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SURVEY OF ADVANCED BOOSTER OPTIONS FOR POTENTIAL SHUTTLE DERATIVE VEHICLES

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Abstract

A never-ending major goal for the Space Shuttle program is to continually improve flight safety, as long as this launch system remains in operational service. One of the options to improve system safety and to enhance vehicle performance as well, that has been seriously studied over the past several decades, is to replace the existing strap-on four segment solid rocket boosters (SRB's) with more capable units. A number of booster upgrade options have been studied in some detail, ranging from five segment solids through hybrids and a wide variety of liquid strap-ons (both pressure and pump fed with various propellants); all the way to a completely reusable liquid fly back booster (complete with air breathing engines for controlled landing and return). All of these possibilities appear to offer improvements in varying degrees; and each has their strengths and weaknesses from both programmatic and technical points of view. The most beneficial booster upgrade/design, if the shuttle program were to continue long enough to justify the required investment, would be an approach that greatly increased both vehicle and crew safety. This would be accomplished by increasing the minimum range/minimum altitude envelope that would readily allow abort to orbit (ATO), possibly even to zero/zero, and possibly reduce or eliminate the Return to Launch Site (RTLS) and even the Trans Atlantic Landing (TAL) abort mode requirements.

This paper will briefly survey and discuss all of the various booster upgrade options studied previously, and compare their relative attributes. The survey will explicitly discuss, in summary comparative form, options that include: five segment solids; several hybrid possibilities; pressure and/or pump-fed liquids using either LO_2/kerosene, H_2O/kerosene and LO_2/J_2, any of which could be either fully expendable, partly or fully reusable; and finally a fully reusable liquid fly back booster system, with a number of propellant and propulsion system options. Performance and configuration comparison illustrations and tables will be included to provide a comprehensive survey for the paper.

INTRODUCTION

During the long successful flight history of the National Space Transportation or Space Shuttle program, a number of studies have been conducted to look at improving both the safety and performance of this dual function, human and cargo transporting space launch system. One element that offers a high potential for major performance and safety gains is in the area of the strap on boosters. During the 1980's and 90's a number of advanced, improved booster designs were studied as candidate concepts. These concepts, as summarized in Figure 1, include:

- Hybrid strap-on boosters.
- Alternate light weight solid rocket motor cases such as filament wound composites.
- Advanced Solid Rocket Motor
- Increased impulse for ATO by adding a fifth segment to the RSRM
- Convert solid strap-ons to higher performance liquid strap-ons, either recoverable or expendable including:
  - Pump fed liquids
  - Pressure fed liquids
  - Trade-offs between expendable liquid versus recoverable liquid boosters
  - Various propellant combinations, e.g.: LO_2/RP-1, LO_2/H_2 or H_2O_2/Kerosene
- Fully recoverable liquid flyback booster leading to a fully reusable two stage to orbit (TSTO, evolved shuttle).

Since these studies were completed in the mid 1990's, several new approaches were defined by NASA for a more modern replacement for a fully reusable launch vehicle. Recently, the whole plan for a shuttle replacement reusable launch vehicle has been subsumed by a NASA new initiative now known as the NASA Integrated Space Transportation Plan (ISTP). This plan is organized into a series of phases or generations of next step launch systems, each with their own well defined goals and objectives. The first phase is to begin with a next generation series of (or generation two, with space shuttle as it exists today being the first generation system) systems engineering and architectural studies, supported by a carefully selected set of technology development and demonstration tasks that will enable the next generation reusable vehicle that will ultimately replace the existing space shuttle that is a partially reusable launch system as it exists and operates today.

Evolving the shuttle transportation system into a more advanced, reliable, higher performance, safer, and lower cost RLV still exists as one of the possible architectural options. The criteria and physical constraints for evolving shuttle into a next generation space launch system are summarized in Figure 2.

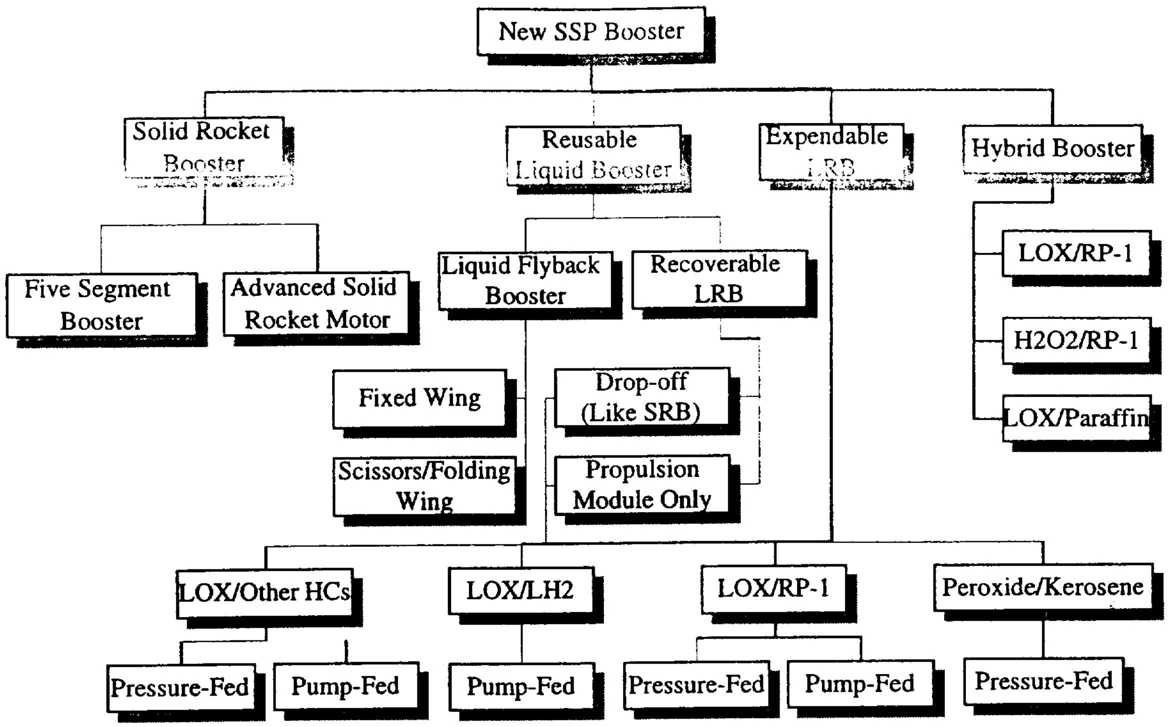


Figure 1 – Alternate Booster Options for Shuttle

BENEFITS OF ADVANCED BOOSTERS

As mentioned in the introduction, one major benefit for pursuing a new advanced booster would be to significantly improve the safety of the current Space Shuttle. This has not been the only objective considered in past studies or programs. Other objectives included reduced operations cost and increased performance. Through each of these studies the needs and benefits from a new booster have been evolving. All studies have had the objective to improve safety but the metric for measuring improvement has changed with each look at the Shuttle system.

