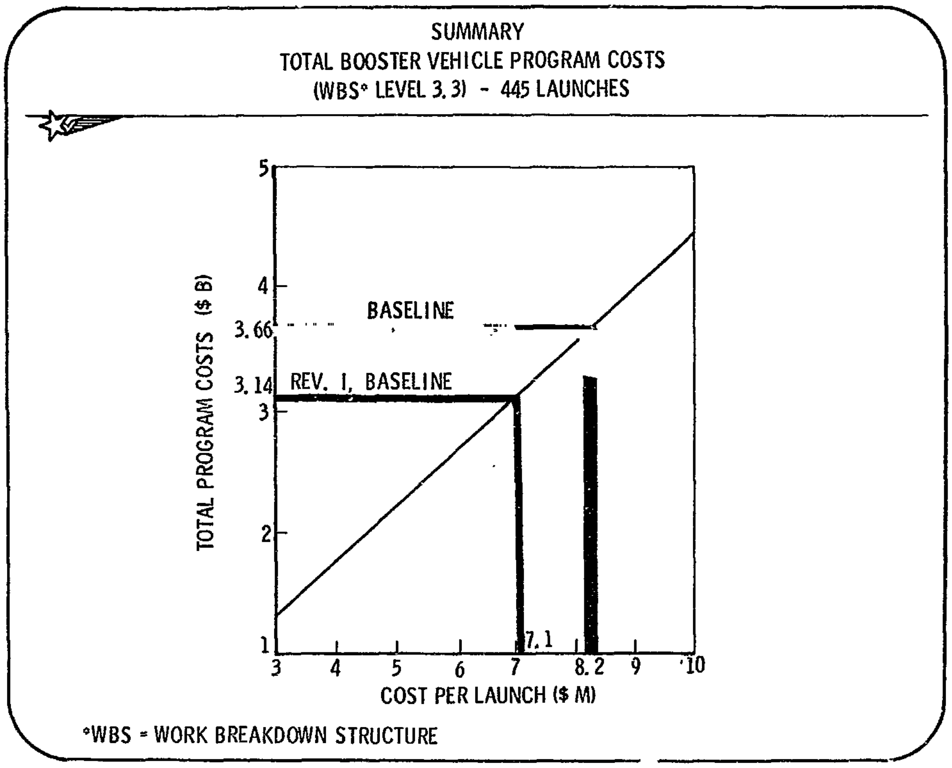
WHAT — SRM BASELINE COSTS ARE CONSERVATIVE

WHY — CONSERVATIVE IN DESIGN APPROACH
- 1.4 SAFETY FACTOR - PRESSURE VESSEL
- 2.0 SAFETY FACTOR - INSULATION

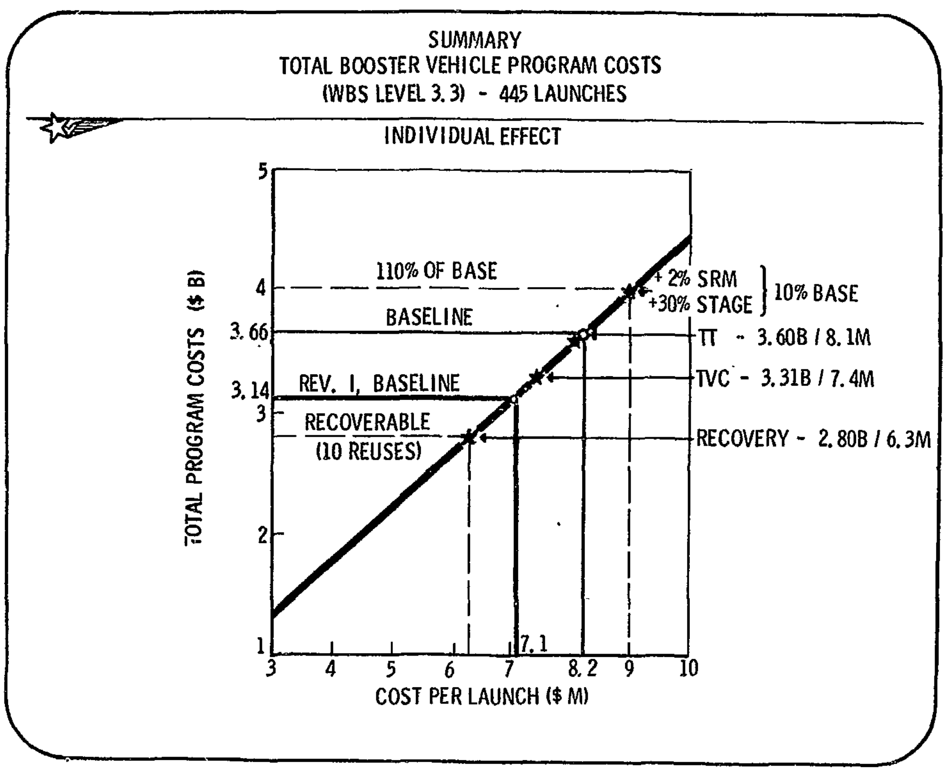
USE OF ACTUAL COST HISTORY
UPDATED SUPPLIER INFORMATION
COSTS BASED ON DEMONSTRATED TECHNOLOGY
COSTS INCLUDE
- THRUST VECTOR CONTROL
- THRUST TERMINATION
- EXPENDABLE BOOSTER

