AIAA 2000-5070

SHUTTLE UPGRADE USING 5-SEGMENT BOOSTER (FSB)

Donald R. Sauvageau and Hal. D. Huppi
Thiokol Propulsion
Brigham City, UT

AIAA Space 2000 Conference
September 19-21, 2000
Long Beach, California

2000-5070

SHUTTLE UPGRADE USING 5-SEGMENT BOOSTER (FSB)

Don Sauvageau
Hal Huppi
Thiokol Propulsion
Brigham City, Utah

In support of NASA's continuing effort to improve the over-all safety and reliability of the Shuttle system, a 5-segment booster (FSB) has been identified as an approach to satisfy that overall objective. To assess the feasibility of a 5-segment booster approach, NASA issued a feasibility study contract to evaluate the potential of a 5-segment booster to improve the overall capability of the Shuttle system, especially evaluating the potential to increase the system reliability and safety. In order to effectively evaluate the feasibility of the 5-segment concept, a four-member contractor team was established under the direction of NASA Marshall Space Flight Center (MSFC). MSFC provided the overall program oversight and integration as well as program contractual management. The contractor team consisted of Thiokol, Boeing North American - Huntington Beach (BNA), Lockheed Martin Mooched Space Systems (LMMSS) and United Space Alliance (USA) and their subcontractor bd Systems (Control Dynamics Division, Huntsville, AL). United Space Alliance included the former members of United Space Booster Incorporated (USBI) who managed the booster element portion of the current Shuttle solid rocket boosters. Thiokol was responsible for the overall integration and coordination of the contractor team across all of the booster elements. They were also responsible for all of the motor modification evaluations. Boeing North American (BNA) was responsible for all systems integration analyses, generation of loads and environments, and performance and abort mode capabilities. Lockheed Martin Michoud Space Systems (LMMSS) was responsible for evaluating the impacts of any changes to the booster on the external tank (ET), and evaluating any design changes on the external tank necessary to accommodate the FSB. USA, including the former USBI contingent, was responsible for evaluating any modifications to facilities at the launch site as well as any booster component design modifications.

The basic objective of the Phase A study was to determine the feasibility of a 5-segment booster design in achieving an increase to the overall Shuttle system safety and reliability. Initially in the study the primary Shuttle systems safety improvement was to eliminate the return to launch site (RLS) abort mode by achieving transatlantic (TAL) abort off the pad. A secondary objective was to increase the overall reliability of the booster itself. These objectives were to be met while minimizing impacts of the FSB design on other Shuttle elements. This included maintaining the current booster interfaces with the external tank (ET) and mobile launch platform (MLP). It was also assumed that there would be no increase in design loads and environments on the orbiter as a result of incorporating the FSB into the overall Shuttle system. The basic design constraints imposed were to minimize changes to the current Shuttle booster hardware and infrastructure and also incorporating into the FSB any of the currently planned Shuttle booster safety and reliability upgrades.

The basic 5-segment booster program objectives were achieved by adding a center segment to the current 4-segment RSRBs (see Figure 1). This resulted in a booster that was 320 inches longer than the current reusable solid rocket booster (RSRB). In order to utilize the existing case metal hardware, a new nozzle had to be included to accommodate the increased mass flow rate resulting from the added segment (see Figures 2 and 3). This new nozzle incorporates many of the features developed during the Advanced Solid Rocket Motor (ASRM) program. One of the key changes is the elimination of the flex boot from the current Shuttle nozzle as a protection for the movable bearing and incorporating a flex bearing protector (see Figure 4). This flex bearing protector is similar to the flexible bearing systems used on expendable rocket motors and will not be a reusable component in the 5-segment nozzle. The 5-segment nozzle will also eliminate one internal joint relative to the current Shuttle boosters. FSB nozzle will also integrate a pressure activated "J-seal" as an additional thermal barrier to improve overall nozzle-to-case joint reliability. There are also other design features currently being evaluated as part of the RSRM program that will be included in the 5-segment booster regardless of whether they become integrated into the current Shuttle boosters. This is allowed because of the inherent nature of designing and qualify a totally new nozzle for the 5-segment booster. As such, all of these features will make the 5-segment booster nozzle somewhat more reliable than the current Shuttle booster nozzle. These nozzle improvements more than compensate for the addition of the added field joints, thus making the FSB more reliable than the current RSRB.

