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Five Segment Booster (FSB) Abort to Orbit (ATO) Studies

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FIVE SEGMENT BOOSTER

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The Five Segment Booster (FSB) concept has been evolving for a number of years as a means to enhance the overall safety and reliability of the Space Shuttle system by minimizing the need to fly the more challenging Return to Launch Site (RTLS) and Transoceanic Abort Landing (TAL) abort profiles. The initial evaluation of the FSB concept was conducted in 1996 to determine the feasibility of the FSB in achieving transatlantic abort landing (TAL) from the pad, thus eliminating the return to launch site (RTLS) abort mode. The initial study was conducted by ATK Thiokol and did show the potential for the FSB to eliminate the RTLS abort mode. Later Rockwell (now Boeing) conducted a similar study utilizing FSB performance characteristics and verified that the FSB could indeed achieve TAL from the pad, thereby eliminating the necessity for the RTLS abort.

s a result of the potential benefit provided by the FSB, Congress provided NASA money to initiate a Phase A feasibility study to assess and mature the basic FSB design approach. In this Phase A feasibility study, all of the major Shuttle elements (Orbiter, External Tank, Booster, Launch and Landing) were involved in assessing the potential implications of the FSB on each of their components. Again, the primary emphasis of the Phase A study was to assess the feasibility of the FSB in eliminating RTLS by achieving TAL from the pad. Another key aspect of the Phase A study was to assess the development cost to qualify a FSB and what the schedule associated with that qualification would be. The Phase A study did confirm the feasibility of developing a FSB with minimal and manageable impacts on other Shuttle elements. It also showed that the FSB enabled the Shuttle to achieve TAL from the pad, thus eliminating RTLS. As a result of the Phase A study, some trajectory enhancements were identified that would be acceptable for an abort mode scenario. With those trajectory enhancements, there was a limited capability to achieve abort to orbit from the pad with the FSBs. The Phase A study also ended up showing the development costs would be approximately $1.1B and the development program would take approximately five years.

As a result of the potential afforded by the FSB as shown in the Phase A study, Boeing and ATK Thiokol Propulsion committed to expending some of their discretionary resources to mature the FSB concept to enhance its ability to achieve ATO from the launch pad. The purpose of this paper is to discuss the details of the enhancements achieved through the internally funded study conducted by Boeing and ATK Thiokol. To better understand the enhancements that were addressed as part of this follow-on study, some background on what was achieved in the Phase A study is appropriate. The basic FSB configuration is shown in Figure 1. Notice the primary aspect of the FSB is the addition of a new center segment to provide the additional impulse. As a

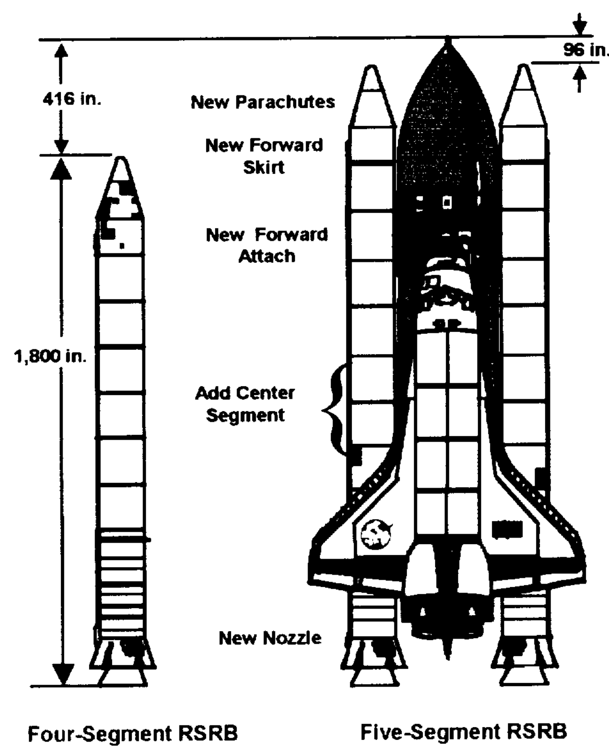


Figure 1. Five-Segment Booster (FSB) Configuration

result of increasing the total impulse, it became necessary to design a new nozzle to ensure that the pressure capability of the current case hardware was maintained, as well as providing the necessary increase in thrust to meet mission needs. This new nozzle had a larger throat diameter to accommodate the increased mass flow rate associated with adding a center segment. By adding a center segment, the forward attach location to the external tank (ET) is now on the external surface of the forward motor cylinder, as opposed to the previous condition where the ET was attached to the forward skirt. Since the forward skirt no longer needs to transmit the loads from the SRB to the ET, a new forward skirt was designed that is a much lighter weight, simpler configuration. As a result of adding an additional center segment, the inert weight of the boosters after separation has increased. Therefore, to maintain the same impact velocity of the booster when it enters the ocean, a new larger diameter parachute was designed. Some of the details of these design changes are shown in Figure 2. Notice the forward motor segment details of the attach are similar to the stiffener segments currently used on the aft segment, which are used to counteract the cavity collapse load after water impact. These stiffeners on the forward segment have a mechanism to allow attaching a thrust post that interfaces with the thrust bolt for the ET. To achieve the desired thrust profile to match the system constraints and accommodate the increased performance capability of the FSB, the forward grain design, inhibitor heights and burn rate had to be changed. Notice the configuration now has 12 fins that are somewhat longer and deeper than the current 11-fin design on the RSRM.

