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HYBRID PROPULSION TECHNOLOGY PROGRAM
PHASE I

FINAL REPORT

VOLUME I

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16. Abstract

This report provides a description of the work performed during the HPT program.

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PREFACE

This volume is part of a four-volume set that describes the work performed from 6 March to 30 November 1989 under contract NAS8-37777 entitled, "The Hybrid Propulsion Technology Program--Phase I." The study was directed by Mr. Ben Shackelford of the NASA/Marshall Space Flight Center. Listed below are major sections from the four volumes that comprise this Final Report.

Volume I	• Executive Summary
Volume II	• General Dynamics Final Report - Concept Definition - Technology Acquisition Plans - Large Subscale Motor System Technology Demonstration Plan
Volume III	• Thiokol Corporation Final Report - Trade Studies and Analyses - Technology Acquisition - Large Subscale Motor Demonstration
Volume IV	• Rockwell International Corporation Final Report - Concept Evaluation - Technology Identification - Technology Acquisition Plan

TABLE OF CONTENTS

VOLUME I
LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

ALS	Advanced Launch System
ASRM	Advanced Solid Rocket Motor
COTR	Contracting Officer's Technical Representative
DDT&E	Design, Development, Test and Evaluation
ERB	Engineering Review Board
GD	General Dynamics
GDSS	General Dynamics Space Systems Division
GR/EP	Graphite/Epoxy
GSE	Ground Support Equipment
HP	Hybrid Propulsion
HPB	Hybrid Propellant Booster
HPT	Hybrid Propulsion Technology
HRB	Hybrid Rocket Booster
HRM	Hybrid Rocket Motor
HTPB	Hydroxy - Terminated Poly Butadiene
IRAD	Internal Research and Development
ISP	Specific Impulse
LBM	Pound Mass
LCC	Life Cycle Costs
LO2	Liquid Oxygen
LRB	Liquid Rocket Booster
LBF	Pounds Force
MSFC	Marshall Space Flight Center
N2H2	Hydrazine
NASA	National Aeronautics and Space Administration
O/F	Oxygen-to-Fuel Ratio
ODE	One Dimensional Equilibrium
RD	Rocketdyne
RP-1	Rocket Propellant
SDV	Shuttle Derived Vehicles
SOW	Statement of Work
SRB	Solid Rocket Booster
SRM	Solid Rocket Motor
SSME	Space Shuttle Main Engine
STS	Space Transportation System
TC	Thiokol Corporation

1.O INTRODUCTION

A number of booster propulsion system concepts are being considered for the next generation of manned and unmanned space launch vehicles. The one propulsion system concept that has potential for reducing costs with increased safety, reliability, and performance is hybrid propulsion (HP).

A HP system may be thought of as a liquid propulsion system with solid fuel or a solid propulsion system with a liquid oxidizer. The HP system in Figure 1-1 extracts the best features of both the liquid and solid propulsion systems, and supplements them with features that neither currently have.

The liquid propulsion features that are most attractive are the higher specific impulse, clean exhaust, separated propellants, and oxidizer loading just prior to launch. The higher specific impulse requires less propellants to reach the specified delta velocity. The clean exhaust is in keeping with current environmental concerns. Keeping propellants separated provides increased safety during manufacturing, processing and flight. With the oxidizer loaded just prior to launch, less weight needs to be transported and erected, and safety is increased by the absence of oxidizer until the area is vacated for launch.

The most attractive solid propulsion features includes low life cycle costs (LCC), no rotating machinery, compact size, and a robust case. In addition, a HP system has a robust LO2 tank; provides thrust control for ignition, to alleviate flight loads, and for

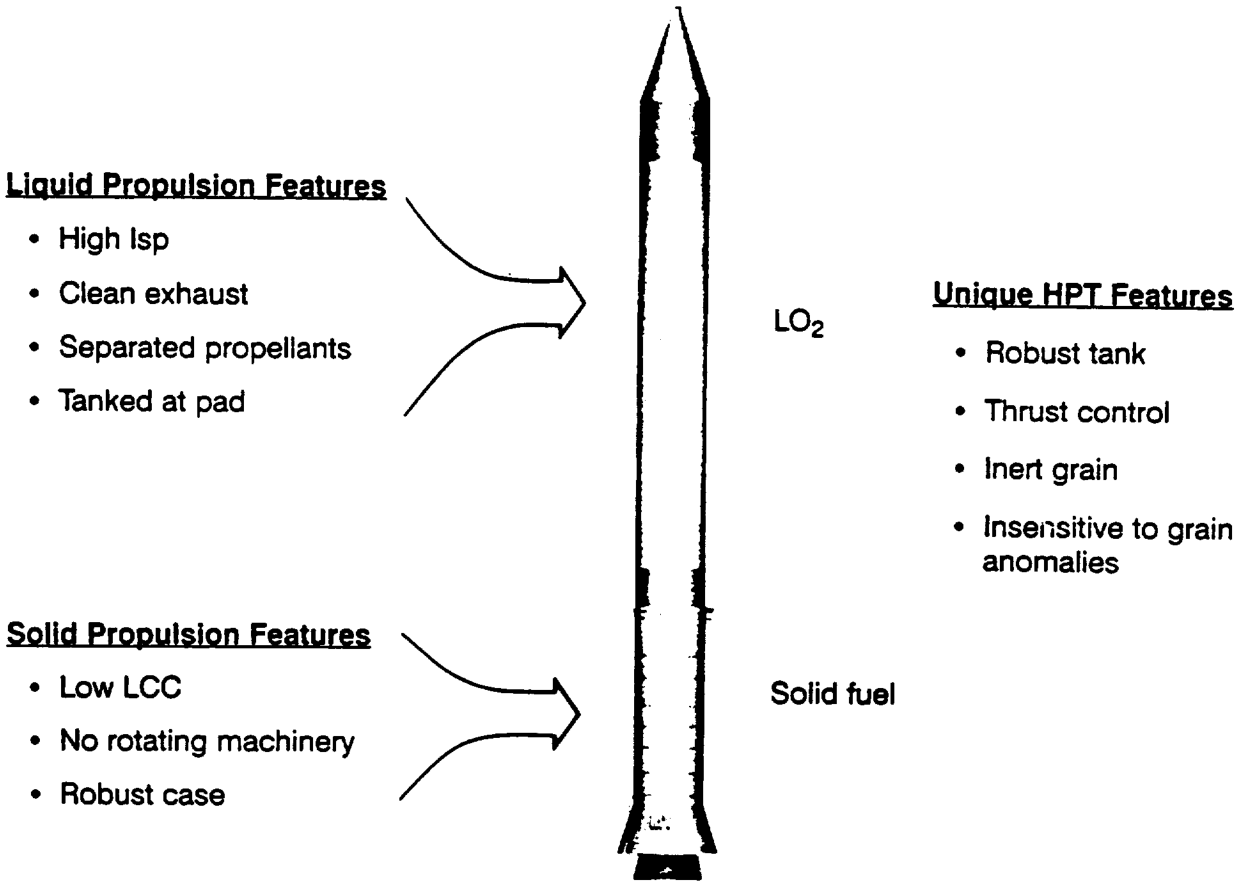


Figure 1-1. HPT integrates the best features of liquid and solid propulsion systems.

thrust termination; and uses an inert grain that is not sensitive to anomalies such as cracks, voids, and separations.

The program team was led by General Dynamics (GD) with Thiokol Corporation (TC) and Rocketdyne (RD) as subcontractors. These three companies bring over 105 years of combined experience in successfully identifying, acquiring, demonstrating, developing, and producing advanced propulsion systems.

Each team member is a proven, recognized expert in a necessary portion of the total technology to be applied to HPT: GD for propulsion system integration, TC for solid propulsion technology, and RD for liquid propulsion technology. The combined expertise of these companies will successfully develop the technologies required to mature hybrid propulsion.

