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FINAL REPORT

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TECHNICAL REPORT

SUPPORTING RESEARCH AND TECHNOLOGY

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

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ABSTRACT

The LPC baseline SRM design for the Space Shuttle employs proven technology based on actual motor firings. Supporting Research and Technology are therefore required only to address system technology that is specific to the Shuttle requirements, and that is needed for optimization of design features. Eight programs are recommended to meet these requirements.

LOCKHEED PROPULSION COMPANY
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FOREWORD

This document is Book 2, Supporting Research and Technology of Volume II Technical Report. It is a part of Lockheed Propulsion Company's final report for the Study of Solid Rocket Motors for a Space Shuttle Booster. The final report consists of the following documents:

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

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ILLUSTRATIONS

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 the 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	~~2,434.9M~~ 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

INTRODUCTION

The Lockheed Propulsion Company SRM design for the Space Shuttle employs the proven technology established in actual firings of 156-inch motors, and other solid rocket motor technology. Requisite technology to support the Shuttle application, therefore, addresses two principal subject areas; (1) system technology specific to the Shuttle booster requirements, and (2) optimization of SRM design features to achieve maximum cost effectiveness over the projected program.

Eight Research and Technology Programs recommended are listed below:

1. Design and Demonstration of SRM Recovery and Reuse
2. Shuttle SRM Thrust Termination System Design and Component Tests
3. Thrust Vector Control System Definition Study
4. Canted, Movable Nozzle Optimization
5. Study of Optimum Solid Rocket Motor Design for Growth Potential
6. Cost Effectiveness Study of Low Cost SRM Technology
7. Comparison of the USAF Titan III C/D and the NASA Space Shuttle Environmental Effects
8. Study of Optimum Steel Selection for a Reusable SRM Motor Case

The summary program schedule is presented in Figure 1-1. A synopsis of each of these programs in accordance with data requirements MA-02, SE-243B is presented in the following sections.

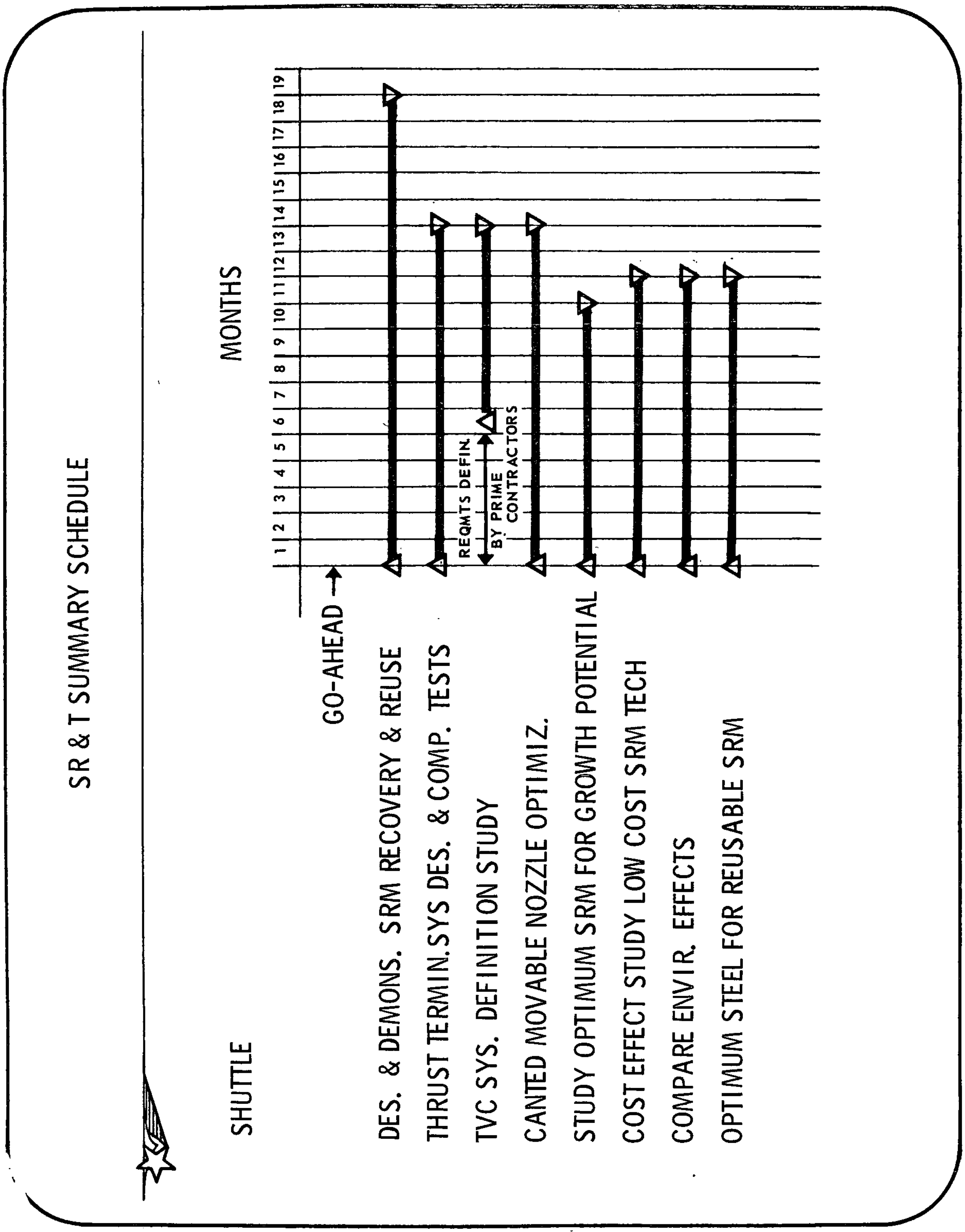

Figure 1-1 SR & T Summary Schedule

Section 2

DESIGN AND DEMONSTRATION OF SRM RECOVERY AND REUSE

2.1 STATUS

Preliminary studies have identified significant cost savings from SRM reuse and potential approaches to recovery. Detailed analysis and evaluation of technical alternatives, followed by component development and tests, are required. All phases of the recovery/reuse cycle require analysis, development and test, including aerodynamics after separation , return, water entry, retrieval, design for recovery/reuse, and refurbish plus reload. The selected recovery method will require demonstration.

2.2 JUSTIFICATION

The technical program consists of determining methods and costs for the recovery and reuse of SRM booster hardware, and demonstrating their feasibility where appropriate. This task is required because the advantages of this system concept for the SRM booster have only recently been determined, and analyses to date have been concerned with feasibility and cost saving assessments. Favorable results of these early studies established need and desirability for a detailed analysis, and the initiation of component hardware development and testing.

2.3 TECHNICAL PLAN

2.3.1 Objectives

The objectives of this program are as follows:

- To define the optimum integrated system for recovery/reuse
- To demonstrate key features of the system
- To establish a detailed plan for system development

This program will provide readiness for initiation of development work on the integrated system.

2.3.2 Technical Approach

The following basic tasks are planned:

- Evaluate, by design and analysis, the technical candidates for recovery, and identify the best method based on risk, cost and performance.
- Conduct component tests of selected key components.
- Develop detailed system design requirements.
- Generate detailed costs for selected design, including facilities and operations.
- Conduct preliminary system demonstration in appropriate areas.
- Generate a detailed development plan.

2.4 TASK OUTLINE

The subjects to be addressed are outlined below:

I. Air Recovery System

A. Aerodynamics after Separation

1. Free-flight path of separated SRM, with and without stage attach hardware

B. Recovery

1. Initial control technique for SRM in free-flight
2. Drogue chute deceleration
3. Main stage chute
4. Optional retro-rockets and airbags for deceleration

5. Combinations of 3. and 4.

6. Final velocity conditions

C. Water Entry

1. Hydrodynamics

(a) Water entry loads

(b) Terminal depth

(c) Water ascent and rebound

(d) Sea state

2. Structural Evaluation

(a) Nose down or nozzle down

(b) Initial impact loads

(c) Secondary impact loads

(d) Hydrodynamic loads under water

(e) Various sea states

D. System Optimization

1. Limit on initial velocity and angle

2. Limit on depth/rebound

E. Design for Recovery/Reuse

1. Design criteria for recovery/reuse

2. Case and dome design for imposed loads

3. Materials selection and protection

II. Water Retrieval System

A. Number and types of vessels

B. Lifting equipment requirements

C. Methods for bringing on board

D. Rinse and disassembly techniques and equipment

E. Discussion/selection of dock sites

III. Refurbish and Reload

A. Facilities requirements and costs

B. Refurbishment techniques

C. Recurring costs

D. Learning curves

Demonstration tests planned include the recovery subsystem, SRM water entry, and SRM exposure to sea water environments.