The Advanced Solid Rocket Motor (ASRM) was initiated shortly after the Challenger accident as a major improvement in solid booster reliability and safety. The Reusable Solid Rocket Motor (RSRM) was initially intended to be an interim solution to get the Shuttle back flying. However, the RSRM program made more significant gains in safety than expected and negated the ultimate need for the ASRM and the program was cancelled.

In the late 80's a study was done to look at whether a new liquid booster could add additional safety features to the Shuttle. Among the perceived benefits would be engine out and enhanced abort options if the booster developed a problem. The current system cannot terminate thrust of the boosters if a problem is detected. This forces the Orbiter to remain attached to the stack until the booster has completed its scheduled burn. A liquid booster could theoretically terminate thrust and allow the Orbiter to separate from the stack and execute additional abort options. Also a liquid booster may be able to provide engine out capability thus adding redundancy to the booster system. A clear answer to these benefits has not been developed to date because a one to one comparison of the reliability and safety of the various booster candidates under the same requirements has never been performed.

A hybrid booster appears to have the potential of providing some of the benefits of both a solid and a liquid booster system. A hybrid has the ability to terminate thrust like a liquid system but in principle has a better packaging density, like a solid booster. Preliminary cost estimates also give a significant advantage over both a solid and an expendable liquid. However, many uncertainties remain with the technology that is required to enable a large scale hybrid booster.

The evolution of the safety requirements for a new booster have gone from just simple improvement in element reliability to a more systems approach to enhancements such as elimination of high risk abort modes, elimination of Space Shuttle Main Engine (SSME) throttle requirements during max Q or reduction of SSME power requirements through out the mission. Figure 3 shows the typical Shuttle abort modes and the windows that apply to each. The current modes are Return to Launch Site (RTLS), Transatlantic Abort (TAL), and Abort to Orbit (ATO). The preferred and safest abort is the ATO. Figure 3 also shows how adding additional performance to various booster options can eliminate the first two, and highest risk, modes and enable ATO capability off the pad without sacrificing current payload capability for any potential missions.

There are several trades that need to be completed to determine how best to achieve ATO capability. One option to achieve ATO and not make the boosters too large is to allow trajectory shaping once an abort is declared. For example, on a Space Station mission this would mean changing the trajectory to an easterly direction and benefiting from a lower inclination orbit. This would not work however for a low inclination orbit. The Shuttle today has a payload capacity to Station of 36,200 pounds. This is equivalent to approximately 45,000 in a due east trajectory. To maintain the ATO option, the Shuttle payload capability due east would be limited to 36,200 pounds. If this performance loss is not acceptable, then the program has the option of making the boosters bigger or to accept a limited improvement in abort windows for a due east mission with a heavy payload.

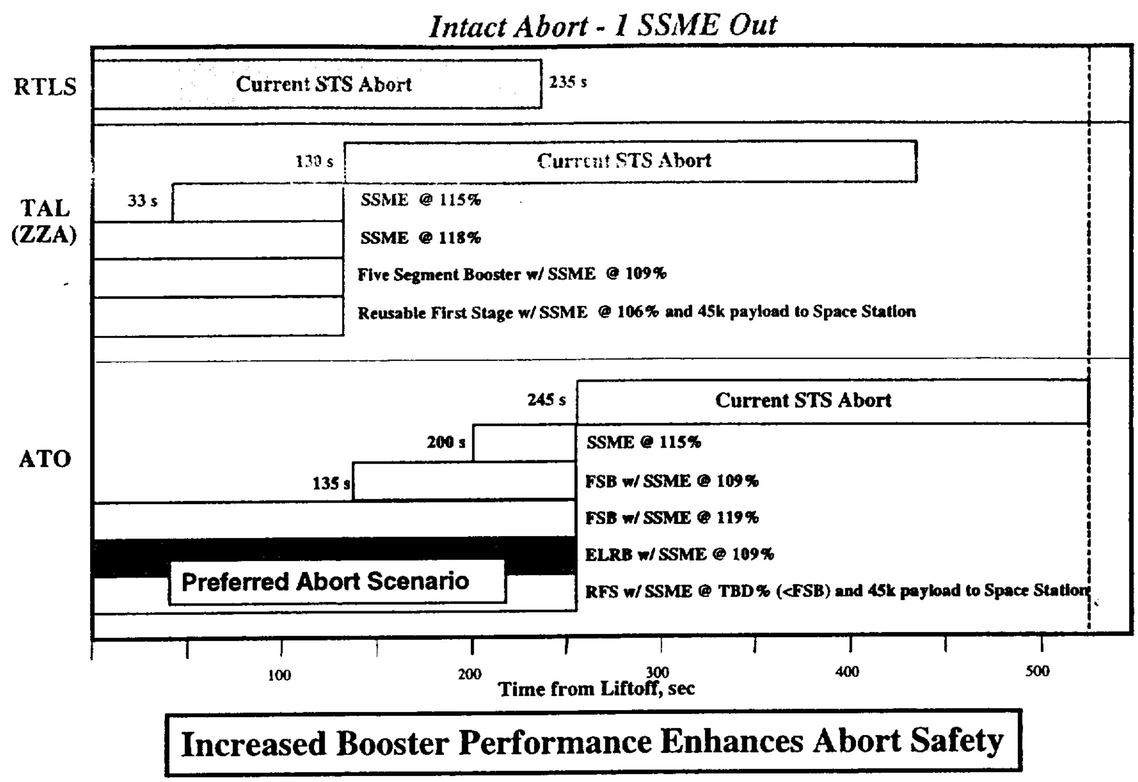


Figure 3 – Space Shuttle Abort Scenarios

Another system level objective that has been considered is the improvement in related systems reliability by the additional performance that a new booster could add. The SSME thrust level could be reduced, increasing its effective reliability by increasing the margin between operation point and design capability. Another trade that could be considered is to trade SSME nozzle area ratio, and thus Isp performance, for booster performance. The benefit to the SSME would be a lighter weight engine and increased options for designing a replacement nozzle for the current engine.