2.0 HPT PROGRAM OBJECTIVE

The objective of the HPT program is to develop the technology to enable the application of hybrid propulsion to manned and unmanned space launch vehicles. This program, Figure 2-1, will identify the necessary technology in Phase I, acquire that technology in Phase II, and demonstrate that technology in a large subscale system in Phase III. The results of Phase I are reported in Volume II.

Phase I consisted of booster propulsion concepts definition, hybrid propulsion technology identification, and planning for technology acquisition and demonstration. Program duration was six months with multiple awards of four parallel contracts.

Phase II is designed to acquire the components of the HPT identified in Phase I. It includes the analytical efforts necessary to develop required codes and verification of these codes through laboratory and rig testing. The testing is at relatively small scale to initially demonstrate HPT development. Current planning is to award two parallel contracts, each for two years duration.

Phase III provides for demonstration of the technologies acquired during Phase II. The acquired HPTs are incorporated into a large subscale motor system and tested to demonstrate the ability of the codes to predict the HPT characteristics when scaled to a large thrust representative of a booster application. Current planning is to award two parallel, two-year contracts.

> "...to develop the technology to enable the application of hybrid propulsion to manned and unmanned space launch vehicles."
>
> — Statement of Work

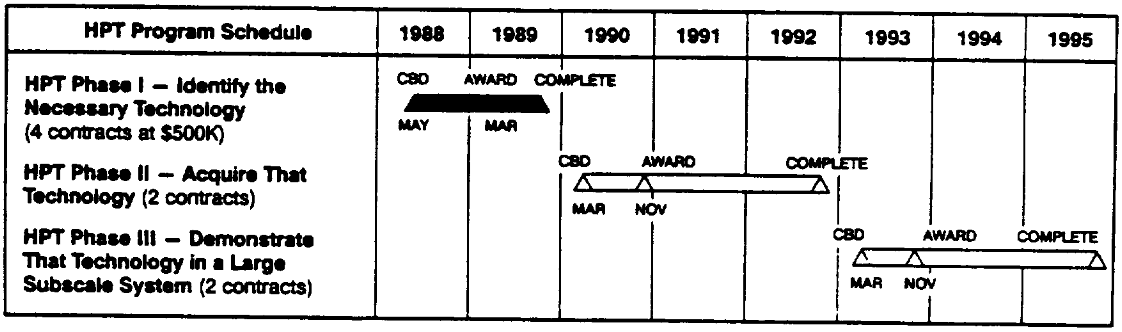


Figure 2-1. HPT program objective.

3.O PHASE I: IDENTIFY THE NECESSARY TECHNOLOGY

3.1 STUDY METHODOLOGY

HPT concepts were identified, optimized, evaluated, and refined through an iterative process that continually forces improvement of the concepts with respect to the criteria against which they were measured and the requirements they must satisfy, Figure 3-1.

For each of the full-size and quarter-size HP systems, one of the refined HP concepts was recommended and further defined with conceptual design and technology identification packages. Phases II and III also were planned during Phase I. Phase II includes technology acquisition through design, laboratory/sub-scale testing, and verification of analyses and scaling. Phase III includes large subscale technology demonstration and verification of analyses and scaling.

The program team had frequent meetings at rotating locations to assure a meaningful interchange of information among all of the program participants. There were four program reviews at Marshall Space Flight Center (MSFC) with the Contracting Officer's Technical Representative (COTR). In addition there were six technical interchange meetings, two at GD, two at TC, and two at RD.

On September 15, the Phase I study was reviewed at a meeting of our HPT Review Board. This board is composed of nine senior members with relevant experience from GD, TC, and RD.

3.1.1 Requirements. Figure 3-2 shows the three requirements that had the most effect on HPT of the 10 requirements contained within Requisition 1-8-EP-98621 and the three additional requirements developed during the study. These performance requirements encompass a range of possible vehicle system requirements. Two HPT sizes were studies: a single unit that meets the performance requirements shown in Figure 3-2 (which is the performance of the ASRM) and a single unit, four of which combined meet the performance requirements. Two of the ASRM-size motors or eight of the quarter-ASRM-size motors would be required for one launch vehicle.

Two-to-one throttling was specified to assure compliance with the thrust shown versus time curve and to provide thrust flexibility to alleviate flight loads.

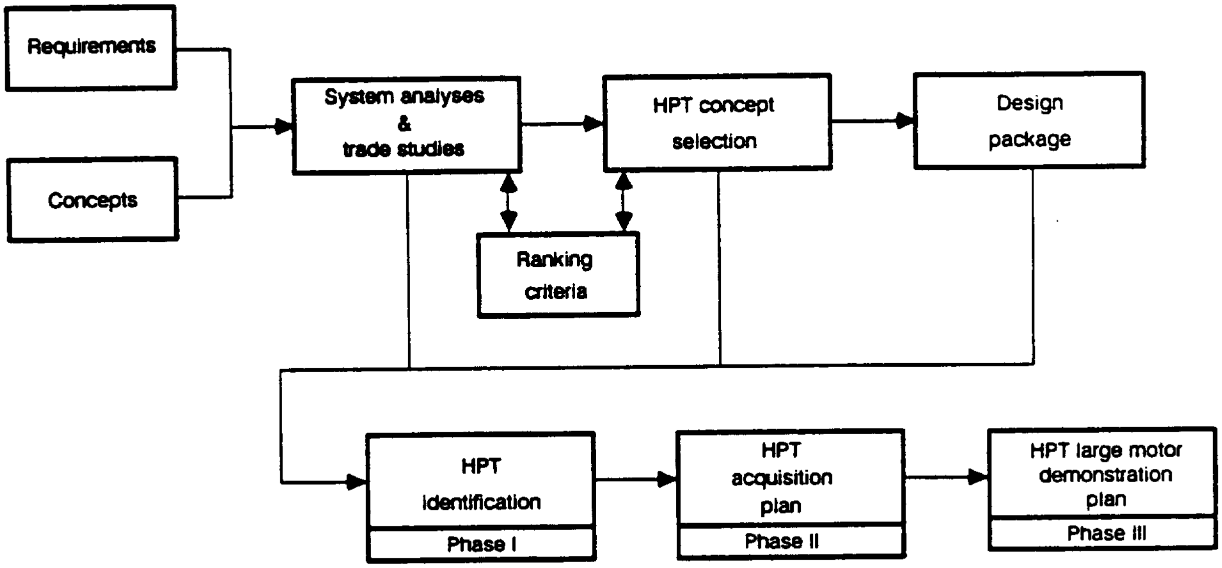


Figure 3-1. A systematic approach identified the HPTs and planned their acquisition and demonstration.

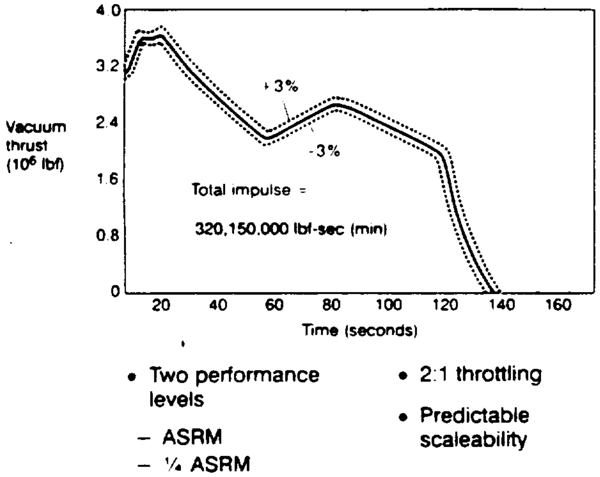
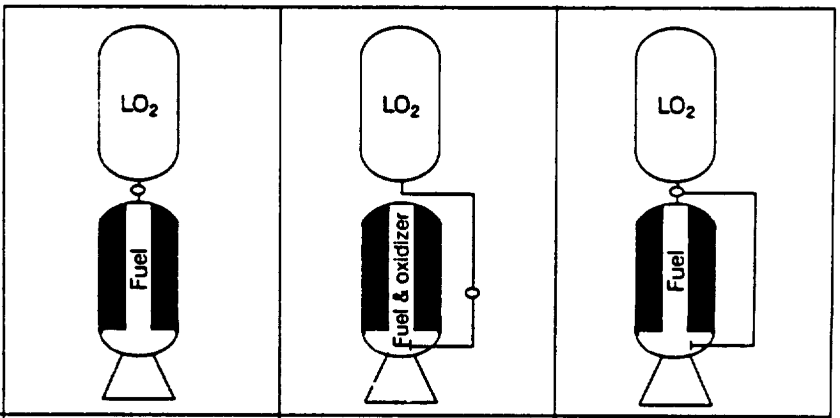


Figure 3-2. These primary HPT requirements greatly influenced our studies.