2.5 RESOURCE REQUIREMENTS

The resources in manpower and facilities required to conduct this program will be determined later.

2.6 TARGET SCHEDULE

An 18-month program span time is tentatively planned.

Section 3

SHUTTLE SRM THRUST TERMINATION SYSTEM DESIGN AND COMPONENT TESTS

3.1 STATUS

Thrust termination concepts have been thoroughly explored and applied on such programs as the Titan IIIC SRMs, Minuteman Third-Stage, and the second stages of Polaris and Poseidon.

It is the intent of this program to evaluate the application of existing SRM thrust termination concepts to the requirements for a Shuttle abort system.

3.2 JUSTIFICATION

The capability of terminating SRM thrust is a key feature in current abort system concepts. This capability is required at any time over the total SRM burn time. By contrast, existing system applications are designed to function only near the end of rocket motor burn for impulse control or separation. System design and component tests will adapt existing technology to Shuttle requirements for abort. The development of optimum components will ensure reliable and safe SRM thrust termination with a fully characterized system.

3.3 TECHNICAL PLAN

3.3.1 Objectives

- Establish thrust termination requirements by continued interchange with the prime contractors.
- Select the thrust termination concept which best meets SRM requirements.

- Design optimum thrust termination components and system.
- Conduct component, subsystem, and system tests to verify the selected thrust termination design on subscale and full-scale hardware.

3.3.2 Technical Plan

Maximum use will be made of existing data. Examples of current designs with a preliminary evaluation against projected SRM requirements are as follows:

Thrust Termination System Type	Propulsion System History	Comments
Explosive spider with cover	Polaris - Stage II, 100 flights	Significant additional debris with scale-up to SRM size
Flexible linear-shaped charge (LSC)/cut dome	Poseidon - Stage II, 42 flights	May be practical approach - will require evaluation for SRM scale-up
Explosive frangible sectors	Minuteman - Stage III, 450 flights	Quantity and shape of debris may give unpredictable trajectory
LSC-actuated single piece cover	120-inch SRM, 1 ground test	Minimum debris, predictable trajectory Basic approach demonstrated on SRM

In the SR&T program, in-depth evaluation of data from these programs will be conducted.

The principle design evaluation tool will be cold-gas testing. All candidate components will be screened, using this device, to determine cover ejection characteristics. Both subscale and full-scale designs will be evaluated using this method.

Debris control tests will be conducted if required. A preliminary evaluation of debris control designs is as follows:

Debris Control	Comments
Tethering of covers	Does not appear to be practical with current port cover size and predicted debris velocities

Debris Control	Comments
Tip-off trajectory control at stack exit plane	May be practical, would require additional development effort
Control by aero-dynamic configu-ration of cover	May be practical. Would require additional development effort

The SR&T Program will include resolution of detail requirements such as debris control.

3.4 RESOURCE REQUIREMENTS

- Manpower - 10 man-years in FY 1973
- Specialized Facilities - None
- Funding - TBDL

3.5 TARGET SCHEDULE

Thrust Termination Study Program Schedule is presented in Figure 3-1.

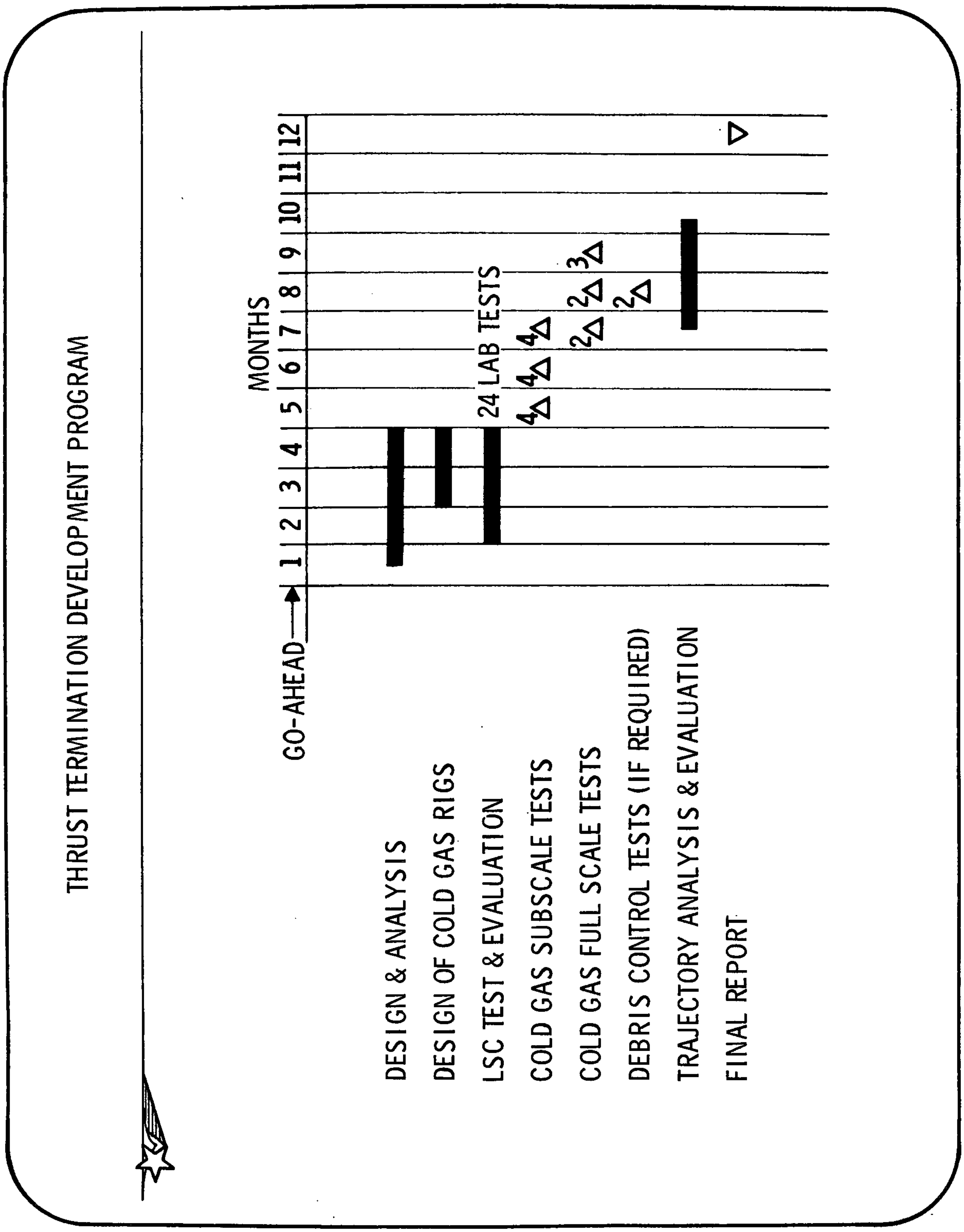

Figure 3-1 Thrust Termination Study Program Schedule

Section 4

THRUST VECTOR CONTROL SYSTEM DEFINITION STUDY

4.1 STATUS

The Space Shuttle SRM Booster TVC System will be a state-of-the-art flexible seal movable nozzle system. No significant break-throughs are required; however, trades and selections must be made to define the optimum booster TVC system in order to clearly establish any needed technology effort.

4.2 JUSTIFICATION

The Space Shuttle Booster System must be a cost-effective and reliable propulsion system. A major component of the SRM booster which affects system cost, performance, and reliability is the Thrust Vector Control (TVC) system. A number of TVC alternatives that affect the overall effectiveness of the shuttle system are available for selection. TVC definition studies must be conducted to establish the cost, reliability, and performance trades available, and select the optimum approach for the shuttle system based on mission requirements.

4.3 TECHNICAL PLAN

The objective of this study is to determine the Space Shuttle SRM Booster TVC System requirements and to establish a minimum cost detail design.

The technical approach will comprise design and analysis activities of requirements, alternatives, and selected approaches. The program will be broken into four primary tasks as defined below:

- Vehicle/booster definition and TVC requirements
- Alternatives definition to reduce TVC system requirements/cost

- TVC system trade studies/selection
- Detailed TVC system design definition

Each of these tasks are discussed in detail in the following subsections.