CRITERIA, CONSTRAINTS, AND ASSUMPTIONS FOR DEFINING ADVANCED BOOSTER CONCEPTS

As a part of the various studies looking at replacing the Shuttle boosters over the past 20 years, impacts to the current flight system and supporting infrastructure have been thoroughly examined. The resulting constraints for a new booster are well anchored and are listed below. The physical constraints are defined in Figure 2.

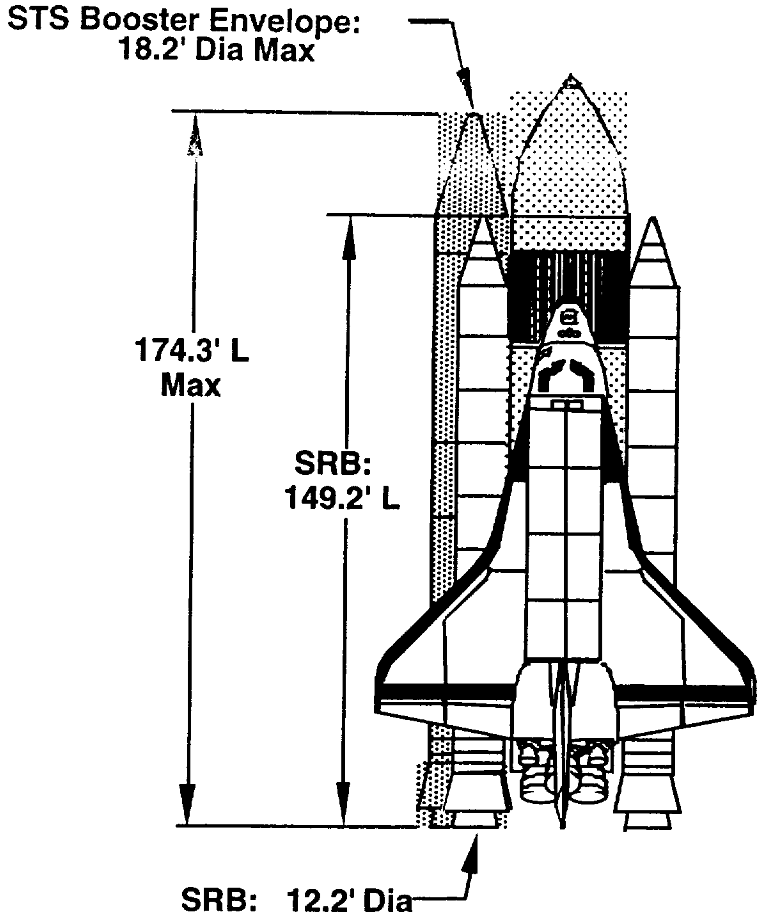


Figure 2 – STS Booster Envelope constraints

These physical constraints were established to meet the following list of ground rules:

- Cannot violate current Orbiter wing loading during ascent.
- Booster length ~170' to avoid interference with ET GOX vent arm
- Must affect a smooth transition from current ISRB to new booster.

Additionally, it is strongly desirable that any new booster must have minimal impacts to other Shuttle elements such as the External Tank and facilities such as the Mobile Launch Platform. Though few in number, these constraints make designing an alternate booster that works within the current Space Shuttle system very difficult.

To establish the limits that meet the first ground rule, extensive wind tunnel testing was performed to determine Orbiter Wing loading sensitivities to the various booster physical parameters. The results indicated that a 15' diameter smooth booster is aerodynamically the same as current 12.2' diameter ISRB and that an approximately 18' diameter smooth booster keeps orbiter wing loading within current design limits. The booster length limit is a soft constraint at present because it is a minor cost impact to the program to move the External Tank GOX vent arm. However, since total program cost is critical, it is important to try early on to keep cost impacts at a minimum.

One of the most difficult problems is in affecting a smooth transition from the current ISRB to any new booster. The current Space Shuttle manifest calls for an average of 7 flights per year using four orbiters. The introduction of the new booster must not impact this schedule in any way. On the surface this may not seem like a major constraint at this low flight rate. But the low flight rate is partly driven by the complexity in processing and preparing the system for the next launch.

Because of these constraints, the criteria that would be used to select between the many potential concepts that meet these constraints is complicated. Table 1 lists several potential criteria that could be used in the selection process. The difficulty is in obtaining consistent data for each of the concepts that can be used to compare them realistically and fairly.

Size		
• Length, ft		
• Diameter, ft		
• Dry Weight per booster, lbs		
Propellants		
Number of Engines per Booster		
Performance		
• Payload capability to ISS, lbs (no margin)		
• Performance margin for abort enhancement		
• Payload capability due east, lbs w/ ATO abort		
Safety		
• Booster Ascent Catastrophic failure probability		
• On pad Hold down checkout & Abort Capability		
• Engine Failure Abort Options	Booster	SSME
	0	1
	0	2
	0	3
	1	0
	1	1
	1	2
	1	3
	2	0
	2	1
	2	2
	2	3
• T+30 sec Booster Shutdown and Separation Capability		
• Operations Safety / Handling Issues		
Vehicle Stack Impacts		
• Envelope		
• Loads		
Facility Impacts		
• MLP		
• VAB		
• Pad		
Acquisition Cost		
• DDT&E ($B) Including Vehicle & Facility Integration		
- Commercial Synergism		
• Operations/ flt ($M)		
• Production / booster ($M)		
Technology Readiness Level		
Cost to TRL 6 ($M)		
Time to TRL 6		

BRIEF DESCRIPTION AND STATUS OF EACH OF THE LEADING REPLACEMENT BOOSTER CANDIDATES

The Advanced Concepts Department of the Space Transportation Directorate at the Marshall Space Flight Center recently performed a top level, sizing trade study for a new Shuttle booster to replace the existing RSRBs. The purpose of the trade study was to determine the performance and sizing attributes of a wide array of new booster candidates. Various propellant combinations and rocket engine systems were included in the trade study to capture a broad spectrum of potential booster candidates.

The booster option trade tree is shown in Figure 4. This shows that options were selected that included solid, liquid, and hybrid propellant systems. Within the liquid booster category, options studied included pump fed and pressure fed propulsion systems, along with cryogenic, hydrocarbon, and storable propellant combinations.

