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HYBRID PROPULSION TECHNOLOGY PROGRAM

Final Report
Volume IV

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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, "Hybrid Propulsion Technology Program—Phase I." The study was directed by Mr. Ben Shackleford 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 Demonstration Plan

Volume III • Thiokol Corporation Final Report

- Trade Studies and Analysis
- Technology Acquisition
- Large Subscale Motor Demonstration

Volume IV • Rockwell International Corporation Final Report

- Concept Evaluation
- Technology Identification
- Technology Acquisition Plan

For Rockwell International, Mr. S. A. Evans of the Rocketdyne Division was Program Manager. Mr. G. L. Briley was Project Engineer. The assistance of S. C. Fisher and J. M. McLeod during the program is gratefully acknowledged.

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1.0 INTRODUCTION

The use of a liquid oxidizer–solid fuel hybrid propellant combination in booster rocket motors appears extremely attractive due to the integration of the best features of liquid and solid propulsions systems. The hybrid rocket combines the high performance, clean exhaust and safety of liquid propellant engines with the low cost and simplicity of solid propellant motors. Additionally, the hybrid rocket has unique advantages such as an inert fuel grain and a relative insensitivity to fuel grain and oxidizer injection anomalies. These advantages mark the hybrid rocket as a potential replacement or alternative for current and future solid propellant booster systems. To assess the technological challenges and to establish recommended concepts for very large (2.5 Mlb thrust) booster systems, a program was established under the sponsorship of National Aeronautics and Space Administration–Marshall Space Flight Center (NASA–MSFC). A contract was awarded to General Dynamics Space Systems Division to which the Rocketdyne Division of Rockwell International is a subcontractor. This document addresses the issues associated with and makes recommendations concerning oxidizer feed systems, injectors, and ignition systems as related to hybrid rocket propulsion.

Early in the program a baseline hybrid configuration was established in which liquid oxygen would be injected through ports in a solid fuel whose composition is based on Hydroxyl Terminated Polybutadiene (HTPB). Liquid oxygen remained the recommended oxidizer and thus all of the injector concepts which were evaluated assumed only liquid oxygen would be utilized as the oxidizer.

2.0 CONCEPT EVALUATION

As mentioned in Volume I of this Final Report, three overall hybrid concepts were considered: the classical hybrid (head-end oxidizer injection), the solid propellant gas generator hybrid (aft-end oxidizer injection), and the after-burner or pre-burner hybrid (both head-end and aft-end oxidizer injection). Due the necessity of having a non-inert fuel grain, the gas generator concept was rejected early in the program. Figure 1 shows the classical and pre-burner concepts which were subject to further consideration. Before injector trade studies could begin, a study was undertaken to determine benefits obtained by (and the necessity of) carrying an aft-end injector.

2.1 ELIMINATION OF AFT-END INJECTION CONCEPT

One of the potential problems with the classical hybrid concept is the inability to maintain or control mixture ratio as the fuel regresses or as the oxidizer is throttled to vary overall thrust. The concern over mixture ratio shifts is the assumption that the shifts will cause an unacceptable loss in performance. To alleviate this concern, a concept has been proposed which employs an injector downstream of the fuel grain in addition to the head-end injector (Figure 1). By operating the head-end injector and solid fuel combination such that fuel-rich combustion products are present at the exit of the fuel port, additional oxidizer can be added to the fuel-rich products to establish a desired mixture ratio. As the mixture ratio of the fuel rich products varies due to grain regression or head-end throttling, the aft-end injector would be throttled to maintain the desired mixture ratio. While relatively high combustion performance could be realized with this system through maintenance of optimum mixture ratio and enhanced aft-end mixing, the negative effect on vehicle performance of the additional weight, complexity, cost, etc. may outweigh the advantages.

In the evaluation of the necessity for aft-end injection, an arbitrary assumption was made that in order to be of benefit to the overall system, the gain in characteristic exhaust velocity (c^*) due to the maintenance of constant mixture ratio must be greater than 5 percent or, conversely, allowing the mixture ratio to vary would not decrease c^* more than 5 percent below the optimum value. Further qualitative consideration was given to the duration of the off-optimum performance period of the burn if mixture ratio was allowed to vary.

Throughout the evaluation of various injector concepts, each concept was required to deliver oxidizer in a manner which satisfied the prescribed thrust profile shown in Figure 2. The required oxidizer flow to meet the thrust trace (and thus mixture ratio and thus performance) is dependent on oxidizer mass flux through the solid fuel grain port. Further, the fuel regression (flow rate) dependence on oxidizer mass flux is a function of the fuel composition. The effect of the fuel composition manifests itself through the oxidizer mass flux exponent and the regression rate coefficient in the equation

$$r = AG_onP_cm$$

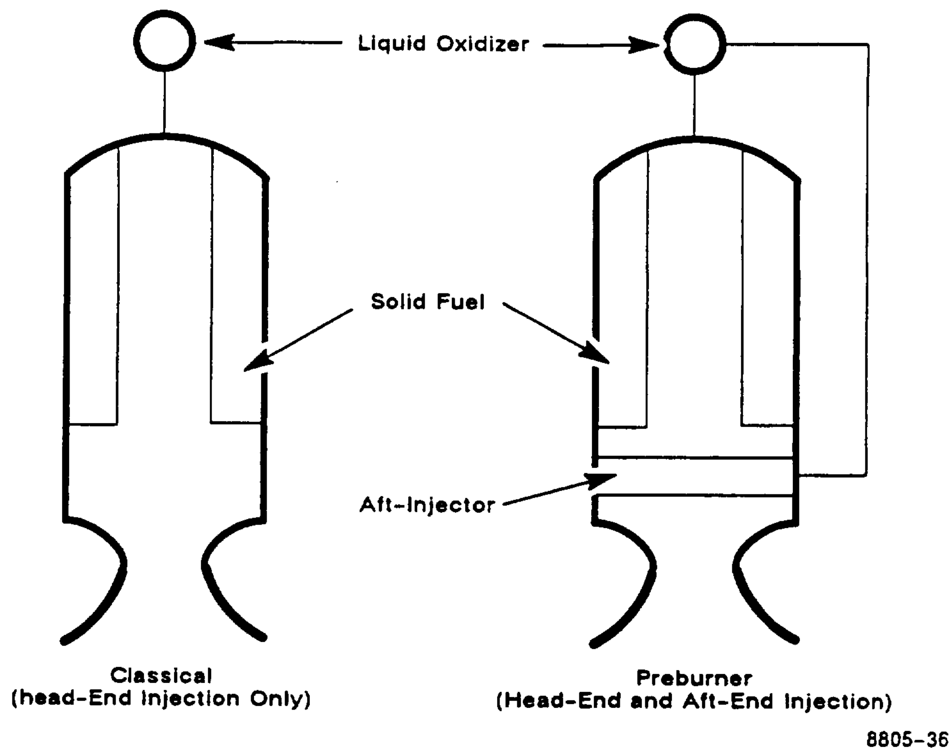

Figure 1. Hybrid Concept Definition

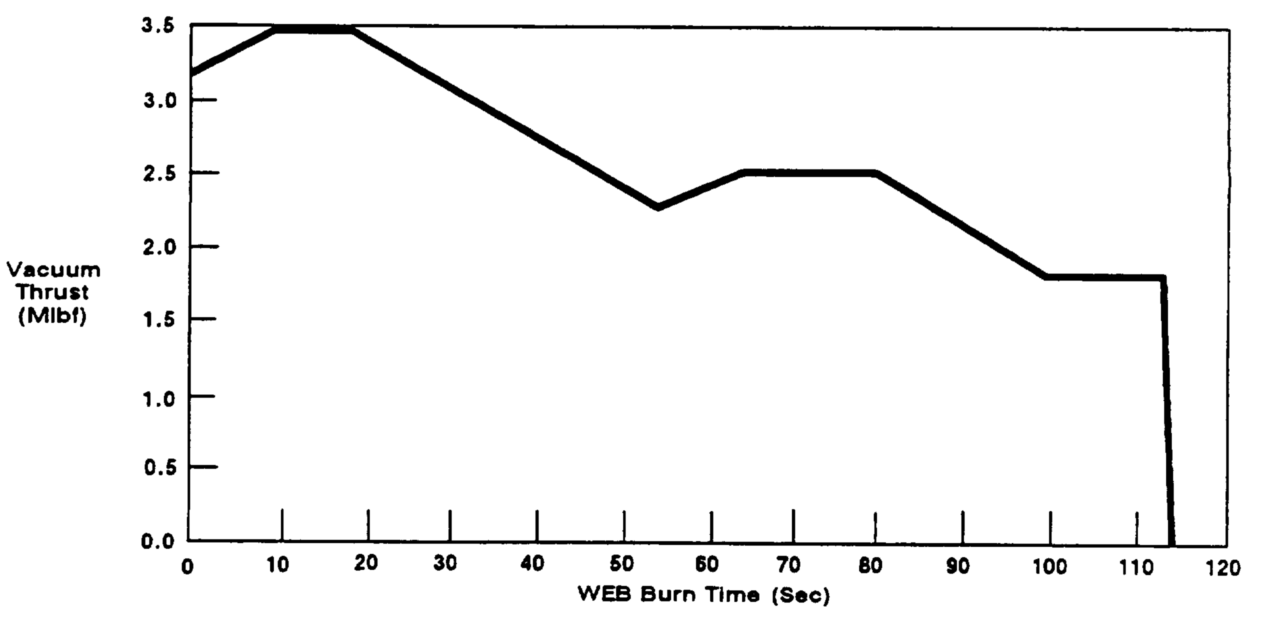

Figure 2. Full-Scale Motor Thrust Requirement

where r is the fuel regression rate, G_o in the oxidizer mass flux, P_c is the chamber pressure and A, n, and m are constants which are a function of fuel composition and the choice of oxidizer. Regression dependence on chamber pressure is typically small due to the lack of large radiative heat transfer component to the fuel surface. An exception occurs with metallized propellants in which radiative heat transfer effects are significant. Chamber pressure effects arise since combustion product emissivity is pressure dependent.

While the regression dependence on oxidizer mass flux and fuel composition complicates ballistic analysis of a hybrid motor, it also provides a tool for tailoring the performance variation during the motor burn. Figure 3 and Figure 4 show the mixture ratio and c^* variation with time for two different fuel grain sizes, geometries and compositions. The plots were generated by determination of oxidizer flow rate through iteration on the chamber pressures required to follow the thrust plot presented in Figure 2. Figure 3 reveals that for a 635 klb. thrust hybrid only very small performance losses may occur during the mixture ratio shift if grain geometry and composition are properly chosen. It should be noted that no attempt was made to optimize the performance in this case thus further performance gains may be possible. For larger scale motors, a grain composition which provides a high regression coefficient and a low mass flux exponent is required in order to meet motor size envelope requirements. The plots in Figure 4 were generated for a 2.5 Mlb. thrust hybrid with an HTPB/Zinc/GAP fuel composition. The low mass flux exponent (n=0.4) produces a mixture ratio variation which is nearly linear with time which yields a small but significant loss of performance during the initial and final portions of the burn. However, during the majority of the burn, the performance loss incurred by letting mixture ratio shift is less than 1 percent.

Figure 5 shows a plot of the aft-end injector flow rate required to recover the performance loss shown in Figure 4. Note that during the latter portion of the burn the aft-end injector flow rates are very low. Deep throttling of the aft-end injector holds the potential for feed system coupled instabilities (chugging) unless a variable geometry injector is employed. Further, it is questionable that the oxidizer flow rates would be sufficient to cool the aft-end injector as it is throttled back.

Thus the aft-end injection concept is not recommended for use on large scale hybrid motors. The aft-end injector adds inert weight, vehicle length, cost, and complexity. A variable geometry injector, an additional throttling system, and increased sequencing complexity would also be required. The performance losses due to shifting mixture ratio without aft-end injection are small and with careful selection of the grain geometry and fuel composition the losses could be minimized or virtually eliminated.

The rest of this document will only consider oxygen injection at the head-end of the main fuel grain (classical hybrid).