4.3.1 Vehicle/Booster Definition and TVC Requirements

The first primary task will be to establish a baseline space shuttle vehicle/ SRM booster configuration in order to conduct system trajectory studies to establish booster thrust vector control requirements. The vehicle and booster configuration will be determined, based on a coordinated effort with NASA and primes to establish the most likely Space Shuttle/SRM Booster approach (parallel versus series). After the prime candidate vehicle approach and mission are defined, LPC will define a baseline booster. Normal, easily achieved thrust asymmetry and misalignment values will be used for the baseline booster. System trajectory studies will be conducted to determine TVC system requirements, i.e., vector angle, slew rate, duty cycle and control stability.

4.3.2 Alternatives Definition to Reduce TVC System Requirements/Cost

Several areas should be explored to reduce thrust vector control system requirements. Areas which will be explored are Booster Thrust Alignment, Booster Thrust versus Time Reproducibility, Motor attachment Alignment, Use of Canted Nozzle, Use of Orbiter Engines with Booster TVC, and Modified Vehicle/Booster Configuration. Comparisons of the various techniques in terms of net cost savings, performance, and system reliability will be defined to allow evaluation of these approaches in terms of reducing TVC system cost.

4.3.3 TVC System Trade Studies/Selection

A number of TVC system design alternatives are available for the Space Shuttle Booster System. These alternatives must be evaluated through trade studies and mission requirements to establish the optimum approach.

Alternatives to be evaluated prior to selection are as follows:

- Power Supply Subsystem
  - Cold gas blowdown
  - Warm gas generator blowdown
  - Warm gas generator turbo pump (recirculating)
  - Developed systems available
  - Advanced systems

- Actuator Subsystem
  - Developed systems available
  - New system
- Movable Nozzle Subsystem
  - Pivot point location (forward versus aft pivot point)
  - Canted nozzle with TVC
  - Flexible seal design

Cost, performance, and reliability trades will be conducted in the above design areas to establish the selected TVC system approach.

4.3.4 Detailed TVC System Design Definition

Once the TVC system selected approach is made, a design will be generated in detail. Configurations, materials, tolerances, and component requirements will be established. Limited flexible seal processing studies and selection will be made. A TVC system development plan also will be defined. Conclusions and recommendations resulting from the design will be made, and future efforts required prior to system development will be defined.

4.4 RESOURCE REQUIREMENTS

- Manpower - 4½ man-years in FY 73
- Facilities - All facilities are existing and available
- Funding

Direct labor	$180,000 (9000 hours)
Computer	20,000
Total	$200,000 in FY 73

4.5 TARGET SCHEDULE

Figure 4-1 contains the Program Schedule for this task. It is recommended that this program be initiated late in CY 72 to allow time for Orbiter and Shuttle system requirements definition.

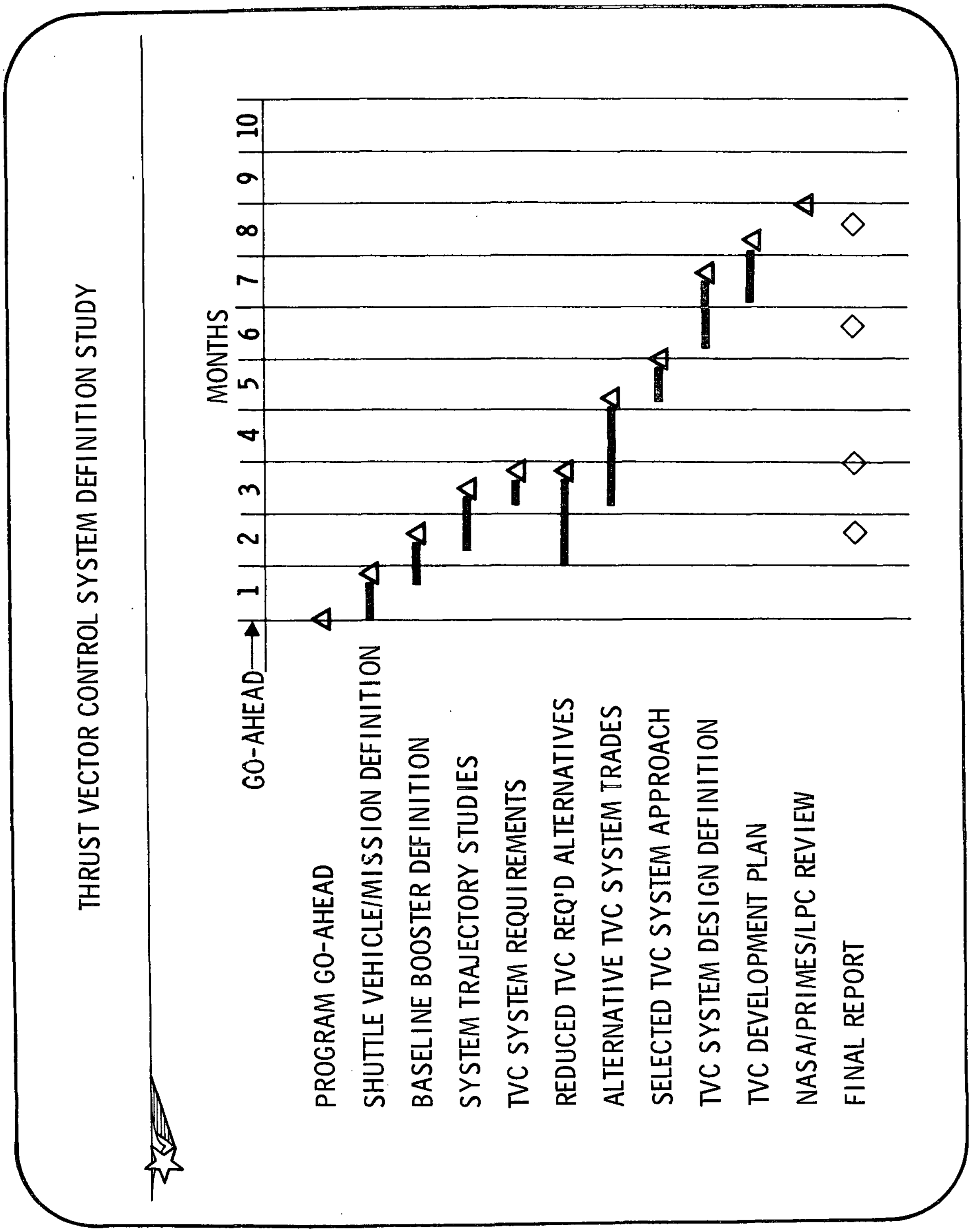

Figure 4-1 Thrust Vector Control System Definition Study Program Schedule

Section 5

CANTED, MOVABLE NOZZLE OPTIMIZATION

5.1 STATUS

One prime candidate Space Shuttle SRM Booster configuration uses a Movable Nozzle TVC System incorporating a fixed cant angle. The effect of a cant angle on TVC system and motor performance should be defined prior to initiation of SRM Booster Development. Establishing this information can be done with cold flow and subscale static motor tests.

5.2 JUSTIFICATION

Determination of the optimum movable nozzle system requires consideration of the general configuration and requirements of the Shuttle SRM. Flow effects on aerodynamic torque and heating of chamber and nozzle materials will depend on configuration and performance requirements such as vector angle. Most data available are for movable nozzles, which do not contain a pre-set cant angle. In addition, data and information for this configuration is required on the change in aerodynamic torque of movable nozzles as a function of pivot point location, especially for larger vector angles. These effects should be evaluated prior to final TVC selection and initiation of development for the Space Shuttle SRM Booster.

5.3 TECHNICAL PLAN

5.3.1 Objective

Program objectives would be to (1) establish aerodynamic torque and stability characteristics of movable nozzles as a function of pivot point location relative to the nozzle throat, and (2) establish the effects of a fixed cant angle on a movable nozzle TVC system.

5.3.2 Technical Approach

Analytical, cold flow and hot subscale static motor tests will be conducted to establish design data and potential problem areas.

The program will be divided into two phases. Phase I will consist of cold flow tests of simulated movable nozzles with pivot points at various positions forward and aft of the throat plane. Canted movable nozzle systems will also be tested to establish the effects on TVC system performance and motor/nozzle flow conditions. Analyses and empirical correlation of test data will be made to establish analytical techniques and trends.

Lockheed Propulsion Company recognizes that NASA has extensive cold-flow facilities. The work in this phase of the program can be conducted in various ways. Alternatives include (1) all work conducted by LPC, (2) all cold-flow testing conducted by NASA under LPC direction, and (3) LPC provide technical support to NASA in conducting Phase I. The selected approach will be coordinated with NASA.