The implications of incorporating a FSB into the Shuttle system relative to the intact abort modes are shown in Figure 3. This figure shows the abort mode opportunities when one SSME goes out at any given time from launch. The time axis shows the total elapsed time from launch when a single SSME is turned off. The abort capability of the Shuttle with the current RSRMs is shown in the blue bar. All conditions are for launches with the International Space Station (ISS) as the destination orbit. With the existing system you can initiate an RTLS at any time between lift off and approximately 250 seconds. The earliest opportunity for a TAL abort occurs at approximately 120 seconds. This means the only abort mode available for the first 120 seconds is an RTLS with the current RSRM boosters. With the current system the ability to achieve an abort to orbit (ATO) becomes available at approximately 250 seconds. The green bars show the enhanced abort capability available when a FSB is substituted for the current RSRM. Notice that the RTLS condition remains essentially the same but the TAL abort opportunity is available from the pad with an SSME throttle setting of 109 percent. By having the ability to initiate a TAL abort from the pad, the necessity for an RTLS abort mode is eliminated.

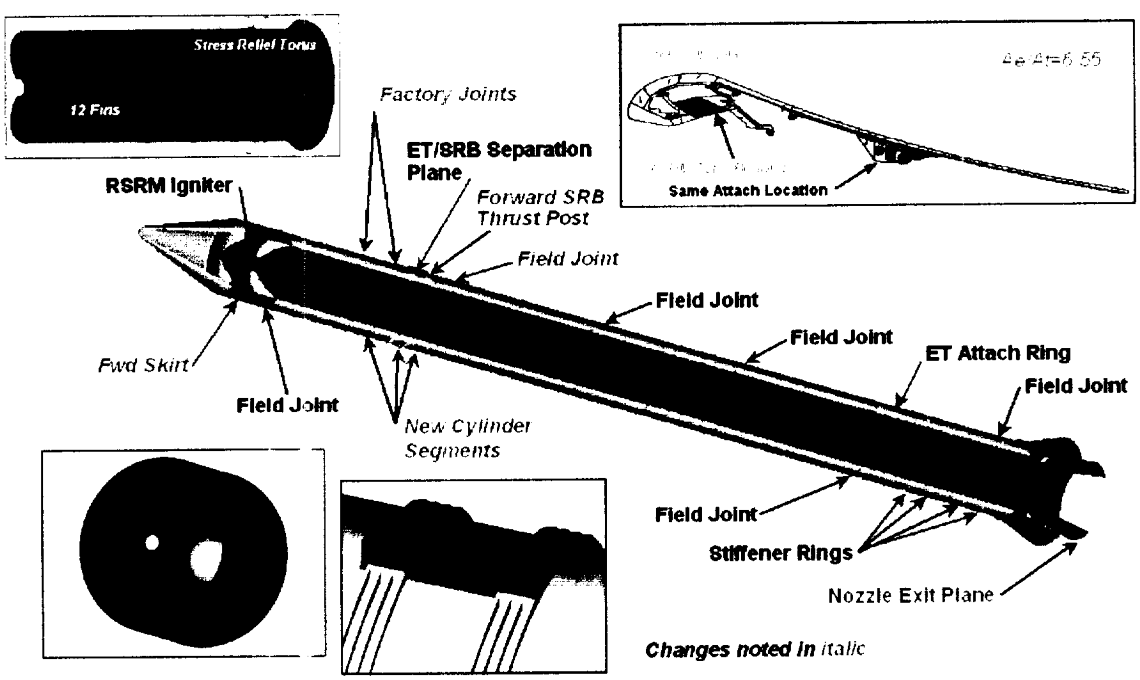


Figure 2. FSB Design Characteristics

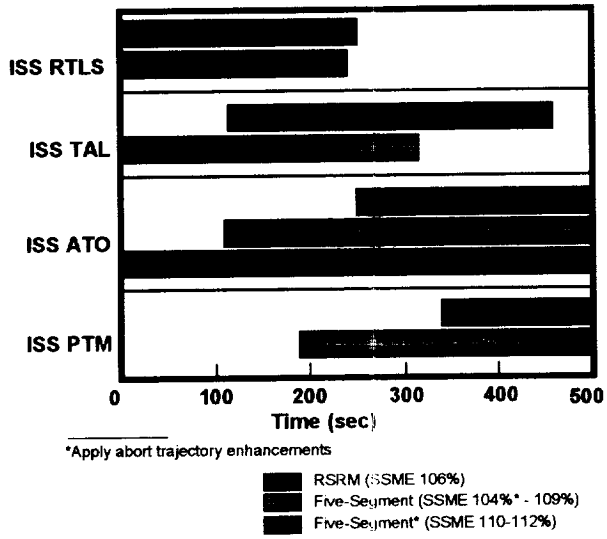


Figure 3. Shuttle Abort Enhancements With FSB

The capability shown in the green bars and blue bars both utilize the current trajectory constraints. As we proceeded through the Phase A study, a number of trajectory enhancements were identified that could be applicable for improving abort capabilities. Many of these enhancements are available due to the extra performance capability afforded by the FSBs. A summary of the potential trajectory enhancements that could be implemented for abort scenarios is shown in Figure 4. Some of the key enhancements include off loading liquid LOX and LH2 from the External Tank. Off loading propellant is possible because there is excess no fail performance when flying with FSBs; therefore, for the nominal missions, you do not need the full load of LOX and LH2, and by eliminating the extra weight associated with the LOX/LH2, abort capability can be greatly enhanced by improving thrust to weight conditions right after booster separation. Additionally, a variety of trajectory design features called abort enhancements have been identified that can improve abort capability, especially for ISS missions. These enhancements are highlighted in Figure 4 in the text box titled Abort Enhancement Trajectory Design. One critical design feature has to do with steering the vehicle more Easterly upon loss of one SSME to benefit from the Earth's rotation. Additionally, the apogee altitude constraint for recovery of the boosters is relaxed for the abort conditions. This is reasonable because the recovery of the orbiter is more important than the potential for increased attrition rate on the booster hardware when you have an abort situation. By incorporating these trajectory enhancements, the thrust level necessary for the Space Shuttle main engines (SSME) to achieve TAL can be reduced from 109 percent to 104 percent, as a conclusion from Phase A. From recent studies, the purple bar shows that you can achieve ATO from the pad with FSB and an SSME throttle setting of between 110 and 112 percent.