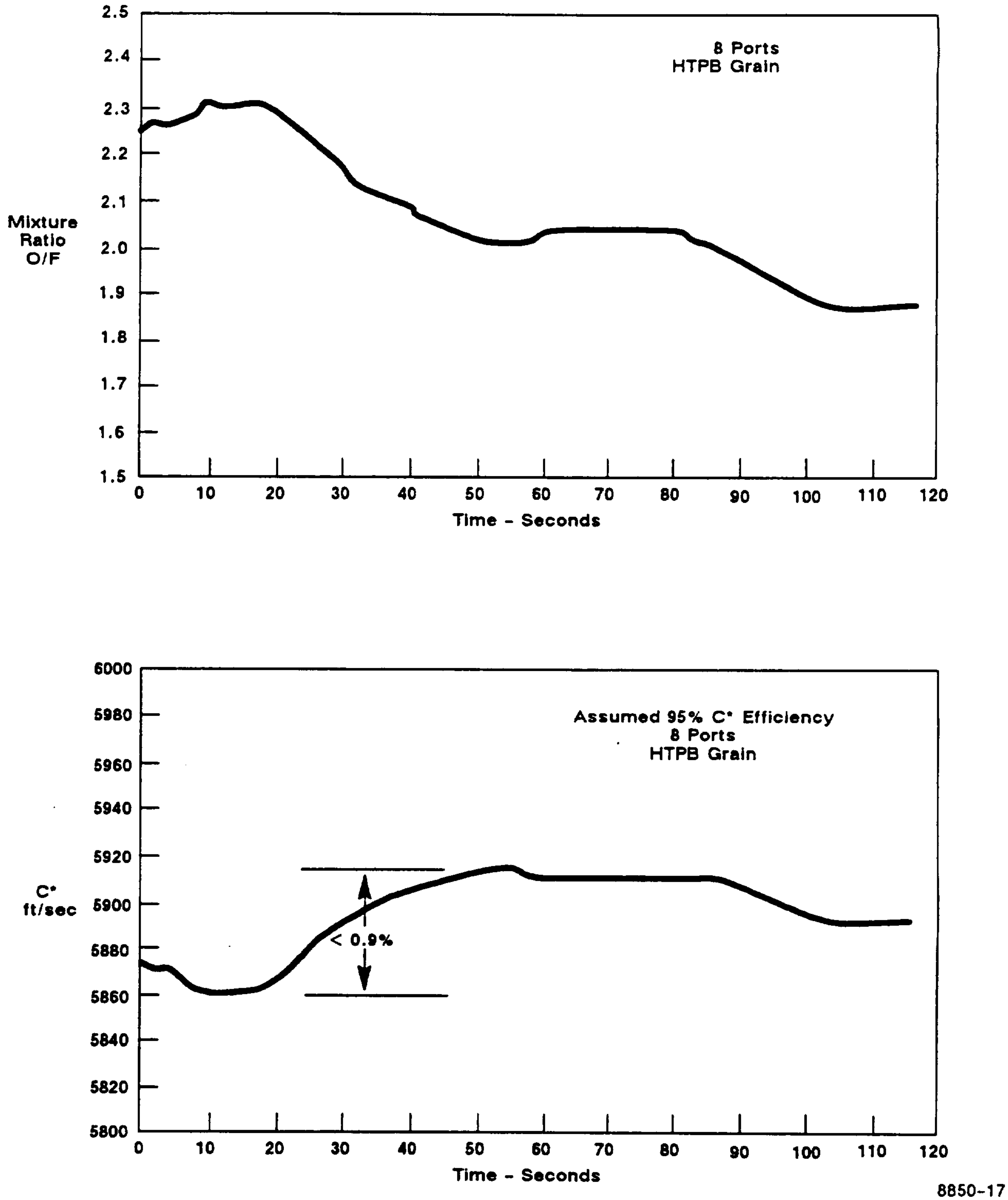

Figure 3. 635 Klb Thrust Hybrid Performance Variation With Time

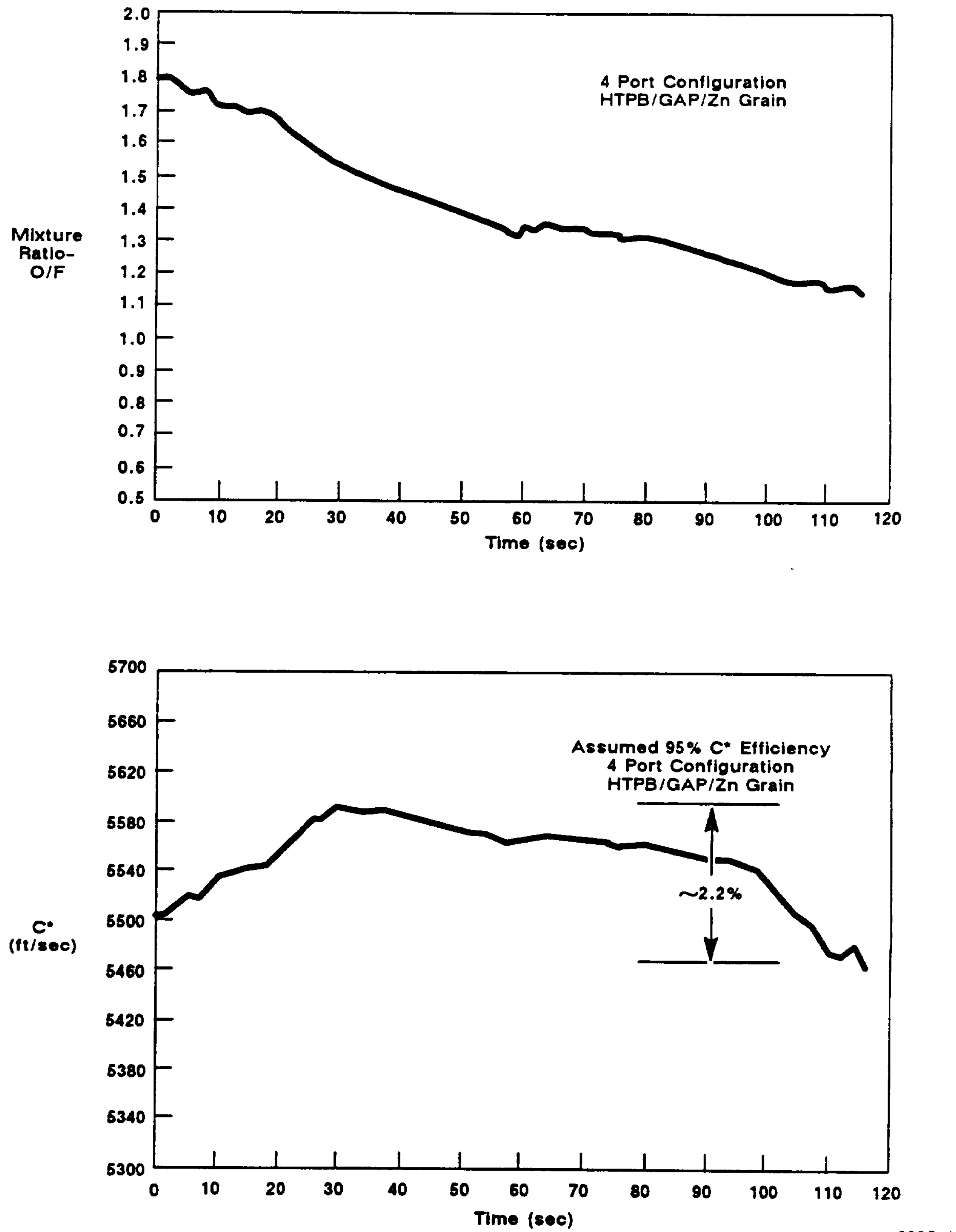

Figure 4. 2.5 Mlb Thrust Hybrid Performance Variation With Time

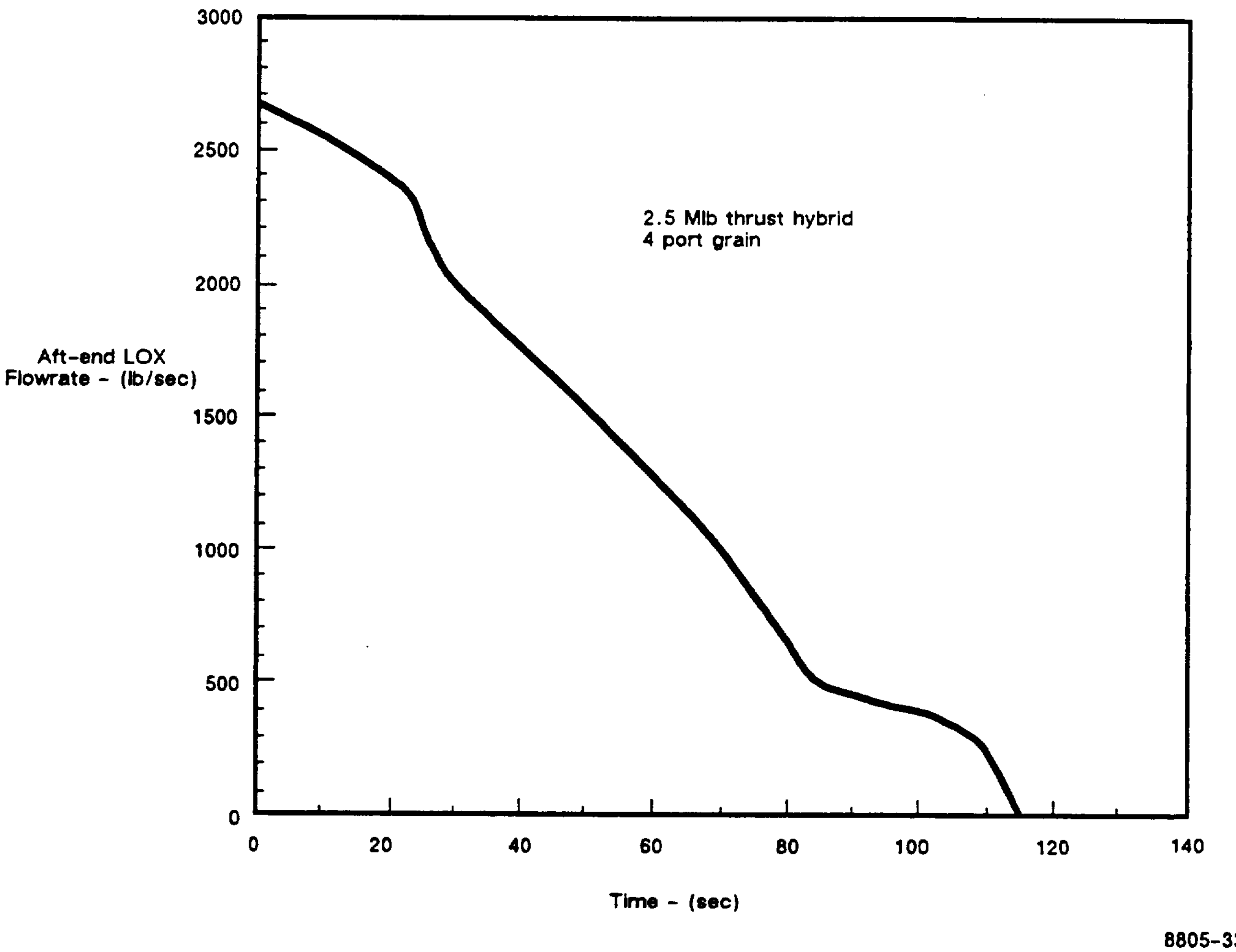

Figure 5. Aft-End LOX Flow Rate Required to Maintain a Constant Mixture Ratio

2.2 HEAD-END INJECTOR CONCEPTS

2.2.1 Ranking Criteria

The overall ranking criteria for a hybrid propulsion system were specified as safety, reliability, cost, and performance. Only injector concepts which satisfied these criteria were considered. When viewed with respect to an overall hybrid motor system, things such as injector cost, performance and safety issues associated with the considered injector concepts have very little impact on the total system cost, performance or safety. Therefore, a set of ranking criteria which were more specifically designed to evaluate injectors were established which could be used to distinguish a preferred injector concept. The pertinent criteria are

1. Scalability
2. Cost
3. Development Risk
4. Weight

The ability to scale the injector concepts to suit hybrid motors which are on the order of 150 inches in diameter may prove to be a critical technology. Injectors of this dimension are certainly outside of the range of liquid rocket injection experience. To minimize the technical risk associated with scaling, injector concepts were chosen which concentrate the fluid injection through a relatively small area. However, things such as LOX stream diameter, stream penetration, and mass distribution remain dependent on the specific injector concept.

As mentioned above, the recurring injector costs were considered low when compared to the total hybrid system costs. An assessment of the effect of a specific injector concept on system costs could not be made accurately. However, an evaluation was made of injector recurring costs relative to other injector concepts. In the cost assessment of injector concepts, the non-recurring development costs were considered to be independent of the concept since the required technologies such as atomization and mass distribution would need to be developed for any selected concept.

Assessment of the development risk associated with each injector was based on several factors. First, account was taken of the size of the current data base associated each concept. Second, for each injector concept an evaluation was made of the number of techniques available to overcome development problems.

In addition to ranking injector concepts, a screening was made of several injector element types. The ranking criteria were

1. Cost
2. Atomization

3. Mass distribution control
4. Cooling
5. Grain compatibility

The cost of each element concept relative to another was based on the cost of fabrication of the element and on the potential cost of an error in fabrication. These costs are closely tied to the injector concept to which each element is associated.

The compatibility of a particular element with the fuel grain refers to the magnitude of the oxidizer radial momentum created by the element. Direct impingement of high momentum oxidizer upon the fuel grain causes an unacceptably high grain erosion rate.

2.2.2 Preliminary Downselection

Many potential injector concepts were initially considered for large scale hybrid motors. As mentioned previously, any concept which was obviously unacceptable in light of the system safety, reliability, cost and performance criteria was immediately rejected. Several preferred concepts arose from the initial screening. These concepts are presented in the form of a trade tree shown in Figure 6. The initial baseline injector configuration was a liquid oxygen swirl spray nozzle at the head end of the main grain. Each of the considered concepts is presented in detail in the next sections.

2.3 LIQUID INJECTORS

Liquid oxygen (LOX) injection was chosen as the baseline condition due to the inherent simplicity and vast experience from liquid propellant rocket engines. Many tools for correcting LOX injection problems exist and the advantages of LOX injection relative to gaseous oxygen (GOX) injection on the overall hybrid system are significant. Technical issues associate with LOX injection are discussed in later paragraphs.

2.3.1 Flat Face Injector

The flat face injector for a hybrid motor is simply an adaptation of injectors commonly used in liquid propellant motors. The flat face injector concept is shown in Figure 7. One injector would be used for each port in the fuel grain. Injection elements associated with the flat face injector configuration are showerhead, impinging, or fan-former elements. The showerhead and impinging elements are commonly used in liquid propellant rockets and are well characterized. The fan-former element shown in Figure 9 is not widely used in rocket propulsion although cold flow testing has been done. Figure 10 shows a cold flow test of a series of edge impinging fan former elements. Cold flow tests indicate that element-to-element fan edge impingement produces increased local flow densities which interferes with effective atomization. In practice, a staggered fan pattern is preferred.

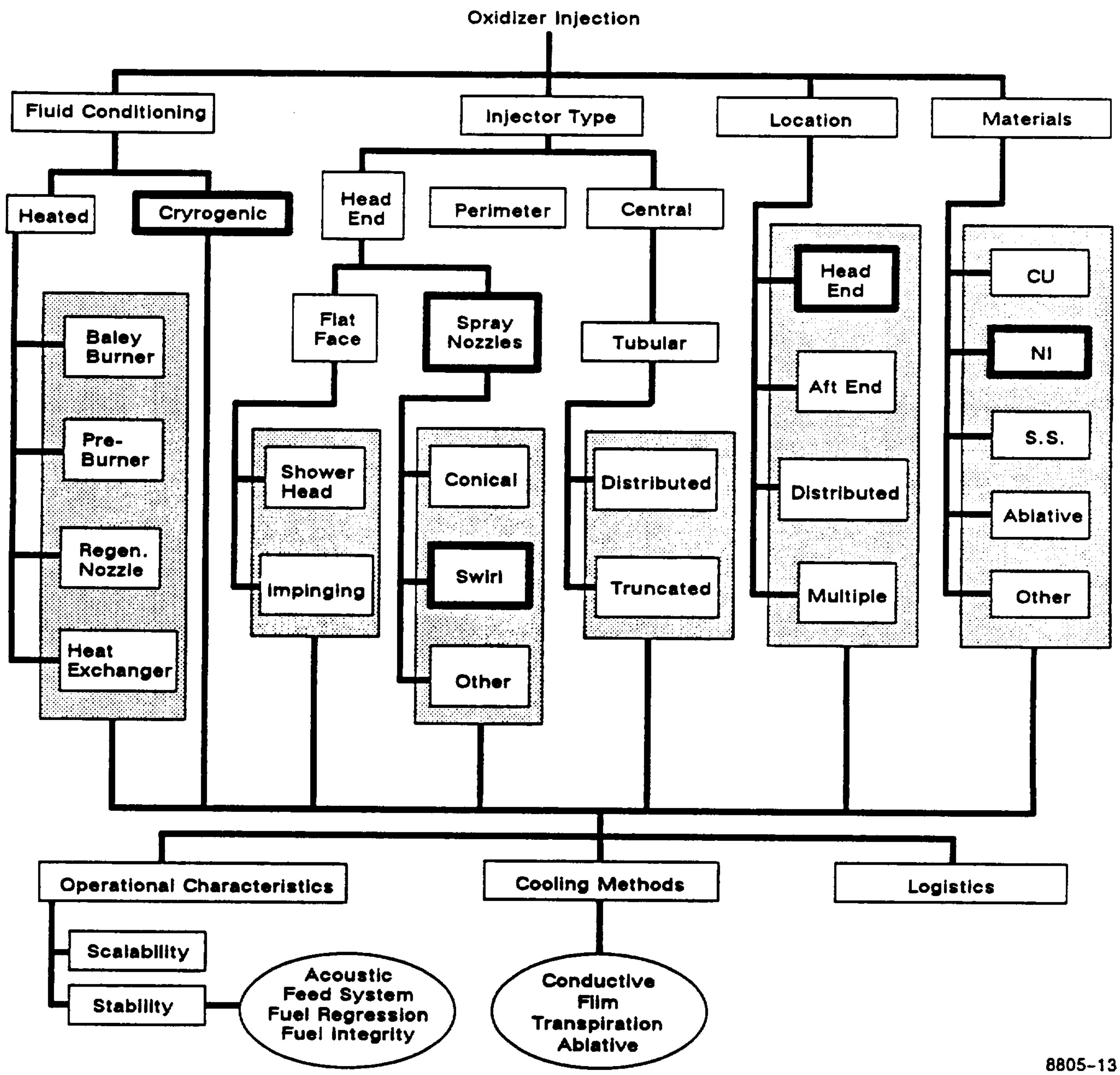

Figure 6. Oxidizer Injection Trade Tree

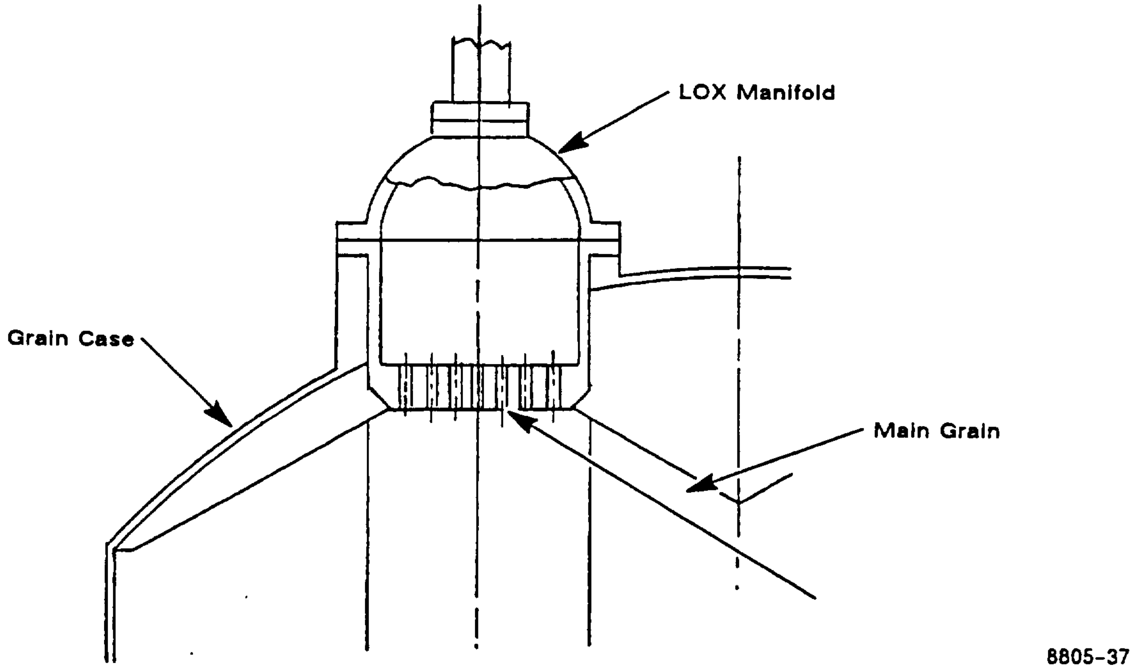

Figure 7. Flat Face Injector Concept

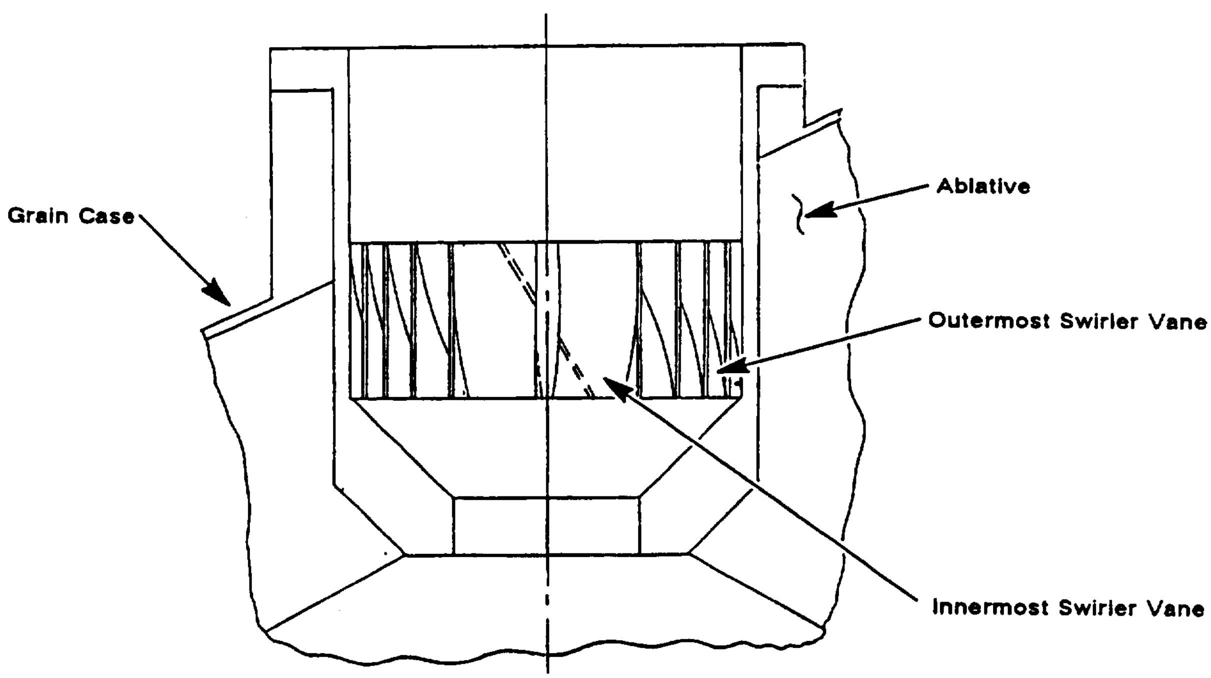

Figure 8. Spray Nozzle Injector
(Shown With Five Concentric Swirl Elements)