Phase II of the program will involve the selection of several cold-flow test configurations (with and without cant) which will be fabricated into subscale, firable units. Hot static motor tests will then be conducted, and the data will be correlated. Prime areas of interest are listed below:

- Aerodynamic torque
- Nozzle/chamber material performance (erosion/char profile)
- TVC performance (nozzle angle versus thrust angle)
- Split line flow conditions and thermal boot performance
- TVC stability characteristics

5.4 RESOURCE REQUIREMENTS

- Manpower - Phase I: 3 man-years, Phase II: 5 man-years; in FY 73
- Facilities - All facilities are existing and available
- Funding

	Phase I	Phase II	Total Program
Direct Labor	$150,000	$250,000	$400,000
Equipment/Material	50,000	50,000	100,000
Facilities	0	0	0
Total	$200,000	$300,000	$500,000

5.3 SCHEDULE

The target schedule is shown in Figure 5-1. As shown, the total program would be of 12-months duration.

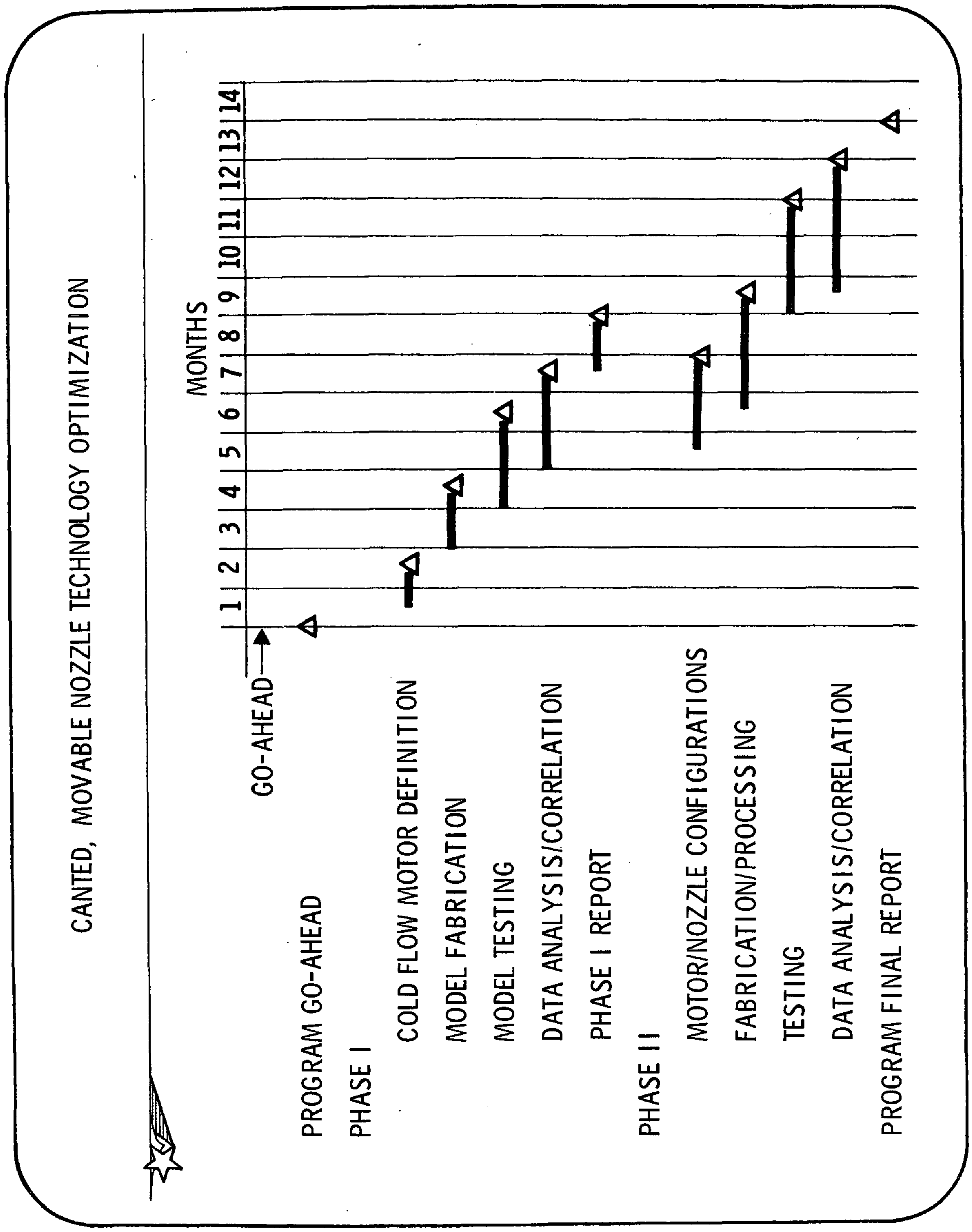

Figure 5-1 Canted, Movable Nozzle Technology Optimization Program Schedule

Section 6

STUDY OF OPTIMUM SOLID ROCKET MOTOR DESIGN FOR GROWTH POTENTIAL

6.1 STATUS

This study will be concerned entirely with state-of-the-art SRM designs

6.2 JUSTIFICATION

Justification for this study is to minimize the cost of providing larger space shuttle boosters, should this need become apparent after initial motor development is completed.

No previous or concurrent study of this type is known.

6.3 TECHNICAL PLAN

6.3.1 Alternatives for Providing Additional Total Impulse

Impulse can be increased by combinations of increased thrust and/or burn time. Practical limitations on these combinations will be established to serve as a basis for evaluation of growth potential alternatives. Typical growth potential alternatives to be studied are as follows:

- Lengthening of individual motor segments. One or more of the booster segments may be lengthened to accommodate additional propellant.

  This method of providing additional impulse does not require additional case joints and, therefore, could offer mass fraction and cost advantages over other alternates.

  The long segments could also be of variable propellant grain geometry allowing flexibility of thrust-time characteristics.

- Adding propellant by decreasing booster grain port diameter. This method of adding impulse requires no changes to the external booster configuration and may be practical if the required overall growth is small.

- Adding booster segments as building blocks. Significant increments of additional impulse can be obtained by the addition of segments identical to those utilized in the baseline development booster.

6.3.2 Detailed Design Studies

Each of the above alternatives will be characterized in terms of detailed designs showing configuration weight and performance limitations. Where applicable, the effects of increasing chamber pressure will be identified.

6.3.3 Development and Program Definition Costs and Plans

Development costs and program definition costs and program plans will be generated for the alternatives investigated. These data, when combined with results of the design studies, will allow relationships to be established between impulse increase and cost increase for all systems studied. Data will be used to determine the optimum solution to growth potential over a wide range of growth margins.

6.3.4 Optimization and Vehicle Integration

- Certain alternatives may require overdesign of the basic booster to accommodate growth. Increased chamber pressure capability, nozzle attachment flange diameter, TVC power requirements, etc., will result in a sub-optimum design if growth potential is not utilized.

  The impact of these findings on basic booster size and cost will be assessed and identified as related to the basic orbiter weight.

- Results of the above will be compared with the alternative of changing the booster, as required, during the development program. Such changes might include propellant burn rate changes, motor case wall thickness changes, longer segments, or grain design changes.

  These costs will be assessed for comparison to the "design for growth" approach.

- Recommendations will be made for the optimum development path as a function of growth target values.

6.4 RESOURCE REQUIREMENTS

Manpower. Approximately 3.0 man-years would be required for this study in FY 73.

Specialized facilities. No specialized facilities are required.

Funding.

1.	Direct Labor	$ 100,000	
2.	Equipment and Material	$ 10,000	(computer)

6.5 TARGET SCHEDULE

Figure 6-1 contains the Program Schedule for this task.