In order to enhance the overall performance of the 5-segment booster, the nozzle length and exit diameter were increased consistent with what had been previously qualified under the earlier Shuttle upgrade program. In order to meet the overall Shuttle system performance constraints, the thrust profile and consequently the internal grain geometry of the 5-segment booster had to be modified. Additionally, the burn rate of the propellant was reduced from 0.368 inch per second to 0.343 inch per second thus maintaining the formulation and flight proven performance heritage. The main grain design feature change was increasing the number of fins in the forward segment geometry from 11 to 13 (see Figure 3).

In order to maintain the same attach interface with the external tank, the booster will now be attached to the external tank with an attach feature on the external surface of the forward segment, in lieu of the forward skirt as is with the current RSRB. The attach feature is mounted on the external surface of the forward segment with integral hooks and a thrust block that holds the thrust attach bolt for integrating with the external tank (see Figure 5). In order to distribute the attach loads between the external tank and the booster, additional stiffeners are machined into the surface of the forward segment.

Since the interface between the external tank and the booster is now accommodated with the forward attach segment, there is no need for the thrust structure currently integrated as part of the forward skirt. Therefore, with the FSB a new simplified light-weight forward skirt will be utilized.

With the addition of a fifth segment to the booster, the overall inert weight of the booster increases by approximately 25 percent. To maintain the same impact velocity for the boosters, when they are recovered in the ocean, larger parachutes are needed to accommodate the higher inert weight. The parachute diameter had to be increased from 136 ft to 140 ft. The basic parachute design and materials were also changed to reflect those developed as part of the earlier Shuttle upgrade program. The new parachute materials also allowed the larger diameter parachute to be packaged in the same volume as the current Shuttle booster parachutes.

Basic comparison of the performance characteristics of the current 4-segment Shuttle boosters and the proposed FSB is shown in Figure 6. Note that both systems maintain the same maximum expected operating pressure (MEOP) to ensure utilization of existing metal hardware. As previously mentioned the nozzle throat diameter had to be increased to maintain that pressure with the increased mass flow rate associated with the additional segment. This increase in throat diameter resulted in a decreased expansion ratio from 7.72 to 6.55, even with the increased nozzle exit diameter for the FSB. This reduced expansion ratio resulted in a decrease in ISP of 3.3 seconds, however the increased propellant from the added segment had a substantial increase in the system total impulse and maximum thrust. One of the key performance features is the maintenance of the initial thrust to weight with the FSB. This is critical in ensuring a proper clearance of the booster as it lifts off from the MLP. The shaded area between the two-thrust time profiles in Figure 6 gives a visual indication of the increase in capability provided by the 5-segment boosters.

To enhance the overall Shuttle system safety and reliability this increase in capability was primarily allocated to an improvement in the abort mode availability for the Shuttle system, which is depicted in Figure 7. This Figure shows which abort modes options are available at given times when a Space Shuttle Main Engine (SSME) fails during ascent. For example, with the current Shuttle boosters, a return to launch site abort (RTLS) can be achieved with an SSME failing any time between lift off and 230 seconds. Similarly, transatlantic (TAL) abort can be be initiated in approximately 120 seconds after liftoff and can be accomplished all the way to approximately 450 seconds after liftoff. This means with the current system the only abort mode option for the first 120 seconds is RTLS. The first available time to achieve abort to orbit (ATO) is approximately 250 seconds after liftoff. With the additional capability provided by FSB, a TAL abort mode can be initiated off the pad with an SSME throttle setting of 109 percent. This means that with the FSB either RTLS or TAL is available to the Shuttle crew as abort mode options, which provides a significant enhancement in overall safety and intact abort capability for the system and crew.

As part of the FSB abort mode evaluation it was determined that abort to orbit (ATO) could be achieved using the current 5-segment booster configuration with a SSME throttle setting of 114 percent. This assumes that the 114 percent would be an available option for the SSME. This may be questionable considering the current block II SSMEs have only been tested at 111 percent throttle setting. In order to achieve 114 percent throttle setting, the nominal International Space Station (ISS) trajectory parameters were relaxed. Those that were modified included assuming that the trajectory would be modified to fly due east immediately when the abort was initiated. Secondly, the booster apogee constraint, which is imposed to maximize recovery success of the boosters was relaxed. This would not necessarily be a concern in an abort mode scenario. Lastly, the angle of attack constraints during ascent were relaxed when the abort mode was initiated. All of these constraint relaxations were felt to be well within the capability of the Shuttle system with only minor modifications to current operating scenarios. As part of this ATO evaluation it was also determined that the SSME throttle setting could be reduced even more by additional modifications to flight parameters, but were not quantified as part of this study. The additional parameters that could be relaxed include: using the orbital maneuvering system (OMS) for thrusting during ascent (at the earliest point possible in the atmosphere where over-expansion in the OMS engines would not be a concern), secondly start dumping the reaction control system (RCS) fuel as soon as the abort mode is initiated, and thirdly optimize the FSB thrust profile to maximize the abort mode potential. Currently the FSB thrust profile was configured to maximize payload potential while satisfying all of the current Shuttle system ascent constraints. Relaxing these additional constraints would result in a probable SSME throttle setting reduction somewhere between 2 and 4 percent.