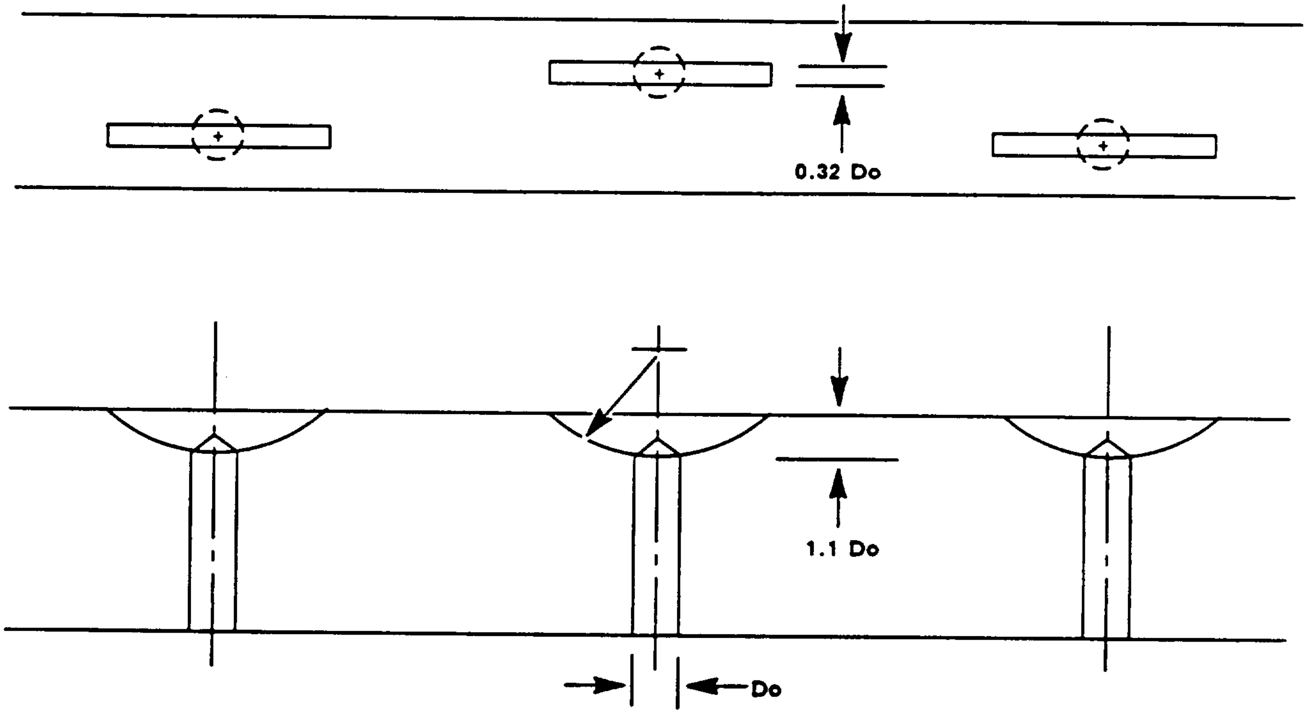

Figure 9. Fan-Former Geometry

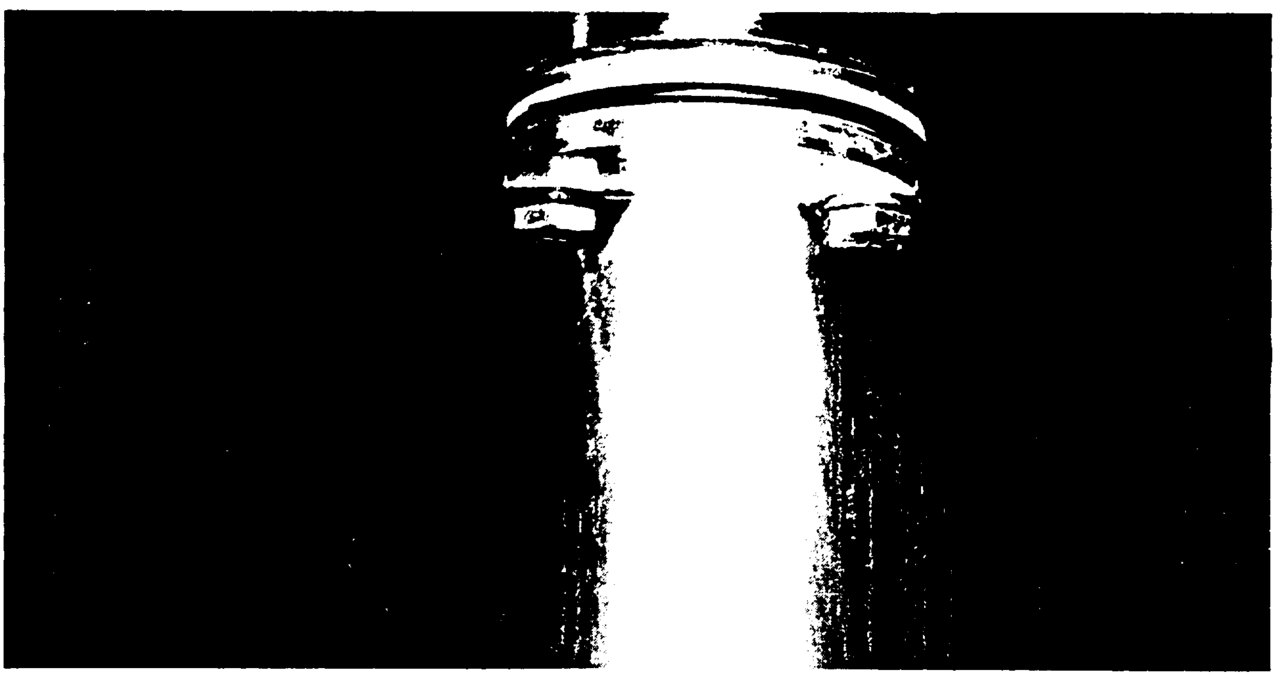

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Figure 10. A Series of Fan-Former Elements During Cold-Flow Testing

The chief advantage of the flat face injector is the increased oxidizer mass distribution control inherent in the large face area which is available across the fuel port. However, to minimize injector weight and complicated manifolding, and to avoid having to cool or protect a large injector face, the injector size should be minimized. Thus a trade-off must be considered between the vehicle performance gains from increased oxidizer injection mass distribution control and the vehicle performance gains from smaller injection area. However, large hybrid motor performance is relatively insensitive to injector characteristics and thus a large injection area is probably unnecessary.

Another advantage of the flat face injector is that the injector elements associated with it are typically good at atomizing oxidizer streams. The exception is showerhead elements. Impinging streams are excellent at atomization, however, hybrid motors are sensitive to misimpingement anomalies. A stream of oxidizer which impinges directly on the fuel surface may cause extreme grain erosion and possible burn-through at the head end of the motor.

The cost of fabricating impinging elements and ensuring accurate impingement of the elements is significantly higher than the cost of non-impinging elements. However, computer controlled laser drilling has demonstrated a significant potential for reducing these costs. In lieu of resorting to laser drilling, the fan former element shown in Figure 9 could be used to provide good atomization yet allow lower fabrication costs because of the greater tolerance allowance of a non-impinging element.

2.3.2 Spray Nozzle Injector

Two different spray nozzle injector configurations were considered: one with a swirl vane (Figure 8) and one without. The latter is termed a conical spray nozzle while the former is called a swirl nozzle. The conical spray nozzle is the simplest injection element considered. The advantage of a conical spray nozzle stems from its simplicity yet it is the simplicity which limits the degree of control over the distribution of the injectant. By adding a swirl vane or system of swirl vanes some control over the injected oxidizer mass distribution is gained. Further, the exit of the spray nozzle may be slotted to provide a non-circular spray pattern.

The spray nozzle injector is the limiting case for concentrated injection area: the entire injector is the injection element. As such, the injector is relatively light weight, low cost, and simple to manifold. The disadvantage to the spray nozzle is that it is only marginally acceptable at atomizing the injectant. The technological issues (stability, grain flooding, etc.) associated with poor atomization are discussed in later sections.

2.3.3 Tubular Injector

In an attempt to devise a method of rapidly vaporizing the injected LOX, a tubular injector concept which protrudes into the fuel port was reviewed. The tubular injector is shown in Figure 11. The LOX would be injected through impinging elements along the length of the tube. A smaller proportion of LOX is injected closer to the head end and would react with the head-end

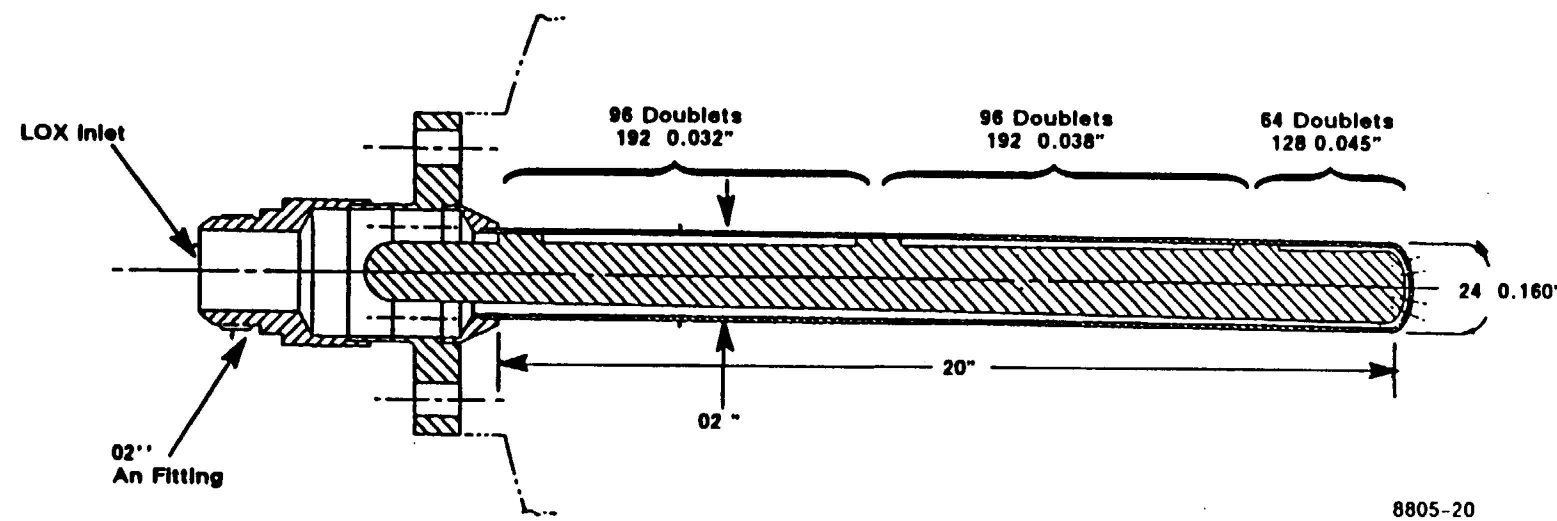

Figure 11. Tubular Injector (Design Shown is for 20 klb Thrust Motor)

fuel. The combustion products would flow down the port and aid in vaporizing the greater proportion of the LOX which is injected further down the tube. Several disadvantages exist with this concept. First, additional structural and thermal failure modes are present by extending the injector into the combustion environment. Second, difficulties may arise due to the large radial component of LOX momentum which exists with such an injection scheme. To minimize the magnitude of the radial LOX momentum, elements would have to be canted downstream. The resultant shallow impingement angle would produce a poorly atomized LOX stream.

2.4 GASEOUS INJECTION

Gasification of LOX before injection into the main fuel grain has some advantages over direct LOX injection. These advantages include increased stability margin, more uniform grain regression, and elimination of grain flooding concerns. Each of these issues is discussed in the section on Technology Identification. The price of the advantages is an increase in system weight, cost and complexity. GOX injection is a technologically conservative scheme in hybrid combustion and thus it is prudent to consider potential GOX injection concepts. It should be noted that with all of the considered concepts, LOX is being gasified prior to injection into the main fuel grain.

2.4.1 Heat Exchanger/Regen Nozzle

The heat exchanger and regeneratively cooled nozzle are considered together because both rely on the main combustion process to gasify the LOX. High temperature oxygen heat exchangers have seen some application in the past (in the preburner exhaust on the Space Shuttle Main Engine, for example) however they represent a considerable development risk. Further, failure modes of high temperature oxygen heat exchangers are not benign. Difficulties also arise from the requirement to throttle the oxidizer flow. As oxidizer flow is throttled, injection temperature and pressure would change since flow through the heat exchanger as well as heat flux to heat exchanger would vary. Maintaining adequate oxidizer flow to cool the heat exchanger while providing the desired injection conditions during throttling is crucial yet would be difficult to achieve. This is illustrated by considering the shut down transients where it is necessary to stop oxidizer flow to the head end injector while maintaining flow through the heat exchanger for adequate cooling until flame extinguishment and blowdown of the remaining combustion products within the case. Throttling the oxidizer flow also raises questions of whether two-phase flow stability could be maintained. Considerable development effort would be required to characterize any oxygen heat exchanger system.

Oxygen heat exchangers impact vehicle performance primarily through weight and volume considerations. The heat exchanger/regen nozzle concept is compact and would add minimal volume to the hybrid system. On the other hand, the weight of such a system would be significant. Besides the inert weight of the heat exchanger, additional weight would arise due to the increased tank pressure and pressurization requirements needed to overcome the oxidizer pressure drop through the heat exchanger/regen nozzle. The weight increase is particularly acute in pressure fed systems.

The effectiveness of a LOX-cooled nozzle in gasifying LOX is also questionable. Preliminary analysis indicates that there is not enough heat flow through the coolant walls of a full-scale regen nozzle to sufficiently raise the LOX temperature. Further consideration was not given to oxygen heat exchanger/regen nozzle concepts since weight, cost, and particularly safety concerns make the concept unattractive.

2.4.2 Bailey Burner (Hydrogen Gas Generator)

The "Bailey burner" (Reference 1) concept utilizes a very oxygen rich gas generator fueled by hydrogen. The Bailey burner is a very compact unit except for the required large volume hydrogen tank. Other similar gas generator concepts using alternate fuels (methane, propane, etc.) would allow more compact tankage but the narrower flammability limits of hydrocarbon fuels relative to hydrogen would necessitate a separate gas generator which would utilize a small proportion of the total LOX flow and a mixing device to combine the remaining LOX with the gas generator combustion products. All of these concepts were eventually rejected because of the requirement for carrying a third propellant and the considerable complexity. Such a system detracts from the hybrid safety and simplicity advantages.

2.4.3 Pre-injector (Hybrid Gas Generator)

The pre-injector concept involves gasification of LOX directly with the exhaust of a small hybrid motor. The concept is shown in Figure 12. As envisioned, a small proportion of the total LOX flow would be directed to a primary injector at the head end of a relatively small hybrid grain while the remaining LOX would be injected radially inward through a secondary ring injector (Figure 13) at the exit of the small grain. The resultant warm GOX would then be injected into the main grain.

The pre-injector concept minimizes the safety concerns associated with other LOX gasification concepts but the resultant system is heavy and voluminous. To reduce the weight and volume of the pre-injector, schemes have been developed in which the pre-injector is included within the main case or is part of the main grain. A problem with the inclusion of the pre-injector within the main case is that the LOX streams or fans emanating from the secondary injector must penetrate great lengths through hot combustion product crossflow. This is true whether the secondary injection is radially inward or radially outward. No acceptable concept has been established in which the pre-injector is included in the main case and acceptable entrance conditions to the main grain (in terms of oxidizer distribution) are present.

Figure 14 and Figure 15 present the operating region for a pre-injector with an HTPB fuel. The desired GOX mixture temperature is between 100 and 300 degrees F. Two contradictory conditions are also desired: 1)minimize pre-injector weight (size) and 2) maximize the ratio of secondary-to-primary LOX flow. The latter criterion arises from the desire to maintain a con-