The third primary requirement was to provide HPT with predictable scaleability to all booster sizes applicable for the next generation of manned and unmanned space launch vehicles. Predictable scaleability is a necessary measure of the maturity of a technology. It assures that the technology will successfully transition through full-scale development into a viable product.

3.1.2 Ranking Criteria. The ranking process provided insight into HPT concept attributes and weaknesses. When comparing concepts, it provided a relative measure of merit, which allowed the concepts to be ranked in order of desirability. A numerical rating factor was assigned to each of the ranking criteria. Numerical rating factors were given to reduce the effect of evaluator bias on the analysis of the alternatives and to facilitate comparison among unrelated criteria. The factors are applied to each criterion by assessing its relative importance to mission capability. Concepts ranking was based upon the criteria presented, as prioritized within Requisition 1-8-EP-98621.

3.1.3 Concepts. The classical hybrid propulsion concept was selected as the preferred concept for subsequent acquisition and demonstration, Figure 3-3. Its main



Ranking criteria	Classical	Gas generator	After-burner
• Flight safety & reliability	• Inert grain • Forward LO$_2$ feed	(None)	• Inert grain
• Life cycle cost	• Inert grain • One oxidizer • One LO$_2$ control system	(None)	• Inert grain • One oxidizer
• Performance	• LO$_2$ only	(None)	• Always at MR • LO$_2$ only
• Launch site operations	• Inert grain • Forward LO$_2$ feed	(None)	• Inert grain

Figure 3-3. These prioritized ranking criteria favorably position HPT for future booster competition.

features are the injection of oxidizer into the forward volume only of a combustion chamber containing an inert fuel grain.

This concept was most attractive because it uses an inert grain that is nonhazardous in the absence of an oxidizer; is forgiving as to anomalies such as cracks, voids, and separations; requires only short oxidizer feed lines with single flow controls; and uses only low-cost energetic liquid oxygen for the oxidizer. Approximately one-half percent of performance is sacrificed to obtain these desirable features. The performance penalties are inherent in a classical concept that throttles as mixture ratio varies off optimum during the grain regression.

The gas generator hybrid propulsion concept combines solid oxidizer and fuel in the grain. As such it requires all the attention and expense of current solid propulsion systems to achieve acceptable safety and reliability. It had no advantages when compared with the other HPT concepts.

The afterburner HP system is identical to the classical with an added aft liquid oxygen system to maintain the combustion mixture ratio near optimum for the entire burn. For the given thrust profile, the performance gained did not justify the complexity added.

3.1.4 Systems Analyses and Trade Studies. The systems analyses and trade studies, Figure 3-4, refined the preliminary hybrid propulsion concepts to their likely configuration at maturity. These analyses and trades also identified the required technology and provided a merit of benefit when applied to HPT. The initial analyses and trades center on the ballistic characterization of the motor. These include propellant selection, motor performance, pressure/area ratio, oxidizer injection, ignition system, thrust control, and combustion stability.

The second set of analyses and trades relate to efficiently providing the oxidizer for combustion. These studies recommended a particular pressurization system, and whether the oxidizer should be pump- or pressure-fed to the injector(s).

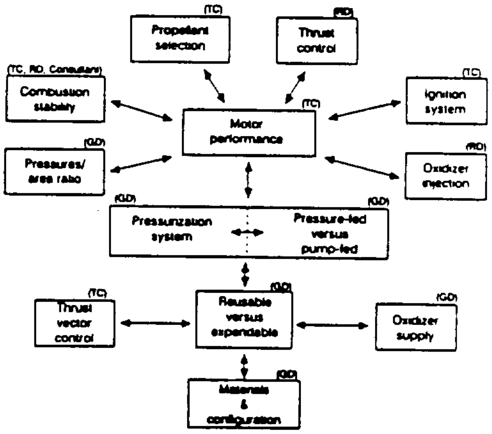


Figure 3-4. System analyses and trade studies selected the preferred approach.

The remaining analyses and trades concern reusable versus expendable, structures and insulation, oxidizer supply, and thrust vector control.

The study leader for each of the system analyses and trade studies was assigned as shown in Figure 3-4. The study leader was selected because he had the best available information and the most involvement in the pertinent subject. The study leader was supported by the other two companies, and each trade study drew on the assets of all three team members.

3.2 SELECTED HPT CONCEPT

The selected hybrid propulsion concept, Figure 3-5, is applicable for all booster sizes. It satisfies both the ASRM-size and the quarter-ASRM-size requirements. As a result, there is only one HPT family to be acquired, identified, and demonstrated.

The selected concept has a pressurization system, the LO2 tank, and the aft case assembly. This configuration is entirely expendable, with new boosters fabricated for subsequent launches. The system analysis and trade study selected an expendable booster because a booster without a recovery system has improved flight safety and reliability, and has less launch site operations since there is one less booster system to manage. The life cycle costs are less using

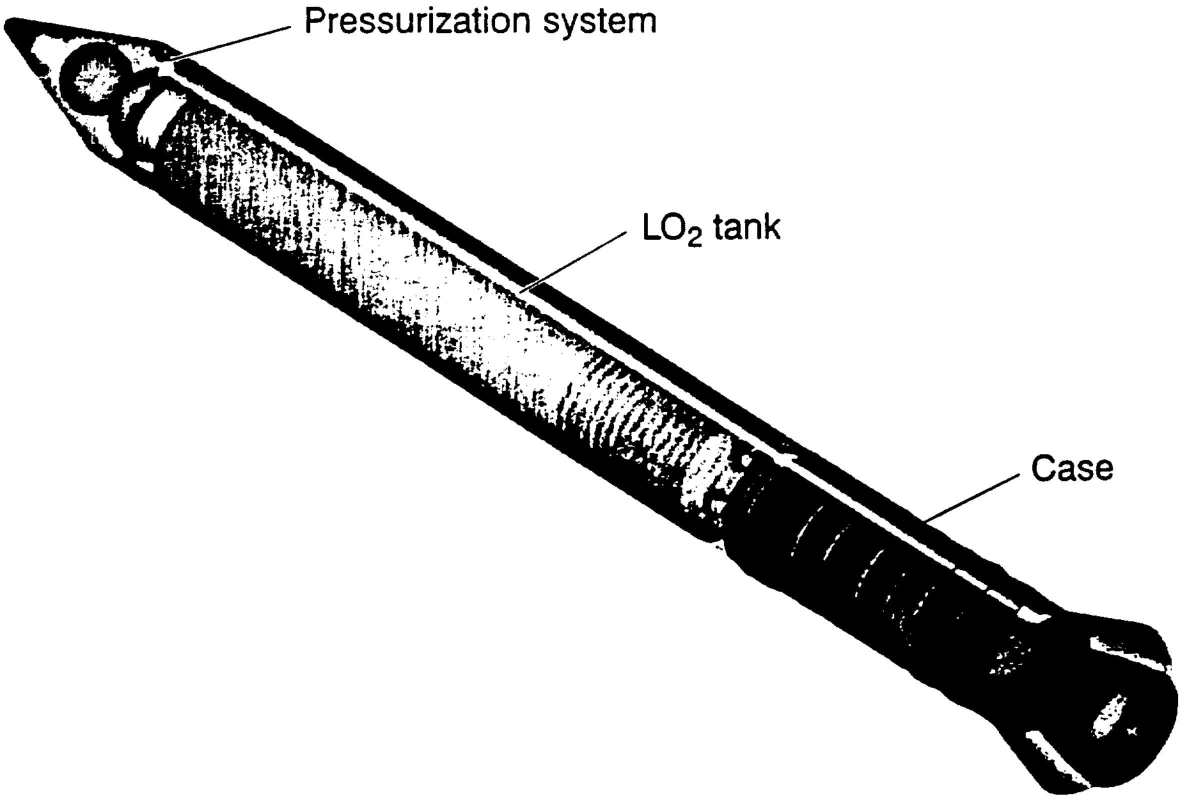


Figure 3-5. The selected HPT concept.