The abort capabilities shown for the FSB configuration utilized the same performance margin that is currently used on the Shuttle RSRM configuration. This may be somewhat conservative relative to incorporating a

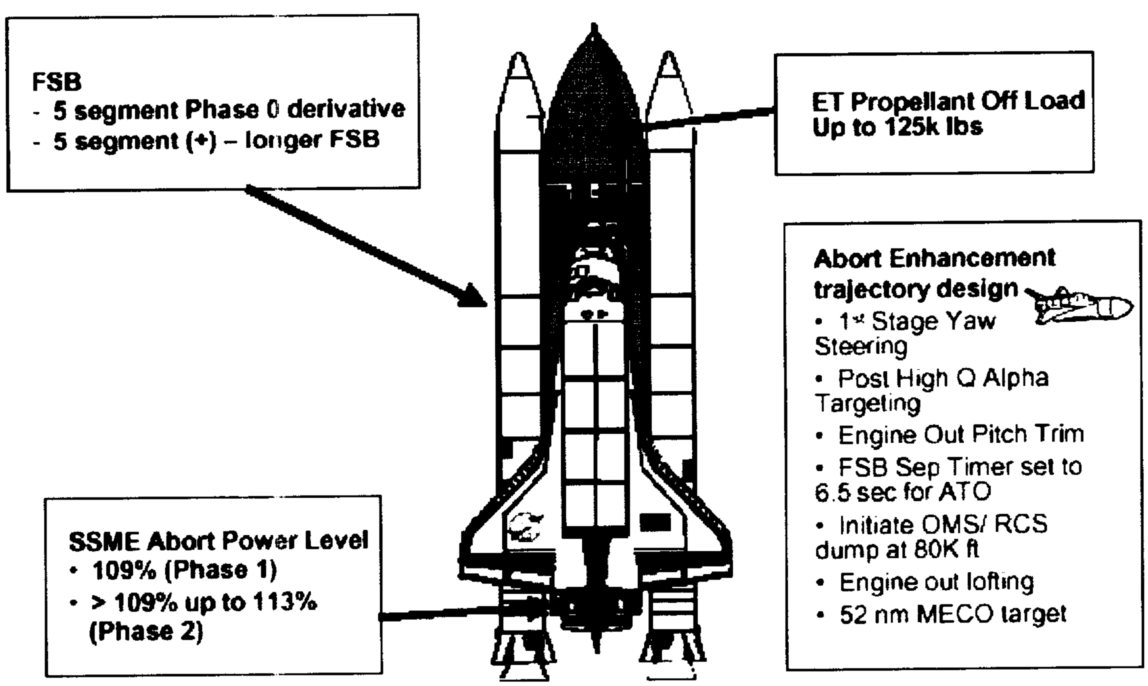


Figure 4. FSB Trajectory Enhancements

fundamental change to the booster performance characteristics. As part of the internal study conducted by Boeing and ATK Thiokol, it was determined it would be more appropriate to increase the performance margin to reflect potential degradations in performance as the FSB and other system implications mature through the development process. A summary of the performance protection considerations to take those maturation effects into account is summarized in Table 1. This indicates it would be appropriate to have additional performance protection on the order of 7,000 to 9,600 lb over and above the current Shuttle performance margins.

Table 1. ATO Performance Protection Considerations

- **ATO FPR (FSB Configuration delta)** — **1,350 lbs**
  - Current protection: 2,350 lbs
  - Proposed FSB: 3,700 lbs
- **FSB Development Reserve** — **2,500 lbs**
  - FSB mass properties: 300 lbs
  - Thrust shape: 1,500 lbs
  - ET mods: 700 lbs
- **RSRM Reconstruction Performance Adjust** — **2,000 lbs**
  - 1.1% Isp
- **Match current SSV Capability (Above PRM)** — **3,800 lbs**

Total **9,650 lbs**

* Currently not included in performance quotes

In order to better define the performance necessary to achieve the desired performance margin, Boeing developed trajectory and performance optimization tools that allowed booster thrust profiles to be optimized to maximize the performance capability of a given booster configuration while adhering to existing Space Shuttle flight environment constraints (Maximum dynamic pressure, Total load factor, load indicators (ET and Orbiter attach), and thermal indicators. Utilizing the optimization tool developed by Boeing, the optimum thrust profile for the FSB configuration utilized in the Phase A study is shown as the FSB1 thrust trace in Figure 5. Figure 6 shows that when optimum thrust trace is utilized a performance margin of 1,300 lb is

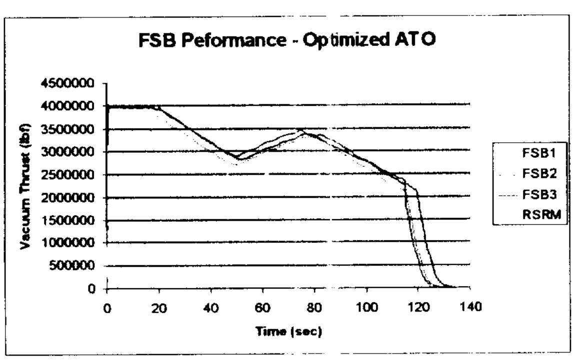


Figure 5. Optimized FSB Thrust Profiles

	Case	Performance
Actual Design (Thiokol)	FSB1 031402	546
Idealized Reference (Boeing)	FSB1	1319
Performance Delta		-773

Performance Delta Breakdown (Thiokol vs. Boeing)	Change	Partial	Performance Delta
Isp (sec)	-0.24	993	-238
Propellant (for a pair)	1582	0.0484	77
Drop Wt (for a pair)	1598	-0.125	-200
Thrust Shape			-411
Total			-773