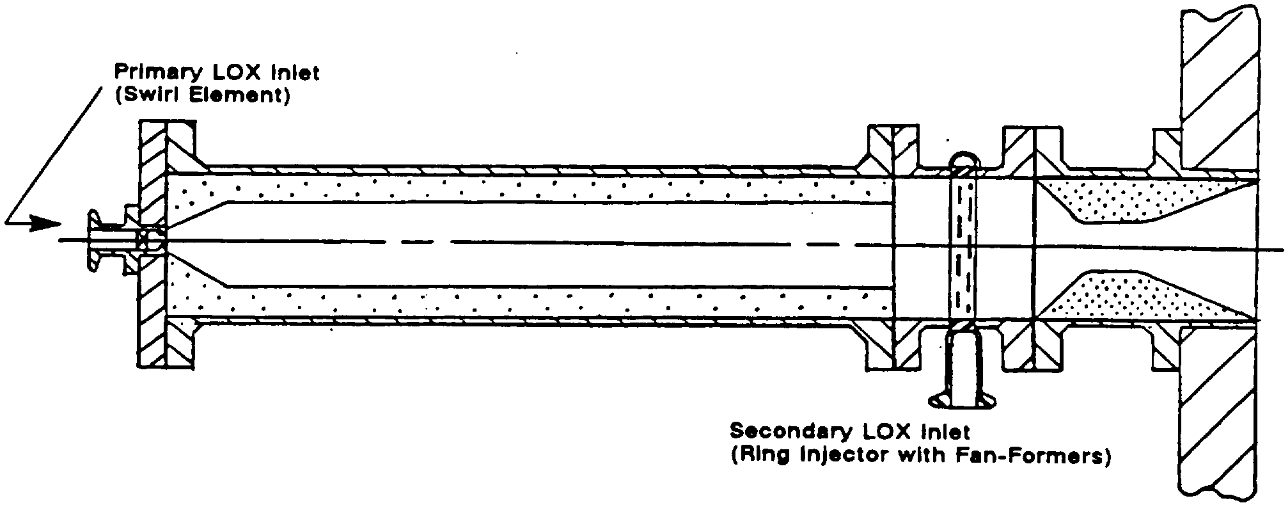

Figure 12. Pre-Injector Concept

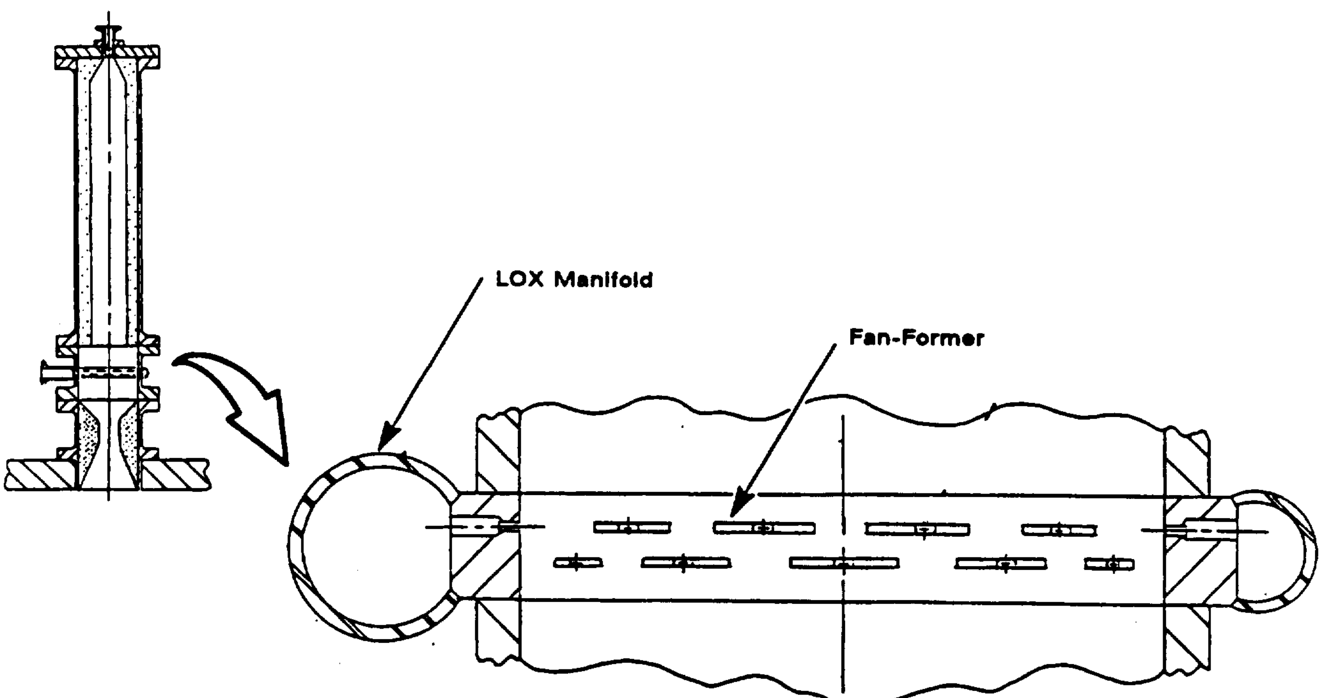

Figure 13. Ring Injector for Pre-Injector Concept

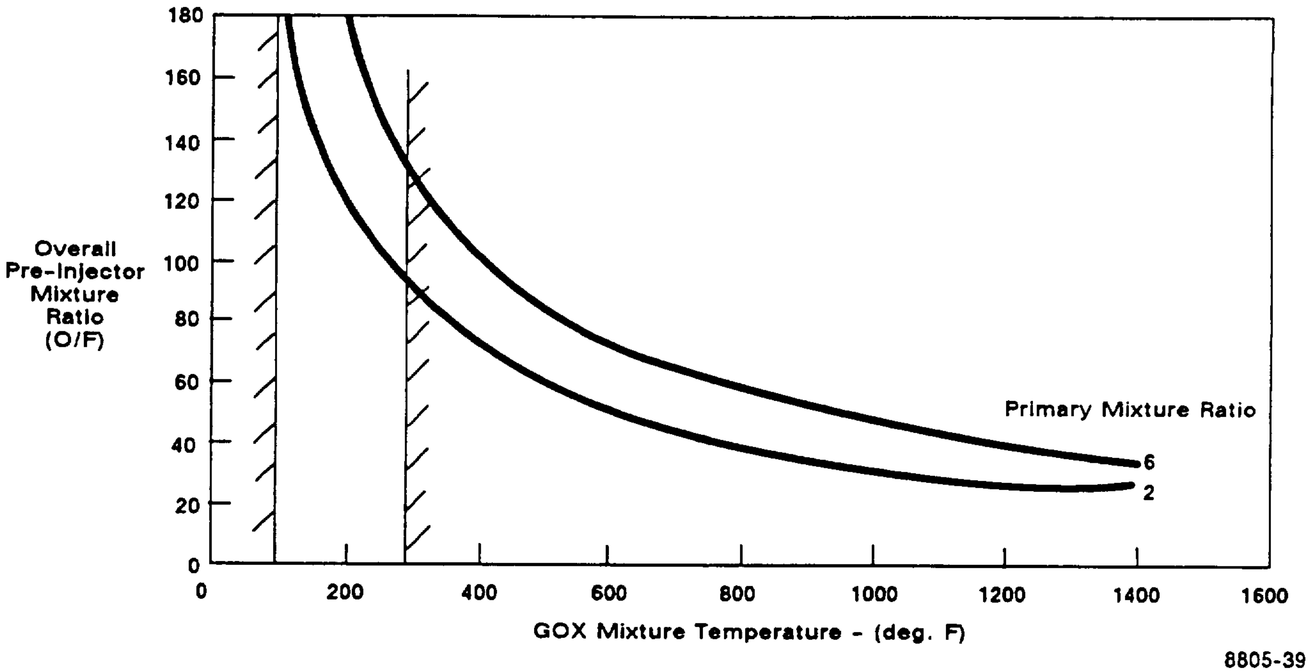

Figure 14. Hybrid Pre-Injector Overall Mixture Ratio Effects on GOX Temperatures

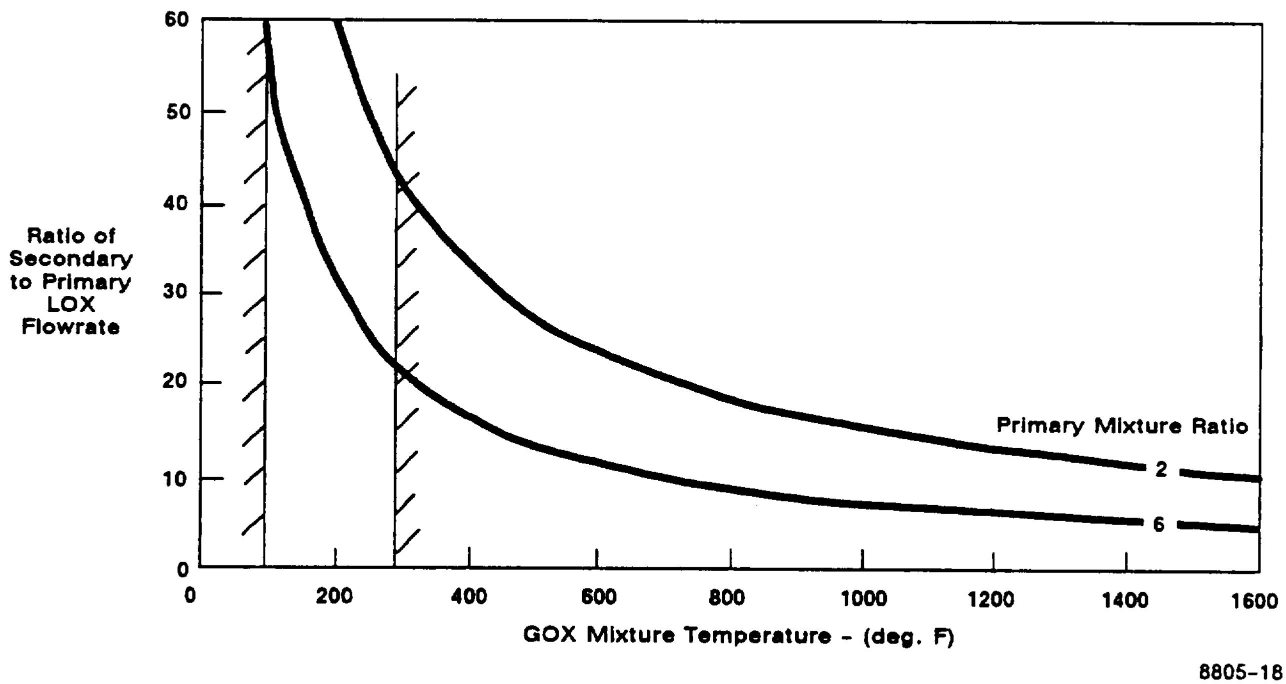

Figure 15. Hybrid Pre-Injector LOX Flow Split Effects on GOX Temperature

stant primary LOX flow while throttling only secondary LOX flow. If the ratio of secondary-to-primary LOX flow is small, deep throttling of the secondary flow or throttling of both primary and secondary flow would be necessary to follow the prescribed thrust requirement. As is evident from Figure 15, primary mixture ratio should be kept low to maximize secondary-to-primary LOX flow split. However, as can be seen from Figure 14, a higher primary mixture ratio is needed to maximize overall pre-injector mixture ratio (minimize pre-injector size and weight).

2.5 CONCEPT EVALUATION

Tables 1 and 2 present the element type screening and the injector concept evaluation, respectively. The fan former element is the preferred element for distributed type injection (flat face, tubular, or ring injectors) whereas the swirl nozzle is preferred for concentrated type injection. As indicated in Table 2, the spray nozzle concept is preferred overall. The advantages stem from the simple, compact, low cost, well characterized nature of the spray nozzle. The spray nozzle has been used with great success in past applications to hybrid systems. Concerns associated with the spray nozzle are due to injection of a high mass flux of large (approximately 2000 micron diameter) LOX droplets and the associated affect on the combustion process. These issues are discussed in the Technology Identification section.

The pre-injector concept circumvents the potential technological problems associated with the spray nozzle but the fabrication costs, weight and complexity are greatly increased. The preferred concept involves a small spray nozzle at the head-end of the pre-injector grain and a circumferential ring injector with fan former elements at the aft-end of the pre-injector grain. The spray nozzle at the head-end of the pre-injector would avoid the combustion associated problems of the full-scale spray nozzle (mentioned above) by operating at a lower oxidizer mass flux and by inherently producing smaller LOX droplets. Combustion stability concerns associated with the full-scale spray nozzle would be alleviated by the greater stability margin inherent in smaller hybrid motors. If the weight, volume, and cost of the pre-injector concept can be reduced by making the pre-injector part of the main fuel grain, the technologically conservative nature of the pre-injector would make it preferable to LOX spray nozzle injector.

The tubular injector is not favored because of the perceived high development risk and the increased number of injector failure modes associated with suspending the injector within the fuel port. Additionally, the failure modes of the tubular injector typically would not be benign. Erosion of the injector may be tolerated on a spray nozzle but could lead to burn-through and complete failure of the tubular injector.

The flat face concept does not appear to be well suited to very large hybrid rockets. The primary advantages of the flat face injector are increased mass distribution control and its utilization of elements which are effective at atomization. However, taking advantage of the attributes of the flat face injector requires and injector with a large (heavy) face area which must be cooled or protected from the hot gas environment.

Table 1. Element Type Screening

	Cost	Atomization	Mass Distribution Control	Cooling	Grain Compatibility
Showerhead	G	P	G	F	G
Impinging	F	G	G	F	*
Fan former	G	G	G	F	G
Conical nozzle	G	F	P	G	**
Swirl nozzle	G	F	F	G	**

G - Good
F - Fair
P - Poor

* Misimpingement causes extreme grain erosion
** Low regression splash block required

Table 2. Injector Concept Evaluation

	Scalability	Cost	Development Risk	Weight	Overall Rank
Pre-injector	G	P	G	P	2
Flat face	P	P	G	P	4
Tubular	F	F	P	F	3
Spray nozzle	F	G	G	G	1

G - Good
F - Fair
P - Poor

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2.6 RECOMMENDED CONCEPTS

As applied to large scale hybrid rocket systems, either LOX swirl spray nozzle injectors or GOX-producing pre-injectors can be used. Table 3 lists the advantages and disadvantages of each concept. As the table indicates, the advantages of the LOX swirl injector affect the overall hybrid vehicle whereas the GOX pre-injector advantages affect the combustion process. Conversely, the disadvantages of the LOX swirl injector affect combustion while the GOX pre-injector disadvantages affect the overall hybrid vehicle. This dichotomy makes it difficult to select one concept over the other until the technical issues are addressed in a test program. Accordingly, recommended full-scale concepts for both injectors will be presented.

Figures 16 and 17 show two possible applications of pre-injectors to large scale hybrid motors. For the concept shown in Figure 16 each port of the main fuel grain would have one pre-injector. This concept allows each pre-injector to have individual throttle valves whose size is more in line with current LOX valve experience. A minor concern of having multiple pre-injectors is the need to ignite each pre-injector separately. Having a single pre-injector for the entire motor as shown in Figure 17 removes the concern of igniting multiple pre-injectors but requires considerably larger secondary LOX throttle valves. Parallel LOX feed lines could alleviate the need for larger valves.

Figure 18 shows the recommended LOX swirl spray nozzle concept for large hybrid motors. The swirl vane has multiple, three-dimensional blades which swirl only a small percentage (less than ten percent) of the LOX flow. The small percentage of swirled LOX flow would be rapidly vaporized and would react with the fuel at the head-end of the motor. The resultant hot gas would sweep downstream to aid in vaporization of the majority of the injected LOX which was poorly atomized. By directing only a small portion of the LOX outward, head-end grain erosion and grain flooding problems may be alleviated.

Table 3. LOX vs GOX Injection Comparison

LOX Swirl Injector

- Advantages (affect vehicle)
  - Light weight
  - Low cost
  - Simple
- Potential disadvantages (affect combustion)
  - Grain flooding
  - Combustion instability
  - Nonuniform grain regression

GOX Preinjector

- Advantages (affect combustion)
  - Technologically conservative
    - Increased stability margin
    - Uniform grain regression
    - Eliminates grain flooding concern
- Disadvantages (affect vehicle)
  - Increased weight/volume
  - Increased cost
  - Increased complexity

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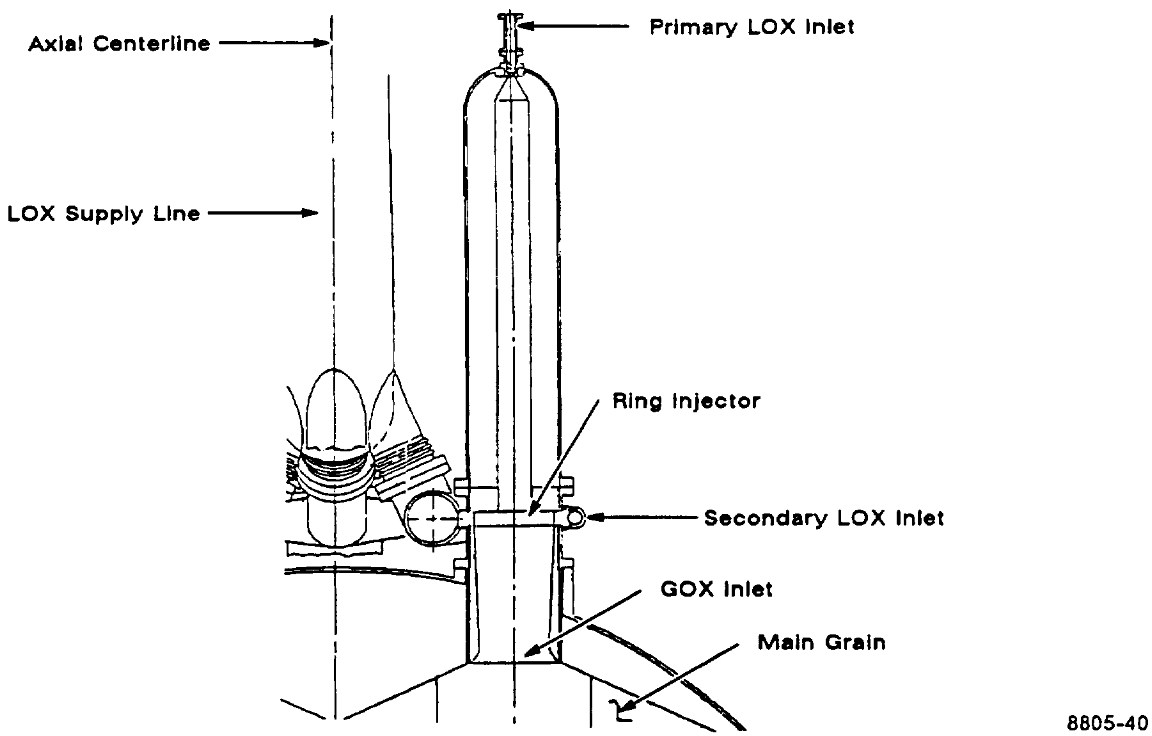