HPT primarily due to the low recurring costs of composite tanks and cases. The expendable booster also has better performance because it eliminates the additional recover system weight.

The presented ASRM-size hybrid propulsion system, Figure 3-6, satisfied the ASRM planned envelope requirements. The quarter-ASRM-size hybrid propulsion system was then sized using the same fuel composition.

Hybrid propulsion systems can use differing solid fuel compositions that will vary the actual specific impulse and mixture ratio of the propulsion system. This, in turn, establishes the size and weight of the resultant booster. The hybrid propulsion parameters can thus be adjusted to satisfy specific booster requirements.

Positive responsiveness to variable propellant compositions is an attractive feature of hybrid propulsion, and the technology developed capitalizes upon this. These various fuel blends are accommodated within the applicable codes.

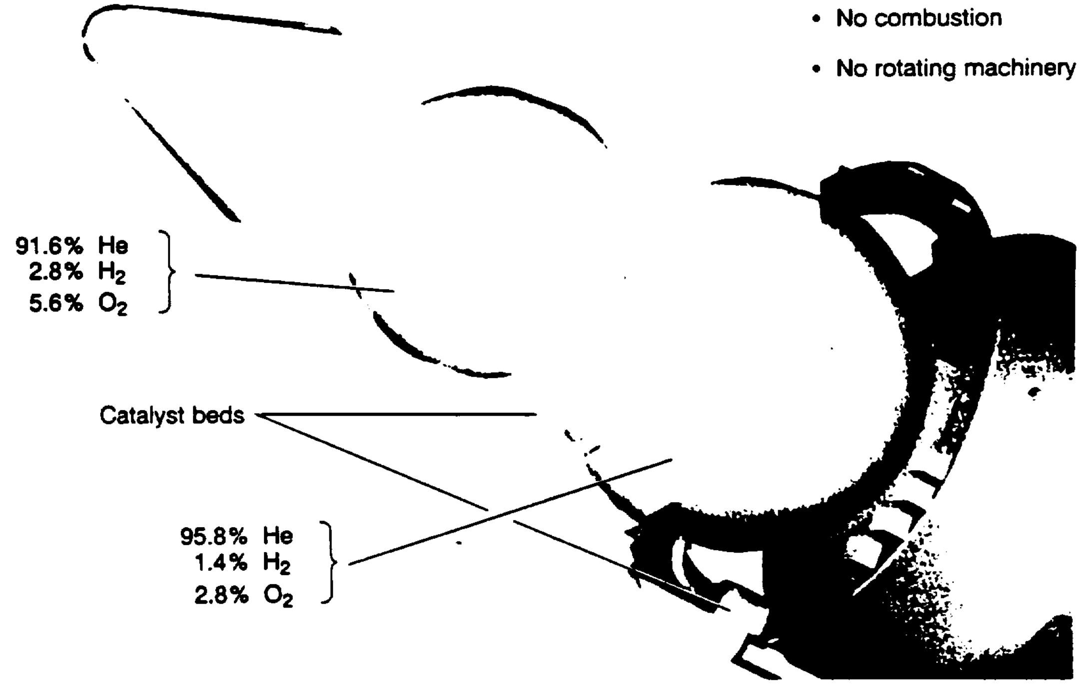
The 500-psia chamber pressure was recommended by our system analysis and trade study as the preferred pressure level for a pressure-fed booster. It remains constant for the range of booster sizes investigated.

A Tridyne cascade pressurization system, Figure 3-7, was selected to pressurize the LO2 tank ullage. This pressurization concept incorporates new technology that benefits hybrid propulsion systems, but its development is not required to realize HPT. Other pressurization concepts using proven technology are available.

The system analysis and trade study recommended a pressure-fed LO2 system instead of a pump-fed system. The pump-fed

ASRM Size	Characteristic	1/4-ASRM Size
2.59 M	Nominal vac thrust (lbf)	648K
150	Diameter (inches)	90
1790	Length (inches)	1248
272.5	Isp, vac actual (sec)	274.7
1.27	Mixture ratio	1.29
500	Average P_c (psia)	500

Figure 3-6. The selected configurations are interchangeable with current boosters.



- No combustion
- No rotating machinery

Figure 3-7. A Tridyne cascade system pressurizes the LO2 tank.

system required pumps as well as another pressurization system to pressurize the LO2 tank ullage sufficiently to provide net positive suction pressure.

Of the pressure-fed systems studied, the Tridyne system was selected because it has neither combustion nor rotating machinery and may be developed as an independent system. In addition, its plumbing requirements are modest.

The new-technology liquid oxygen tank, Figure 3-8, reduces the HPT booster burnout weights when compared to current-technology tanks. The reduction in weight is reflected as an increase in payload for the fixed envelope booster or as a reduction in booster size for a given performance level.

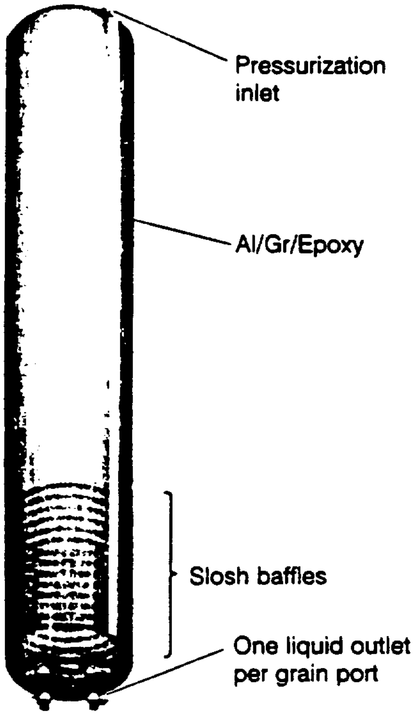
The maximum operating pressure requires a tank wall thickness sufficient to support the STS stack during launch processing. When pressurized, it is more than sufficient to resist the "twang" loads during main engine ignition.

While a composite LO2 tank is very attractive to support a pressure-fed LO2 system, it is not an enabling technology. A 2219 aluminum tank processed using current technology is an acceptable alternative.

Electromechanical actuators are recommended for each of the LO2 flow control valves. The valves vary their flow position during flight to follow the desired booster thrust profile, to balance the thrust between ports and multiple boosters, and to provide a soft ignition and shutdown.

Electromechanical actuators are recommended for a HPT propulsion system, but are not required. They are currently funded as a new technology in support of the Advanced Launch System.

Relative motion compensators have been used on flight vehicles and in commercial applications. Only system-unique development is necessary to adapt existing technology.



Dimension	ASRM size	1/4 size
Diameter (inches)	150	90
Length (inches)	877	679
Wall thickness (inches)	1.03	0.62
Weight (lbm)	33,217	8,229
MOP (psig)	892	892

Figure 3-8. A new technology LO2 tank increases payload for less cost.

All new enabling HPT occurs within the case, Figure 3-9, but the materials and composite case will increase flight safety and reliability, and will improve performance for a lower cost. Existing steel cases are still satisfactory for HPT, however.