Booster and Engine Options for Trade Study

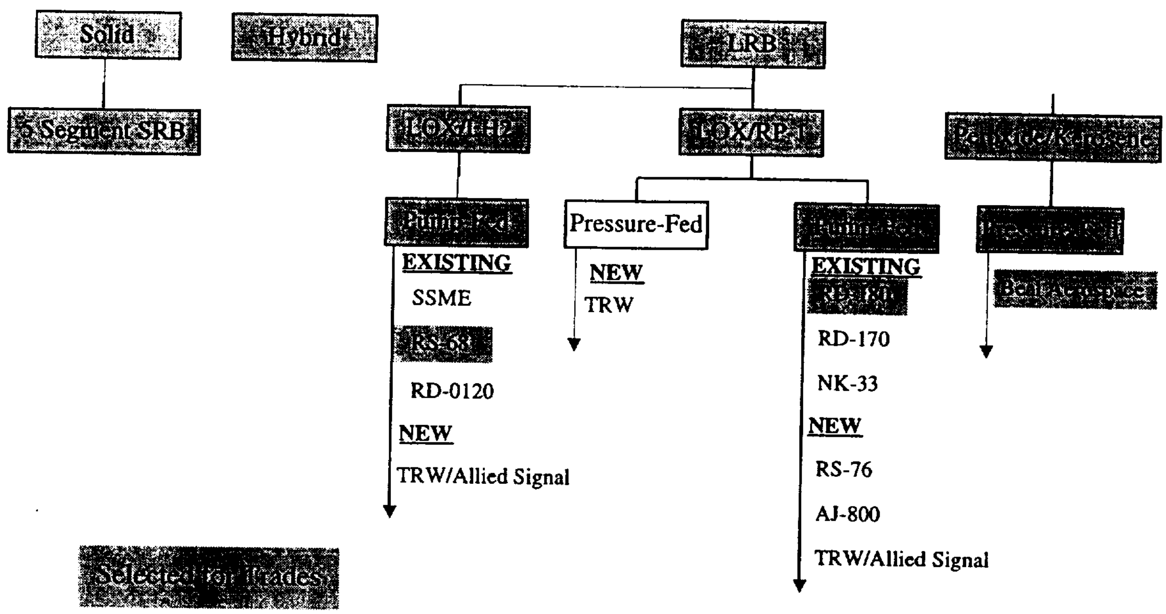


Figure 4 – Booster Options Sized for ATO

The ground rules and assumptions for the new booster trade study are shown below. The most driving of these was the top level mission safety requirement from JSC that sized the boosters to provide Abort-to-Orbit (ATO) capability for the Shuttle when it lost one SSME at liftoff. One booster engine out was also accounted for in all LRB options. The ATO orbit was set at 100 nmi circular to provide multiple sites and opportunities for landing. All booster options were sized for the nominal payload capability to the International Space Station (ISS).

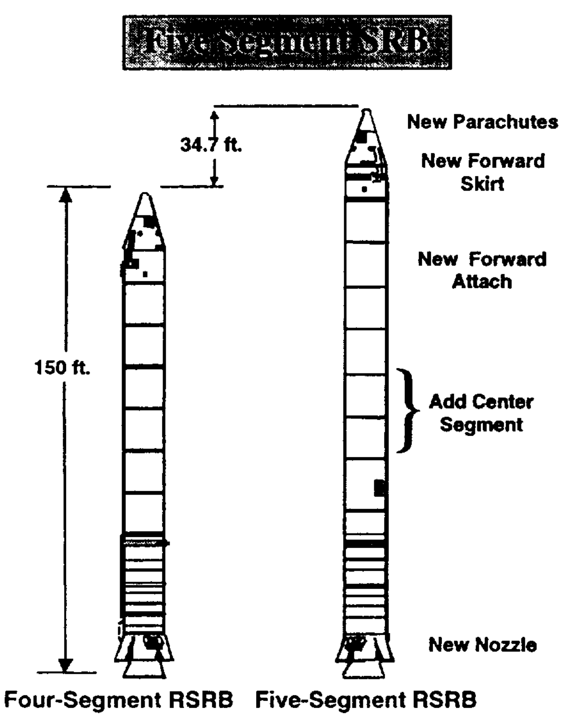
GROUND RULES AND ASSUMPTIONS

- Boosters Sized to Meet Top Level Mission Safety Requirement from JSC
  - Abort to Orbit (ATO) Capability to Eliminate RTLS and TAL for One SSME out at Liftoff (Desired Safety Improvement for Shuttle Upgrades/Evolution)
    - -- ATO Destination is 100 nmi circ @ 28.5°
- Nominal STS Mission Sized for Full Payload Capability to ISS
  - 36.2Klb Payload to 248 nmi circ @ 51.6°
- For One SSME Out (ATO), Remaining Two SSME's Operated at 109% Power Level
- Liquid Rocket Booster (LRB) and Hybrid Options are Expendable
- LRB's Sized for Booster Engine Out for Nominal Mission

• Booster Diameter Constrained to 18 ft. Diameter (Max. for Shuttle Aerodynamic Envelope)
• Composites for LRB Structures
• Weight Contingency = 20% for LRB Options

The solid option selected for the New Booster Trade Study was the 5 segment SRB. The data on this option was provided by Thiokol Propulsion. The 5 segment SRB is a modification to the existing 4 segment RSRB currently in use with the Shuttle. Modifications to the RSRB to produce the 5 segment booster include: a new, added center propellant segment; grain/inhibitor modification; reduced burn rate; new forward skirt; and a new nozzle. The total Increase in booster length for the 5 segment SRB over the RSRB is 34.7 ft. The diameter remains unchanged.

The added performance of the 5 segment SRB allows the Shuttle to achieve Abort-To-Orbit (ATO) capability within certain flight trajectory constraints in the event of losing an SSME after liftoff. These trajectory constraints include: remaining SSME's power up to 109%; a 20,000 lb LOX offload at liftoff (reduction in nominal performance); OMS engine assent assist; and an inflight RCS propellant dump of 50%. These trajectory constraints are rigorous and will affect nominal performance (with LOX offload) and inflight operations (OMS ascent assist and RCS propellant Dump), but will allow for ATO and eliminate the risky Return-To-Launch-Site (RTLS) or trans-Atlantic-Landing (TAL) abort scenarios according to Thiokol predictions.