Summary

- **The Thiokol thrust shape is very similar to the Boeing motor thrust shape**
- **Sep time is 1.22 sec later for the Thiokol motor**
- **Perf losses for Thiokol case due to lower Isp, increased drop wt and tailoff**
- **Clears all preliminary checks on: Loads/ Thermal/ Dynamic Pressure/ Max Acceleration**

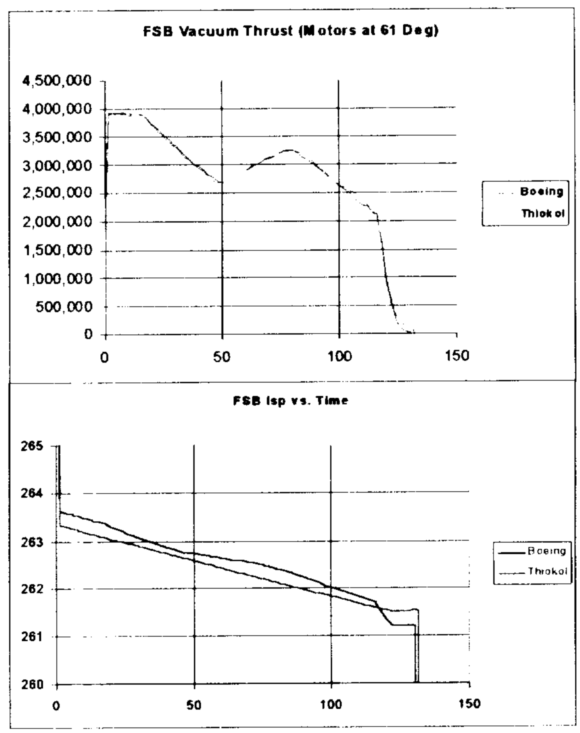


Figure 6. FSB1 Motor Development Summary

achievable with this FSB in conjunction with a SSME abort throttle setting of 109 percent, abort enhancements, and 118,000 lb propellant off load. The lower thrust trace in Figure 6 shows a comparison of the idealized thrust time profile provided from the Boeing optimization tool, compared to an actual grain design developed by ATK Thiokol. Notice that there is an excellent correlation between the actual performance characteristics and the optimum performance characteristics. When the actual characteristics are input into the Boeing trajectory simulation, a performance margin of 550 lb is achieved, so there is a reasonably good correlation between optimum and actual performance capability. However, this particular configuration is still well short of the desired 9,000 lb of performance margin goal. To help us come closer to achieving the desired performance goal while maintaining an SSME throttle setting of 109 percent, we extended the length of the FSB an additional 65 in. beyond the configuration evaluated in Phase A. This optimum thrust profile is shown as FSB2 in Figure 5. The optimum performance capability for the FSB2 stretched configuration is shown in Figure 7. Notice that by increasing the length of the FSB an additional 65 in., the performance margin is improved to approximately 7,000 lb. Again, there is a good correlation between the ideal thrust and the actual thrust characteristics from the grain design developed by ATK Thiokol. Since the 65 in. stretch is still short of the desired 9,000 lb performance margin, an additional increase in length was evaluated to determine if additional performance was available from the FSB. FSB-3, shown in Figure 8, is the maximum length that was evaluated as part of the internal study. This increased length was 96 in., which corresponds with a booster length where the tip of the nose cone would be co-planer with the tip of the ET. In this particular configuration, you will notice in Figure 8 the

	Case	Performance
Actual Design (Thiokol)	FSB2 120301 60deg	6817
Idealized Reference (Boeing)	FSB2	6999
Performance Delta		-182

Performance Delta Breakdown (Thiokol vs Boeing)	Change	Partial	Performance Delta
Isp (sec)	-0.25	993	-248
Propellant (for a pair)	2805	0.0484	136
Drop Wt (for a pair)	-2585	-0.125	323
Thrust Shape			-393
Total			-182

- **Summary**
- **Sep time is 1.44 sec later for the Thiokol motor**
- **Increase in prop and decrease in drop weight (along with slight progressive thrust in first 20 sec) help offset Isp and tailoff losses**
- **Clears all preliminary checks on: Loads/ Thermal/ Dynamic Pressure**
- **Max Acceleration is 3.018 g's for July High Energy case with dispersons @ 104 sec**

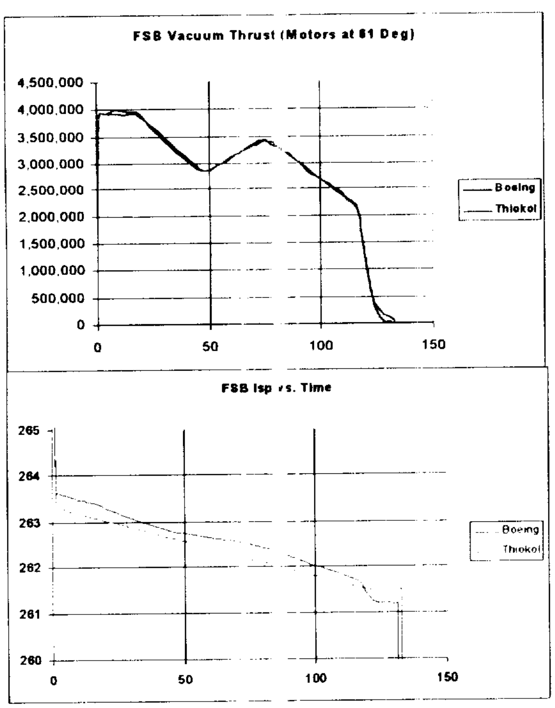


Figure 7. 65 Motor Development Summary

	Case	Performance
Actual Design (Thiokol)	FSB3 96b	9537
Idealized Reference (Boeing)	FSB2	6999
Performance Delta		2538