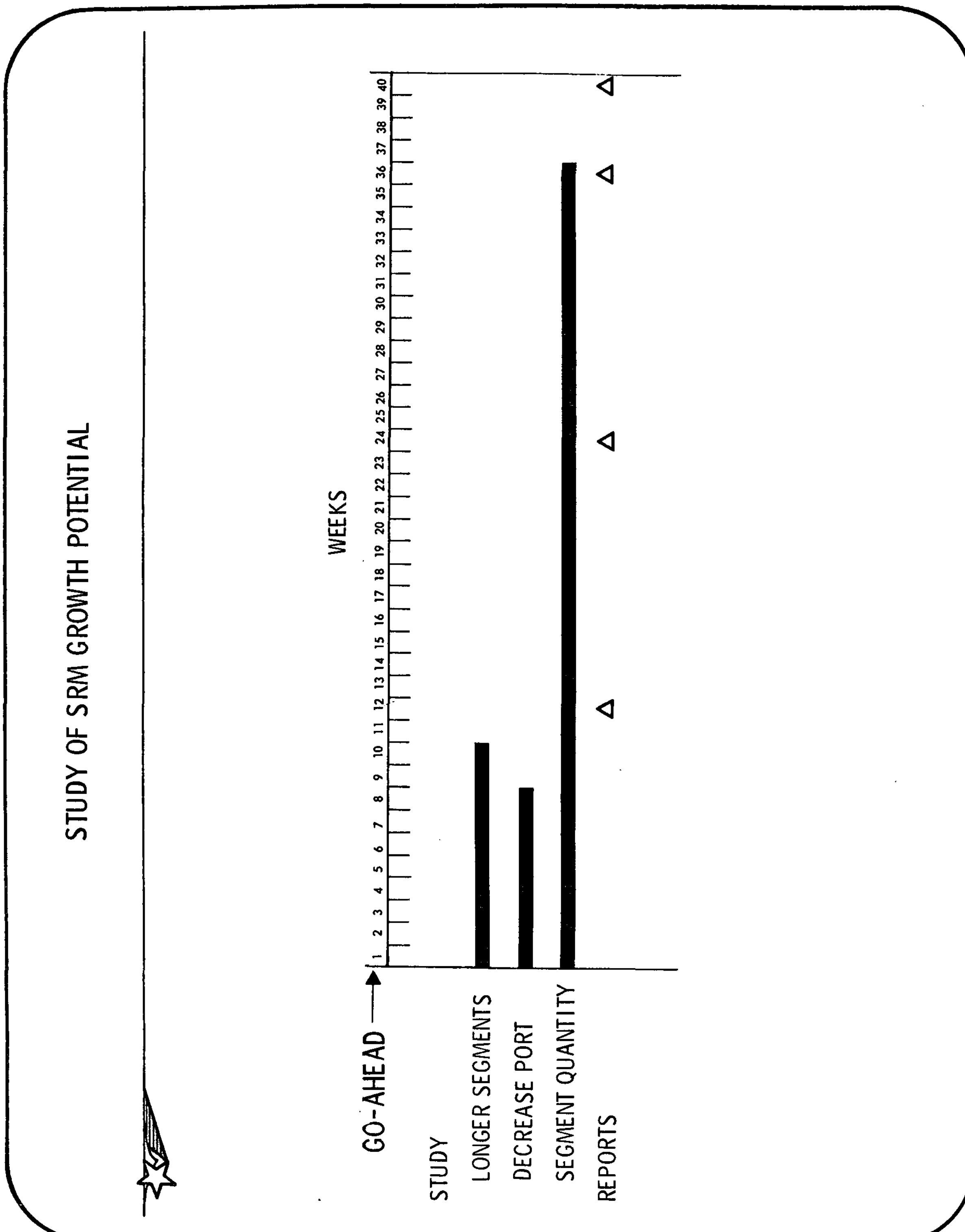

Figure 6-1 Study of SRM Growth Potential Program Schedule

Section 7

COST EFFECTIVENESS STUDY OF LOW COST SRM TECHNOLOGY

7.1 STATUS

The basic inert components of the SRM are nozzle, case, and internal insulation. Thrust vector control and termination are considered to be subsystems. Because the nozzle, case, and insulation costs represent more than 60 percent of the total component cost (including TVC and thrust termination), it is appropriate that a detailed study be conducted to assure the most cost-effective design.

7.2 JUSTIFICATION

To date, the large SRM boosters of 120 inches in diameter and larger have utilized a near common approach to component design and materials application. Cases have been limited to 18-percent nickel maraging steel (156-inch and 260-inch cases) and D6AC steel (120-inch cases). The nozzles have been ablative, using industry standard carbon and silica phenolics. Similarly, the internal insulation material has been a filled nitrile butadiene rubber (NBR) calendered and pressure-cured in place.

NASA and the Air Force have long recognized that these approaches offer potential cost saving areas when projected into a flight program of any magnitude. As a result, these agencies (particularly NASA) have sponsored a number of low-cost component programs. The objectives, however, were directed to 260-inch-diameter SRMs, which had less severe design requirements than those required for the Space Shuttle Booster.

It is necessary to apply the existing subscale data to shuttle booster SRM requirements in order to determine the true cost effectiveness, and to investigate new cost reduction techniques not previously studied.

A 25-percent reduction of inert component cost would reduce the total program motor cost by about $250 million.

7.3 TECHNICAL APPROACH

The objective of this study is to determine the optimum materials and fabrication approach for SRM development which will produce the most cost-effective booster system.

The technical approach will be to pursue, for all three components, the following tasks:

- Develop preliminary SRM designs as deviations from the baseline
- Generate cost information for the designs considered.
- Conduct detailed trade-off analysis against the baseline and support with testing as required
- Generate detailed development plans for promising new technologies.

A discussion of the technical approach to each of the components is given in the following subsections.

7.3.1 Case

The baseline design utilizes a D6AC steel case fabricated by techniques currently used on Titan III, 120-inch-diameter SRM boosters. The 120-inch cases are roll-formed and the closures are swaged roll ring forgings. This approach will be more cost effective if present size and shape limitations are eliminated. By reducing the number of segments per motor, handling costs in processing and transporting will be reduced, and since the number of joints are decreased, machining inspection and assembly costs will be compressed. In addition, a weight savings will result. Specific areas of study include:

- Removing the length limitation on roll formed cylinders by increased ingot size, increased roll form equipment capacity, and increase in metal working percent
- Advanced techniques for end closure forming, which will include a study of ingot size increase and minor modification to the forming technique
- Advancements in thrust termination port forming where welding is eliminated and machining is minimized.

7.3.2 Nozzle

This investigation will be based upon the application of data generated by two NASA-Lewis Research Center programs, both entitled "Development of Low Cost Ablative Nozzles for Solid Propellant Rocket Motors". * These programs included a number of subscale firings and scaled the results to 260-inch size motors with straight nozzles and no TVC. These data must be evaluated for application to the latest SRM requirements which are anticipated to include a canted nozzle as well as a movable nozzle TVC system. The maximum cant utilized on a large (120-inch diameter) SRM is 6 degrees. Based on the latest system study, the Space Shuttle booster SRM cant, including TVC, will be in the 15- to 20-degree range.

Specific areas of study will include:

- Evaluation of the published physical, mechanical, thermal and ablative data (support with new laboratory testing as required)
- Coordination and update of the material suppliers and component fabricators input to assure availability, fabricability, and cost integrity.
- Select materials and fabrication processes, and develop preliminary designs for comparison to the established baseline.
- Build and test-fire a subscale nozzle to demonstrate the best approach

7.3.3 Case Insulation

This investigation will be based on the application of data generated by the NASA-Lewis Research Center program entitled "Development of Cost-Optimized Insulation System for Use in Large Solid Rocket Motors".** As with the NASA nozzle programs, this work was directed toward 260-inch motors and the results must be re-evaluated for application to the latest SRM requirements.

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* 1. Development of Low Cost Ablative Nozzles for Solid Propellant Rocket Motors - Final Report, NASA CR-72641, NASA-Lewis Research Center, 12 February 1970

2. Development of Low Cost Ablative Nozzles for Solid Propellant Rocket Motors - Final Report, NASA CR-72973, NASA-Lewis Research Center, January 1971

** Development of Cost-Optimized Insulation System for Use in Large Solid Rocket Motors - Final Report, NASA CR-72581, NASA-Lewis Research Center, August 1969

The specific areas of study will be identical with those of the nozzle and the final task, a demonstration firing, will be integrated with the nozzle.

Emphasis in this study will be placed on low cost methods of installing the insulator in the motor case, since raw material cost will not vary appreciably. Casting and trowling techniques appear to be the most promising, however, the number of production units per year may strongly influence this approach. Refurbishment of the internal insulation is a new area of study which will also have strong affect on the final results.

7.4 RESOURCE REQUIREMENTS

	Case	Nozzle	Insulation	Total
Manpower (man-years)	2	$2\frac{3}{4}$	2	$6\frac{3}{4}$ in FY 73
Specialized facilities		None required		
Funding				
Direct Labor	$85,000	$115,000	$83,000	$283,000
Equipment and Material	5,000	50,000	10,000	65,000
Facilities	0	0	0	0
Total				$348,000

7.5 TARGET SCHEDULE

This program is estimated to require a 12-month span time. Detailed major milestone schedules for the case, nozzle, and internal insulation are shown in Figures 7-1, 7-2, and 7-3.