Figure 16. GOX Pre-Injector Configuration—One Grain Per Port

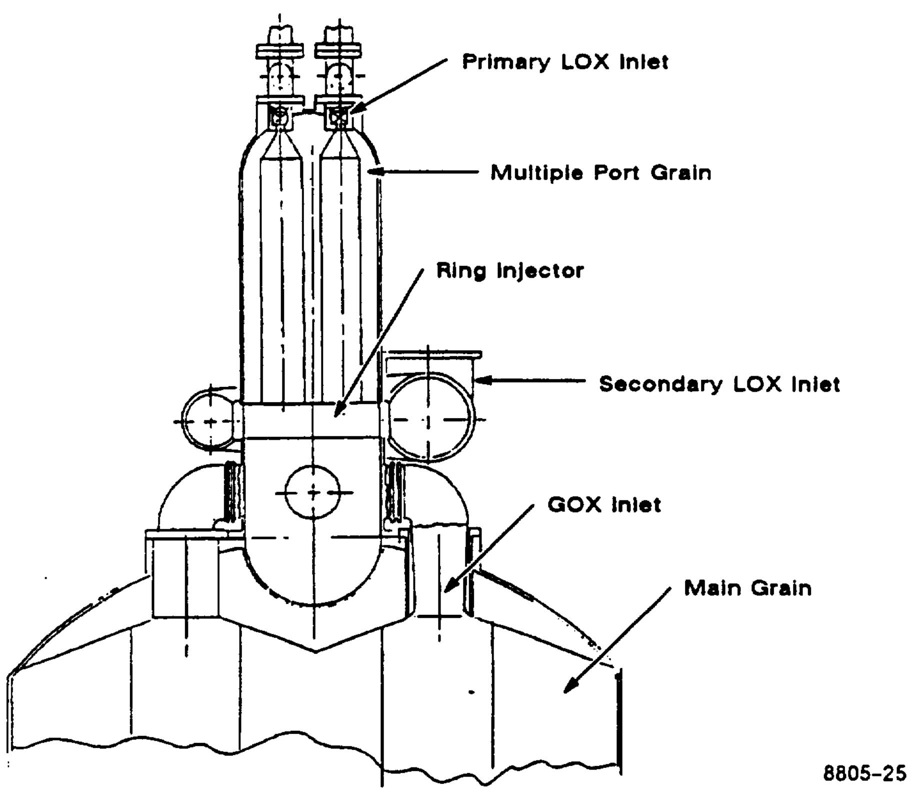

Figure 17. GOX Pre-Injector Configuration—One Grain Per Motor

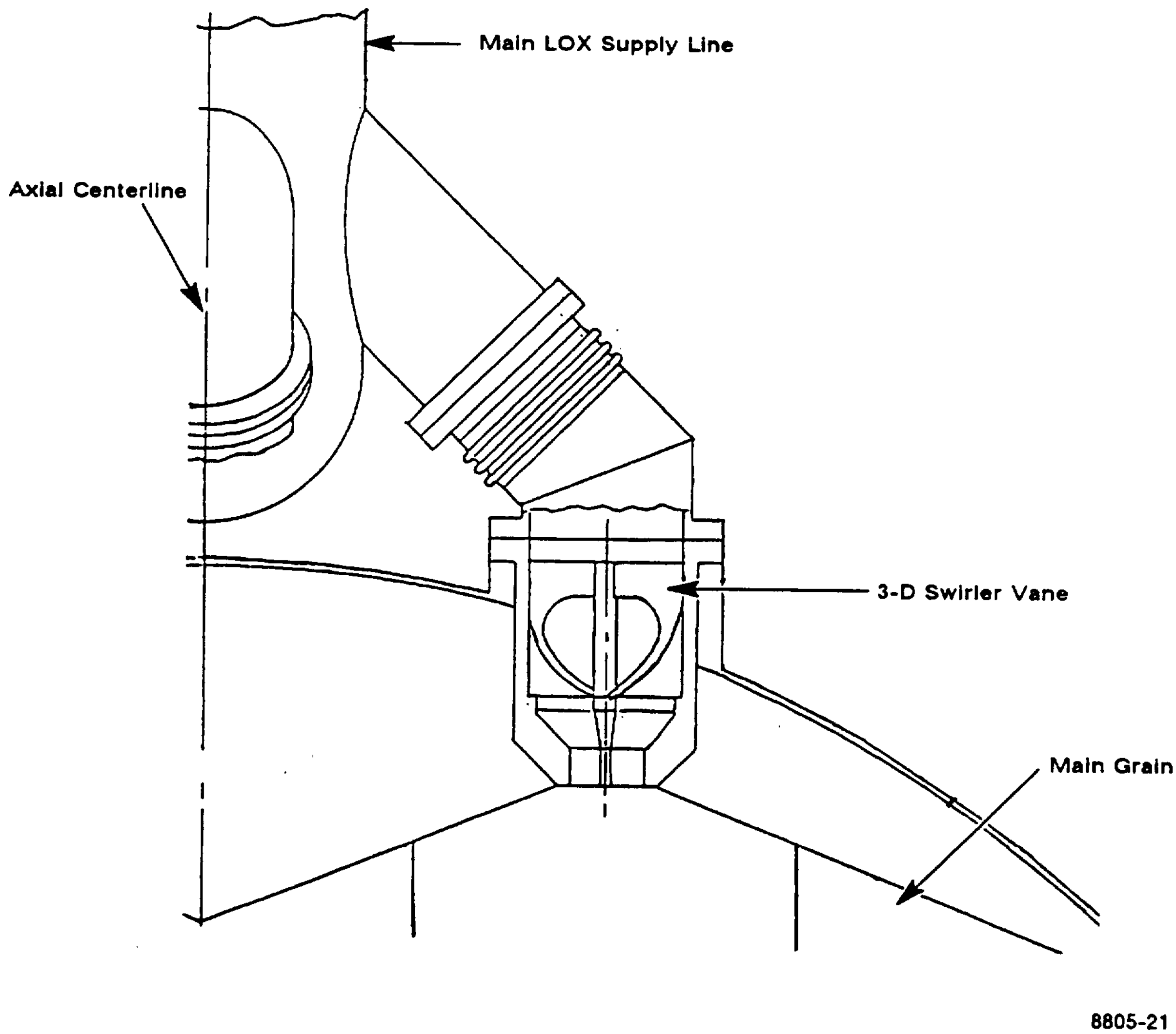

Figure 18. Recommended LOX Swirl Configuration

3.0 TECHNOLOGY IDENTIFICATION

3.1 CRITICAL TECHNOLOGIES

Acquisition of several key technologies is critical for the development of large hybrid rocket systems. The pre-injector concept reduces or eliminates many of the technology concerns but the currently envisioned pre-injector concepts have a negative impact the vehicle performance. Resolution of the technical problems and understanding of controlling mechanisms behind the problems will allow more efficient and higher performing systems to be developed and utilized.

3.1.1 Grain Flooding

Grain flooding is a phenomenon in which the combustion of the solid fuel is extinguished or never established due to very high oxidizer mass flux levels through the fuel port. Grain flooding can occur during ignition and during rapid increases in oxidizer flow rate. Grain flooding has been observed experimentally with hypergolic propellants at an oxidizer mass flux through the fuel grain port of approximately 0.5 lb/sec/sq.in. Initial oxidizer mass flux levels of approximately 1.5 lb/sec/sq.in. are required for the 2.5 Mlb. thrust motor under consideration.

Grain flooding is believed to be related to insufficient heat transfer from the ignition or combustion source to the fuel and oxidizer. If the energy released from the initiating reaction or combustion process is insufficient to pyrolyze the fuel, vaporize the oxidizer and raise the constituents to the reaction temperature, then flooding will occur. This simple assessment is complicated by that fact that hybrid internal ballistics and heat transfer rates are affected by oxidizer injectant conditions, chamber pressure, boundary layer development along the length of the fuel port and, of course, by the fuel composition. The maximum oxidizer mass flux limit for a high energy fuel with a hot, gaseous oxidizer should be considerable greater than for a low energy fuel with a cryogenic, liquid oxidizer.

Steps can be taken to reduce the potential for grain flooding. Minimizing the rate of change of oxidizer flow rate during ignition and throttling transients may be the simplest way to reduce the flooding problem. Raising the enthalpy of the oxidizer prior to injection into the main grain is another example of what can be done. The pre-injector concept utilizes this technique. For LOX injection, a high energy fuel at the head-end of the main grain could be utilized to provide a high initial heat release for vaporizing the oxidizer and maintaining combustion. Additionally, by using a three-dimensional swirl vane so that only a small portion of the oxidizer flow is directed outward to the combustion zone, less energy would be locally required to raise the oxidizer enthalpy and thus flooding potential would be reduced. Further, by simply providing a low oxidizer mass flux region at the head end of the grain, as shown in Figure 19, flooding may be averted.

At present, very little experience with and insight into the grain flooding phenomenon has been established. The phenomenon is not well characterized or well understood. Investigation

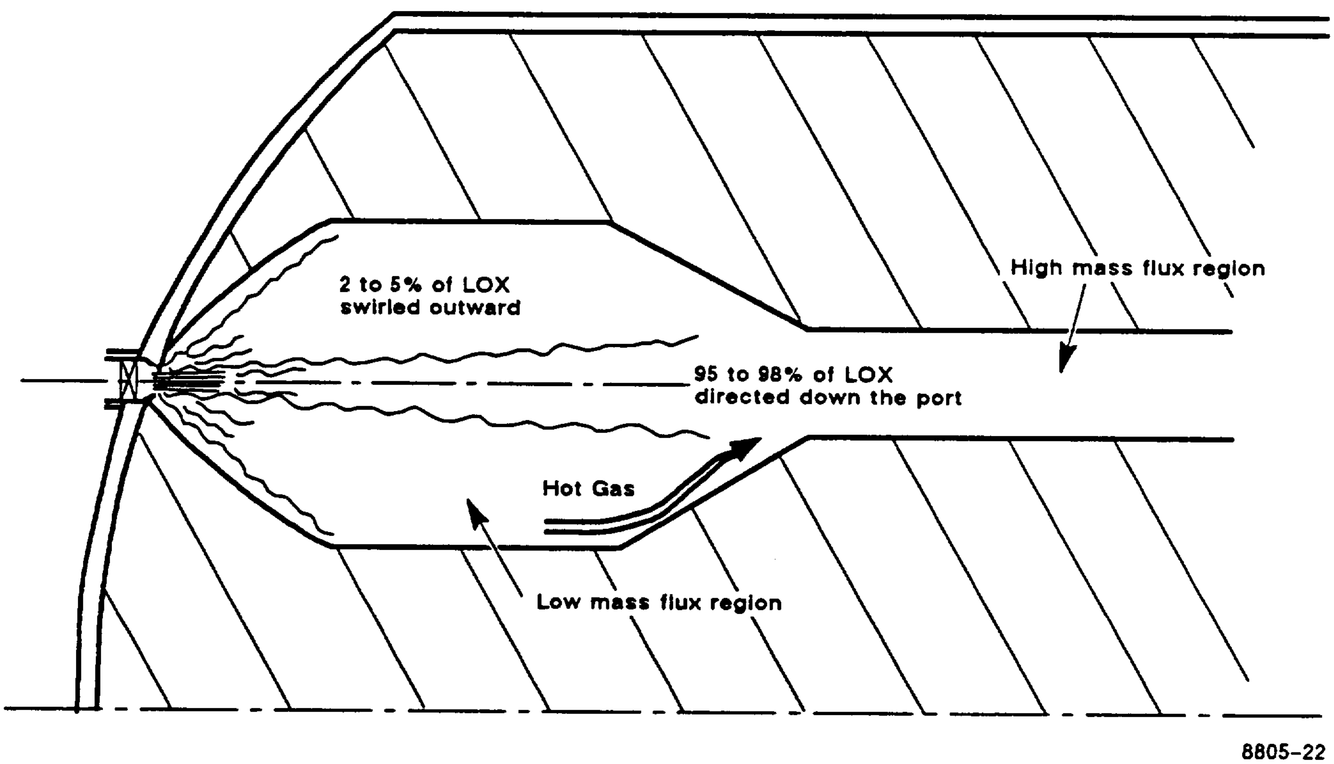

Figure 19. Potential LOX Injector/Fuel Grain Interface

into grain flooding must be performed due to the high oxidizer mass flux levels which are required to achieve high grain loading in large scale motors.

3.1.2 Grain Compatibility

Compatibility between the injector and the head-end of the fuel grain refers to influence which the injector has over the head-end grain regression characteristics. Failure to consider the influence of the injector on head-end regression can lead to either excessive head-end grain erosion or to poor fuel utilization.

Fortunately, a significant data base exists for injector/grain compatibility for motors from three to seventeen inches in diameter. Experience has shown that direct impingement of the oxidizer upon the fuel near the injector leads to excessive fuel erosion near the point of impingement although injector effects are negligible at distances greater than four port diameters downstream of the injector. Alternatively, a central jet of injectant is ineffective at utilizing the head-end fuel and tapering of the port will occur. The present database indicates that for liquid injection, a solid cone spray injector with a 30 degree included angle produces uniform grain regression along the port provided the axis of the cone aligns with the port axis. Additionally, for helium aerated cone injectors, a cone angle of 20 degrees produces near-uniform grain regression. For injectors which produce excessive head-end grain erosion, it is possible, even preferable, to use a low regressing fuel "splashblock" adjacent to the injector to minimize head-end erosion. Since the splashblock is consumable, very little, if any, performance penalty is incurred by employing one.

The main technological concerns regarding injector/grain compatibility as applied to large-scale hybrid motors are 1) injectant impingement effects on regression of very dense, high regression rate fuels and 2) port diameter/injector flowrate (scale) effects on head-end erosion. Additionally, analytical codes which combine droplet trajectory, vaporization, wall interaction, and reaction capabilities need to be developed to allow accurate prediction of large-scale injector/fuel grain influences on head-end fuel regression.

3.1.3 Combustion Stability

The presence of classical feed system coupled or acoustic combustion instabilities in hybrid motors has not been documented. However, non-periodic oscillations in chamber pressure which are much lower than the lowest chamber acoustic resonant frequency have been frequently noted. For the purposes of this document, the non-periodic oscillations (which are better termed "rough combustion") will be termed an instability. The lack of classic modes of instability in a hybrid motor is primarily due to the fact that large scale gas-phase mixing dominates the combustion process. Accordingly, hybrid instability is a relatively benign condition. The chief problem with hybrid instability is the increased heat load to the injector which is exposed to unreacted oxidizer. Instability induced failure of injectors utilizing fluorinated (highly reactive) oxidizers has been documented.

Hybrid combustion instability can be attributed to either the oxidizer injectant or the solid fuel grain. Only injector effects on hybrid stability are considered here. Previous hybrid experience has established a strong correlation between the atomization effectiveness of an injector and combustion instability. From this point of view, large LOX spray injectors appear unattractive and the pre-injector concept appears to alleviate the problem. Increased atomization through utilization of a swirl element would surely aid in reducing the magnitude of chamber pressure oscillations. The magnitude of the pressure oscillations may also be reduced by lowering the oxidizer mass flux and a configuration like that presented in Figure 19 may be effective. Further, mixing devices which break up oxygen-rich and fuel-rich regions may be effective.

The mechanisms of hybrid instability are not well characterized or understood and methods for the elimination of hybrid instability have not been systematically developed. An understanding of hybrid instability mechanisms is critical to development of large-scale hybrid motors. At present, hybrid instability does not appear to be scalable and thus accurate predictive analytical methods must be acquired prior to committing to large-scale motor development.

The lack of experimental evidence for acoustic mode instabilities in hybrid motors does not preclude acoustic modes from appearing in large-scale motors. Additionally, there are no assurances that a given motor configuration will be stable or remain stable under all test conditions. Implementation of acoustic absorbers to handle potential instabilities is a simple matter. The technology involved is mature and an extensive experimental and operational data base is available from the liquid rocket engine industry. A series of Helmholz cavities located around the periphery of each injector and/or around the nozzle entrance could be utilized to increase the acoustic stability margin.

With the requirement for throttling comes a concern over feed system coupled instabilities. Fortunately, the mixture ratio shifts and the oxidizer/fuel interactions associated with the large-scale classical hybrid motors which were considered aided in reducing the degree of oxidizer throttling required to follow the prescribed thrust trace in Figure 2. A 1.6:1 oxidizer throttling range was all that was required to produce a 2:1 thrust variation. Figure 20 shows the variation of maximum injector pressure drop to minimum injector pressure drop resultant from the required throttling. To minimize vehicle tank weight and pressurization requirements, the maximum injector pressure drop must be minimized. To avoid feed system coupled instability, the minimum injector pressure drop must be maximized. As Figure 20 clearly shows, these conditions are in conflict. A standard "rule of thumb" for avoiding feed system instabilities is to maintain an injector delta-P of at least 20 percent. From Figure 20, this yields a maximum delta-P of over 35 percent. However, if feed system coupled instability could be avoided with a minimum injector delta-P of only 14 percent, the maximum injector delta-P drops to just over 25 percent. This latter condition seems reasonable with current technology. It should be noticed that a one percent drop in the throttled (low thrust) injector delta-P which can be tolerated yields a 1.8 percent drop in the injector pressure drop at maximum thrust. Thus even modest gains in

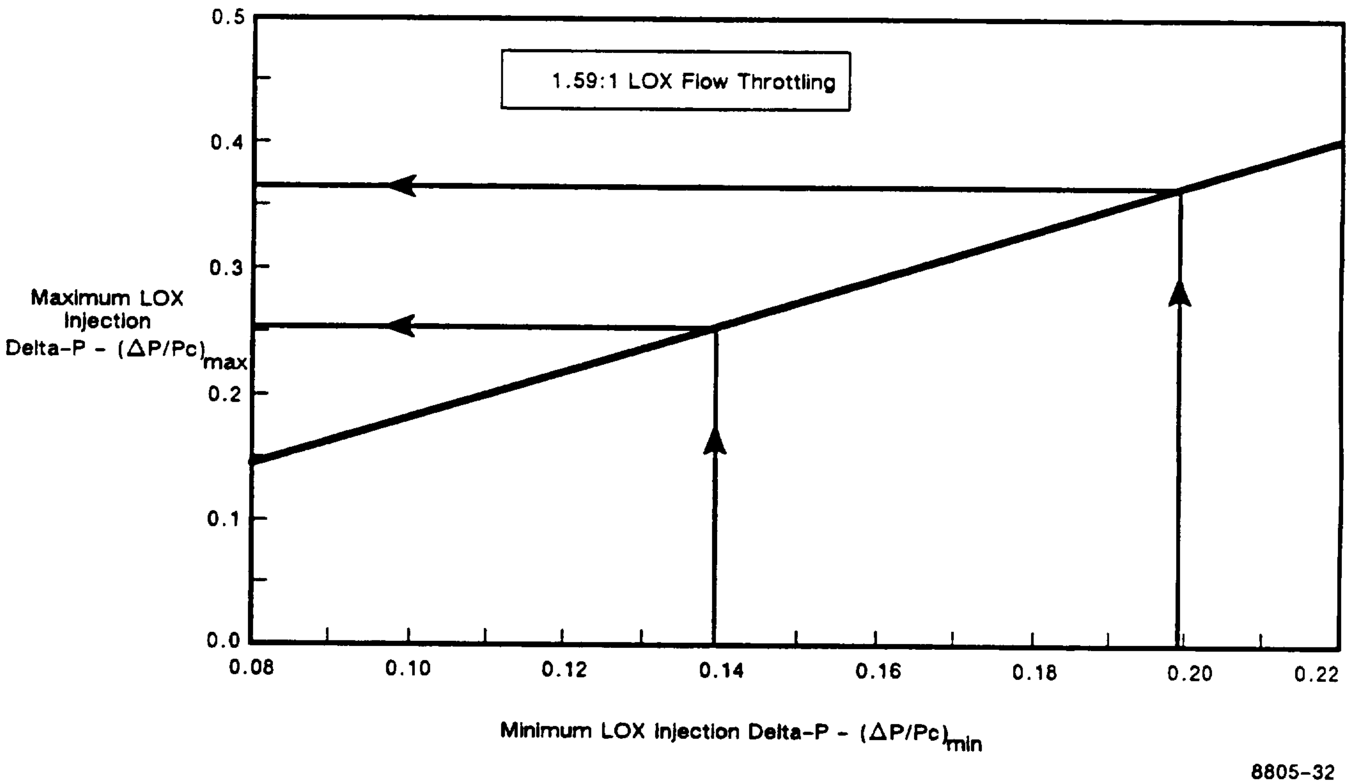

Figure 20. Head-End Delta-P Variation for Throttling with No Aft-End Injection

technology aimed at reducing feed system coupled instabilities would yield significant overall vehicle performance gains.

3.1.4 Mass Distribution Effects

A technology base must be developed which establishes the effect of injectant mass distribution on

1. Grain flooding/ignition
2. Grain utilization/compatibility
3. Combustion stability

Fortunately, determination of oxidizer mass distribution effects on these phenomena can be part of a more extensive investigation into each. Varying oxidizer mass distribution holds potential as a useful (albeit limited) tool for tailoring hybrid combustion characteristics.

A cursory experimental investigation into the oxidizer mass distribution effects on head-end regression has been performed previously (reference 2). Unfortunately, only a qualitative assessment of the oxidizer mass distribution was made.