Hypergolic ignition was selected during our analysis and study as an aid to assure complete, smooth ignition.

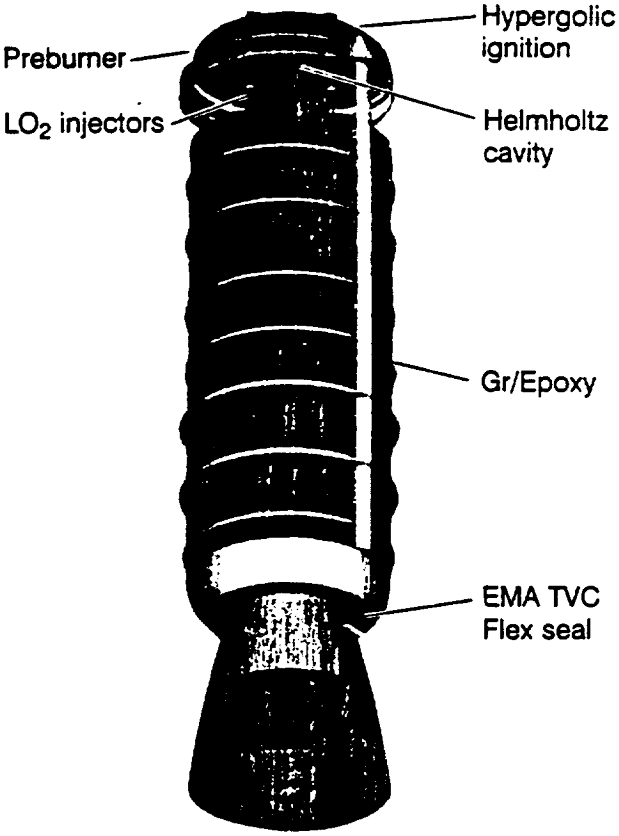
LO2 injectors are recommended to eliminate the complex extra systems necessary to convert the LO2 to gas.

A preburner with Helmholtz chambers is included to improve combustion stability and scaleability.

A current technology flex seal permits nozzle vectoring by the electromechanical actuators currently in development for ALS technology.

3.3 HPT IDENTIFIED

The enabling HPTs, Table 3-1, involve development of codes to fully characterize the combustion processes. Of interest is the smooth, complete ignition of the grain and the retention of the flame over the entire grain surface without causing local flooding, with resultant incomplete and/or rough combustion.



Dimension	ASRM size	1/4-ASRM size
Diameter (inches)	150	90
Length (inches)	682	460
Wall thickness (inches)	0.86	0.52
Case weight (lbm)	13,362	3,405
MEOP (psig)	743	743

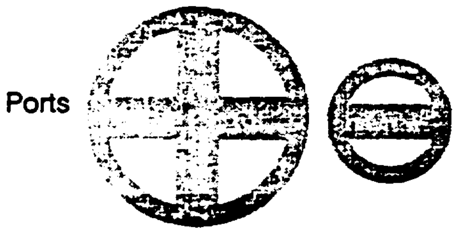


Figure 3-9. The combustion process occurs within the case.

The type of LO2 injectors and the size and discharge concentration of the droplets need more coding to reliably support combustion codes. Of primary interest is whether liquid or gaseous oxygen will better provide smooth, scaleable combustion in large ports with varying length-to-diameter ratios.

Efficient gas mixing, combustion, and flow within the ports and through the nozzle at various pressure and mixture ratios are desirable in order to have high, acceptable specific impulses.

Grain regression rates are dependent on the chemical composition of the fuel. Higher regression rates without charring are attractive because they decrease the port area required, thus increasing the loading efficiency and decreasing the burnout weight of the booster at staging.

The other noted HPT technologies are derivatives of proven technologies. They can be characterized during development of the enabling HPTs.

Verification of current codes and theories through tests is necessary to acquire HPT. Current HPT codes do not have the maturity of codes developed for liquid and solid propulsion systems. Some are in their embryonic stages and need further development, while others need only the databases created during a logical, systematic test program.

Table 3-1. Stable, efficient combustion is the most important technology required to enable the development of hybrid propulsion systems.

The HPT enabling issues are:

- Grain ignition
- Flame holding/ flooding
- LO2 injection
- Gas mixing, flow, and combustion
- Grain regression
- Combustion stability

These HPTs may be characterized when satisfying the enabling issues:

- Nozzle materials & configuration
- Case internal insulation
- LO2 flow control
- Ignition type/ sequencing
- O2 conditioning
- Injector durability

Testing four motor sizes of increasing thrust capability will provide the needed databases. The acquired codes will then enable the definition of a specific hybrid propulsion system to support a requested launch vehicle. Because the codes will have been verified, we will more confidently be able to develop the propulsion system into an operational vehicle.

4.0 PHASE II: ACQUIRE HPT

The recommended acquisition plan uses a 2-inch motor, Figure 4-1, to evaluate grain chemistry and characterization. This motor is large enough to provide the information requested, yet it is small enough to test economically and quickly.

The injector's test rig provides for injector testing with water and/or cryogenic fluids prior to installation for hot firing. This test rig will allow documentation of injector performance for later comparison during the motor firing and for better characterization with the injector and combustion codes.

The 10-, 24-, and 48-inch motor tests will record pertinent information to acquire the ignition, injection, combustion, and grain regression of HPT. These engines are of increasing size and length. They inject both liquid and gaseous oxygen into the primary grain. There will be an adequate number of firings of each configuration to confirm the recorded data without incurring unmanageable costs.

The last firing is a sequential firing of a sector of the recommended demonstration motor. In addition to acquiring HPT, this firing will provide assurance of a successful Phase III.

The injector cold tests are planned at the existing Rocketdyne Cold Flow Facility, Figure 4-2, near Canoga Park, California.