Performance Delta Breakdown (Thiokol vs. Boeing)	Change	Partial	Performance Delta
Isp (sec)	-0.24	993	-238
Propellant (for a pair)	52773	0.0484	2,554
Drop Wt (for a pair)	3543	-0.125	-443
Thrust Shape			665
Total			2,538

- **Summary**
- **Thiokol FSB2 - 96 case causes FTB 5/6 FSB/ ET Attach loads violations from about 72 sec. to 82 sec. Downward slope needs to be started sooner**
- **Max dynamic pressure violations (10 psf) appear in high energy case from 30 sec. to 42 sec. Most likely caused by progressive thrust not ramping into downward slope soon enough**
- **Max acceleration violations (3.10 g's) also appear for high energy case at 104 sec. A reduction in thrust starting about 94 sec. and continued until tailoff would likely solve this**

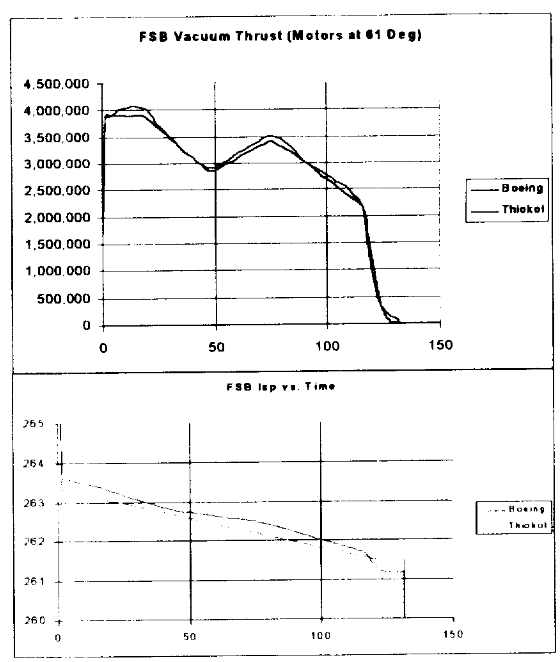
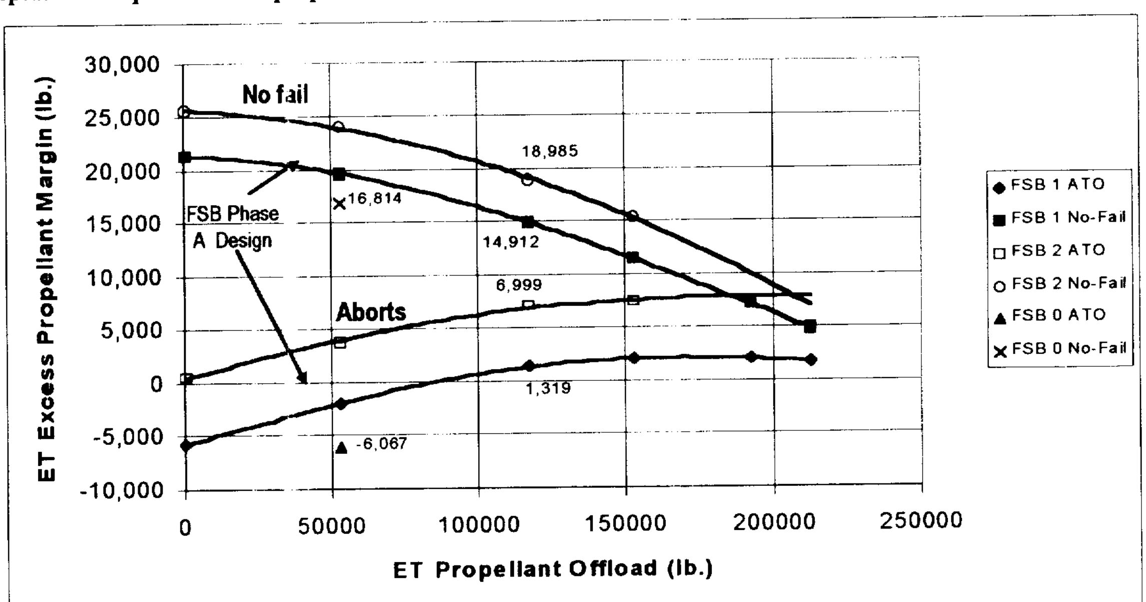


Figure 8. FSB2-96 Motor Development Summary

performance margin was increased to approximately 9,500 lb. This is consistent with the desired performance goal of approximately 9,600 lb. There are some issues associated with this increased length having to do with dynamic pressure and maximum acceleration considerations both of which can be mitigated through additional design refinement, which will be done in future studies.

As mentioned earlier, one of the key aspects of achieving ATO from the launch pad (lift off) is off-loading propellant from the ET. This effect is shown in Figure 9. Notice that the top two curves show the effect of propellant off load in the nominal no fail mission scenario. Because of the enhanced capability afforded by the FSB, one can off load propellant from the ET up to approximately 200,000 lb and still achieve the desired performance capability, which corresponds with a zero propellant margin condition. However, if you observe the bottom two curves for abort scenarios, the abort capability increases as propellant is off loaded. The lower abort curve shows the condition for the Phase A FSB configuration with the optimized thrust profile designated FSB-1. This configuration achieves a 1,300 lb propellant margin with a 118,000 lb propellant off-load. Similarly, the 65-in. stretch FSB-2 configuration achieves 7,000 lb of increased propellant margin capability with the 118,000 lb propellant off-load. The design attributes that were incorporated into the FSB grain designs to help match the optimum thrust profile are summarized in Figures 10, 11, and 12. Commonalities exist among all three designs from a conceptual standpoint. The propellant burn rate was adjusted to match the target web time. Significant modifications to the forward segment fin geometry were made to achieve maximum thrust and control maximum Q at the bottom of the thrust bucket near fifty seconds. Center segment inhibitor heights were tailored to provide the desired performance ramping up out of the thrust bucket. Aft segment bore tapers were altered to control the thrust time trace slope during maximum vehicle acceleration. Generally speaking, these grain design approaches were applied to all three FSB concepts. The degree to which each design change was required and various other grain design subtleties varies between the concepts. It is interesting to note that there are relatively minor design feature changes required to achieve the desired correlation with the optimum profile, thereby showing there is a significant amount of flexibility in tailoring the performance characteristics of the booster to achieve optimum capability.