Even though enhancing the abort modes is the primary approach evaluated as part of this Phase A study in enhancing the overall safety and reliability of the Shuttle system, the additional capability provided by the 5-segment enables a number of different options for using the enhanced capability. If the additional capability of the FSB were used entirely for payload capability improvement, the overall payload to ISS could be increased by approximately 20,000 lbs. This, however, exceeds the down-weight capability of the orbiter and, as such, the majority of that equivalent payload would have to be used for abort mode enhancement or other options. An additional option would be to use the extra capability for enabling other Shuttle system upgrades such as crew escape where these additional upgrades detract from the overall payload capability of the Shuttle because they increase the inert weight of the orbiter. Therefore, the FSB enables other upgrades to be incorporated with no overall degradation to the orbital payload capability of the Shuttle system. The additional capability could also be used to reduce SSME throttle settings, thus enhancing the overall reliability of the SSMEs. The additional capability could also be used to enable off-nominal flight conditions, such as Chandra mission. The overall capability improvement offers mission planners for the Shuttle system significant increase in flexibility and options available, which is especially important when considering the utilization of the Shuttle for an extended period into this Century.

In order to effectively address the technical feasibility of the FSB approach, a number of technical issues were addressed during the Phase A Study effort. Table 1 highlights some of the major issues that were evaluated, with associated technical impacts and proposed resolutions incorporated as part of Phase A design or to be addressed during full scale engineering development.

Table 1
FSB Technical Issues

Technical Issue	Impact	Resolution
Propellant Erosive Burning	Potential for propellant burn rate enhancement during first 1-2 seconds of burn time, resulting in increased pressure	Analysis shows that pressure increase is on the order of 30 psi. Subscale testing being conducted to validate analysis
Nozzle Torque	Increased flex bearing stiffness due to new bozzle aggravates SRB TVC capability	Evaluation conducted and no TVC redesign anticipated for nominal TVC Operation
Booster Reentry Environments	Increased vibroacoustic and aeroheating environments aggravates current SRB component and TPS capability	Analysis indicates no major redesign anticipated – will require requalification of some electronic components and increased TPS thickness
Aerodynamic Heating Environments	Increased Aero & shifted shock heating aggravates current TPS capability	Analysis indicates no major redesign anticipated – will require localized TPS thickness increases on forward SRB and ET components
Plume Induced Heating Environments	Increased radiation and recirculation heating aggravates current TPS capability	Analysis indicates no major redesign anticipated - will require localized TPS thickness increases on aft SRB and ET components
Prelaunch Loads	Increased weight & length enhances overturning moment which aggravates current SRB Aft skirt & case capability	Analysis indicates that case and skirt are adequate. Will require aft skirt structural testing to validate analysis and use of standard weight case stiffener cylinders
Ignition Over Pressure & MLP Plume Impingement Environment	Increased environment aggravates liftoff loads and SRB thermal curtain & MLP capability	No feasibility issues but may require some redesign during development program
Liftoff Loads	Larger exit cone	TBD
Liftoff Clearance with MLP	Increased FSB weight and nozzle length required higher thrust to weight to clear MLP hold down parts	Will require system control biasing and modifications to GN2 purge line only
FCS Liftoff & Flight Stability	Changes in stability aggravates acceptable flex criteria	No major redesign anticipated – will require returned bending filters & software architecture
1st Stage Ascent Loads	Increased high q and max g loads aggravates current et component structure capability	Analysis shows localized structure thickness increases required in intertank region
Pre-separation Loads	Increased load aggravates current SRB fwd separation bolt capability	Redesign of separation bolt will be needed during development
Booster Separation Clearance	Changes in booster length, mass oroperties and thrust tailoff changes clearance characteristics	Analysis shows that FSB meets 3σ clearance requirements