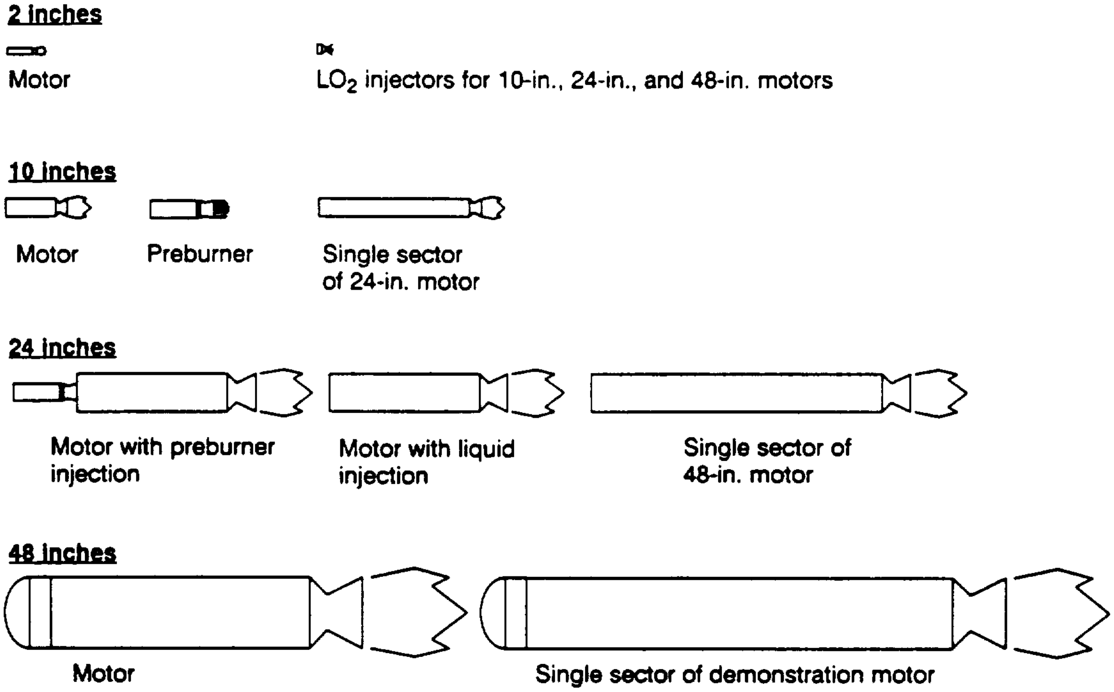
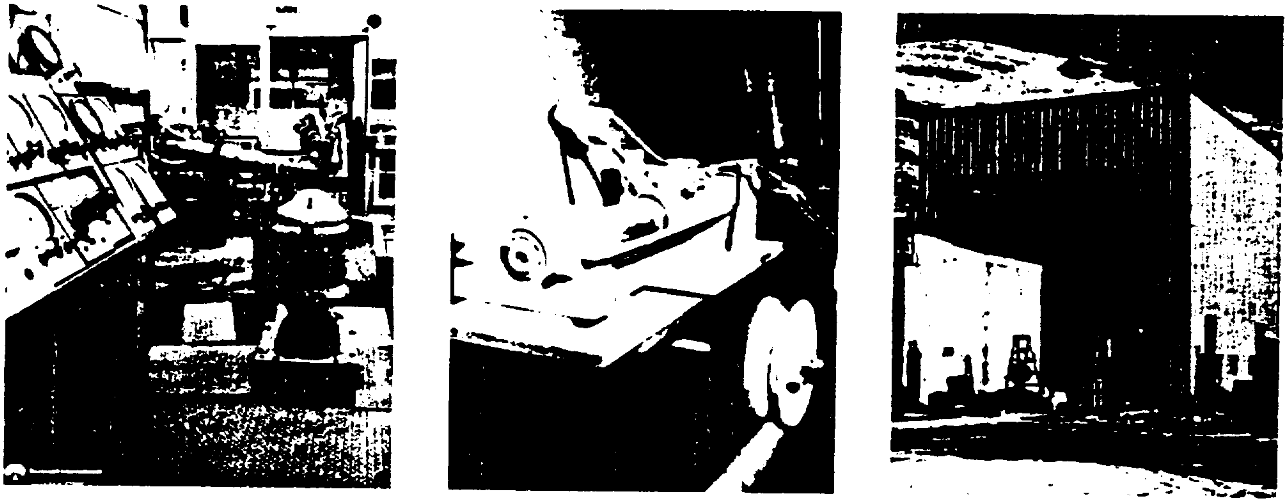


Figure 4-1. Four motor sizes are recommended to assure HPT acquisition.



Rocketdyne Cold Flow Facility

Thiokol 2-in. Motor Facility

Thiokol T-93 Site for 10-in., 24-in. & 48-in. Motor Tests

Figure 4-2. Three existing test sites can satisfy the facility requirements for HPT acquisition.

Thiokol is firing grains in their 2-inch motor at their test site near Ogden, Utah. These continuing firings were initiated last year with a portion of their discretionary funds.

The 10-, 24-, and 48-inch motors may be fired at Thiokol's T-93 test site. This site is fully supported with a rollback building and a hardened control center. It will be activated shortly by the joint efforts of General Dynamics, Rocketdyne, and Thiokol.

HPT will be acquired in two years for $12.53 million, as shown in Figure 4-3. The two-year schedule assumes an orderly progression through the tests, data reduction, and code revisions.

The tests would use conservatively designed hardware to preclude the loss of test hardware or facilities due to unforeseen problems. Personnel safety would be assured at all times.

Cold flow tests of the injectors and each modification of the rig are planned prior to use of the propellant and oxidizer. The T-93 stand is supported with sufficient motor cases and grain cartridges, as well as computer-based data reductions and analyses, to fully and efficiently use the stand.

5.0 PHASE III: DEMONSTRATE HPT IN A LARGE SUBSCALE SYSTEM

A series of three firings costing $34.3 million, Figure 5-1, that examine combustion stability, regression rate, and scaleability, will demonstrate the technology developed. The 90-inch-diameter test motor used will develop a maximum thrust of 880,000 lbf in each of two proposed configurations. In the first two tests, the dimensions of the motor case will be those of the recommended quarter-size booster case. While the first grain will allow evaluation of transient conditions, a full-duration burn of the second set will verify thrust tailoring and the end of run termination sequence. An extension segment will be added for the third firing to

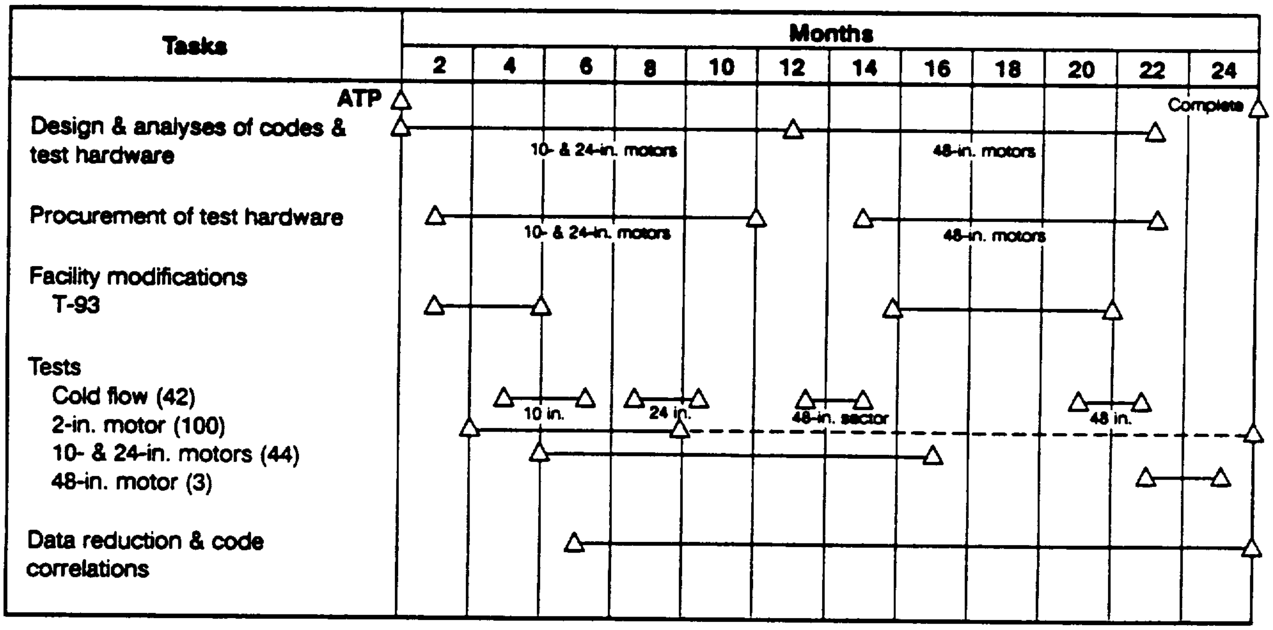


Figure 4-3. Two years are required to acquire the identified HPT.

accommodate a different grain geometry. With a length and port profile matching one of the four ports to be used in the ASRM-size motor, additional runs will be used to verify scaling for the next program phase. Since the operating parameters of the two configurations will be similar, use of the same stand is possible without major modification to either the support structure or the LO2 supply system.

Due to the basic nature of the hybrid motor configuration, the liquid oxidizer supply system, Figure 5-2, does not need to contain exotic components or be overly complex. Since a HP system requires only a single fluid, precise valve timing and synchronization are not necessary as with a liquid engine test rig. All the recommended hardware is commercially available, with no development or testing time needed.

For the proposed testing, a pressurized LO2 supply tank is required. A compressed gas source is shown as the pressurization system, but any functionally equivalent system would be acceptable.