Prior to any future hybrid hot-fire testing, a simple cold-flow mass distribution analysis should be performed on all liquid injector elements which are destined for hot-fire testing. An estimate of the mass distribution of oxidizer exiting a pre-injector can be established by using a temperature and pressure rake suspended across pre-injector exhaust during a pre-injector only hot-fire test.

3.1.5 Scaling

The greatest technical concern in the development of oxidizer injectors for large-scale hybrid motors is the effect of scaling on grain flooding, injector/grain compatibility, and combustion stability. The flow rate per element and element sizes for both the 1/4-scale (635 klb. thrust) and full-scale (2.5 Mlb. thrust) are well outside of current rocket experience. Figures 21 and 22 show the approximate element size of the LOX swirl spray nozzles for the 1/4-scale and full-scale motors respectfully. Assuming one spray nozzle per port in a four port, full-scale motor, each injector element would be over 6.5 inches in diameter. Current methods of estimating oxidizer droplet sizes are not accurate at this dimension.

The LOX injectors within the pre-injector concept would be less susceptible to scaling difficulties due to smaller injector sizes resultant from the more distributed LOX injection. Further, the pre-injector may be less susceptible to stability problems which arise from scaling. A private rocket company in Camarillo, CA has reported encountering unexpected stability problems when a hybrid motor was geometrically scaled up. No stability problems were evident at the

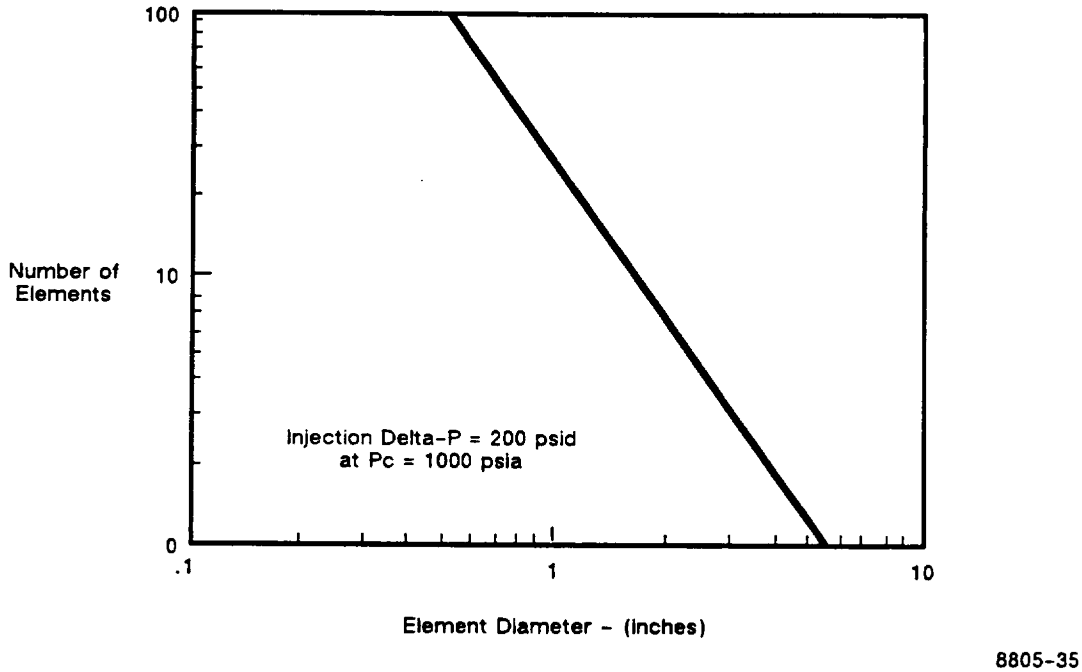

Figure 21. 635 Klb Thrust Hybrid Element Sizing (Swirl Spray Nozzles)

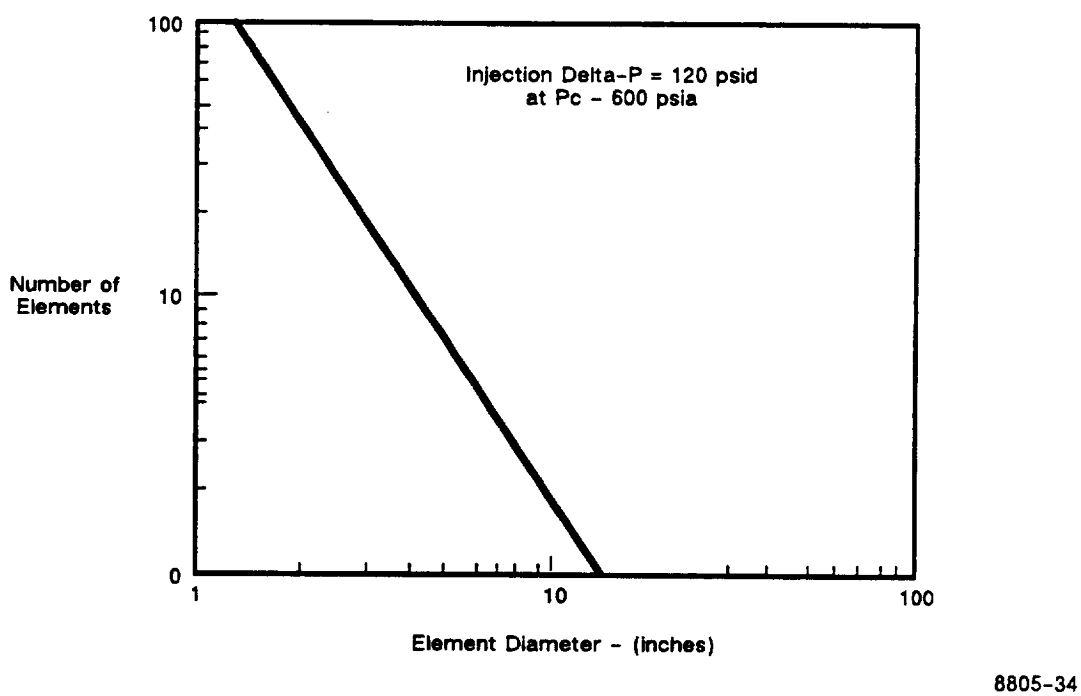

Figure 22. 2.5 Mlb Thrust Hybrid Element Sizing (Swirl Spray Nozzles)

smaller scale. Accordingly, the increased stability margin inherent in smaller hybrids may work in favor of the pre-injector concept.

An integral part of the development of scaling technology and relations is the development of accurate predictive computer codes. As shown in the Technology Acquisition Plan section, a test program which systematically increases motor size is recommended. With each increase in motor size, computers codes will be used to make predictions of the motor behavior prior to test. The pre-test predictions will be compared to test results and the codes will be evaluated and modified accordingly. The development of accurate predictive techniques is crucial to efficient and successful development of large-scale hybrid motors

3.2 ENHANCING TECHNOLOGIES

Technical issues which are of concern, but not critical to enabling the operation of a hybrid rocket motor, are identified as enhancing technology issues. These issues can be resolved using current technology, but further work is needed for proper application and verification of these technologies to ensure successful hybrid operation.

3.2.1 Thrust Control

The requirements for thrust control are:

- Match the ASRM (Advanced Solid Rocket Motor) thrust profile
- A smooth repeatable start
- A smooth repeatable shutdown
- Provide abort capability throughout mission

3.2.1.1 Throttling

These requirements were refined into three regimes: throttling, ignition, and thrust termination. The most technically challenging item on the list is throttling a hybrid motor to meet the given thrust profile. Throttling concepts considered were:

- Varying oxidizer supply pressure
- Varying fuel grain geometry
- Varying fuel grain composition
- A variable area nozzle
- Servo controlled oxidizer valves

These concepts were chosen based on their feasibility to throttle a hybrid motor. Note that none of the concepts are on the leading edge of technology eliminating the need for a specific technology acquisition program. A study was conducted to downselect the hybrid throttling concepts using flight safety (complexity), reliability, and recurring cost as criteria.

The results of the study are presented in Table 4. In the study a positive, negative, or questionable evaluation was given to each concept/criteria.

Varying oxidizer supply pressure received a negative rating based on the slow response time and complexity of a system needed to generate and purge the enormous tank ullage to meet throttling requirements. The booster system would be further complicated by additional sequencing needs to control the throttling system throughout the mission. Reliability and cost are negatively influenced by the added complexity required for this system.

Tailoring a solid fuel grain, casting the grain port in a geometric configuration to provide a fixed thrust profile, is current technology and is safe by industry standards. However, the reliability of injecting oxidizer into a tailored grain received a poor rating, based on the the identification of key technologies discussed in earlier sections. In this method of thrust control throttling is fixed by geometry. A hybrid booster using this method of thrust control will be unable to adapt to changes in mission profile without a change in grain geometry. The design of a fuel grain port geometry compatible with oxidizer injection, and fabrication of the necessary casting tooling for a hybrid is extremely expensive compared to recurring cost of casting the grain.

Varying the fuel grain composition, altering fuel density as a function of web, received a negative rating for flight safety. This is due in part to the complexity of casting consistent grains which could result in thrust imbalances during flight. The reliability of this arrangement is very questionable when the issue of debonding between layers of differing density propellants is taken into consideration. This method of throttling is also inflexible to meet further throttling requirements without a costly redesign. Like grain tailoring, the recurring cost of casting exotic grains is small compared to the design and development of such a grain.

Theoretically, a variable area nozzle is capable of throttling a hybrid motor, however, the cost, complexity, and reliability of a nozzle for the throttle range required presents major challenges. These challenges include: system complication, unreliable hot gas seals, and further sequencing requirements.

Servo controlled valves have proven themselves as safe and reliable, but present an expensive solution for oxidizer flow control needed to throttle a hybrid motor To accommodate the magnitude of oxidizer flow in the full scale hybrid requires either a combination of current valves or fabrication of new larger valves.

To further evaluate throttling concepts, advantages and disadvantages of each concept were examined and are tabulated in Table 5. Although the screening process for throttling concepts is top level only, it was sufficient to identify servo controlled valves as the suitable solution to meet throttling requirements.

Table 4. Throttling Study

Criteria \ Concept	Oxidizer Supply Pressure	Fuel Grain Geometry	Fuel Grain Composition	Variable Area Nozzle	Servo Oxidizer Valves
Flight safety (complexity)	–	+	–	–	+
Reliability	–	–	?	–	+
Nonrecurring cost	–	–	–	–	–
Recurring cost	–	+	+	–	–

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Table 5. Throttling Concept Evaluation

Concept	Advantages	Disadvantages
Oxidizer supply pressure		Slow response time Large complicated pressurization system Additional sequencing
Fuel grain geometry	No oxidizer throttling System simplicity	Difficult to configure port geometry Fixed thrust profile
Fuel grain composition	No oxidizer throttling System simplicity	Uncertain composition Fixed thrust profile
Variable area nozzle		System complication Hot gas seal Additional sequencing
Servo controlled valves	Off the shelf technology	Additional sequencing

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3.2.1.2 Ignition

Ignition of a hybrid motor was the next issue investigated. Ignition concepts which were considered include: hypergolics, pyrotechnics, and a oxidizer/fuel torch. Again, these concepts are well developed and do not require a technology acquisition program. Preliminary evaluation of these concepts (which is similar to the throttling evaluation), is shown in Table 6.

The three ignition systems rated evenly based on the prescribed criteria. The torch received a poor evaluation for non-recurring cost since this ignition method would require extensive injector area modifications, necessitate a high energy source, and the introduction of another propellant. Both the hypergolic, and the pyrotechnic charge introduce higher recurring costs due to the need for new charges, or cartridges for each firing.

This study was supplemented by an evaluation, which lists advantages and disadvantages of each ignition concept shown in Table 7. Based on the results of the study and evaluation hypergolic cartridges were chosen as the ignition baseline. Further criteria for this selection stem from the successful use of hypergolic, TEA/TEB, cartridge systems on commercial production liquid rockets.

3.2.1.3 Thrust Termination

Simplified schematics of the oxidizer valves and corresponding ducting were developed for both the pre-injector and point injection schemes, (Figures 23 and 24 respectively). These schematics were used to establish a smooth repeatable starting sequence for each injector concept. These starting sequences also provided for abort capability during start transients. To abort a firing, whether it is during start or later in the mission, the isolation valve is closed discontinuing oxidizer flow to the main fuel grain. A controlled shutdown of the motor is accomplished by throttling the servo controlled valves to meet the thrust profile and finally closing the isolation valve to terminate thrust. Figures 25 and 26 present the sequence graphs for both the pre-injector and point injector schemes.

3.2.2 Performance

Although performance played a limited role in vehicle trade studies, it is of importance on an operational level. Both operating conditions and hardware configurations, which have a direct effect on performance,and the magnitude of their effect, need to be identified and evaluated. Past hybrid experience indicates that injectors and injection systems have no effect on motor c* performance. However, the weight of the injectors and the feed system can have a significant effect on vehicle delta-V performance. A discussion of injector weight issues is presented in the Concept Evaluation section. Feed system weight savings will be achieved by keeping high pressure lines short and of a minimum diameter. Further feed system weight savings will come from high strength-to-weight ratio valve materials and development of high efficiency valve actuators.

Table 6. Ignition Study

Criteria \ Concept	Hypergolic	Pyrotechnic	Torch
Flight safety	+	+	+
Reliability	+	+	+
Nonrecurring cost	+	+	-
Recurring cost	–	–	+
Performance	+	+	+

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Table 7. Ignition Concept Evaluation

Concept	Advantages	Disadvantages
Hypergolic	No high voltage source needed	Handling (toxic)
Pyrotechnic	Weight savings Simplistic system	Needs electric source Handling (explosive)
Torch	Restart capability	Needs electric source Separate propellant system

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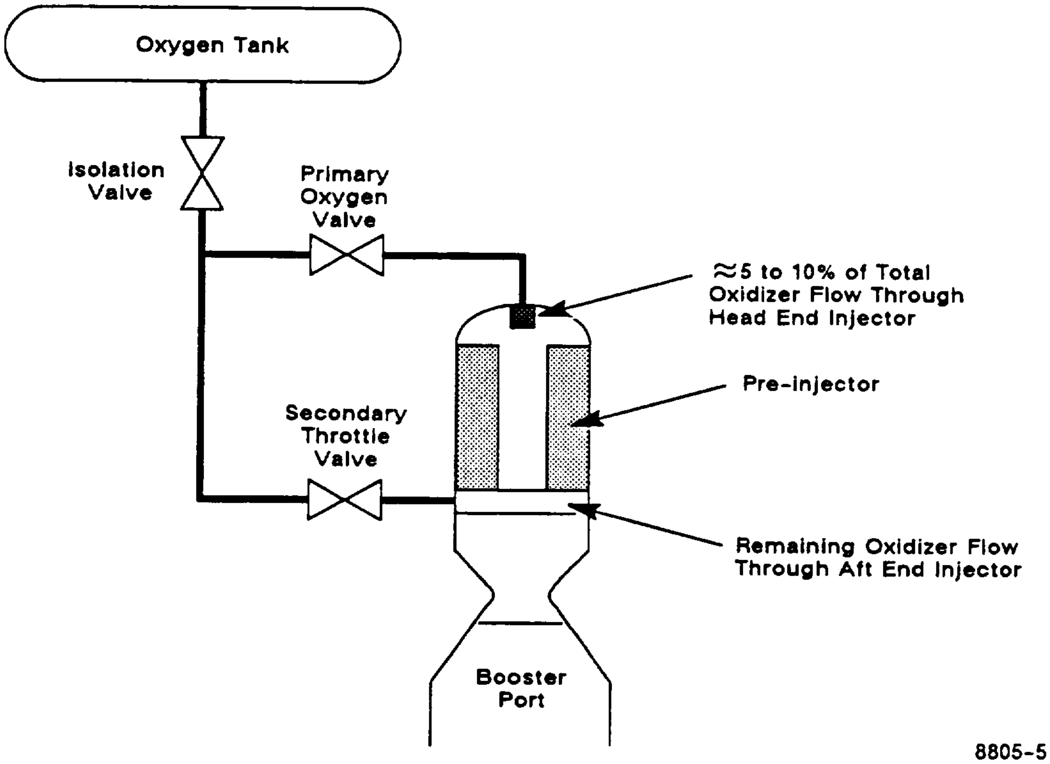