The following figure presents a summary of total program costs for the baseline, expendable-booster system. The costs of the thrust vector control system and the thrust termination system are included.

The original baseline total program cost was 3.66 billion dollars and the cost per launch was 8.2 million dollars. The current baseline (Revision I) total program cost is 3.14 billion dollars and the cost per launch is 7.1 million dollars. The Revision I baseline cost is still considered to be conservative in the KSC operation effort, and may be further reduced by as much as 30 percent in this area with additional study and detailed task definition. The total program cost includes all development and production costs. The total cost divided by the total number of launches (445) equals the cost per launch.

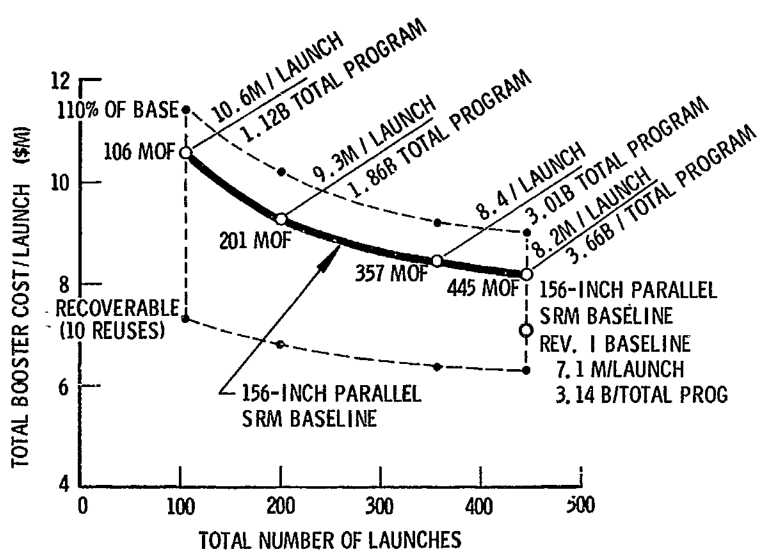


As directed by NASA, LPC also attempted to determine "hard" versus "soft" costs, and an upper band was estimated above the baseline for a "worst condition". Due to LPC's solid rocket motor experience, the propulsion system costs are "hard" and, therefore, an upper limit of 2 percent on the SRM cost has been identified. LPC believes that the Stage costs are "soft" and a 30-percent upper limit on the Stage cost was established. With the SRM and Stage combined, a total of 10-percent upward variation has been identified in the Booster Vehicle (WBS 3.3) Program costs. A lower range has also been established, which identifies potential reductions for thrust vector control, thrust termination, and recovery.