Booster Performance

	5-Segment	4-Segment
Total Impulse (Mlbf-sec)	368.0	296.3
Max Thrust(lbf)	3,799,000	3,331,400
Average Thrust(lbf)	2,843,500	2,395,000
Average Pressure	639	625
Ispv (sec)	264.7	268.0
Burn Time (sec)	129.6	123.5
Expansion Ratio	6.55	7.72
Throat Diameter (in)	59.62	53.86
Initial Thrust/Weight	1.57	1.52

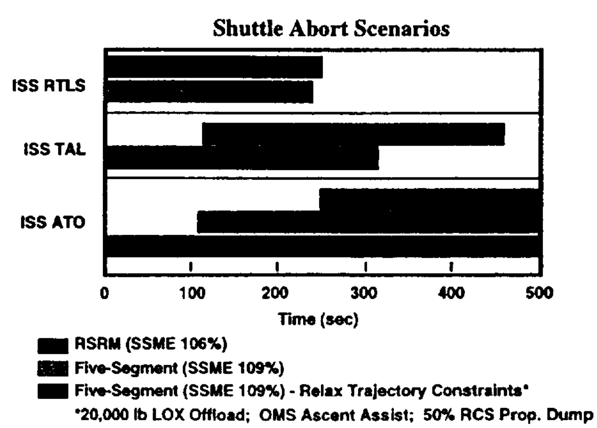


Figure 5 – Five Segment Booster

A hybrid booster was included in the New Booster Trade Study and is shown in Fig X.X.

Hybrid propulsion has traditionally been considered the combination of solid and liquid propulsion. The hybrid booster has certain advantages over solid boosters in that the propellant, even though in solid form, is inert (since it does not contain an oxidizing source) and can be handled and stored much safer than solid propellants. The hybrid booster can also be throttled by controlling the liquid oxider flow and can be shut off in an emergency situation.

The hybrid booster sized in the trade study uses HTP and LOX as the propellant combination. To provide ATO performance, the booster is 16.2 ft. in diameter and 155 ft. long containing 1.47 Mlb of propellant in each of the 2 boosters.

Even though there is safety advantages projected for hybrid boosters over the segmented solid RSRB currently in use with the Shuttle, hybrid rocket technology is still in its early stages and will require much more development and associated costs before it is to be considered a viable alternative.

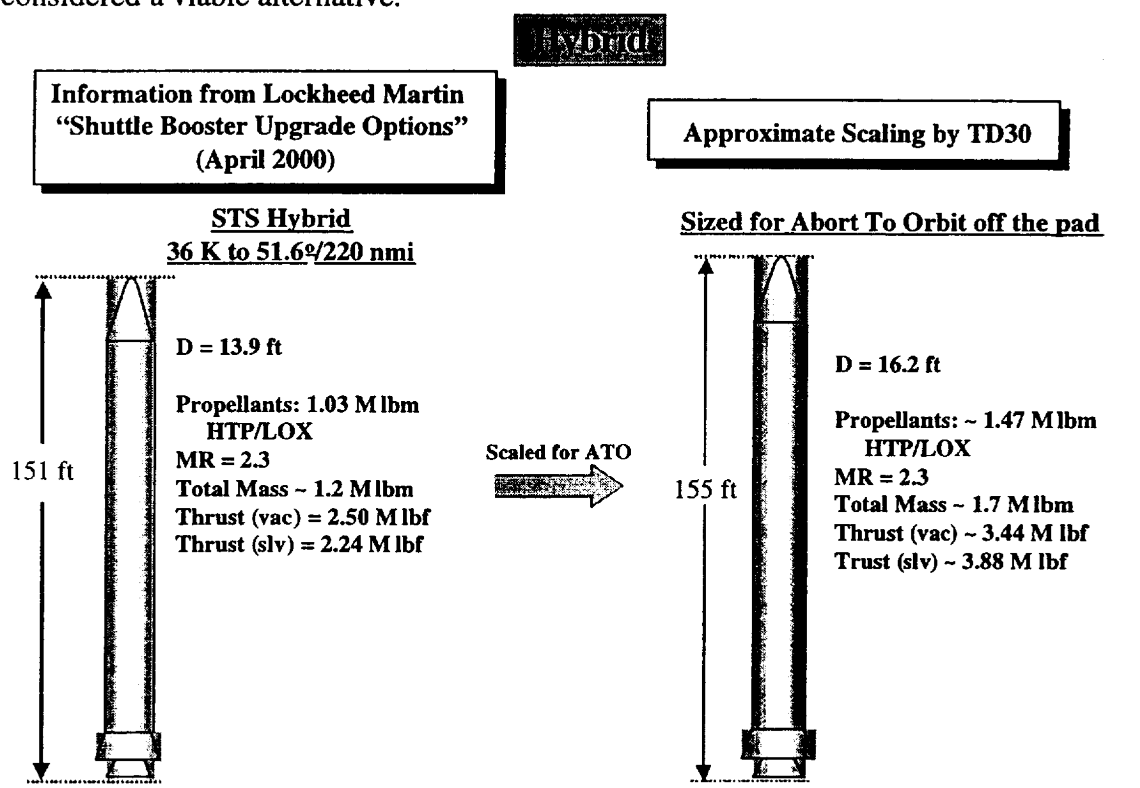


Figure 6 – Hybrid Booster

The hydrocarbon, pump fed booster that was sized for the New Booster Study is shown in Fig. X.X. A high performance staged combustion cycle engine such as the RD-180 was selected for this application for its availability to reduce development costs and performance. The booster is 151.2 ft. in height with a diameter of 14.4 ft. Each of the two RP-1 / LOX boosters contain a little more than 1.0 Mlb of propellant producing a mass fraction of 0.872. The booster contains four engines and is designed for booster engine out.