Figure 23. Pre-injector Feed System Schematic

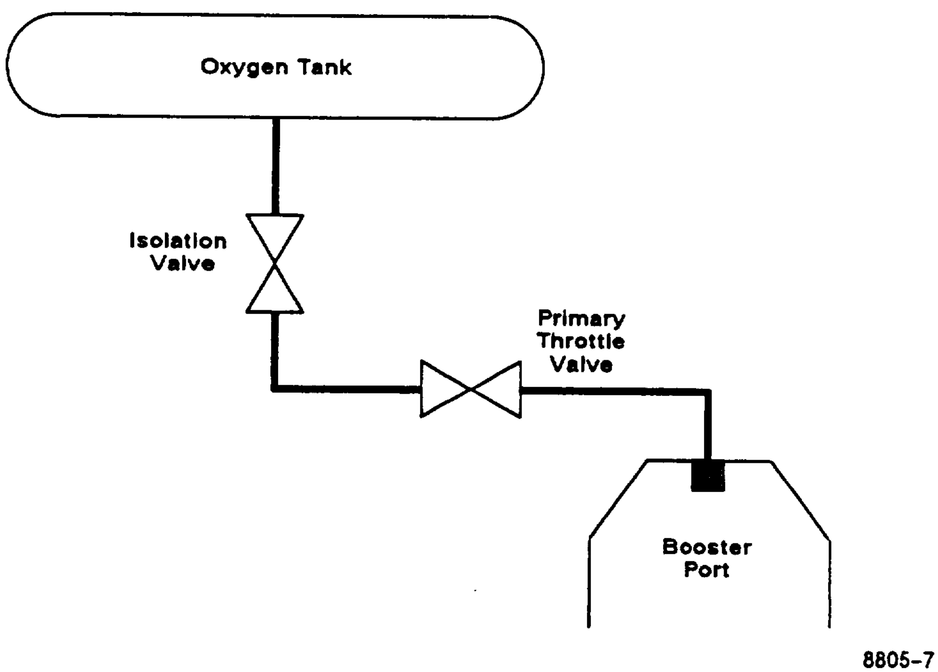

Figure 24. Point Injector Feed System Schematic

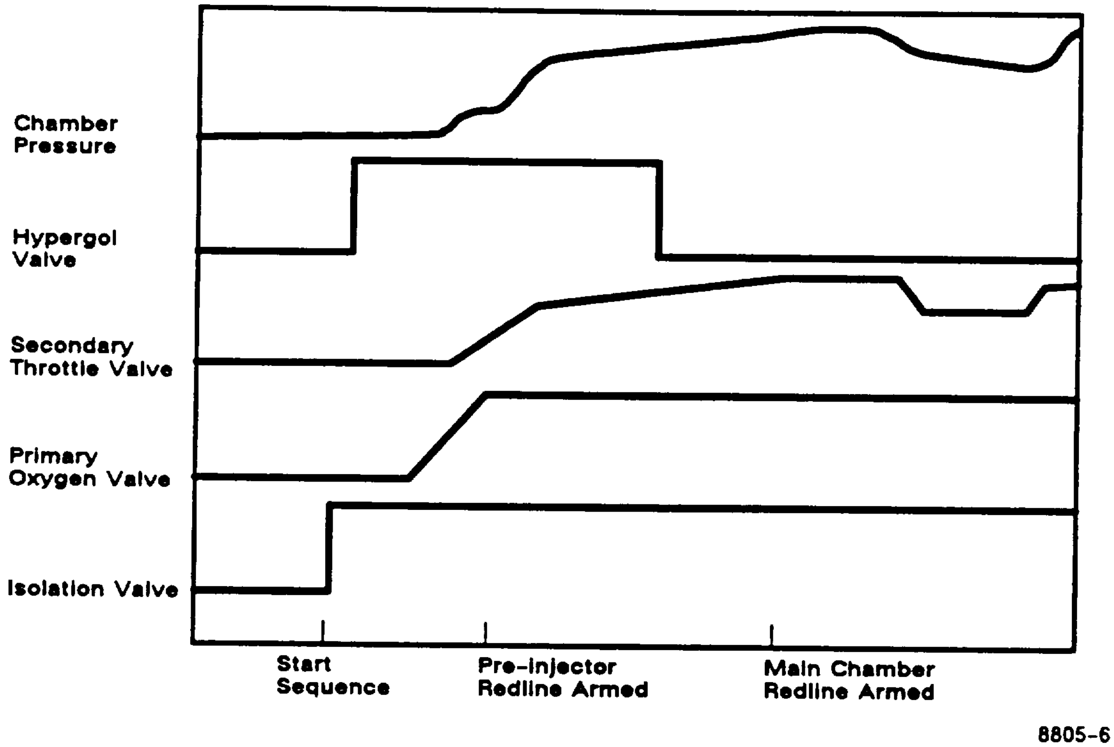

Figure 25. Pre-injector Start Sequence

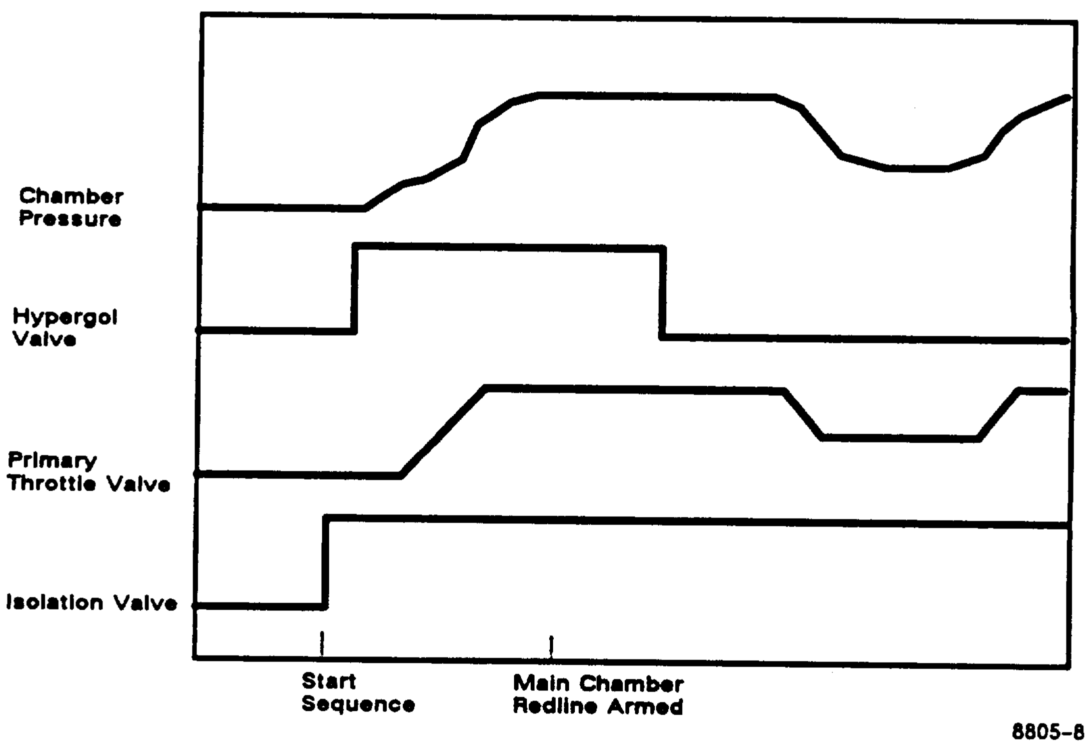

Figure 26. Point Injector Start Sequence

3.2.3 Injector Durability

Active cooling and insulation techniques for hybrid injectors need to be investigated further to ensure injector durability. Current technology for cooling injectors is sufficient, but further investigation and demonstration will be required for detailed injector concepts.

4.0 TECHNOLOGY ACQUISITION PLAN

Computer modeling, cold flow testing, and a hot fire test program including dynamic bomb testing will be implemented to fulfill the objectives for Phase II. The objectives of Phase II are as follows:

1. Acquire enabling technologies identified in Phase I
   - Grain compatibility
   - Grain flooding
   - Mass distribution effects
   - Combustion stability
   - Scaling
2. Acquire/anchor analytical codes and correlations for hybrid design/development
3. Establish oxidizer injection condition
4. Address minor technology items
   - Thrust control
   - Motor performance
   - Injector durability

Fulfillment of these objectives, using the tools mentioned above will provide acquisition of the enabling technologies and allow for an easy transition into Phase III motor development.

4.1 GRAIN COMPATIBILITY/FLOODING AND MASS DISTRIBUTION EFFECTS

Figure 27 presents an overview of how cold flow testing and a hot fire test program will be coordinated to resolve the technical issues of grain compatibility/flooding and mass distribution effects.

Cold flow testing, flowing water through candidate injectors, will be used to determine spray distribution and droplet sizes. The objective of the cold-flow tests is to provide data to support the assessments of the stability and performance of the candidate injectors and to serve as an experimental means by which the injector designs can be screened and optimized.

These cold-flow tests support the stability and performance analysis codes and techniques by providing critical input data. The most critical data required are the droplet sizes that will be produced by the spray nozzle injectors. However, in addition to droplet size data, the codes require other types of atomization information such as the initial direction and distribution of the droplets produced. And all CFD combustor codes contain adjustable parameters that must be

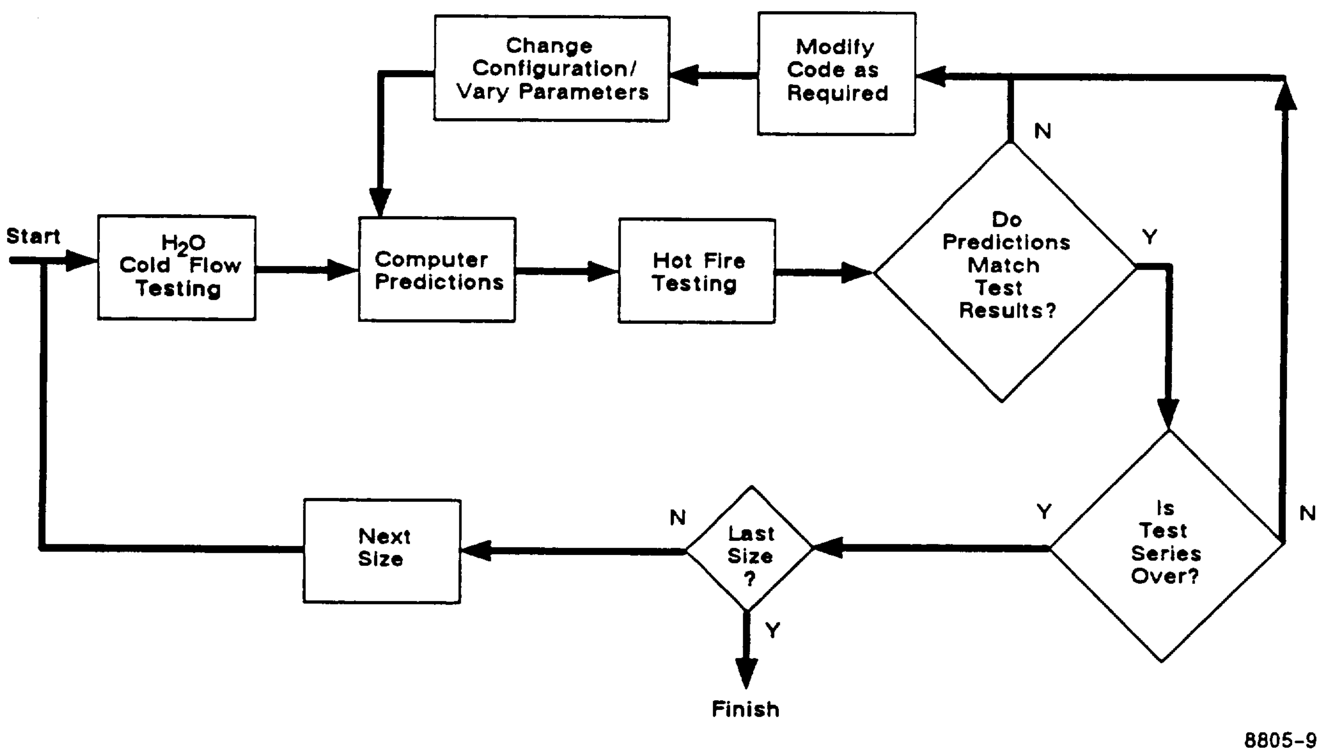

Figure 27. Technology Acquisition Logic

- Grain Flooding
- Grain Compatibility
- Mass Distribution Effects
- Scaling

selected. The turbulence parameters, diffusivities, droplet turbulent dispersion parameters, and the chemistry models are examples of such adjustable parameters. In most cases, there are few physical data available by which to select these parameters. Therefore, it is imperative that computations be correlated and verified by comparison with experiments. For example, cold-flow and hot-fire experiments can be performed to determine the length of a liquid jet. The combustor code's stripping rate model is then adjusted to match that observed length. After similarly selecting the other adjustable parameters, the code must be further verified by comparison with experimental motor firing data. Then it can be used to analyze and examine the results of hot-fire tests and to extrapolate the results of these tests to other conditions (e.g. higher pressures, larger motors) that were not tested. Such a coupling between experimental and analytical results is a necessary and critical part of a program such as this.

There is, of course, some uncertainty and inaccuracy associated with the application of cold flow test results to actual combustion conditions. It must be recognized that 1) this is a preliminary screening and optimization task designed to reject only the least promising candidate injector designs and to provide preliminary design guidance to support injector concept optimization and 2) these results will be complemented by sub-scale tests and extensive analysis. Although all of these test and analysis methods have deficiencies, they are the best and least expensive means to develop the hybrid injector technology base and to screen and optimize the injector concepts.

Figure 28 shows a typical mass distribution collector used in cold flow testing. The mass distribution collector will be installed in a test stand, as shown in Figure 29, with each element connected to a separate measuring container. Mass distribution and spray pattern are determined by flowing the injector directly above the mass collector and recording the acquired amounts of water in each measuring container.

Droplet size measurements will be accomplished in the Rocketdyne Atomization and Mixing laboratory. All required tankage, pressurization, exhaust, control, and other hardware/systems required to produce sprays of various inert liquids within pressurized vessels or in the open, are available. Two droplet sizing instruments may be utilized: A Malvern droplet sizing system (diffraction based) which provides quick, simple line-of-sight droplet size distribution data in dense sprays, and a Droplet Sizing Interferometer which provides more detailed, spatially resolved, droplet size distribution, and droplet velocity data.

Cold flow test results initially will be used to select injectors based on initial injection requirements and the ability to model spray patterns for analytical combustion predictions. Prior to hot fire testing, combustion predictions will be made. Following hot fire tests these codes will be anchored to reflect hot fire test results. Firing multiple configurations, (injectors, port geometry, etc.), while varying operating conditions, (injection pressure, chamber pressure, etc.), for each motor will establish an extensive data base and develop the necessary tools for combustion code predictions. A relationship between cold flow test data and hot fire test results will be determined to allow more accurate hot fire predictions based on cold flow data. By repeating this same logic on a larger motor, injector scaling trends can be identified. A combination of the

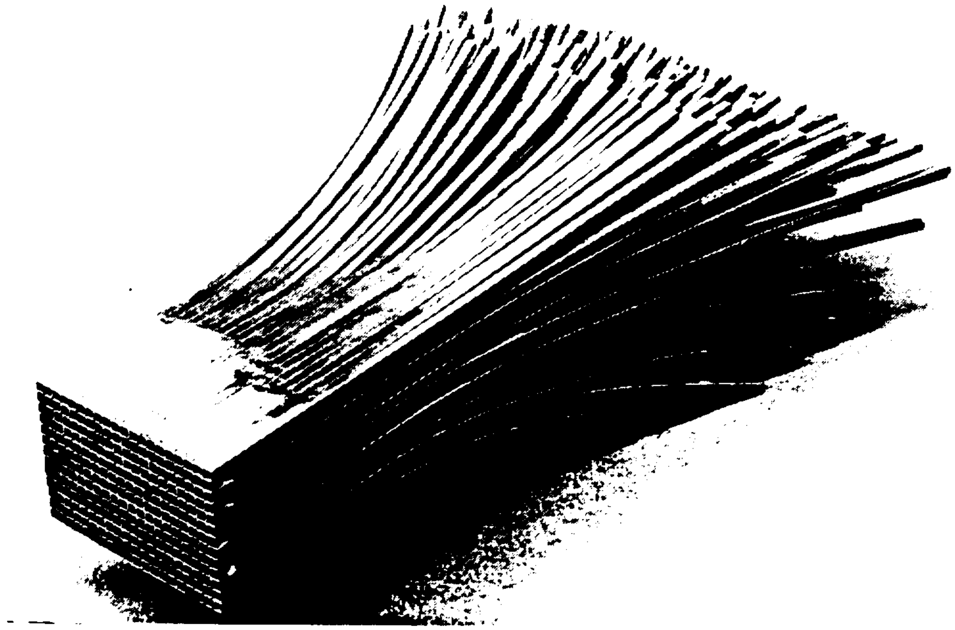

Figure 28. Typical Mass Distribution Collector

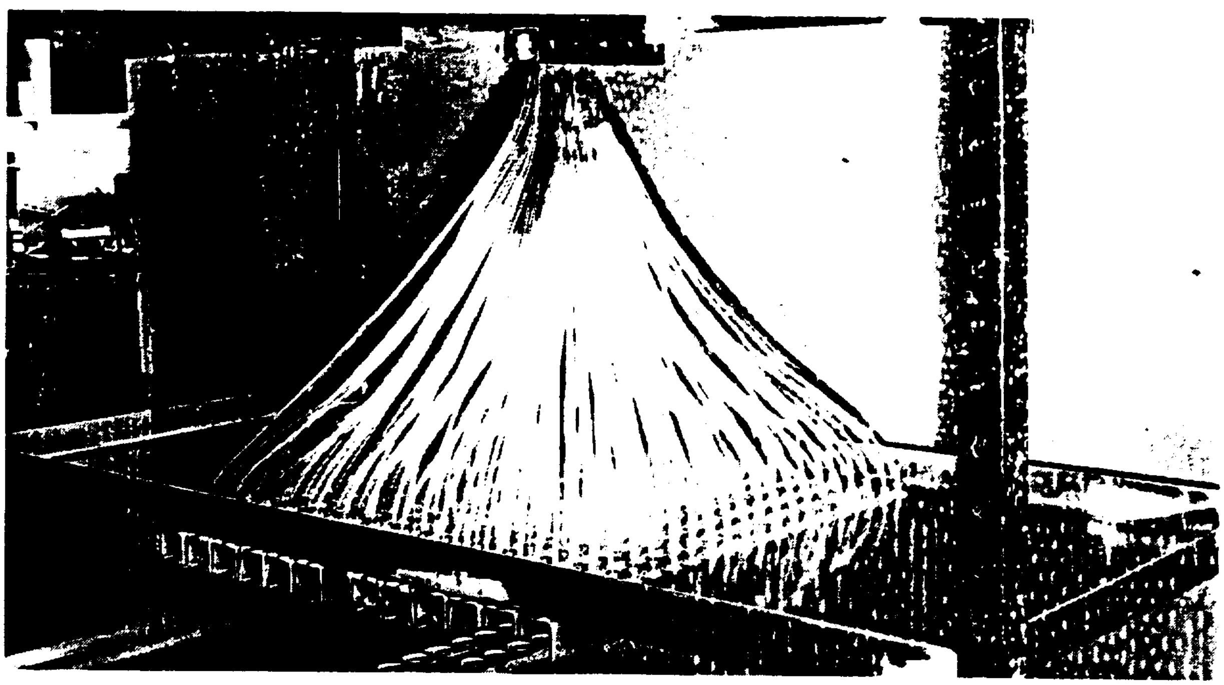

Figure 29. Mass Collector Testing Arrangement

combustion codes and injector scaling trends will be used to determine optimal injection conditions for larger scale motors. Cold flow testing will be used to verify injector design.

4.2 STABILITY

The stability issue will be resolved through the use of dynamic bomb testing, computer codes, and the hot fire test program. The logic chart for this is shown in Figure 30.

Computer predictions will be made concerning the stability of the feed system, injector elements, and chamber acoustics prior to hot fire testing. A electrically fired pyrotechnic stability rating bomb similar to that shown in Figure 31, will be detonated in the combustion chamber to create a pressure perturbation during a hot fire test. The resulting chamber pressure fluctuations will be analyzed to identify if chugging, buzzing, or high frequency acoustic modes of instability are present, and determine the frequency, magnitude, and growth rate of that instability.

Following hot fire tests, the analytical codes will be anchored to reflect test results. A data base for combustion instability in hybrid motors will be generated by hot firing multiple configurations and conditions for each motor size. If an instability mode should persist, the addition of an acoustic absorber will be investigated.

4.3 COMPUTER CODES

Table 8 lists the analytical codes to be used for both combustion and stability predictions in Phase II and provides a brief description of each.