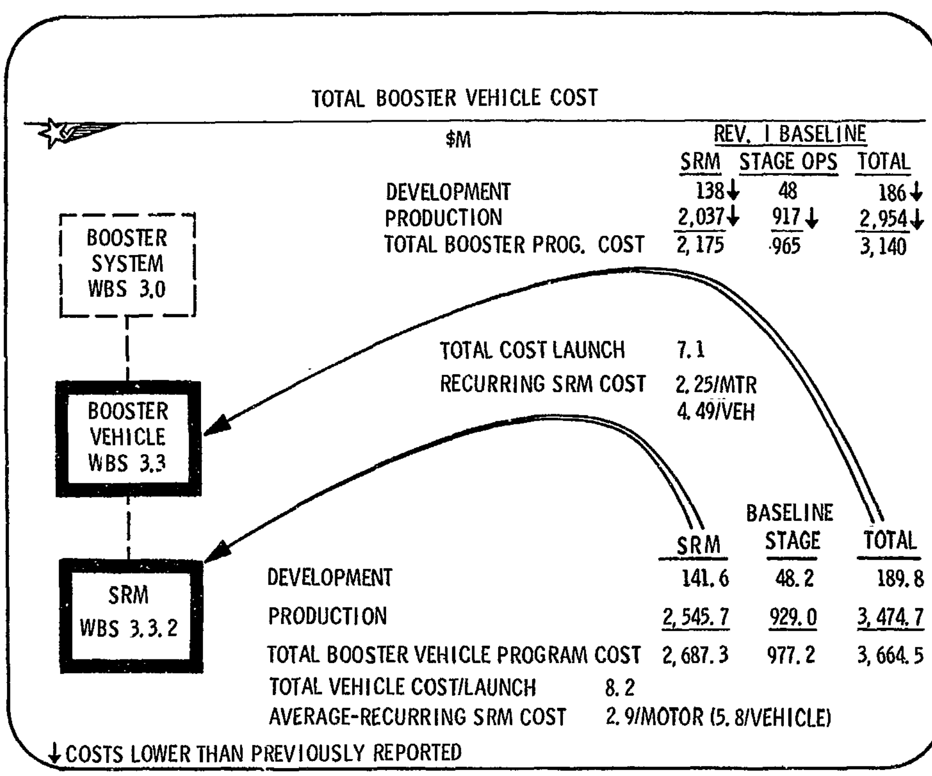


The next graph shows the effect of a reduced number of launches on total program cost and the total booster vehicle cost per launch. Both the initial baseline and the current Revision I baseline costs are presented. The upper limit and recovery bands are referenced to the initial baseline costs.

SUMMARY
PARAMETRIC COST ANALYSIS - TOTAL BOOSTER VEHICLE
(WBS 3.3)



Key baseline costs are summarized on the chart below. Both baseline costs and baseline Revision I costs have been generated, with the Revision I numbers resulting from later review of all estimates, to obtain a refinement not feasible in the limited time available before release of the initial baseline numbers. The current Revision I baseline total program for the Booster Vehicle (Work Breakdown Structure Item 3.3) is 3.14 billion dollars. These values result in a total program cost per launch of 7.1 million dollars, or a recurring cost per SRM of 2.25 million dollars.



$M	REV. I BASELINE SRM	STAGE OPS	TOTAL
DEVELOPMENT	138↓	48	186↓
PRODUCTION	2,037↓	917↓	2,954↓
TOTAL BOOSTER PROG. COST	2,175	965	3,140

TOTAL COST LAUNCH 7.1
RECURRING SRM COST 2.25/MTR
4.49/VEH

	BASELINE SRM	STAGE	TOTAL
DEVELOPMENT	141.6	48.2	189.8
PRODUCTION	2,545.7	929.0	3,474.7
TOTAL BOOSTER VEHICLE PROGRAM COST	2,687.3	977.2	3,664.5

TOTAL VEHICLE COST/LAUNCH 8.2
AVERAGE-RECURRING SRM COST 2.9/MOTOR (5.8/VEHICLE)

AVERAGE MOTOR COMPONENT COST
- MAJOR COMPONENTS -

MATERIAL COST PER SRM	INITIAL BASELINE $M	REV. I BASELINE $M
WHY		
CASE	0.717	$0.657
INTERNAL INSULATION	0.100	0.100
NOZZLE	0.303	0.273
LOCKSEAL	0.070	0.070
IGNITER	0.025	0.023
THRUST TERMINATION	0.034	0.034
PROPELLANT (RAW MATERIAL ONLY)	0.324	0.324
TVC (ACTUATOR, HYDRAULICS, POWER)	0.189	0.168
TOTAL SRM MATERIAL COST/MOTOR	$1.762M	$1.551M
MATERIAL COST - TOTAL PROGRAM		
MATERIALS DOLLARS/MOTOR X 908 MOTORS =	$1.60B	$1.36B
TOTAL PROGRAM SRM COST CHECK TOTAL MATERIAL DOLLARS ÷ 60% =	$2.67B	$2.27B