Based upon the structural and thermal interface loads provided by BNA, LMSS evaluated the impact of those load changes on the external tank. The increased structural loads resulted in higher loading of the intertank region, which can easily be accommodated by localized increases by thickness in the intertank structure. This means that less material will need to be removed during the fabrication/ machining of the intertank. With the increased length of the booster, the aerodynamic and aerothermal loads on the external tank changed somewhat where the maximum aerothermal loads are now on the ogive of the ET, as opposed to in the vicinity of the booster attach for the current boosters. This results in a shifting of thermal protection material into the ogive region of the external tank. With the added segment, the mass flow rate and burn time increase the heat flux load on the aft dome of the external tank, as such additional thermal protection material needs to be added in this region. The total impact of increasing the intertank thickness to accommodate the extra structural loading as well as the modification to the thermal protection material on the external tank resulted in a total tank weight increase of less than 500 lbs. Upon evaluating the impact of changes in loads and environments on the orbiter, there were no increases in aerostructural or aerothermal loading that were greater than the current design conditions for the orbiter.

An initial evaluation of the implications to the facilities at the launch site has also been completed. As a result of this evaluation a few facility modifications and process modifications have been identified that will need to be incorporated to accommodate processing of the 5-segment at the KSC launch site. Those include adding work platforms in the Vehicle Assembly Building (VAB) for the added segment. With the increased length of the booster due to the added segment, the access to the forward skirt on the pad will require an extension to the current access platforms. Also with the increased length of the boosters, the GOX vent arm will have to be modified to clear the tip of the booster. The added segment will also necessitate an additional joint heater on the boosters and as such the T_0 umbilical will need to have an additional circuit added. With the change to the liftoff characteristics of the booster, there is an interference with the gaseous nitrogen (GN_2) purge line on the MLP, which will have to be modified. With the addition of the segment for each booster the storage facilities at the rotation process surge facility (RPSF) will have to be increased. There will also need to be additional ground support equipment (GSE) added in hanger AF to handle and process the expended boosters after they are recovered and readied to transport back to the production facility at Thiokol. The longer 5-segment booster will also necessitate a change to the retrieval operations. In the current 4-segment boosters, the nozzle plug is installed by divers at about 80 feet under water. But with the additional segment that has now increased to 100 feet under water which changes the diving procedures. Therefore, the current mini-sub that is being qualified, will be required for the 5-segment booster retrieval operations. None of the changes to the orbiter external tank or launch facilities will result in a change to the reliability or systems safety of the overall Shuttle system.

To date the Phase A study has demonstrated that the 5-segment booster design is a feasible concept with only minor implications to the other elements of the Shuttle system. These implications identified as part of the Phase A study can be reasonably accommodated through development program activities. However, it has been noted that during the Phase A study a number of the loads and environments imposed by the FSB are more severe than the current RSRB and as such upgrades currently being considered for the 4-segment Shuttle boosters should incorporate the more severe FSB loads and environments. This will more easily accommodate incorporation of the 5-segment booster into the Shuttle system in the future and eliminating the need for requalification if the current upgrades to the booster are incorporated.

The remaining three months of the Phase A study will concentrate on quantifying the reliability improvements for the FSB as well as defining the scope, schedule, and cost associated with developing and implementing a 5-segment booster.