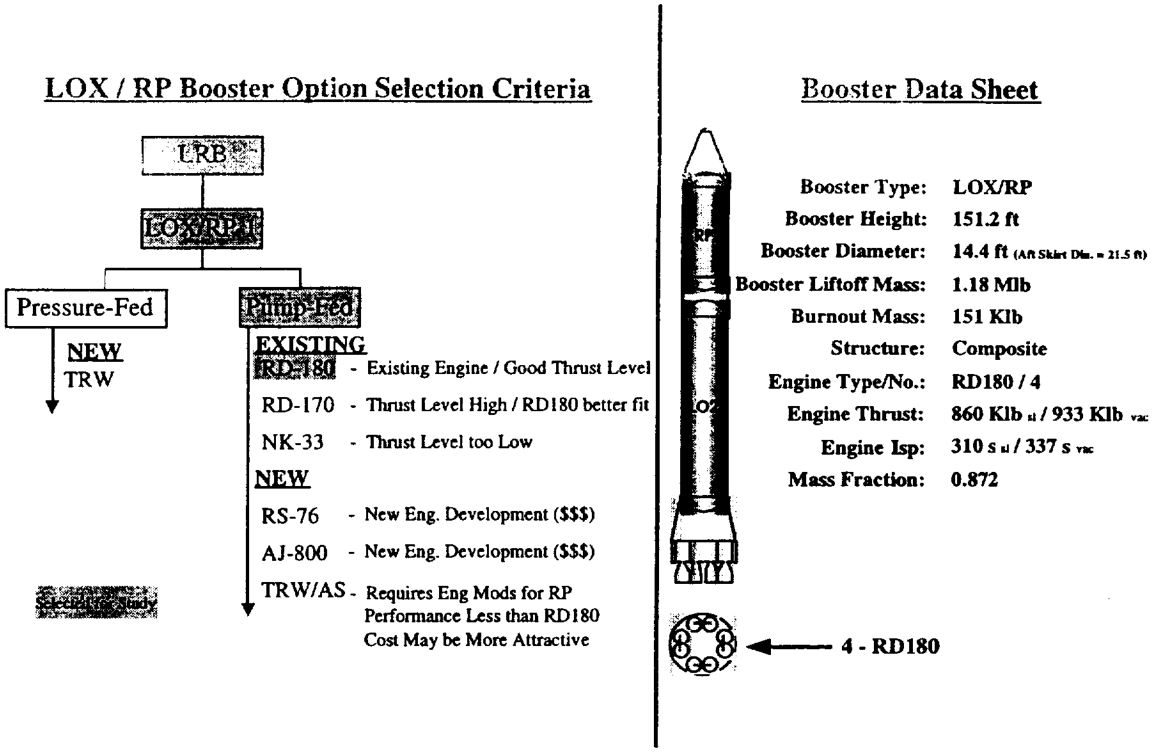


Figure 7 – Expendable Hydrocarbon Pump Fed Liquid Booster

The cryogenic pump fed booster that was sized for the New Booster Study is shown in Fig. X.X. A gas generator cycle engine such as the RS-68 was selected for this application for its availability to reduce development costs and for its higher thrust level to minimize the number of engines in each booster. Because of the low density of the LH2 fuel, the booster sized is at the maximum diameter (18.0 ft.) for the Shuttle aerodynamic envelope and its height of 209.5 ft. exceeds existing Shuttle pad limitations with the External Tank GOX vent arm. The LOX / LH2 boosters contain about 850 klb of propellant each producing a mass fraction of 0.820. The booster contains five engines and is designed for booster engine out.

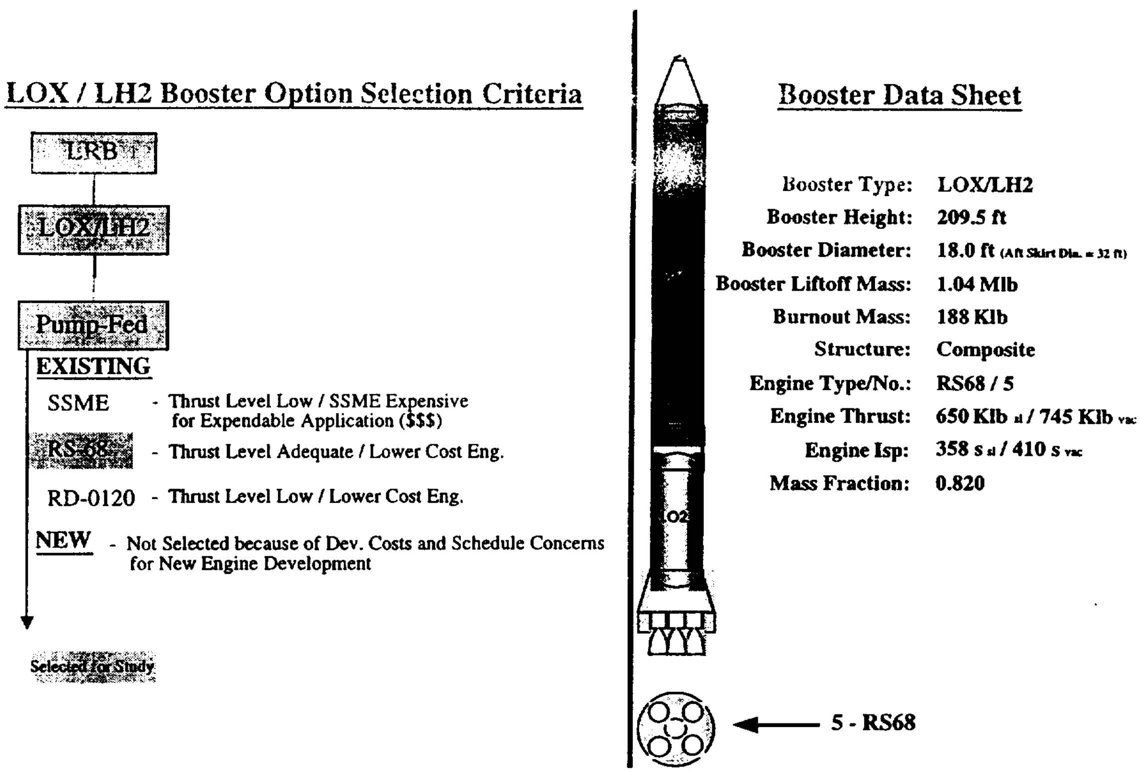


Figure 8 – Expendable Hydrogen Pump Fed Liquid Booster

A pressure fed booster option was also sized for the New Booster Study is shown in Fig. 9. Pressure fed boosters have potential advantages over pump fed boosters in the area of safety and reliability because of the much simpler propulsion / engine system design. The tradeoff for this less complex propulsion system design is lower performance and much heavier components such as tanks, pressurization systems, and higher thrust engines.

A storable propellant combination of peroxide and kerosene was chosen for the pressure fed booster to include this type of propellant in the trades and for potential operational benefits of not having to handle cryogenics. Because of the low performance of the storable, pressure fed propulsion system (Isp = 260 s vacuum) compared to the pump fed systems that were sized in the study and the high structural weights associated with the pressurization system and increased tank pressures, the mass fraction of the booster was very low (0.832).

In order to achieve the ATO capability required by the study, the pressure fed booster option had to be sized considerably larger than the other options. The booster sized is at the maximum diameter (18.0 ft.) for the Shuttle aerodynamic envelope and its height of 212.4 ft. exceeds existing Shuttle pad limitations with the External Tank GOX vent arm. The peroxide / kerosene boosters contain about 2.1 Mlb of propellant each. The booster contains four engines with each engine having a sea level thrust of 1.4 Mlb. and is designed for booster engine out.