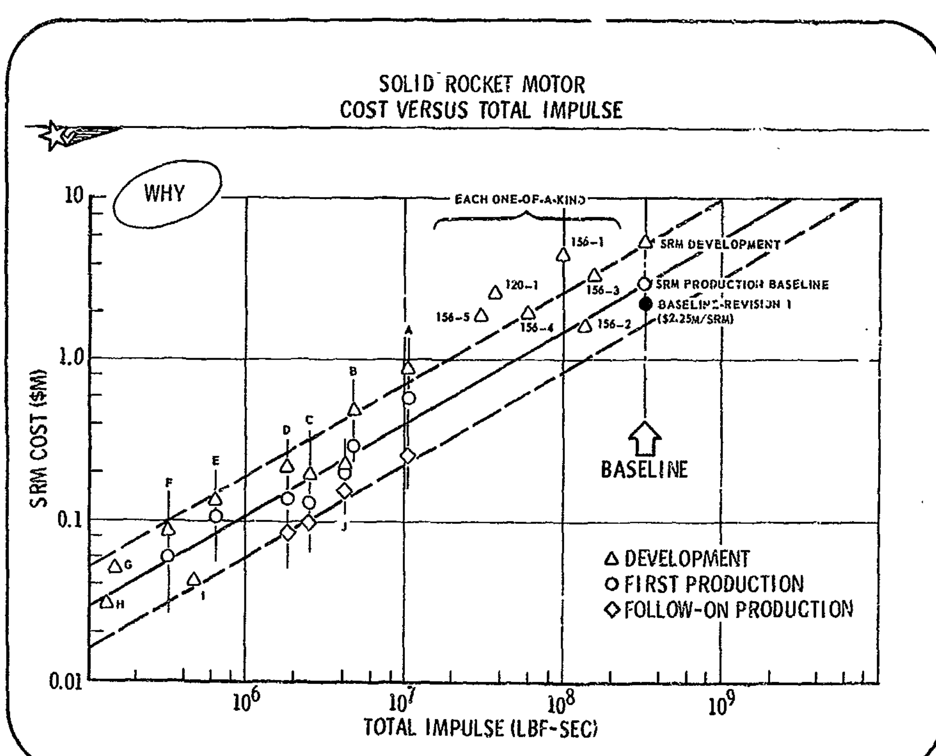
In order to evaluate the validity of the baseline costs, several analyses were conducted. This chart summarizes the cost of major components and raw materials in an SRM. The initial baseline material cost per SRM was 1.762 million dollars, or a total program cost for motor material of 1.6 billion dollars. Since experience from prior programs indicates that material should account for at least 60 percent of the total program for the contemplated make or buy ratio, a conservative estimate for the initial baseline SRM total cost was 2.67 billion dollars. This number compared well with the 2.69 billion dollars in LPC's baseline costs and verified the conservatism of the LPC costs.

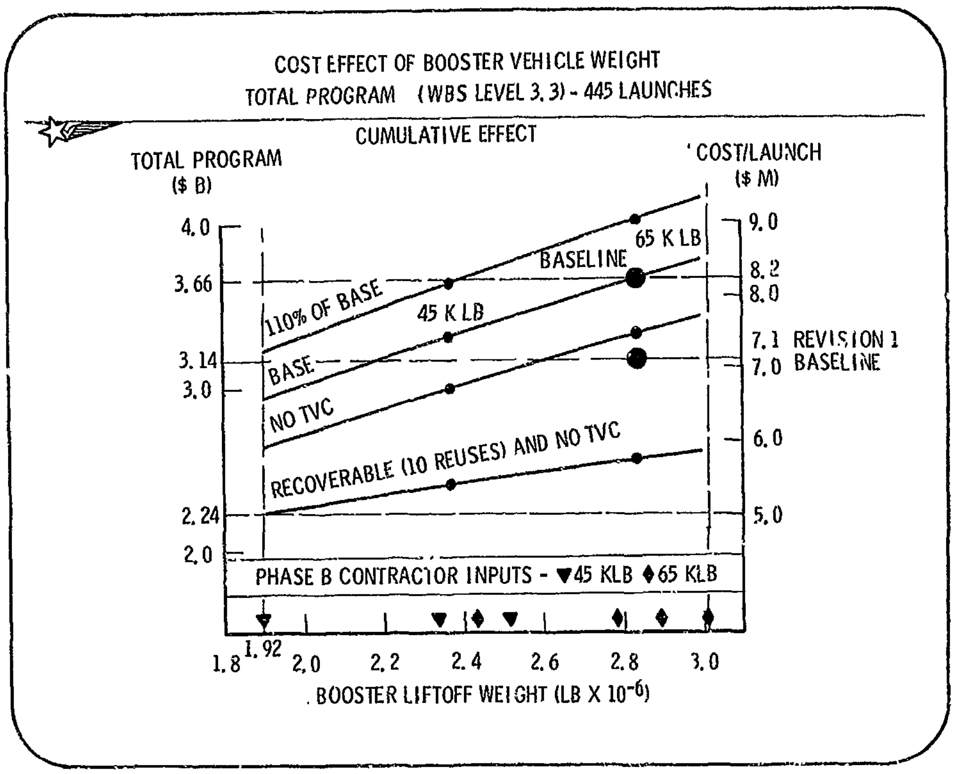
Further refinement of material costs achieved by working with LPC's material suppliers has resulted in a Revision I, baseline material cost per SRM of 1.551 million dollars. Using the same rationale as above, this number results in a projected total program SRM cost of 2.27 billion dollars, which again compares well with the 2.18 billion dollar total SRM cost contained in the Revision I baseline costs.