In the Phase A study the maximum propellant off load that was evaluated was 50,000 lb of LOX. This off load was selected to correspond with a 5.85 mixture ratio for the SSME. The 5.85 was selected because that was the lowest mixture ratio evaluated and tested by the SSME program. From the results shown in Figure 9, it is apparent that offloads beyond 50,000 lb are desirable to maximize abort capability. It became, therefore, important to determine whether the current 6.032 or a 5.85 mixture ratio would be most beneficial for off loads beyond 50,000 lb. A summary of the SSME performance characteristics for the two mixture ratios of interest is shown in Table 2. A comparison of the performance characteristics for both the nominal no fail



Notes:
- **0 lb. Offload cases run with 6.04 Mixture Ratio**
- **All other Offload cases run with 5.83 Mixture Ratio**

Figure 9. ET Offload Performance

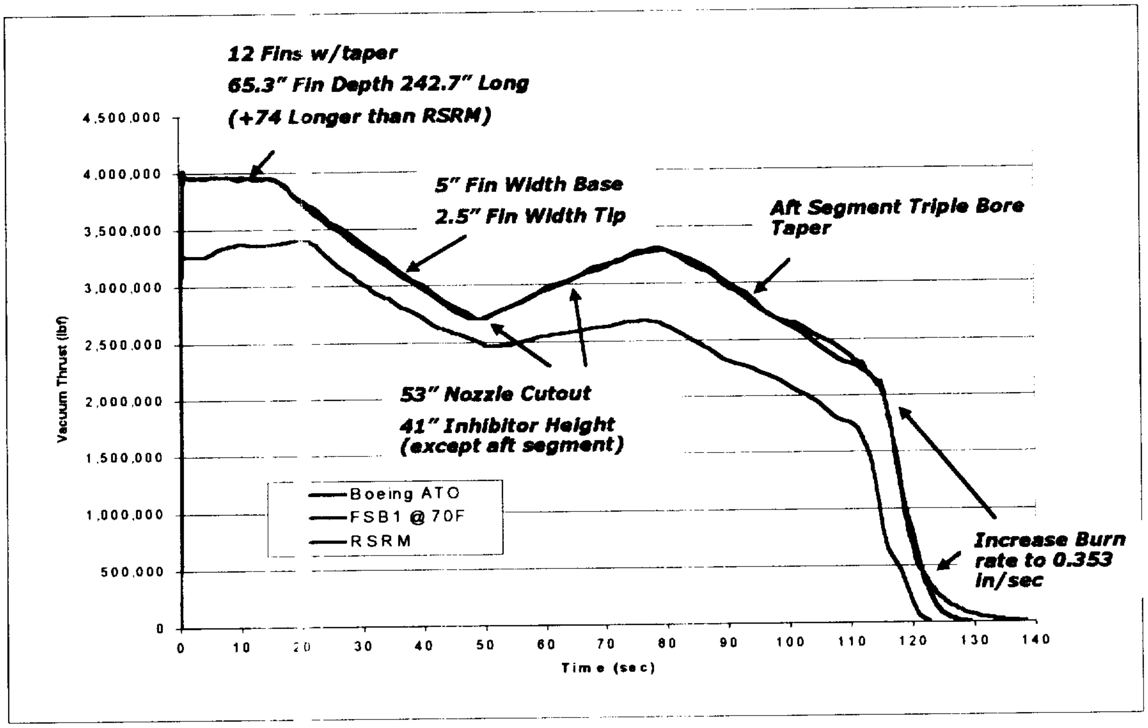


Figure 10. FSB1 Grain Design Status

mission condition and the abort condition for various propellant off-load scenarios is shown in Figure 13. Notice that for the no failure condition a mixture ratio of 5.85 provides more capability, but in both cases, there is sufficient capability to meet the station requirements. For the abort scenario, the 6.032 is slightly better than the 5.85 mixture ratio. As a result of this comparison, it was determined to continue utilizing the current 6.032