By the time the technology demonstration phase of the HPT program is contracted, the Booster Technology Simulator at MSFC, Figure 5-3, will be completed and ready for use. The facility will consist of a modified F-1 test stand adapted for use as a vertical firing (nozzle-down) stand for large booster testing. It will be altered to include a 4,055-ft3, heavy-walled LO2 tank, a high-capacity pressurization system, and the necessary structure to accommodate a booster of the quarter-ASRM size.

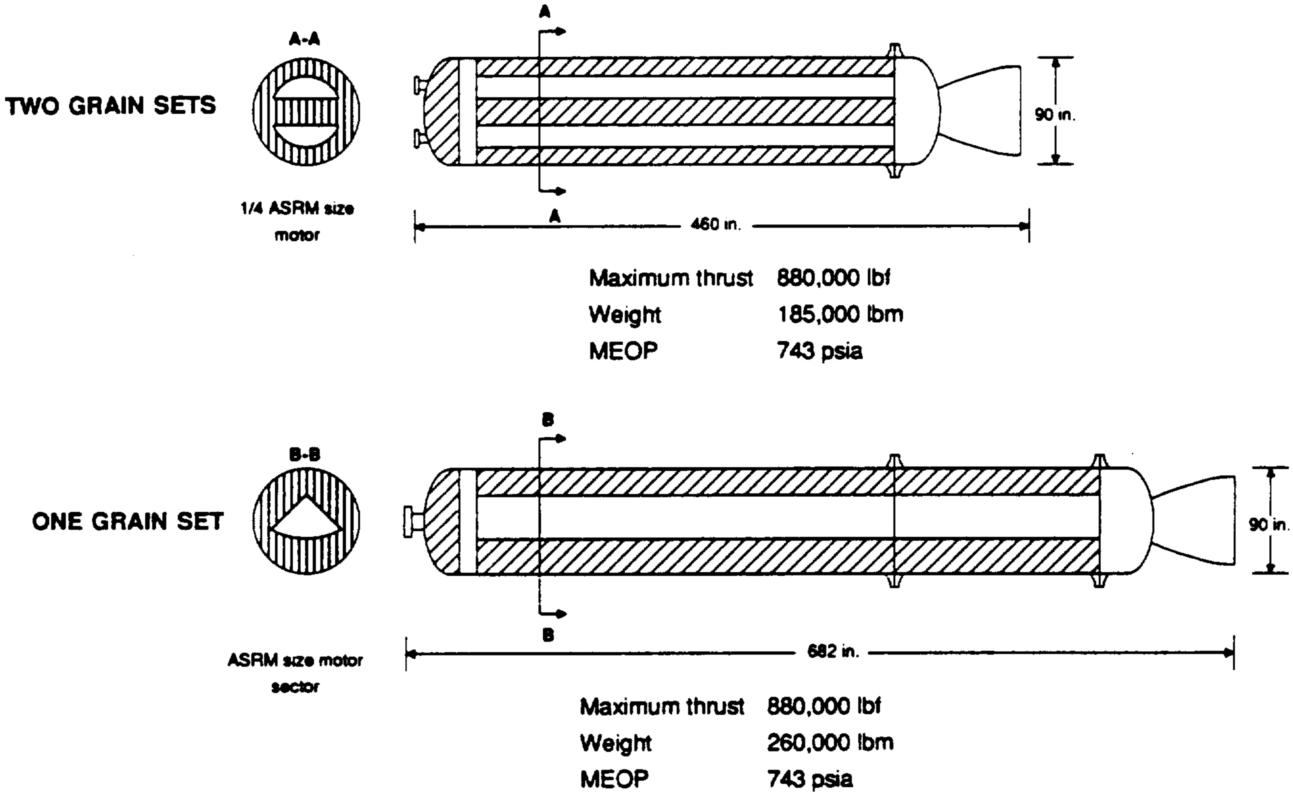


Figure 5-1. Three large subscale motor system firings are recommended to demonstrate HPT.

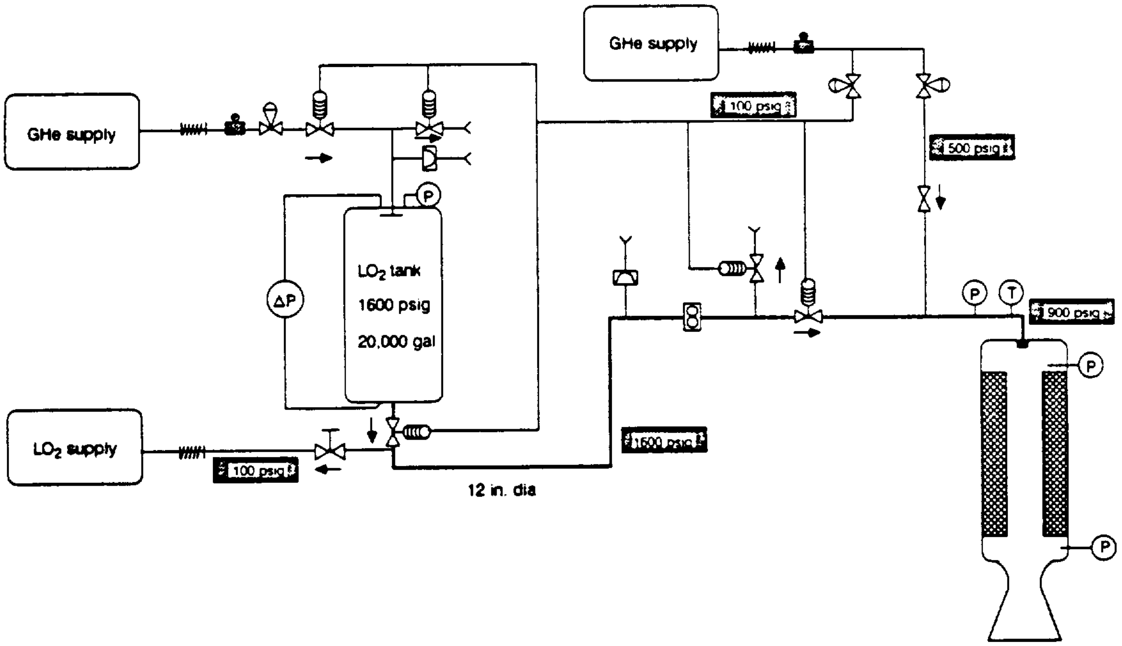


Figure 5-2. The supporting LO2 system for the demonstration motor firings uses commercially available hardware.