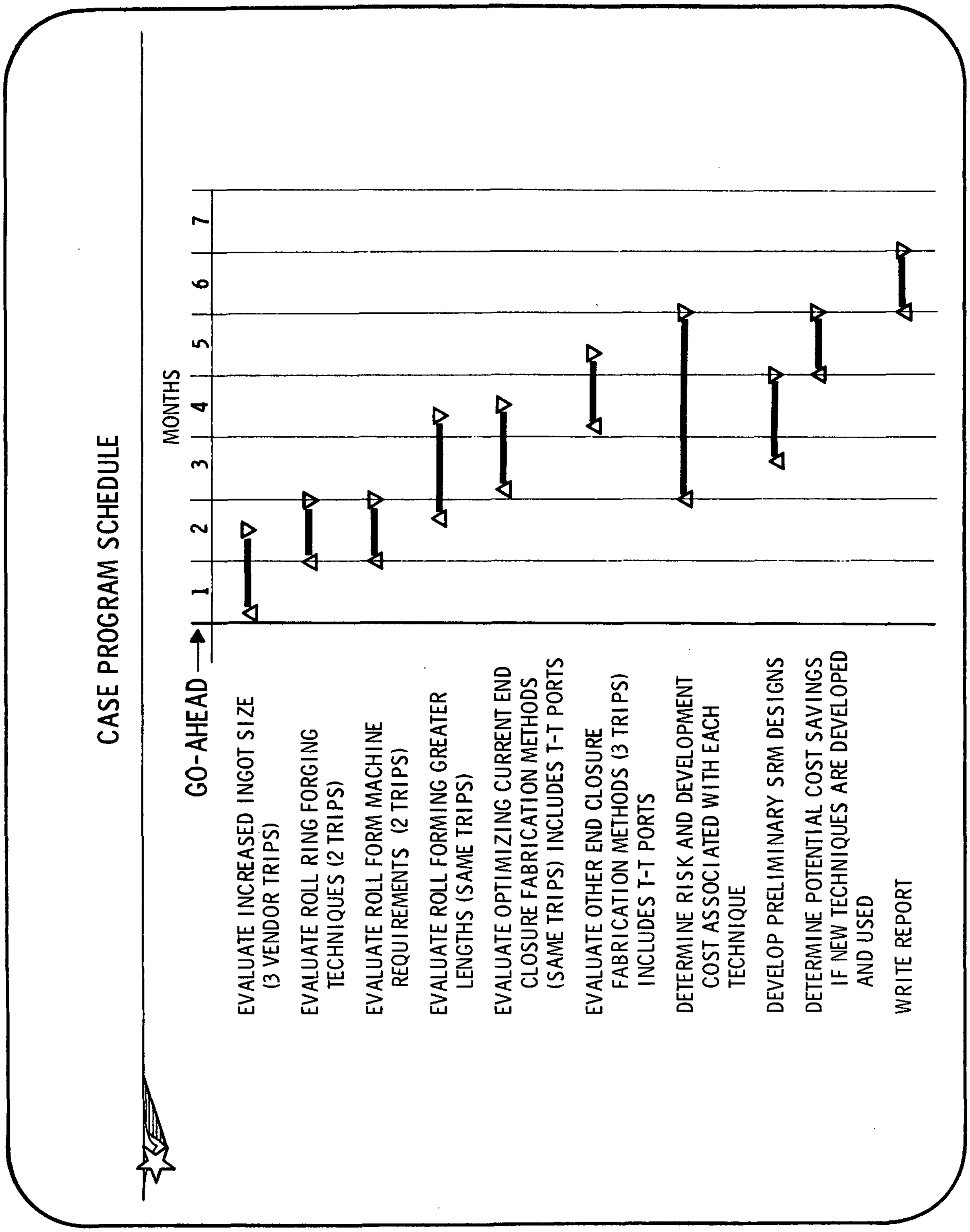

Figure 7-1 Cost Effectiveness Study of Low Cost SRM Technology - Case Program Schedule

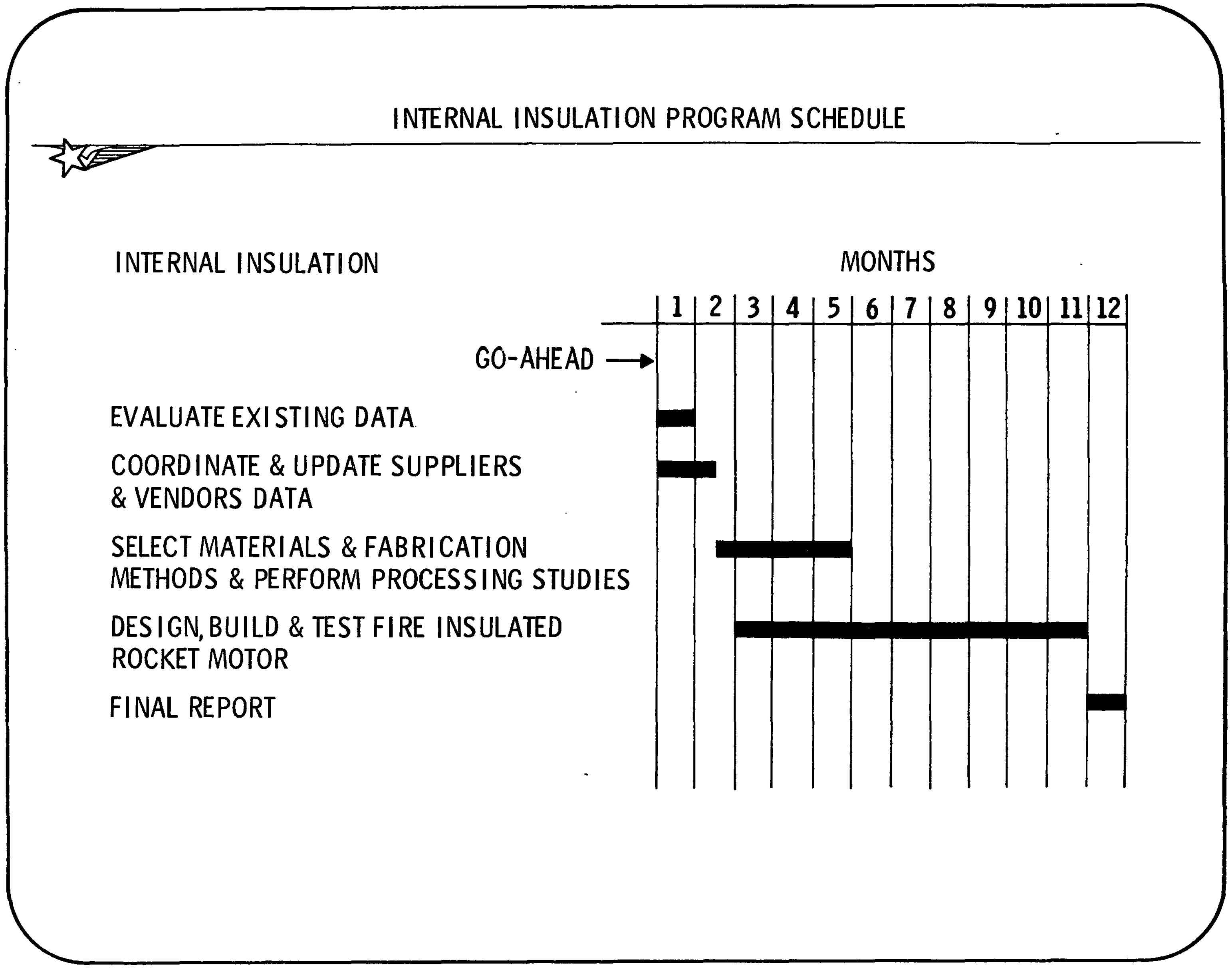

Figure 7-2 Cost Effectiveness Study of Low Cost SRM Technology - Nozzle Program Schedule