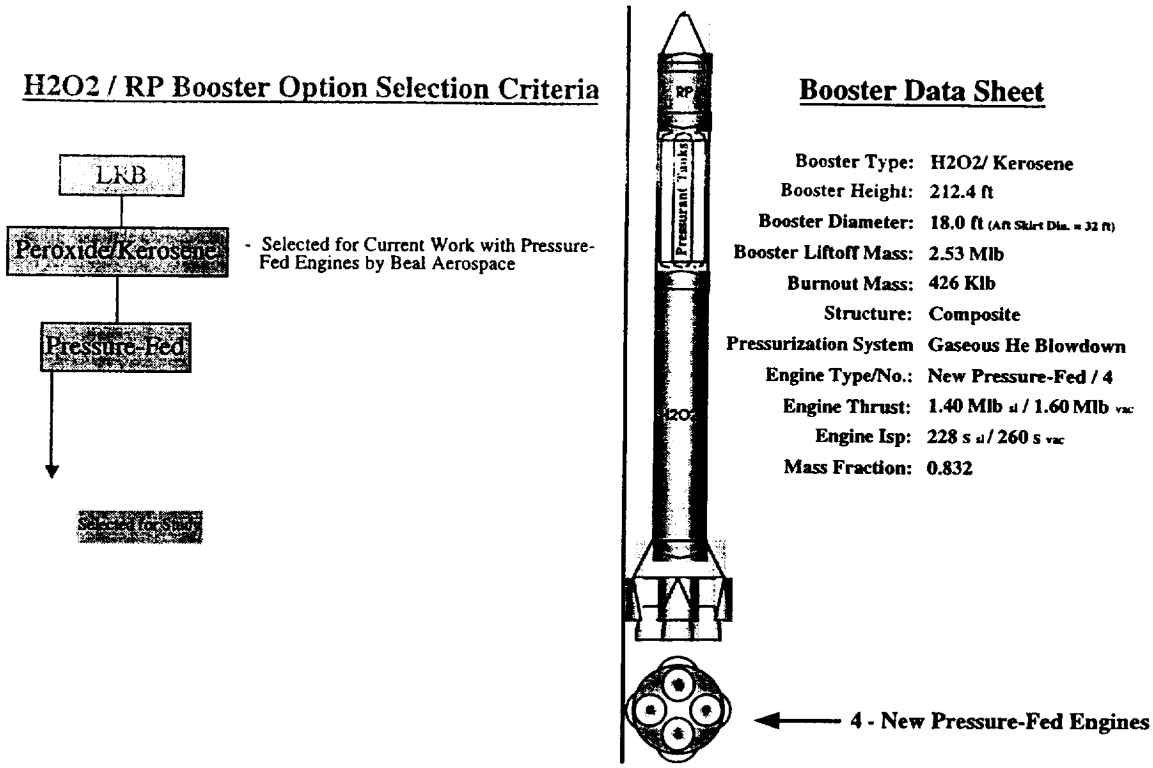
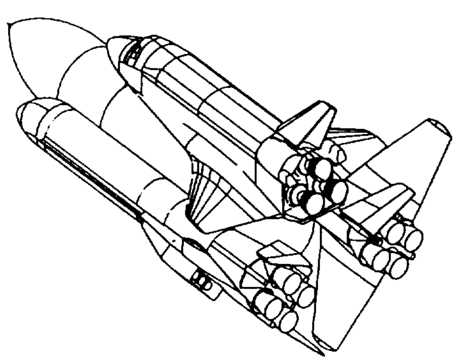
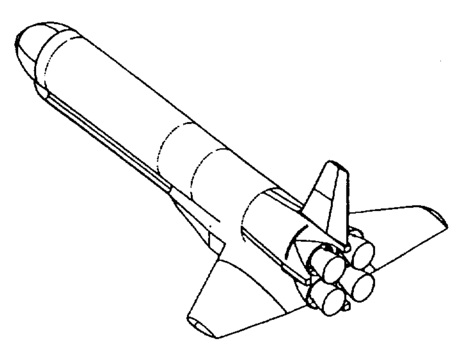


Figure 9 – Expendable Pressure Fed Peroxide Hydrocarbon Liquid Booster

In addition to these booster options studied by the Advanced Concepts Department, NASA MSFC has funded other studies that have looked at Liquid Fly Back Boosters and other types of expendable liquid boosters. Figures 10 and 11 show the LFBB concepts that were studied by Boeing and Lockheed Martin. While the specific performance requirements that were used in the studies did not include ATO as an objective, the performance assumed was equivalent to that required to achieve ATO. In other words, the added payload capability designed into the LFBBs could be traded to meet the previously discussed ATO capability without loosing current Shuttle payload capability.



LAUNCH CONFIGURATION



FLY BACK CONFIGURATION

Figure 10.Boeing LFBB - Dual Configuration

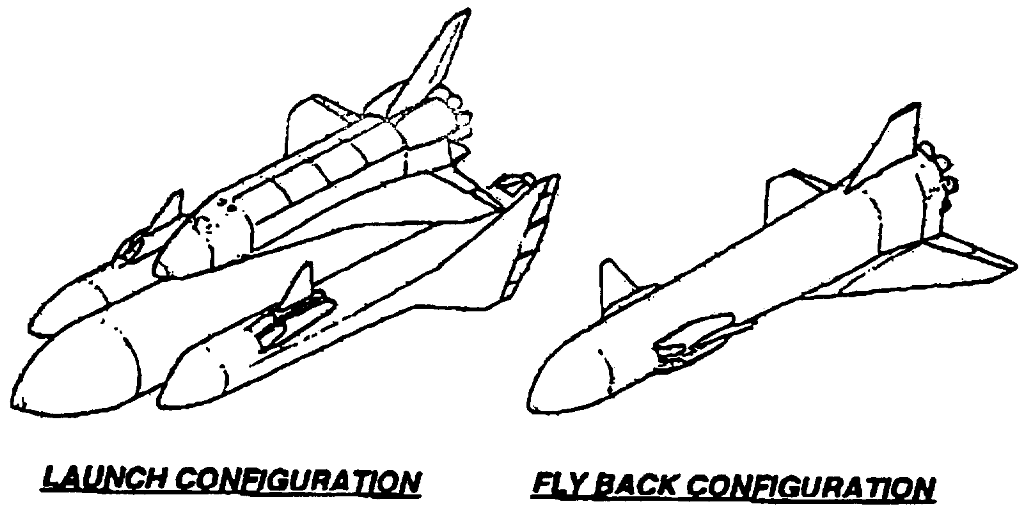


Figure 11.Lockheed-Martin LFBB - Dual Configuration

TECHNOLOGY ISSUES FOR EACH LEADING CANDIDATE

??? Getting Pretty Long. Do we need this section?