A further analysis of LPC's baseline cost is summarized on the figure below. The costs of various SRMs are plotted versus the total impulse (total energy) in the motor. The various data points on the left half of the chart represent actual cost history from major solid rocket motor development and production programs. The triangles represent the development phase, the circles the first production buy, and the squares subsequent production buys. The development phase of each of these programs consisted of more than 50 rocket motors, with further production learning indicated by the decreasing cost for each production buy.

The triangles in the center of the chart represent the actual cost of the large solid motor programs conducted by LPC. These programs, designated by 120-1 and 156-1 through 156-5, were single-motor programs with each motor a different configuration. The costs shown include all nonrecurring expenses such as design, tooling, and test.

The baseline SRM development and production costs are shown at the extreme right side of the chart. The development cost appears to be reasonable, but conservative, considering that the baseline program has 25 development motors as compared to the one-of-a-kind large solid motor development costs previously discussed. The initial baseline production cost also appears to be realistic, and conservative based on experience. Earlier experience (shown on the left half of the chart) also indicates that production motors may well fall into the lower half of the cost bands. The Revision I baseline cost of 2.25 million dollars per SRM reflects production experience on previous programs.

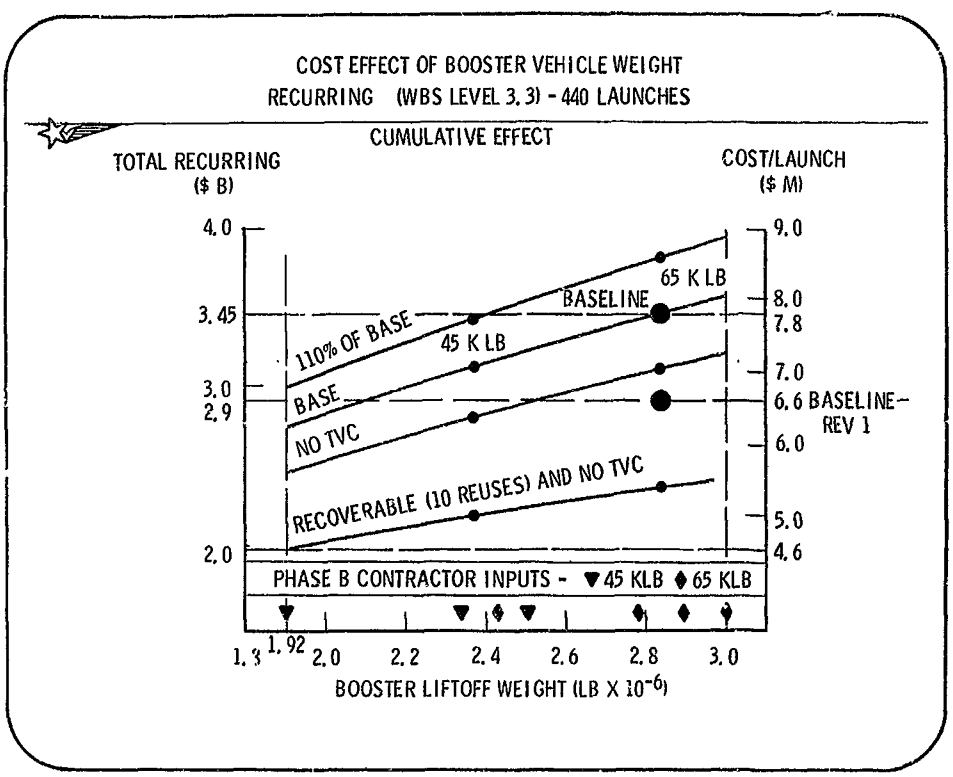




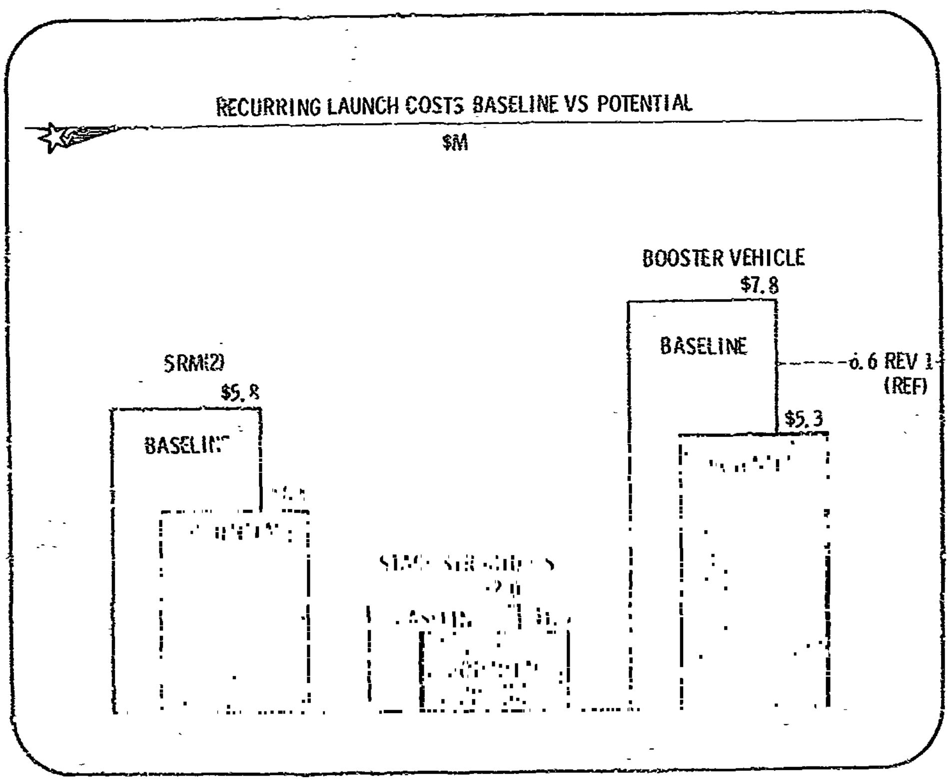
An analysis was also conducted to determine the variation of program costs as a function of booster lift-off weight. The range of lift-off weights considered reflects the variation noted in the inputs received by LPC from the individual Phase B system contractors. The figure above shows the effect on total program costs and cost per launch. It can be noted from the graph that LPC's baseline design is at the conservative end, and that the range of contractor inputs for booster lift-off weight can affect the costs by as much as 20 percent. This fact is significant when comparing costs submitted by different prime and SRM contractors. This study permitted selections within this entire range, and therefore costs must be normalized before an accurate comparison can be made. This amount of variation can result in bringing the total program cost down to 3.0 billion dollars and the total cost per launch to 6.7 million dollars. The Revision I baseline cost per launch is also shown for reference.