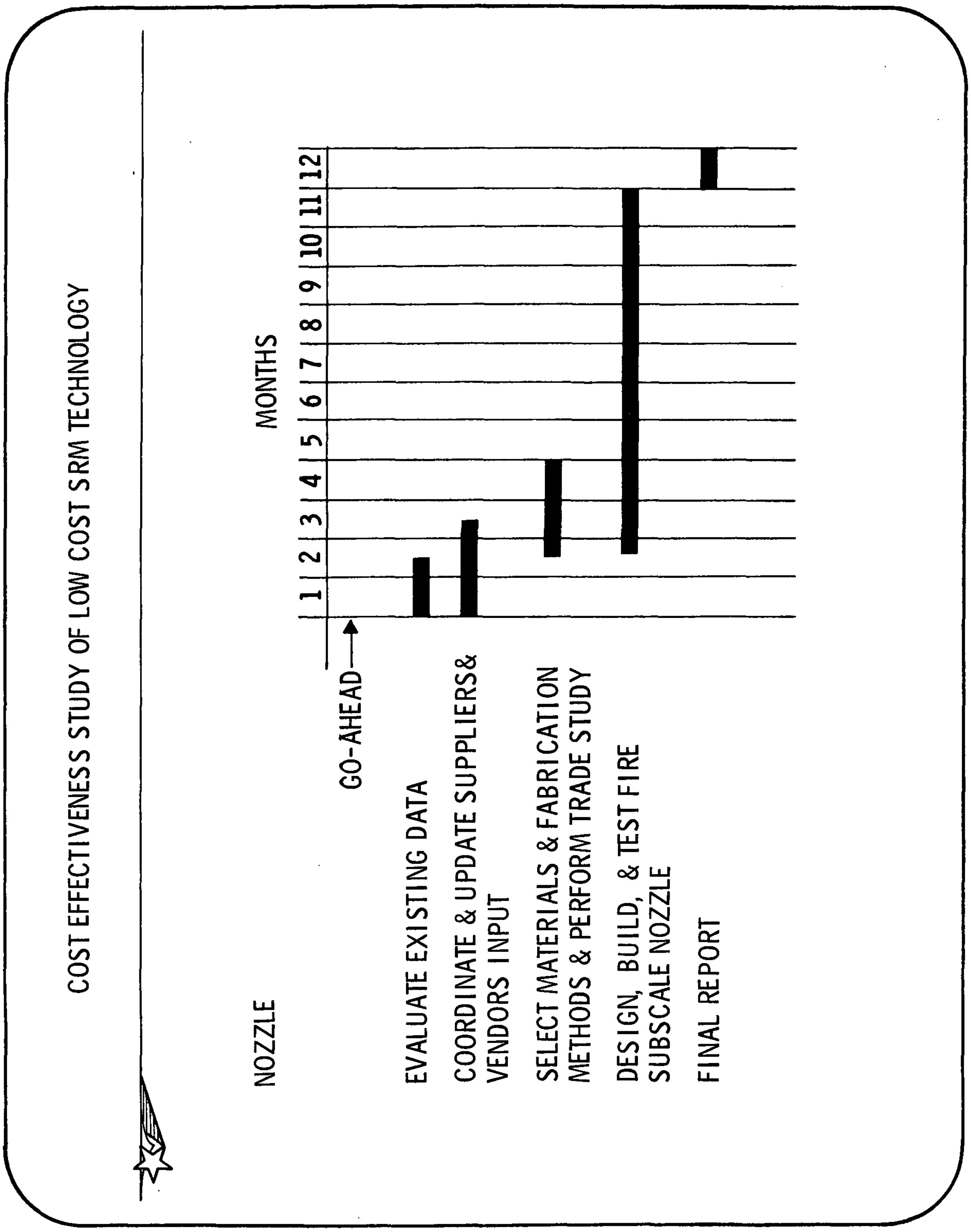

Figure 7-3 Cost Effectiveness Study of Low Cost SRM Technology - Internal Insulation Program Schedule

Section 8

COMPARISON OF THE USAF TITAN III C/D AND THE NASA SPACE SHUTTLE ENVIRONMENTAL EFFECTS

8.1 STATUS

Through USAF funding, several studies have been conducted to determine the characteristics of the launch pad environment produced during the ignition, thrust build-up, and lift-off of the Titan III series of standard launch vehicles. These studies indicate no unacceptable modifications of the local environment result from these launches. Methods for predicting the composition of the launch pad plume cloud, and its location versus time, have been developed and have produced good agreement with actual launch histories. These methods and prediction techniques are available for application to the NASA Space Shuttle Program.

8.2 JUSTIFICATION

The use of large (156-inch-diameter) solid propellant rocket motors as boosters for the NASA Space Shuttle is similar to the USAF use of 120-inch-diameter strap-on solid rocket boosters on the Titan III C/D. These solid rocket boosters produce, as a characteristic exhaust product, quantities of hydrogen chloride and aluminum oxide. Because of concern for possible deleterious effects on local plant and animal life, the USAF investigated the quantitative composition of the launch pad plume cloud both through analysis and field measurements. This work has been valuable in providing an understanding of the mixing and transport mechanisms limiting the dispersion of potential pollutants.

The NASA Space Shuttle Program is also concerned with acquiring a detailed understanding of the environmental effects caused by the solid rocket motor exhaust products. This understanding is necessary to preclude degradation of the local environment subsequent to a shuttle launch. The prediction techniques prepared through funding of this SR&T task will provide the necessary computer programs for accurate determination of the plume cloud location and composition at any time after launch. This data will be studied by the Range Safety Officer before permitting a launch.

8.3 TECHNICAL PLAN

8.3.1 Objectives

This SR&T task will provide a detailed computer program that will, when inputed with the current launch site meteorological conditions, accurately predict the characteristics of the launch pad plume cloud (size, composition, location, etc) and will provide real-time predictions as to changes in this plume cloud. In short, the computer program will predict the path and composition of the plume cloud from ignition of the booster rockets until dispersion/diffusion of the plume cloud, and will include such non-normal operation modes as on- and near-pad abort.

8.3.2 Technical Approach

Existing material will be used as baseline data and will be modified to fit the NASA Space Shuttle Booster. Previous work performed by the USAF Titan III SPO and by the Aerospace Corporation will be examined, and an assessment made as to applicability to the NASA Space Shuttle Booster launch. A comparison of pre-launch predictions and actual field measurements following Titan III C/D launches will be made to determine the accuracy of the existing prediction techniques. Factors influencing the accuracy of the prediction will be identified, and approaches to increasing the accuracy defined. Emphasis shall be placed on preparation of a computer program that accurately models the launch and operation conditions at Kennedy Space Center. Additional effort will be conducted to model the launch conditions at Vandenberg AFB and at a typical booster static test facility. The program will comprise a program definition phase and a computer program preparation phase.

8.4 RESOURCE REQUIREMENT

Manpower. This program will require approximately 5 man-years of effort in FY 73.

Specialized Facilities. The computer program will be designed for use on the CDC 6600.

Funding. Funding during FY 73 is estimated at $200,000.

8.5 TARGET SCHEDULE

The applicable program schedule for this task is presented in Figure 8-1.