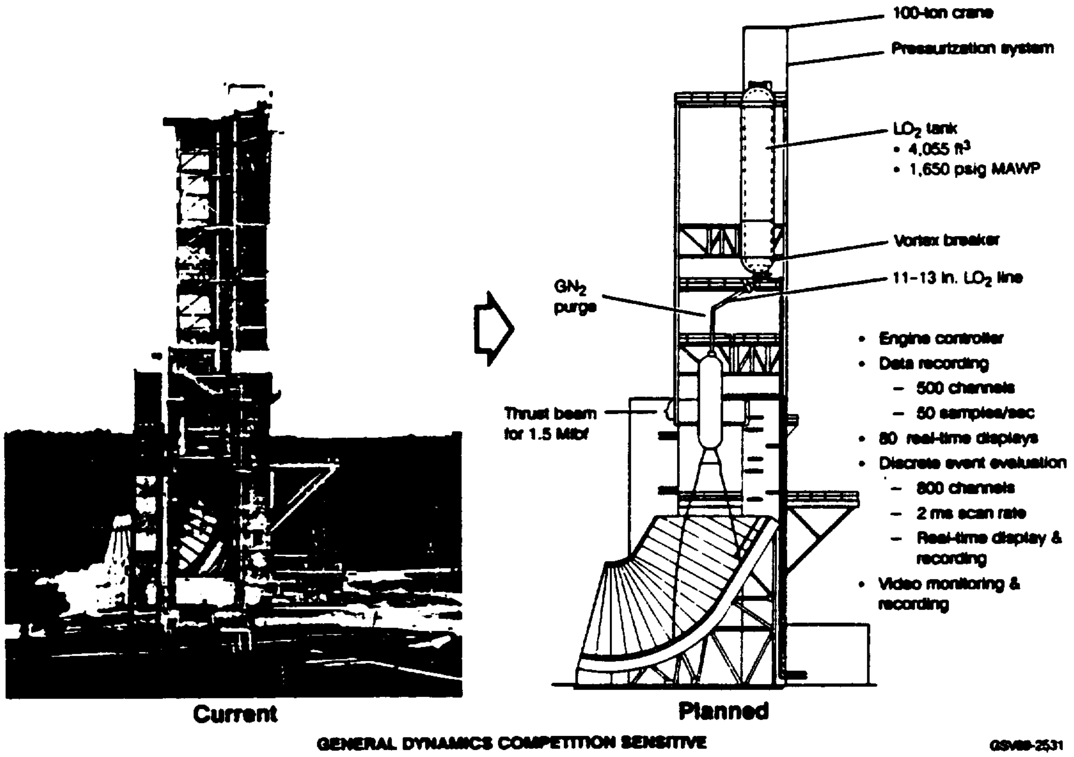


Figure 5-3. The Booster Technology Simulator at MSFC can satisfy the test stand requirements to demonstrate HPT.

Also available on the stand will be a 100-ton crane. This allows the erection of the 460-inch-long motor as a single unit. The 682-inch motor will be built up as a two-piece assembly, joined at the case extension interface. An all-new data collection/analysis and control system will also be in place, allowing motor characterization, regulation, and redline monitoring.

The schedule for Phase III, Figure 5-4, of the HPT program includes design, construction, testing, and evaluation of the three 90-inch-diameter motors. By identifying and procuring long-lead items at the outset of the program, schedule delays will be avoided. Wherever possible, tasks will be worked in parallel to ensure timely completion of testing and allow sufficient time for data reduction and code correlation.

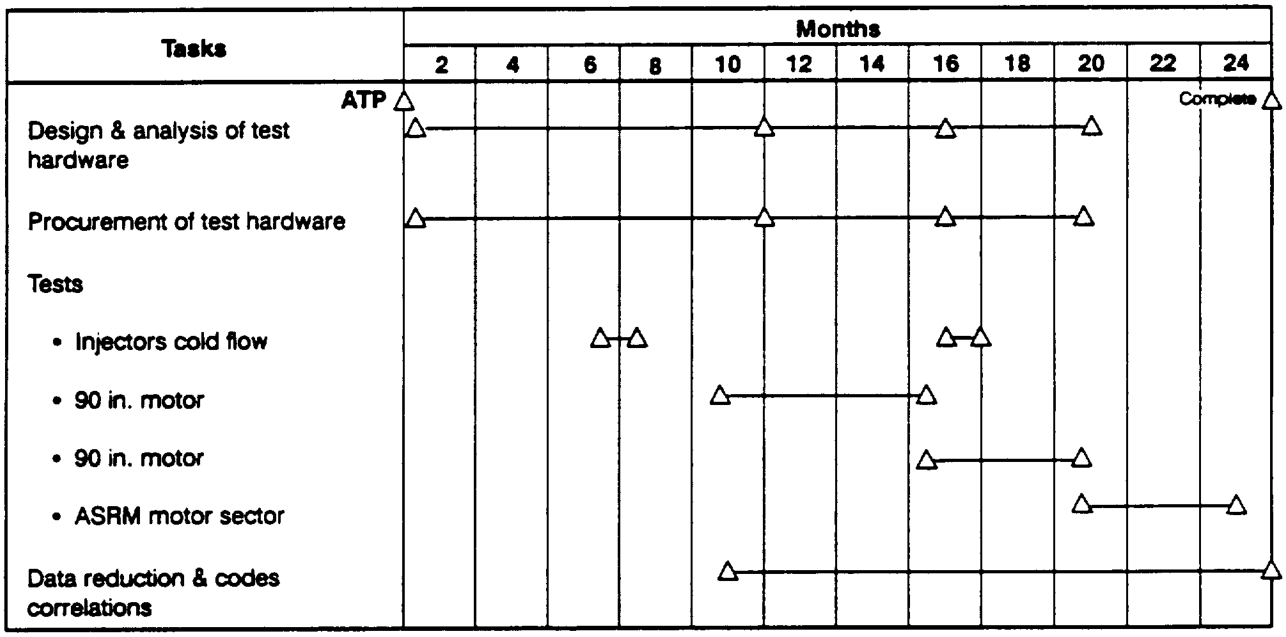


Figure 5-4. Two years are required to demonstrate the identified HPT.

6.0 CONCLUSION

Current launch vehicles use a common solid propulsion concept, Figure 6-1, for their boosters. If an anomaly occurred that was common to all boosters, our national launch capability would be adversely affected.

When HPT is acquired and demonstrated, it will provide a safe, reliable, cost-competitive, environmentally clean alternative that is directly interchangeable with current booster propulsion systems.

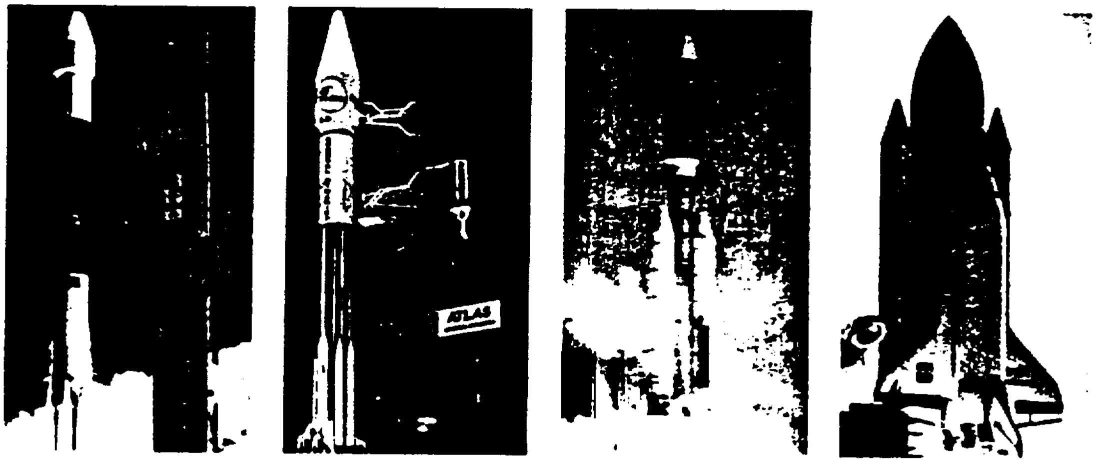
MSFC awarded Contract NAS-34183 to Martin Marietta for a Shuttle-Derived Vehicles (SDV) technology requirements study. In that study's Volume II, "Supporting Research and Technology Report," dated May 1982, they concluded that the hybrid propulsion booster had the highest priority by economic leverage of the 23 technologies studies. This economic leverage was the quotient of the delta life cycle cost divided by the research and test investment required.

The researchers also presented a ranking by priority according to expert opinion. Hybrid propellant boosters (HPBs) had the lowest priority. Their normalized overall priority ranking place the HPB as sixth.

In 1982, HPT was probably not attainable due to the complexity of technology and the limitations of analyses then available.

Today, seven years later, we have both the analytical processes and the computers to obtain this technology. Now we can realize this technology with the highest economic leverage through the acquisition and demonstration of HPT.

General Dynamics strongly advocates the development of HP for the next generation of manned and unmanned space launch vehicles. HP provides a safe, reliable, low-cost, non-polluting, compact, high-performance system. The technology is very achievable because the NASA HPT Phase I contracts have been completed, IRAD vehicle studies have been initiated, and over 100 two-inch hybrid motor firings have been completed.



Delta Atlas IIAS Titan STS

- Current launch vehicles use Solid Rocket Boosters
- HPT systems provide a viable alternative

Figure 6-1. HPT increases assured access to space.