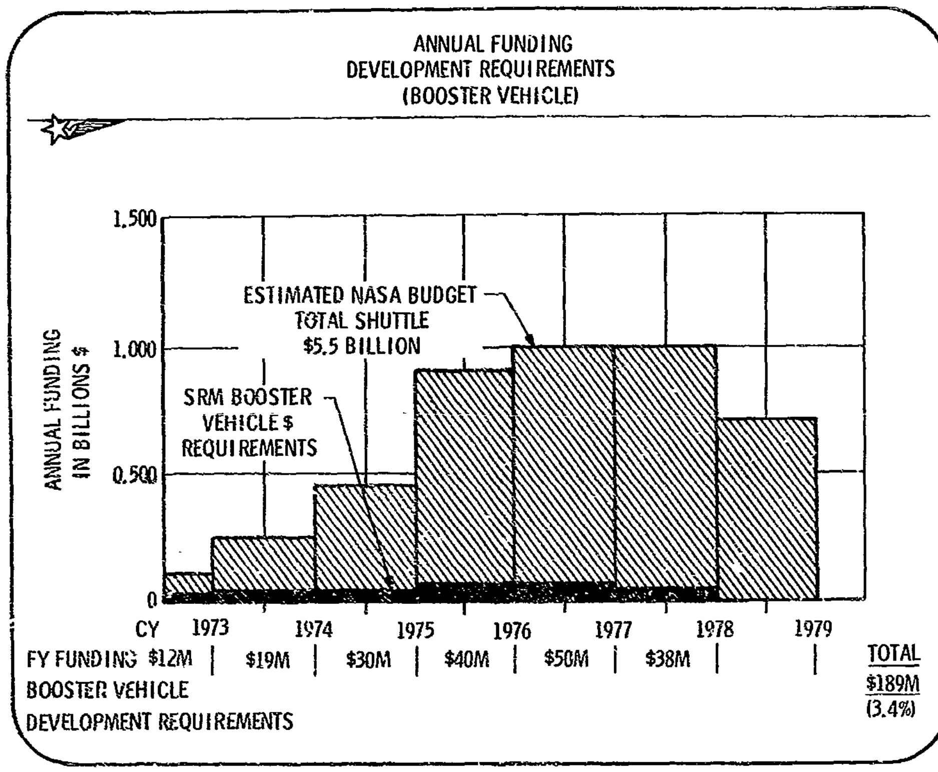
The figure below shows the same effect on the total recurring cost and the total recurring cost per launch. In this case, the total recurring cost and cost per launch can also vary as much as 20 percent, down to 2.75 billion dollars total cost and to 6.75 million dollars per launch. The Revision I baseline cost per launch is also shown for reference.

These numbers are for fully expendable SRMs. If recovery and reuse are considered, the recurring cost per launch will approach 5 million dollars.



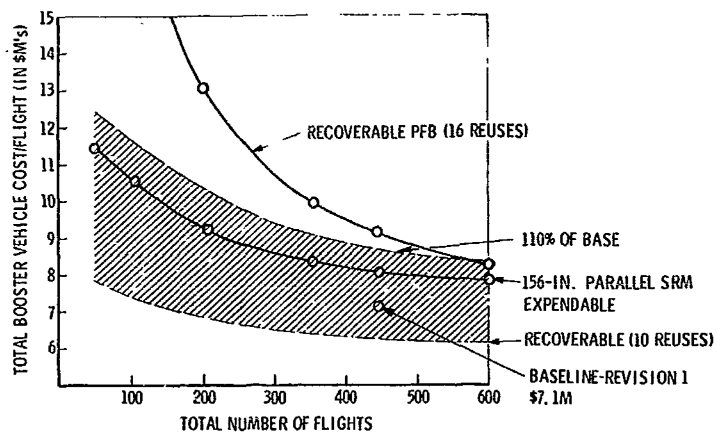
The following chart presents a graphic comparison of the original baseline costs versus the potential costs that LPC believes to be attainable. The comparison shows a potential 32-percent reduction in vehicle cost (from 7.8 to 5.3 million dollars). The Revision I baseline costs already show that an expendable vehicle cost per launch of 6.6 million dollars can be achieved. The use of a recoverable system could potentially reduce the recurring cost per launch to as low as 5.3 million dollars.





Annual funding requirements of the SRM Booster Vehicle are shown in the figure above to be a small fraction of the anticipated NASA Space Shuttle budget for development. The peak annual funding is 50 million dollars per year. Total DDT&E costs are 3.4 percent of the 5.5 billion dollar development budget.