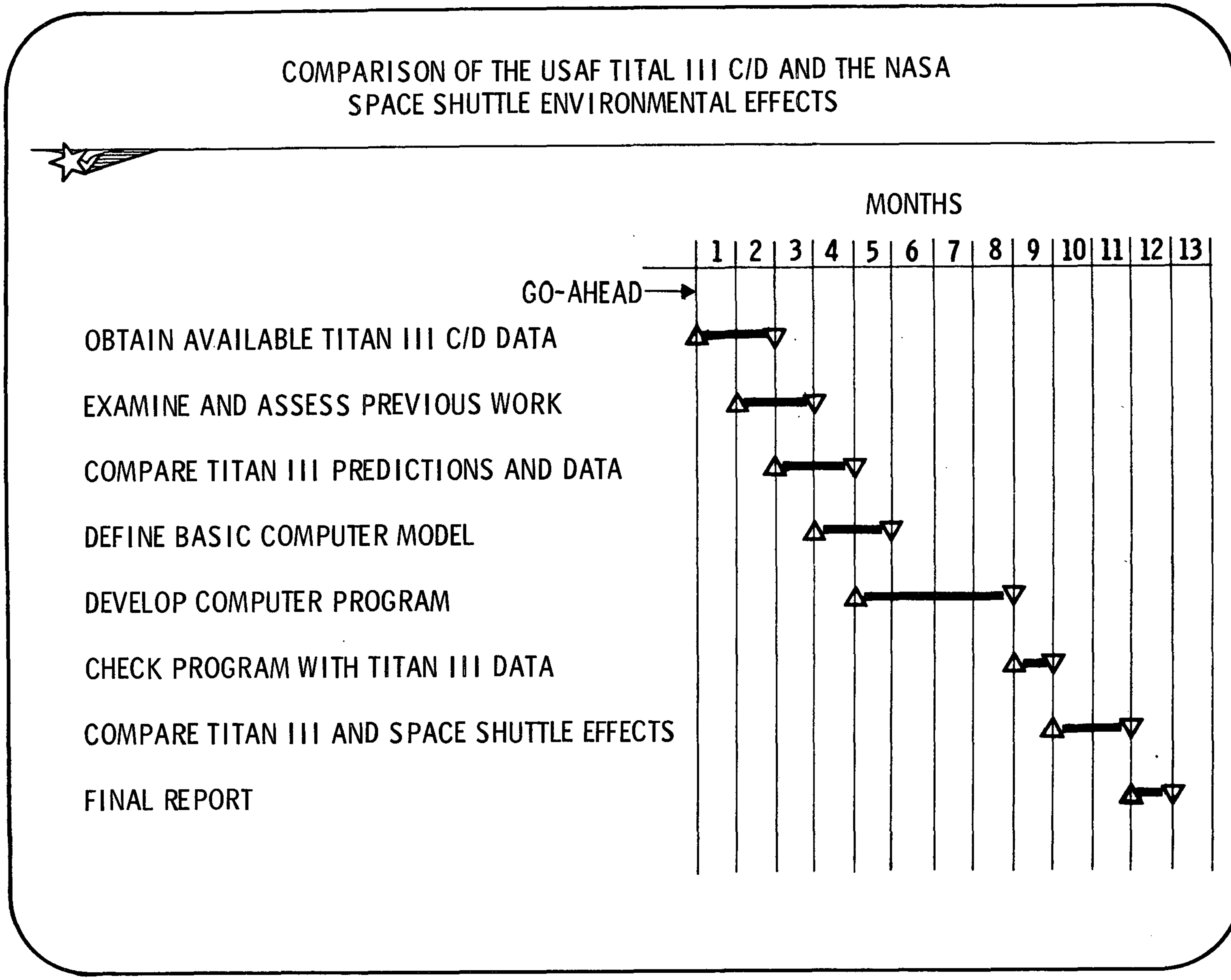

Figure 8-1 Comparison of the USAF Titan III C/D and the NASA Space Shuttle Environmental Effects Program Schedule

Section 9

STUDY OF OPTIMUM STEEL SELECTION FOR A REUSABLE SRM MOTOR CASE

9.1 STATUS

High-strength materials currently used for ocean exposure applications offer potential advantages for an SRM case with reuse capabilities. Process development, within the current state of the art, would be required to adapt the current fabrication technology for these steels to SRM cases. NASA study* of HY series steel applied to a 260-inch-diameter motor case has established basic feasibility. However, consideration of production application requirements such as material variability, tooling, production rate processes, facilities, and costs have not been made. In addition, consideration must be made of the impact on SRM design resulting from the lower tensile strength compared to D6AC steels in a reusable motor design.

9.2 JUSTIFICATION

Steels such as HY-140, which were developed for deep submergence vehicles, have many properties which are desirable for a recoverable SRM case. These steels have excellent toughness, are resistent to stress corrosion cracking and flaw growth, and are easily repaired. In addition, welding is easy, heat treatment or stress relief are not required, and inspection requirements are minimal. For these reasons, the HY series steels, which were developed for use in sea water environments, offer potential advantages for a reusable SRM motor case for the Shuttle application. Furthermore, cost savings are possible, as compared with proven LSM case fabrication methods which utilize D6AC or 18-percent nickel maraging steel. Considerable additional information is required, however, before selection of one of these steels for the SRM booster Shuttle can be made, since there is no direct rocket motor production experience. Some steels in the series, such as HY-180, have been produced only as experimental mill runs. Production details and motor design impact must be studied so that realistic performance and cost comparisons can be made with the baseline D6AC steel.

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* A Study of Weldments and Pressure Vessels Made of HY-150 Steel Plates, Final Report, NASA CR-72155, NASA-Lewis Research Center, January 1967

9.3 TECHNICAL PLAN

The objectives of the program will be to evaluate the advantages of an SRM case fabricated from HY-140 or HY-180 steel alloys. The risk, reliability, performance, and cost of a case made from these steels will be evaluated and will be compared to a D6AC steel case. The evaluations will consider both 10 and 20 reuses. Extensive study will be made of the development work required before motor cases of either steel could be fabricated reproducibly and reliably. The following technical areas will be highlighted:

- Size limitations on plate and forgings of both alloys
- Material variability
- Welding techniques
- Material properties of base metal and welds
- Inspection requirements of base metal and welds
- Tooling and facilities requirements for production
- Process details for high-volume production
- SRM design using these materials
- Effects of recovery and reuse

The evaluation will require establishment of detailed production processes and existing and projected industry capability. Supporting laboratory studies will be conducted. The study will culminate in a detailed performance and cost comparison between the approaches using the various material candidates.

9.4 RESOURCE REQUIREMENTS

Manpower - 4 man-years in FY 73

Facilities - No special facilities required

Funding -	Labor	$ 175,000
	Materials	75,000
	Total	$ 250,000

9.5 TARGET SCHEDULE

Figure 9-1 presents the program schedule for this effort.

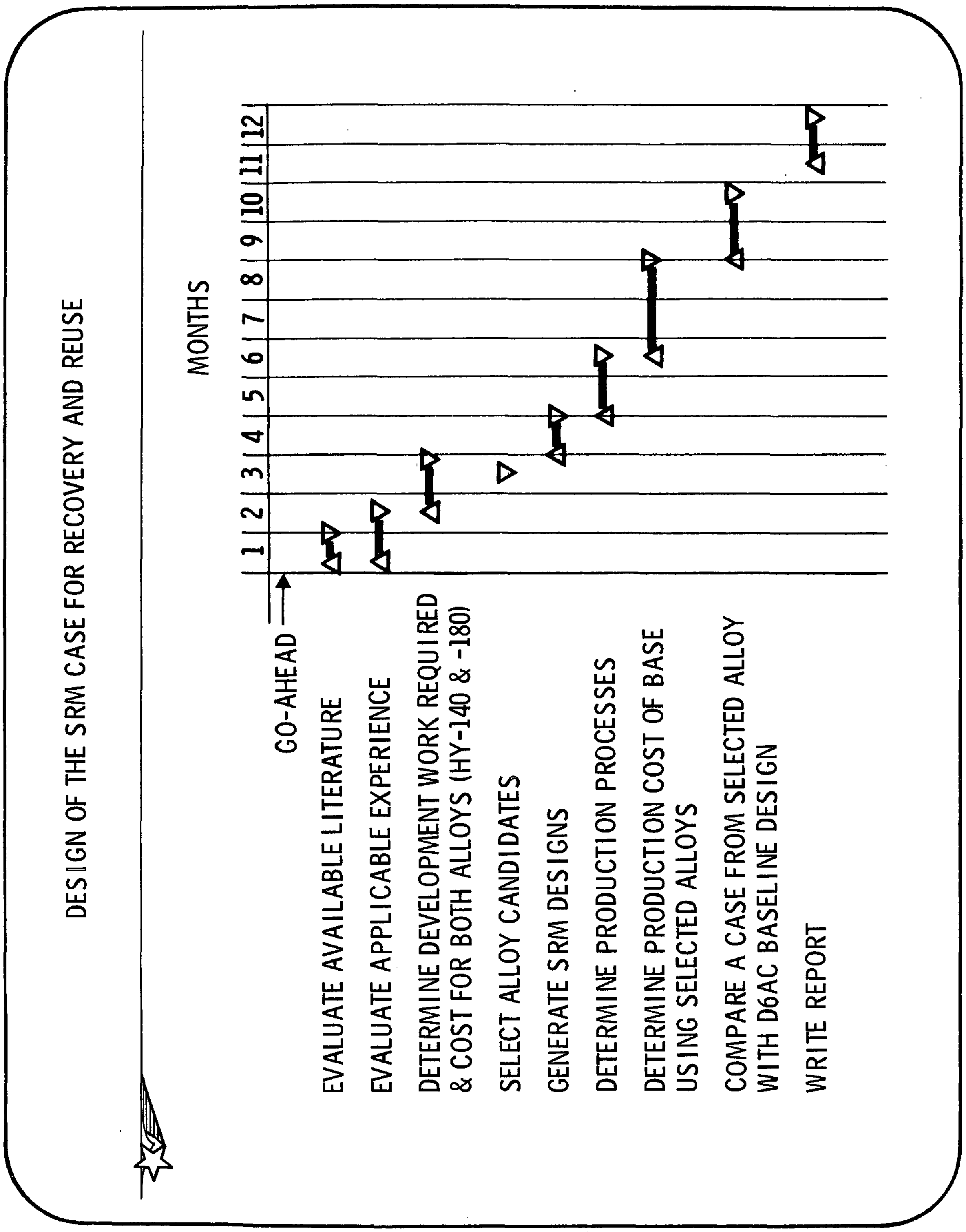

Figure 9-1 Design of the SRM Case for Recovery and Reuse Program Schedule