COMPARISON OF BOOSTER FEATURES, ATTRIBUTES AND LIMITATIONS

A comparison of the boosters that were sized in the New Booster Trade study is shown in Fig. 12. Also shown in this figure is the current Shuttle RSRB for a point of comparison. As can be seen from this figure, the LOX / LH2 pump fed booster and the Peroxide / Kerosene pressure fed booster are very large. The booster body diameters were constrained to 18 ft. in all cases which is the maximum to stay within Orbiter wing loading constraints. The boat tail diameters however were larger to accommodate the size and number of engines required for ATO capability and engine out. Three of the boosters; the Five Segment SRB, the LOX/LH2 pump fed, and the Peroxide / Kerosene pressure fed, exceeded the maximum envelope length to avoid nterfering with the Gox vent arm on the pad. This is not a show stopper for these options, but will require pad modifications. The hybrid booster and the LOX / RP pump fed booster are the most similar in size to the RSRB of those options selected for the trade study. A more in depth booster study should be performed to fully assess new booster options, not only from a sizing standpoint, but to also evaluate other attributes such as operations, cost, modifications to the existing Shuttle infrastructure required, and Reliability / crew safety.

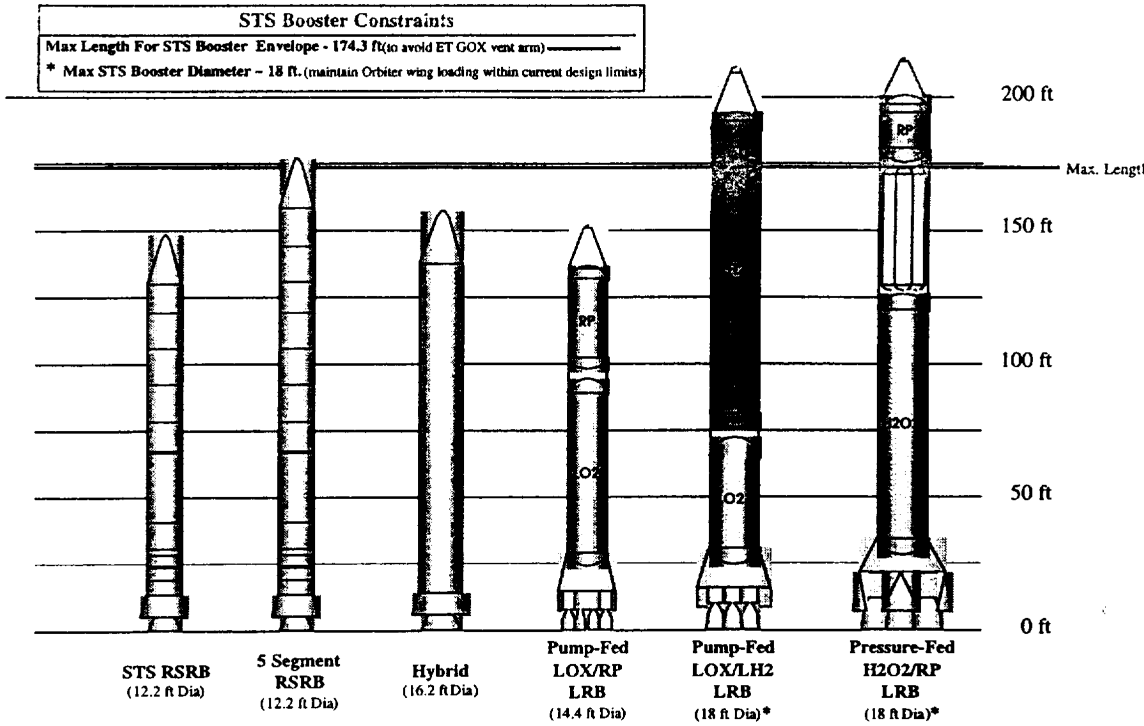


Figure 12 – Alternate Booster Size Comparison

STATUS OF BOOSTER UPGRADE ACTIVITIES

With the implementation of the approved Integrated Space Transportation Plan (ISTP), all work on any major shuttle architectural upgrades, such as the advanced booster, has been put on hold. The major effort, now underway, in the ISTP is the Space Launch Initiative (SLI) or Generation 2 (2 Gen RLV) Reusable Launch Vehicle, to ultimately supersede the shuttle as NASA's work horse RLV. A long, logical procurement process under NRA-80 has just recently been concluded and 22 new space transportation contracts have been let to various industry – government partnership teams. These contracts consist of five architectural/system engineering studies to launch vehicle prime and/or systems engineering contractors, and a series of technology development/demonstration tasks for advanced airframes, avionics, health management, upper stages, propulsion, operations methods, flight mechanics, and thermal protection systems. These studies and technology development activities will be conducted over the next 1 to 5 years in various funding cycles to see what the next RLV design can achieve. The results of many, if not most, of these 2 Gen RLV activities will likely be applicable to either a new RLV or to an advanced version of today's space shuttle.

Because of these specific focused 2 Gen RLV activities in such a wide range of technology and systems engineering areas, there are no plans at this time to conduct the detailed booster upgrade studies and trade off that would be required to make a sound technical and programmatic decision on whether to upgrade or replace the current shuttle SRBs. These studies, if they are to be continued at all, will have to wait until substantial progress and results have been generated by the SLI program. However, it is important to note that much of the SLI results could be applied to booster upgrades, if this approach was desirable.

CONCLUSIONS AND RECOMMENDATIONS

As can be seen from the above discussions, a number of potential candidates to upgrade or replace the existing shuttle RSRM booster have been identified and studied for more than a decade. Each of these booster improvement candidates offers some benefits in flight safety and vehicle performance. Each have their strengths and potential disadvantages that would have to be addressed in much more detail to select the optimum approach. If the shuttle were to remain operational for an extended period of time beyond the current planned "phase down", sometime after 2010, the continuation of these studies in more detail would be justified. However, this activity has now been overtaken by the carefully thought out and comprehensive SLI program, which will play out over the next several years. At this time then, NASA has no plans for further booster upgrade studies, until we see where the 2 Gen RLV is heading. It is quite possible that much of the previous booster advancement studies could work their way into newer advanced shuttle configurations or even a brand new two stage to orbit (TSTO) reusable vehicle design. It remains to be seen then, just how this design and new technology development process will build on or evolve from these preliminary new strap on booster design and trade studies.