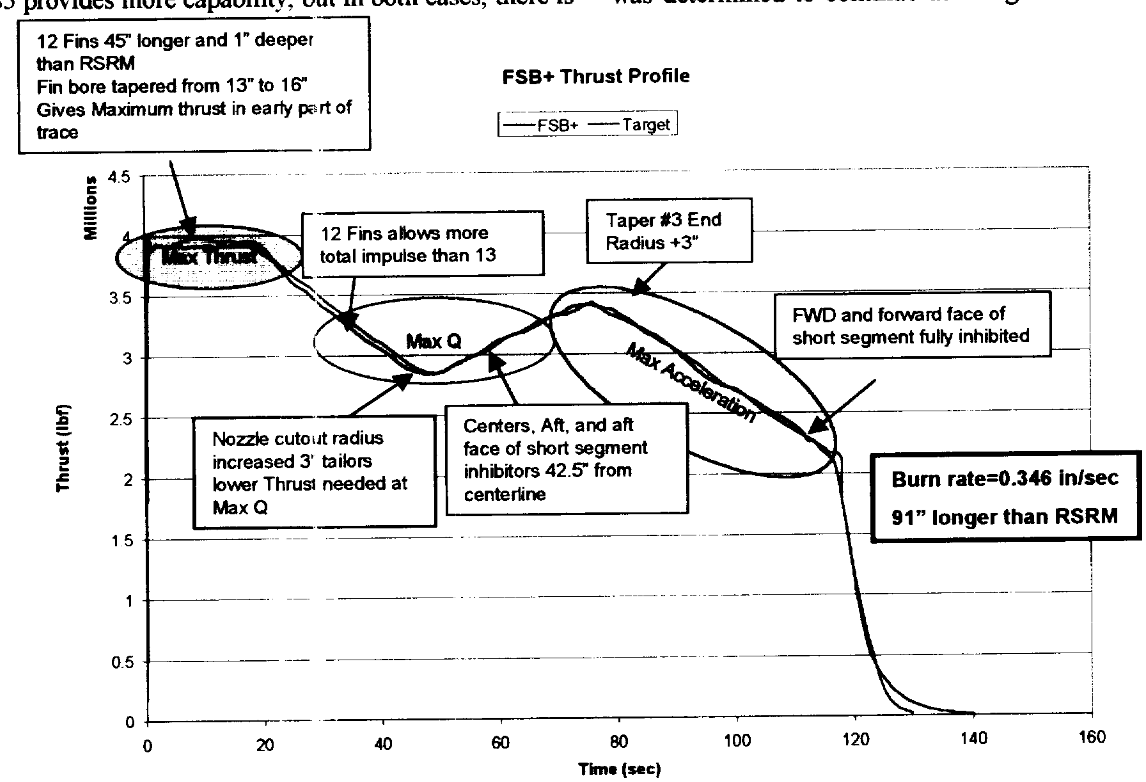


Figure 11. FSB + 65 Grain Design Status

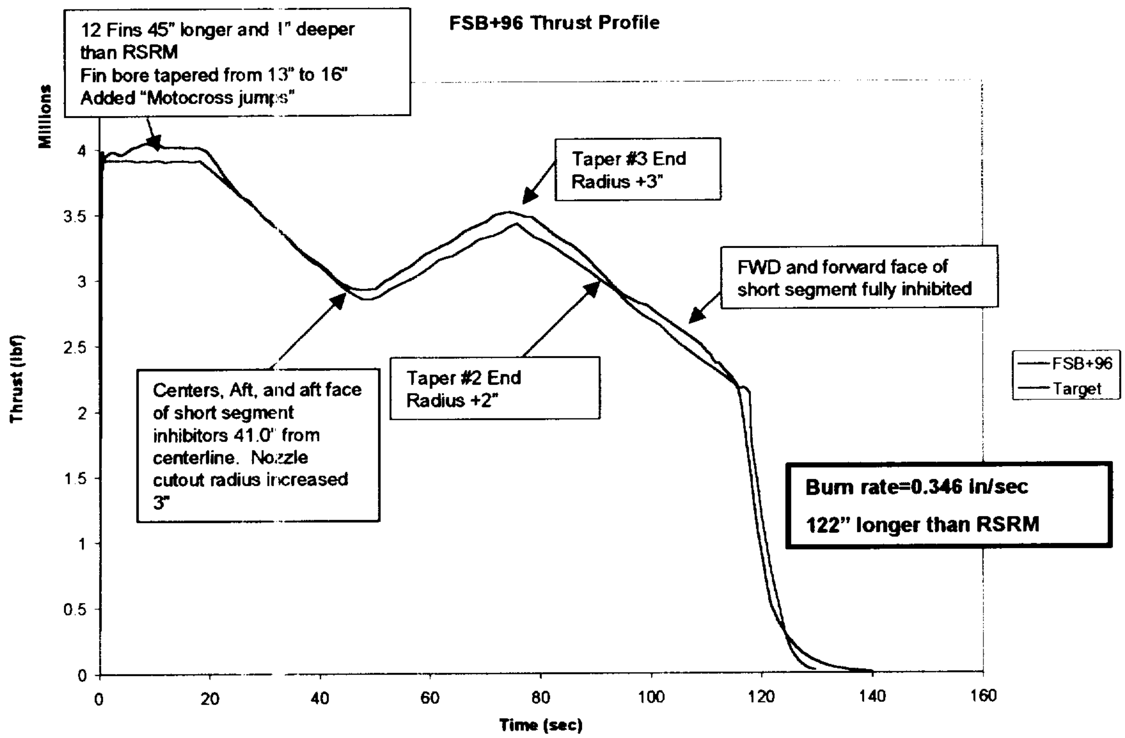


Figure 12. FSB + 96 Grain Design Status

mixture ratio as the nominal condition for future abort mode evaluations. Evaluating the difference in performance between 6.032 and 5.85 mixture ratios as a function of propellant off load is shown in Figure 14, confirming the evaluation from Figure 13 where the 6.032 mixture ratio is more optimum for the "no fail" condition.

TYPE: BLOCK II		
ENGINE NUMBER:	OFFICIAL AVG	
TDDP:	splgs084	
DATA ID:	MS125-00H	MS346-00H
TAG DATE:	07/06/00	~12/04/00
CONTROLLER M/R =	6.032	5.85
POWER LEVEL %	100	100
LO2 FLOWRATE (LBM/SEC)	894.87	883.23
LH2 FLOWRATE (LBM/SEC)	148.16	151.92
GO2 FLOWRATE (LBM/SEC)	1.85	1.85
GH2 FLOWRATE (LBM/SEC)	0.66	0.66
THRUST (LBF)	471002	468789
CONTROLLER PC (PSIA)	2747	2747
MIXTURE RATIO	6.0397	5.8136
ISP (SEC)	452.66	453.97
NOZ. EXIT AREA (IN2)	6507.5	6507.5

Table 2. SSME Tag Data for 6.032 and 5.85 Controller Mixture Ratios

This follow-on study confirms the capability for the FSB to enable ATO from the pad, thus eliminating the necessity for TAL and RTLS abort modes. This study also indicates the ability to not only achieve ATO, but to do so at a SSME throttle setting of 109 percent and reasonable performance margin consistent with performance changes that occur as a result of design maturation during development. These results reaffirm the importance of proceeding with more detailed evaluation and maturation of the FSB design concept. A more effective evaluation of the implications on other Shuttle elements to ensure the optimum capability identified as a result of the optimization studies and the associated grain configurations can indeed be achieved when incorporated into the elements of the Shuttle system.