TOTAL BOOSTER VEHICLE COST COMPARISON

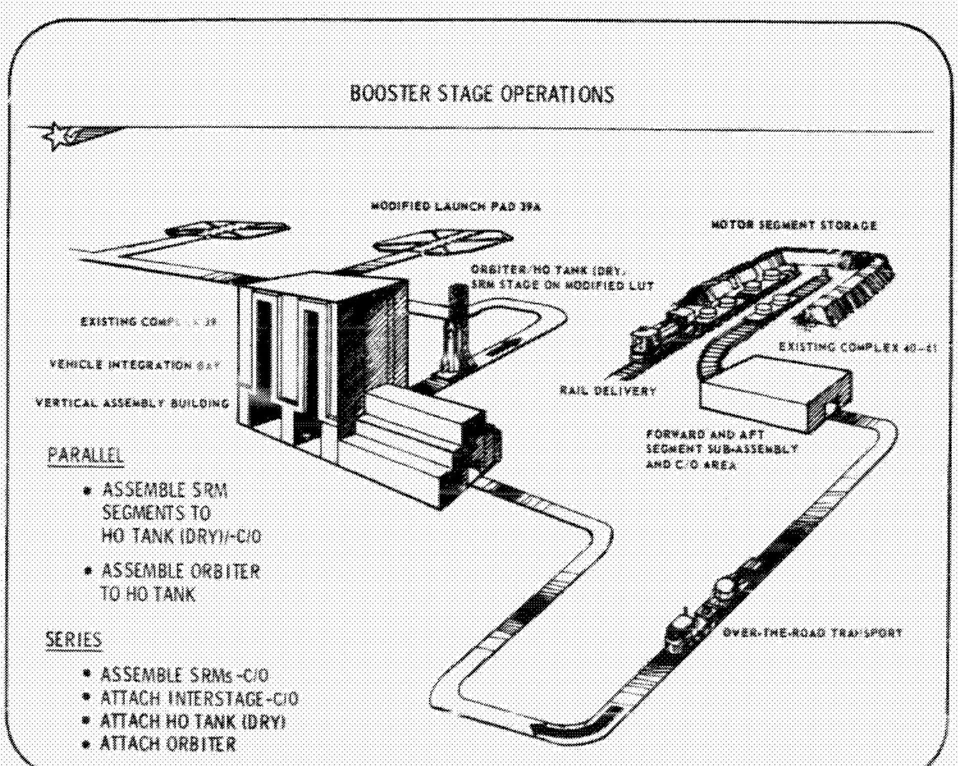


	EXPENDABLE SOLID VS RECOVERABLE LIQUID		RECOVERABLE SOLID VS RECOVERABLE LIQUID	
NUMBER OF LAUNCHES	445	201	445	201
COST PER LAUNCH - LIQUID ($M)	9.2	13.1	9.2	13.1
COST PER LAUNCH - SOLID ($M)	8.2	9.2	6.3	6.8
SAVINGS PER LAUNCH ($M)	1.0	3.9	2.9	6.3
TOTAL PROGRAM SAVINGS ($M)	445	784	1,291	1,266

The figure above compares costs of the SRM booster with those of a pressure-fed liquid booster.

3.5 BOOSTER STAGE OPERATIONS

A typical stage assembly sequence at Kennedy Space Center is shown below. SRM components and loaded case segments will be delivered by rail to the storage area. Forward and aft segment subassembly to the ignition, thrust termination, and thrust vector control subsystems will be accomplished in Complex 40-41. The booster stage and total vehicle will then be assembled in the Vertical Assembly Building and transported to the launch area on the modified Launch Umbilical Transport.



3.6 SUPPORTING RESEARCH AND TECHNOLOGY

As the result of this study program, LPC has identified eight areas of supporting research and technology which it recommends for future study. These areas are summarized below.

RECOMMENDED SUPPORTING RESEARCH AND TECHNOLOGY

- DESIGN AND DEMONSTRATION OF SRM RECOVERY AND REUSE
- SHUTTLE SRM THRUST TERMINATION SYSTEM DESIGN AND COMPONENT TESTS
- THRUST VECTOR CONTROL SYSTEM DEFINITION STUDY
- CANTED, MOVABLE NOZZLE OPTIMIZATION
- STUDY OF OPTIMUM SOLID ROCKET MOTOR DESIGN FOR GROWTH POTENTIAL
- COST EFFECTIVENESS STUDY OF LOW COST SRM TECHNOLOGY
- COMPARISON OF THE USAF TITAN III C/D AND THE NASA SPACE SHUTTLE ENVIRONMENTAL EFFECTS
- STUDY OF OPTIMUM STEEL SELECTION FOR A REUSABLE SRM MOTOR CASE

3.7 LIAISON WITH PHASE B SYSTEMS CONTRACTORS

In order to secure performance requirements from, and to provide timely study data to, Phase B systems contractors, Lockheed Propulsion Company provided a full-time liaison staff. The LPC baseline SRM design resulted from review of the design requirements received from each of the Phase B contractors.

3.8 PRESENTATIONS AND SUPPORTING DOCUMENTATION

In conformance with the study requirements, Lockheed Propulsion Company presented formal program reviews at the George C. Marshall Space Flight Center, Huntsville, Alabama, on 14 February 1972 and at NASA Headquarters, Washington, D. C., on 23 February 1972.

A tabulation of supporting documentation prepared during the study program is presented in Section 9 of Book 1, Volume II, of this report.