4.4 HOT FIRE TEST PROGRAM

Hot fire testing program flow and test hardware are schematically illustrated in Figure 32. As noted earlier, multiple configurations and operating conditions will be used for each size of motor. the program will utilize several sizes of subscale hardware. Objectives and approaches for testing each motor configuration are listed in Table 9.

Testing will begin using a 10 in. diameter case and a classical hybrid configuration. These tests will provide initial code and scale anchoring, and demonstrate minor technology issues such as ignition, valve sequencing, throttling, performance, and injector durability.

The next series of 10 in. case diameter tests involves the pre–injector configuration. In this series of tests, approximately 5 to 10% of the oxidizer will be introduced to the fuel grain through the head end injector. The remaining oxidizer will be introduced through a ring injector located at the aft end of the grain in an attempt to gasify this oxidizer for injection into a main grain port. These tests will investigate the use of a hybrid as a gas generator. Oxidizer flow splits will be varied between the head and aft end injectors. The exhaust products will be examined to verify the effectiveness and uniformity of gasification over a throttle range. The results of these tests will be used for gaseous oxidizer predictions. These tests also will provide further code and

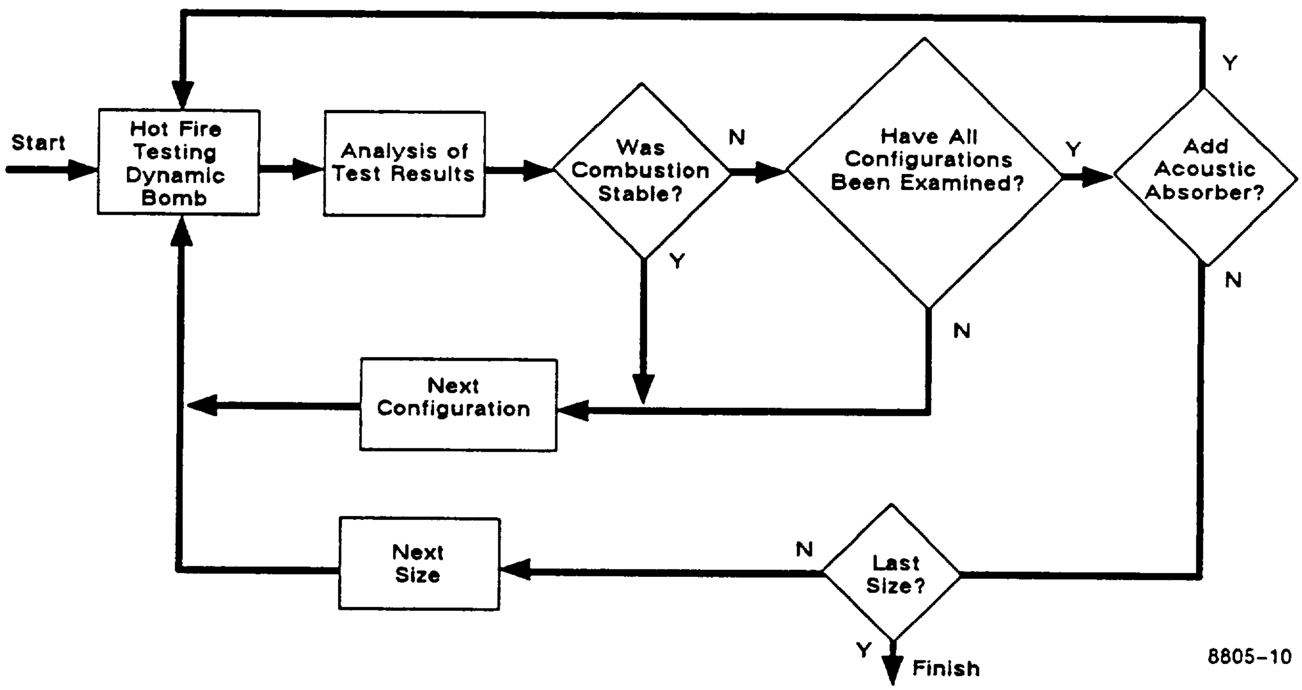

Figure 30. Stability Technology Acquisition Logic

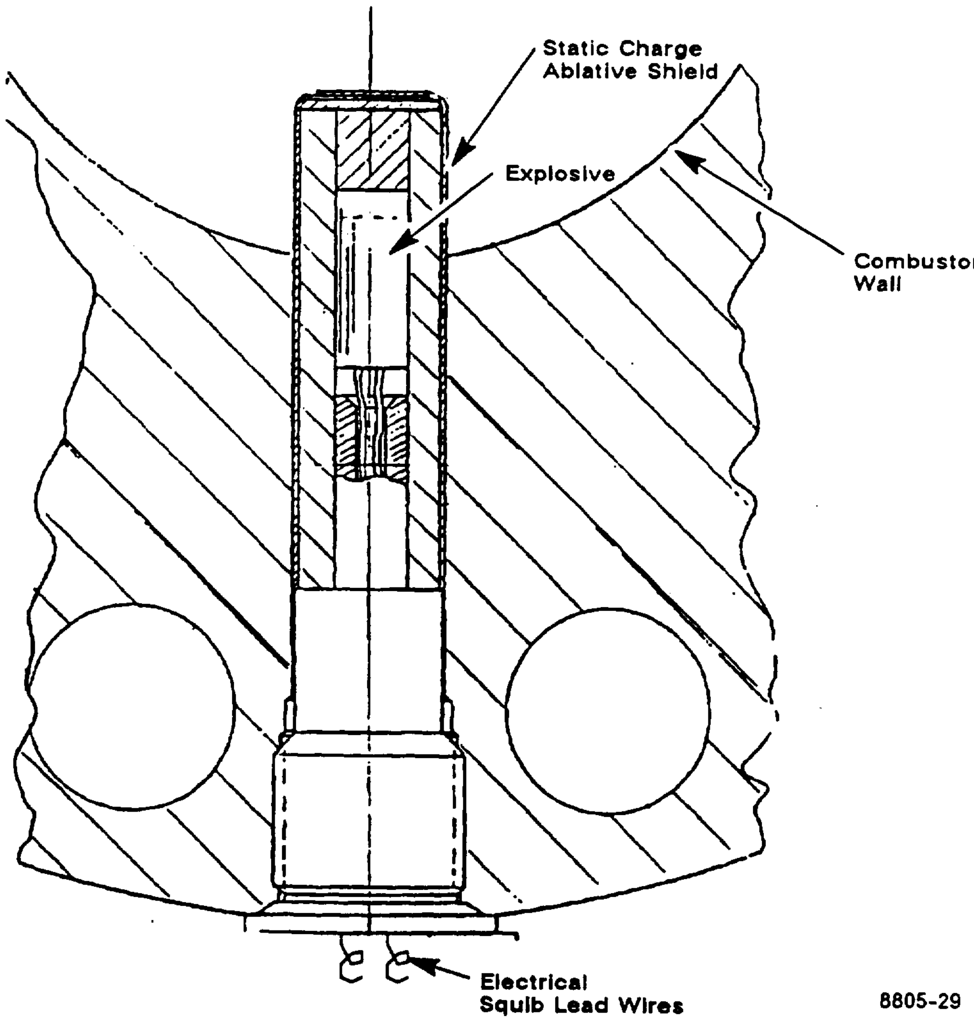

Figure 31. Typical Stability Bomb Assembly

Table 8. Analytical Codes

Type	Code	Uses
Combustion	SDER	Droplet Vaporization
	TPP	Droplet Trajectories Droplet Vaporization
	ARICC	Combined Liquid/Solid Combustion Zone Model
Stability	PIPGEN	Feed System Resonant Frequency Feed System Response
	Post	Injector Element Resonant Frequency Injector Element Response
	Module	Chamber Acoustic Resonant Frequencies Chamber Response
	EIGEN	Tune Acoustic Cavities
	NDORC	Chamber & Nozzle Resonant Frequencies Chamber & Nozzle Response

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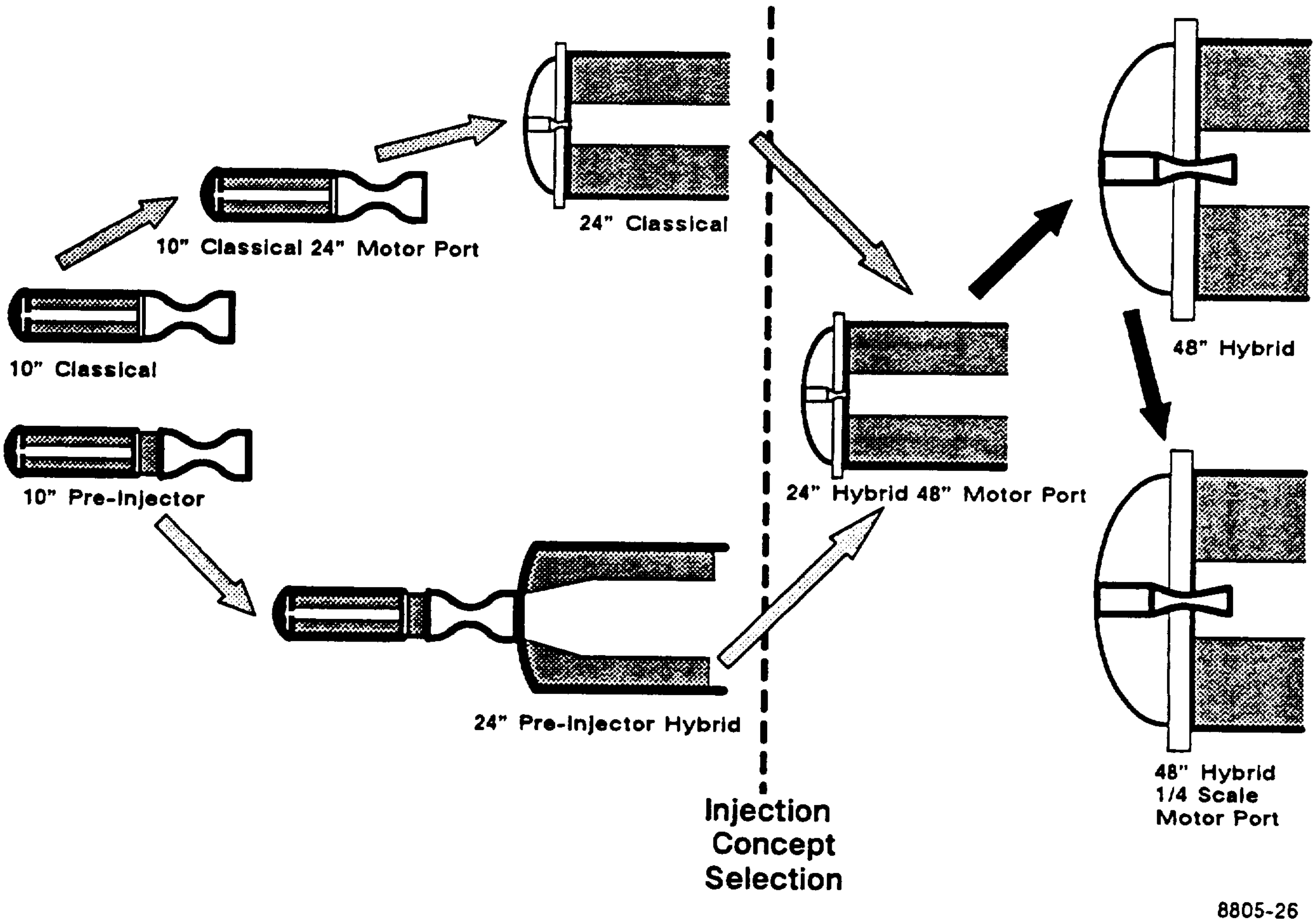

Figure 32. Hot Fire Test Program Flow

Table 9. Hot Fire Test Program Objectives & Approach Matrix

Test Article \ Objectives & Approach	Objectives: Grain Compatibility					Combustion Stability		Other					Approach			
	LOX Code Verification	GOX Code Verification	Code Scaling	Investigate Head End Regression	Investigate Grain Flooding	Code Verification	Code Scaling	Verify Aft End Injector Durability	Verify Head End Injector Durability	Establish Throttling Data	Investigate Performance	Establish Safe & Reliable Starting Sequence	Hot Fire Multiple Configurations	Vary R_c	Vary Oxidizer Flow Rates	Vary Oxidizer Flow Splits
10 in. Classical Hybrid	X			X	X	X				X	X	X	X	X	X	
10 in. Classical Hybrid (Pre-Injector)	X	X		X	X	X		X	X	X	X	X	X	X	X	X
10 in. Classical Hybrid (24 in. Motor Port)	X		X	X	X	X	X		X	X	X		X	X	X	
24 in. Pre-Injector Hybrid	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X
24 in. Classical Hybrid	X		X	X	X	X	X		X	X	X		X	X	X	
24 in. Classical Hybrid (48 in. Motor Port)	X		X	X	X	X	X		X	X	X		X	X	X	
48 in. Hybrid	X	?	X	X	X	X	X	?	X	X	X		X	X	X	?
48 in. Hybrid (1/4 scale Motor Port)	X	?	X	X	X	X	X	?	X	X	X		X	X	X	?

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scale anchoring for the key technology items since liquid oxidizer will be introduced through the head end injector. In addition, aft end injector durability also will be investigated.

The 10 in. diameter test series will be completed using a single 24 in. scale port in the 10 in. diameter casing, and a classical configuration. This permits preliminary code scaling while still using sub-scale hardware. These tests also will be used to acquire key and minor technologies mentioned above for a classical hybrid.

The next test series involves scaling up from a 10 in. to a 24 in. motor case diameter. For the first series the 10 in. pre-injector from the previous section will be attached to the head end of a 24 in. grain. This will be the first test in which gaseous oxidizer is introduced to the main grain. These tests will provide the anchoring points to be used for gaseous injection codes. The effects of gaseous injection on key technology items also will be investigated.

This testing will be followed by a 24 in. classical hybrid to provide a direct comparison between gaseous and liquid oxidizer injection and their effect on key technology issues. After completion of these tests, a full evaluation of both liquid and gaseous oxidizer injection will be conducted, and a new baseline injector will be chosen based on results of the evaluation.

The selected injection concept will be further scaled by testing it in the 24 in. motor case with a port which is geometrically similar to a single port from a multi-port 48 in. motor. Further tests to refine and scale the decided injection concept include a 48 in. multi-port motor and a single quarter scale motor port in a 48 in. case.

After successful completion of this hot fire test program the objectives for Phase II will have been attained and test firings will have been conducted up to the level for the start of Phase III. Final anchoring/validation of computer codes and analysis techniques will ensure an easy transition into the next size motor to be demonstrated in Phase III.

5.0 SCHEDULE

The Phase II schedule shown in Figure 33 shows top level tasks for the acquisition of key technologies identified in Phase I. All tasks represent the efforts of Rocketdyne which will be coordinated with General Dynamics and Thiokol Corp for joint participation in the hot fire test program mentioned above. Note that the continuous bars for the 10 in. and 24 in. motor test programs do not represent continuous testing but an overall time frame to complete those test programs. The test program outlined features a stepped format, so that lessons learned from one test series can be applied to the next. This allows for a full evaluation and utilization of technologies acquired earlier in the test program. The step size, or test motor size increments have been chosen to eliminate program risk. Using these step sizes, key technologies can be identified at a level which might be overlooked by taking a larger size step in a more aggressive program. Overall risk is reduced by resolving issues at a lower level before they become critical issues at larger levels.

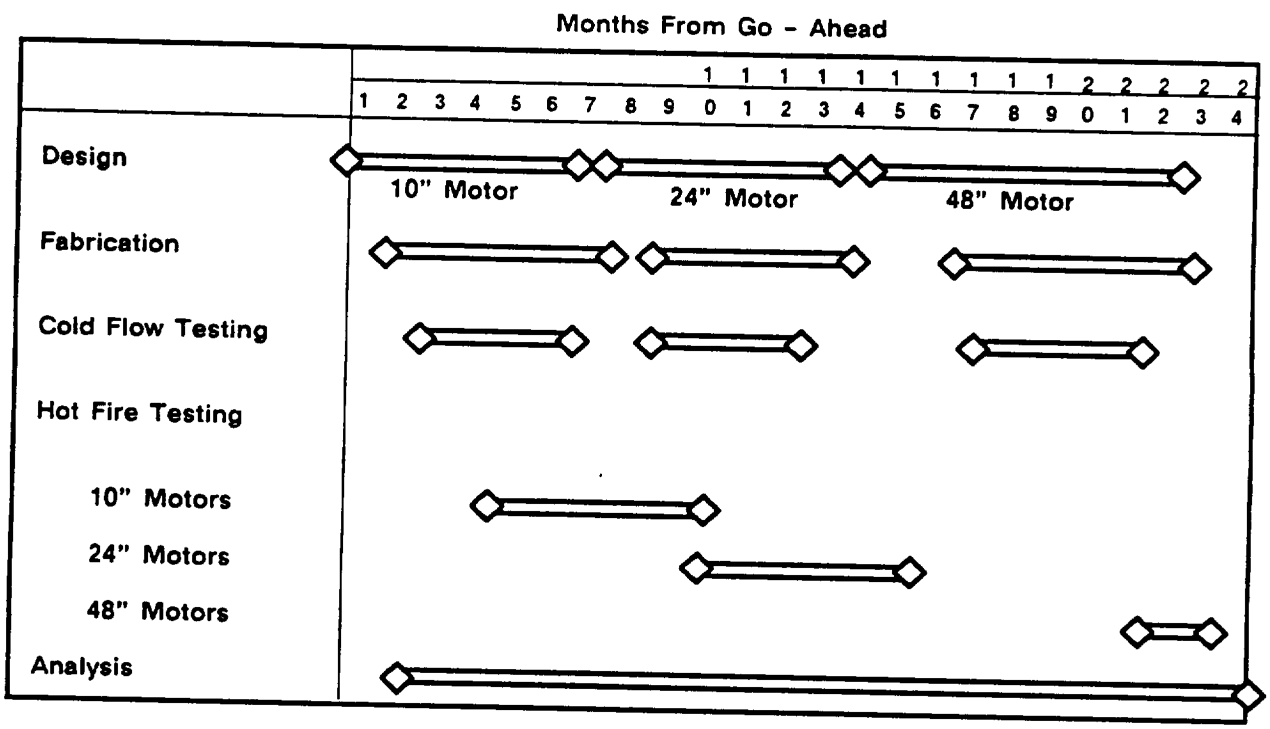

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Figure 33. Phase II Schedule

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