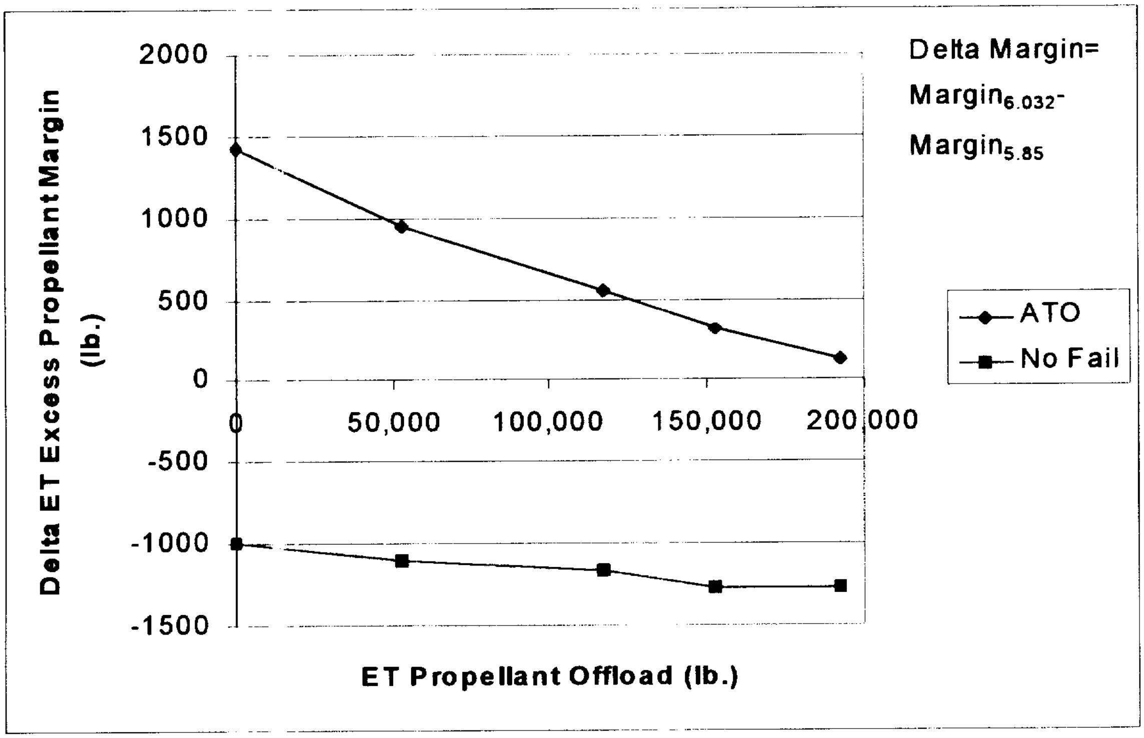


Figure 14. FSB-1 No-Fail/ATO Delta Performance with 6.032 and 5.85 SSME Controller Mixture Ratios

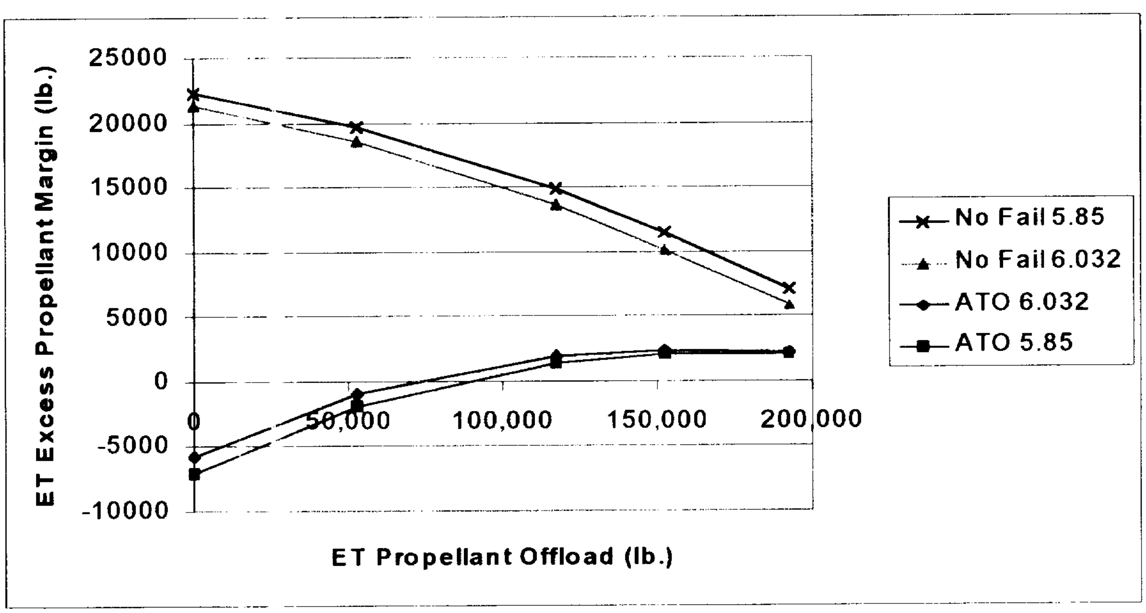


Figure 13. FSB-1 No-Fail/ATO Performance with 6.032 and 5.85 SSME Controller Mixture Ratios

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