Figure 1 Four-Segment Versus Five-Segment Booster

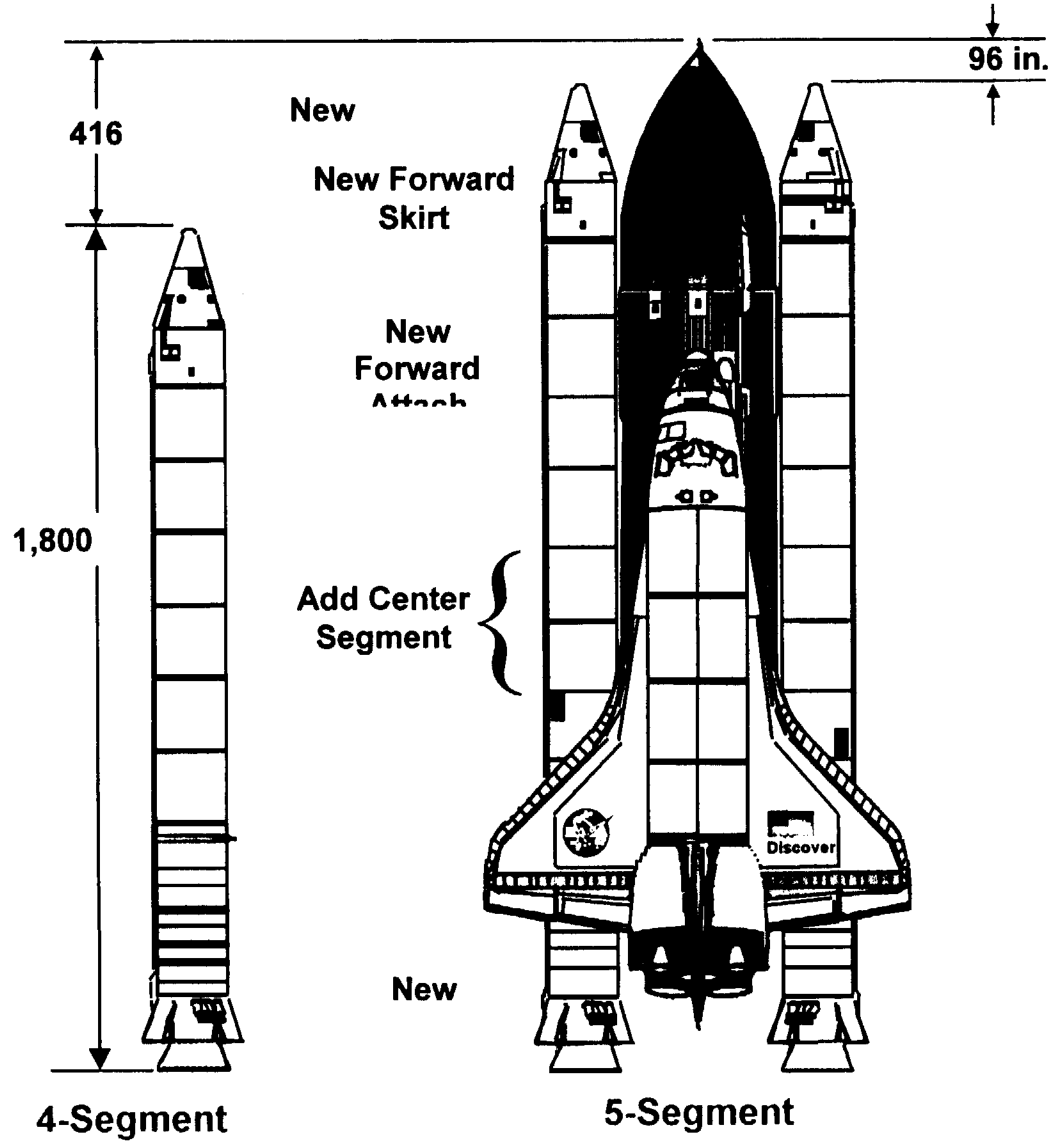
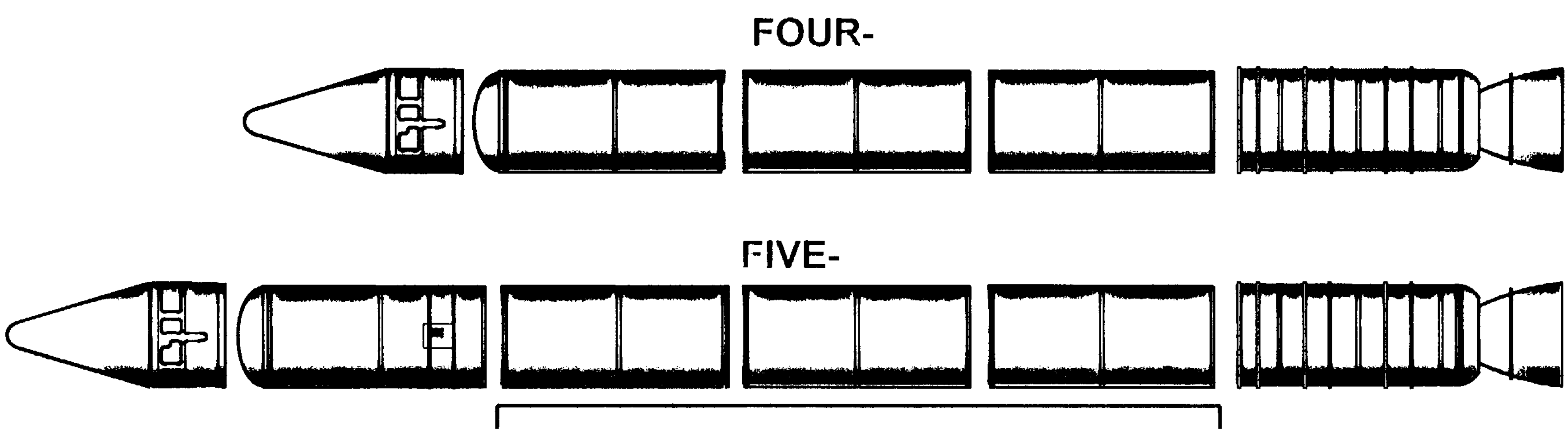


Figure 2 FSB Design Summary



- New forward skirt (-26 in.)
- New medium weight parachutes

- New attach case segments
- Increased segment length (26 in.)
- Grain/inhibitor modification
- Reduced burn rate
- Insulation modification
- System tunnel modification

- Added center segment
- Insulation modification
- Reduced burn rate
- Modified inhibitor height
- Lead-in chamfers on bore

- Standard weight stiffeners
- Added stiffener ring
- New nozzle
- Increased nozzle throat diameter (5.8 in.)
- Increase nozzle length (8 in.)
- Increase nozzle exit dia (3 in.)
- Insulation modification
- Reduced burn rate
- Lead-in chamfers on bore

Figure 3 Five Segment Booster Design Features

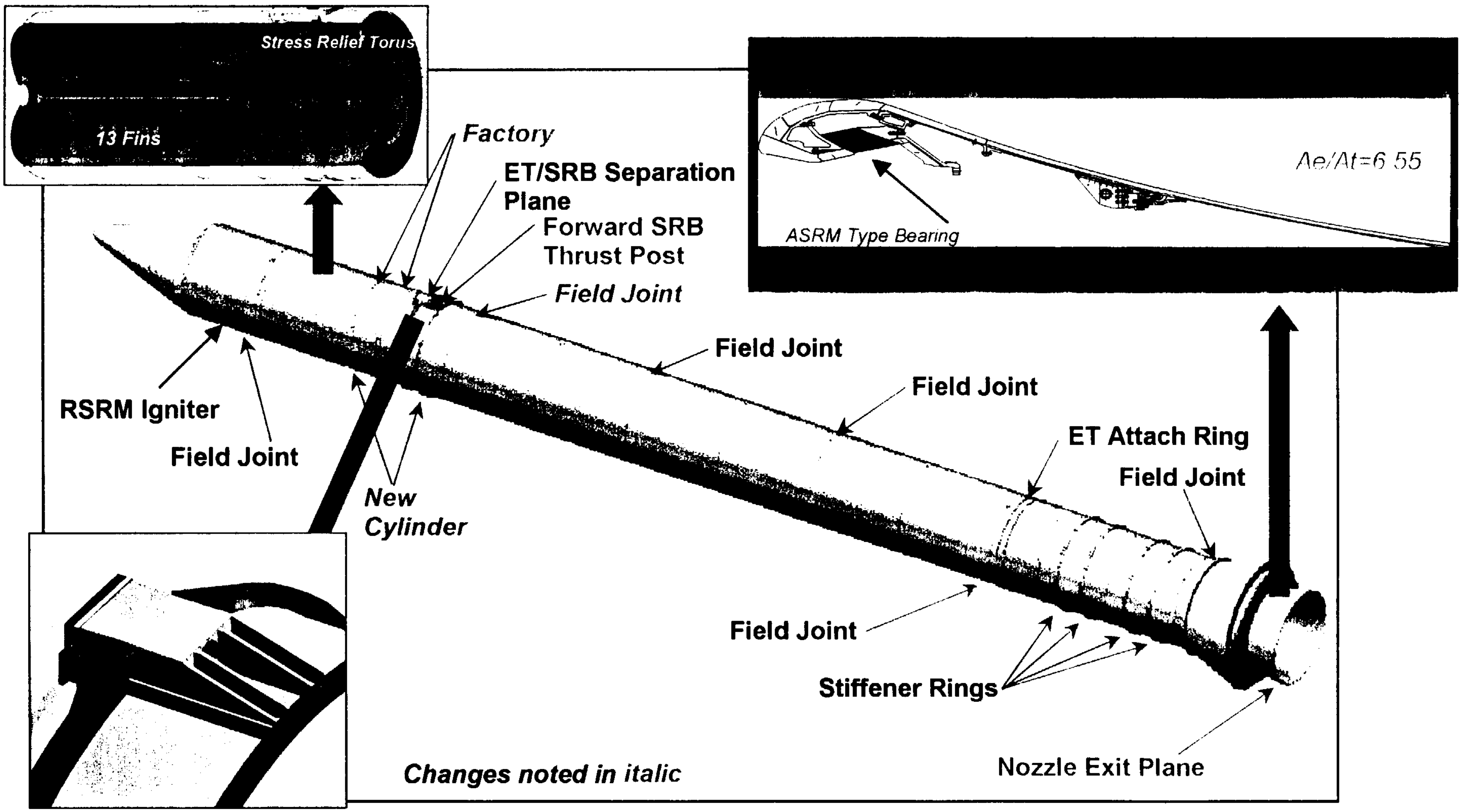


Figure 4 FSB Nozzle

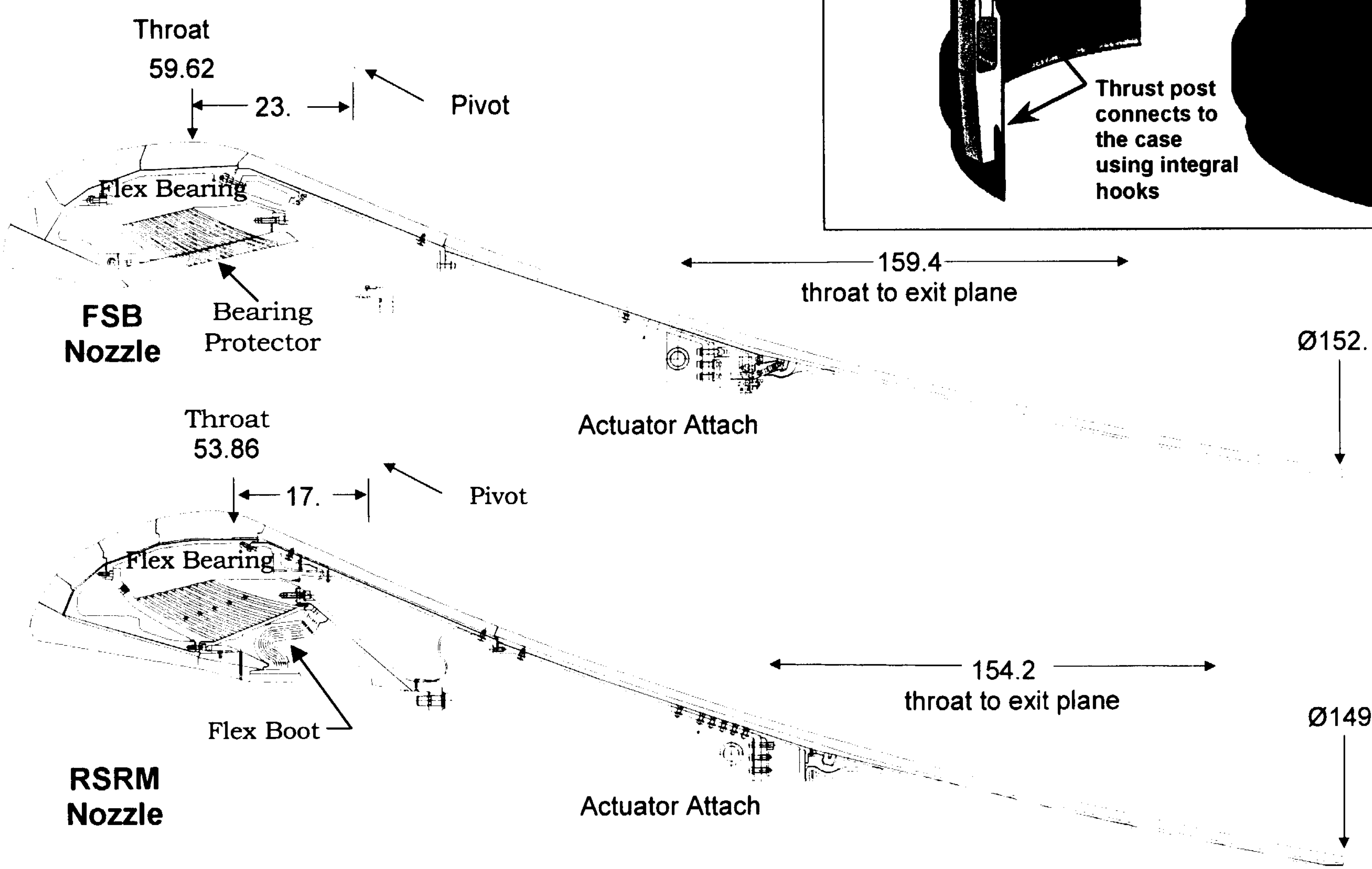


Figure 5 Forward Attach Cylinder Approach

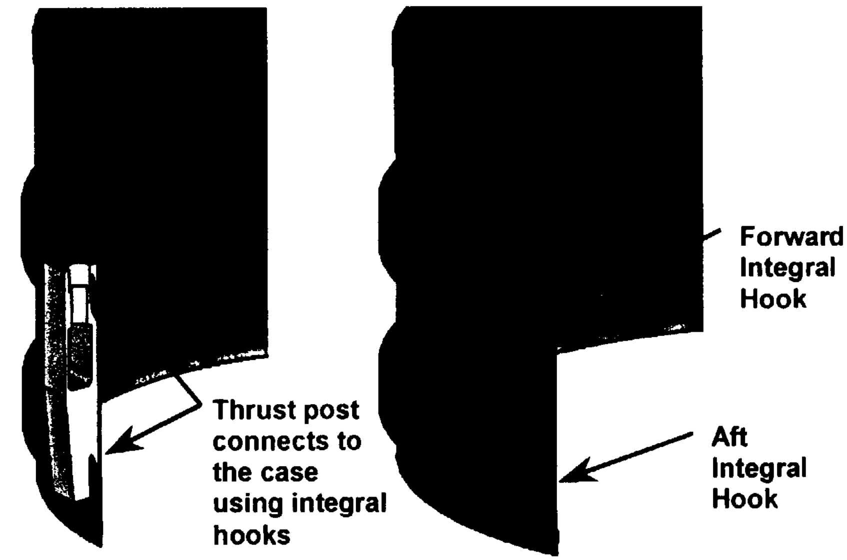


Figure 6 Five-Segment Booster Design Performance Summary

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
MEOP (psi)	1016	1016
Ispv (sec)	264.7	268.0
Burn Time (sec)	129.6	123.5
Burn Rate (in/sec)	0.343	0.368
Expansion Ratio	6.55	7.72
Throat Diameter (in)	59.62	53.86
Initial Thrust/Weight	1.57	1.52

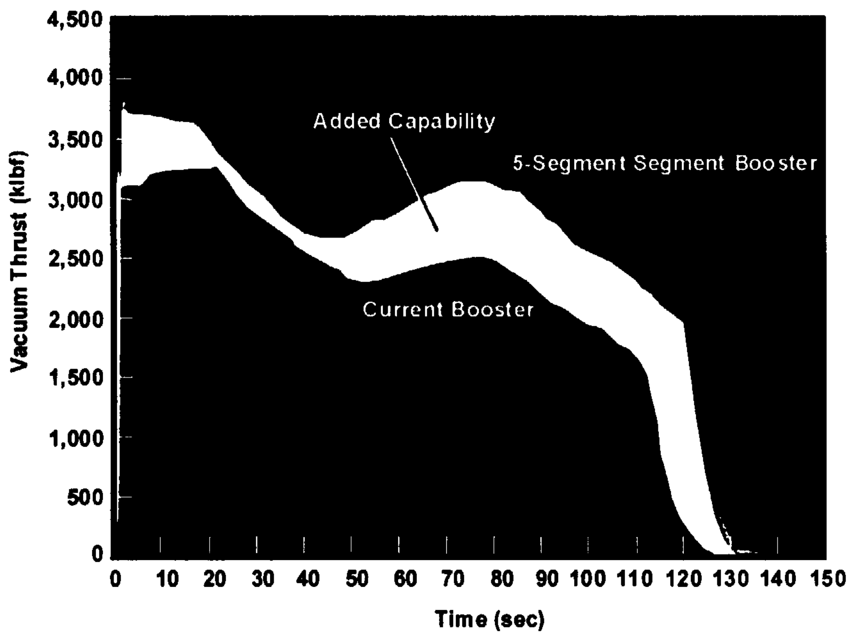


Figure 7 Abort Mode (one SSME out) Results