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# SSME Evolutions

A.L.Worlund And J.H.Hastings
SSME Project Office
NASA Marshall Space Flight Center, Huntsville, AL

## Abstract

The SSME when developed in the 1970's was a technological leap in space launch propulsion system design. The engine has safely supported the space shuttle for the last two decades and will be required for at least another decade to support human space flight to the international space station. This paper discusses the continued improvements and maturing of the system to its current state and future considerations for its critical role in the nations space program. Discussed are the initiatives of the late 1980's, which lead to three major upgrades thru the 1990's. The current capabilities of the propulsion system are defined in the areas of highest programmatic importance: ascent risk, in-flight abort thrust, reusability, and operability. Future initiatives for improved shuttle safety, the paramount priority of the Space Shuttle program are discussed.

## Introduction

The Space Shuttle, the primary launcher for United States human space flight missions, is powered from lift-off to the targeted sub orbited velocity by the world's only operational, reusable liquid oxygen/liquid hydrogen booster engine. The Space Shuttle Main Engine (SSME) was designed in the early 1970's, flown in 1981 and has performed outstandingly on 104 space missions with 312 engine flights. For SSME, improvement evolution has been a continuous process. Changes were implemented in the early1980's to address deficiencies and/or life issues identified in the ground test program.

Operability and reusability improvements were implemented in the mid-1980's, during the flight standdown period following the challenger accident. A series of component redesign were introduced in the mid to late 1990's.

## SSME Evolution in the 1990's

In the late 1980's, a program was initiated to evolve the SSME such that the national space transportation system could be support beyond the year 2000 (Ref 1). The goals of this evolution program were as follows:

(a) Enhance safety and reliability

    a. Reduce criticality one failure modes

    b. Enhance crew safety by increasing operating margins

(b) Lower recurring costs

    a. Improve component life to lower maintenance cost

    b. Substantially lower unit cost

    c. Counter obsolescence

(c) Increased capability

    a. Support 109% thrust level operation

    b. Technology for increased performance reduced weight and low cost

The initiatives targeted to evolve the SSME were focused primarily on safety and reliability and incrementally introduced into the fleet as block changes as shown in **Figure 1**. The initiatives lead to major upgrades of several SSME componets. The upgrades are summarized in **Figure 2** and described in more detailed below.

The redesign of the components eliminated critical failure modes and increased margin relative to the operating environment. The design approach was different than that used on earlier modifications, i.e., they were not required to be performance neutral. Small performance decreases were traded for significant improvements in safety. The loss of specific impulse and/or weight increases to the SSME was offset by weight reduction in other elements such that vehicle performance was not compromised. The new designs significantly reduced the re-flight/turnaround efforts by eliminating the requirements to remove hardware between flights for inspection and/or maintenance.

The SSME Block I configuration introduced on STS-70 in 1995 includes the two-duct powerhead, single coil heat exchanger, hot gas temperature sensors and a high pressure oxidizer pump.

<u>Powerhead:</u> The powerhead redesign replaced the three small hot gas transfer ducts with two large ducts. The powerhead flow environments were reduced by the increase in the hot gas flow area between the high-pressure turbine discharges and the main injector. The two-duct configuration provides more uniform pressure fields such that the flow loads on the lox posts are reduced. The simplified design has 52 fewer piece parts and 74 fewer welds. The fabrication and assembly time was reduced 40% and cost of rework was reduced approximately 50%. The design provided high margins for the main injector assembly and less unit-to-unit variation. The weight increase was 170 pounds/engine. The baffles in the main injector were removed and the boundary layer coolant was

decreased to increase ISP to offset the performance loss associated with the robust design features.

Single Tube Heat Exchanger: The Powerhead includes a heat exchanger that converts liquid oxygen to gaseous oxygen to pressure the external tank. The heat exchanger is located in a high pressure hydrogen rich environment with inlet and outlet penetrations of the powerhead pressure shell. The initial configuration was a small primary coil and a coil of two larger parallel tubes jointed by a welded bifurcation joint. The single tube design eliminated all seven inter propellant welds (critically one) in the hot gas region. The tube wall thickness was increased to (a) improved wear resistances at the tube-to-tube bracket interface and (b) to greatly reduce the susceptibility to foreign object damage. The powerhead and heat exchangers have successfully completed **114?** missions in ground test program exceeding the design life of 55 missions.

Advanced High Pressure Oxidizer Turbopump (HPOTP/AT): The new pump addressed all of the safety, life and maintenance issues of the earlier configuration. This pump was designed for 60 missions at 109% rated thrust levels. Fine grain casting were utilized to eliminate 293 welds including all 250 welds without the capability for backside inspection. The rotor assembly is supported by liquid oxygen cooled ball bearing on the pump end and liquid hydrogen cooled roller bearing on the turbine end. The single piece disk/shaft rotor provides for a 20% critical speed margin. The thin walled thermally compliant single crystal blades and vanes greatly increase the fatigue capability of the turbine. The 10 mission service intervals were initially demonstrated by two certification units that completed 22 mission cycles without removal of the turbopump from the engine. Currently, the oxidizer pump fleet leader has demonstrated 65 missions in ground test.

The advance high pressure fuel pump was delayed by technical and programmatic issue. Therefore, Block IIA was an interim engine configuration flown initially on STS-89. The major change in the Block IIA engine was the large throat main combustion chamber (LTMCC). Modifications were made to other components to improve operating margins and address maintenance issues. These components were the low pressure oxidizer turbopump, low pressure fuel turbopump, high pressure fuel turbopump, purge check valves and controller software. The main injector was modified to recover some performance loss. The engine provides 104.5% rated thrust at an equivalent six percent lower operating environment for the high pressure pumps and the combustion components.

The LTMCC also includes features that addressed robustness and producability issues encountered with a prior configuration. Integral castings for the inlet and outlet manifolds eliminated 46 welds including 28 classified as criticality one. The casting also reduced fabrication/assembly time and increased the quality of the component. The outlet manifold and duct were fabricated with a material that is not sensitive to hydrogen environmental embrittlement (HEE). This material changes eliminated the critical processes required to copper plate the outlet manifold and duct for HEE protection. A ten percent increase in cooling improved chamber wall durability and added margin to the turbine discharge temperature redline system??.

The Block II engine configuration to be flown on STS-104 implements the Advanced High Pressure Fuel Turbopump (HPFTP/AT). The advanced HPFTP/AT offers robust features that improve flight safety, life, maintenance, and performance. The extensive use of investment castings eliminated welds and sheet metal flow path shielding. The cast pump inlet housing provides a large margin against the surge/burst failure mode. The rotor/rotor support system is a very significant improvement. The bearing design has increased load capability and reduced heat generation in the rolling elements. Synchronous vibrations are reduced by factors of 2 to 4 relative to earlier configurations. The single piece shaft/disk and the robust bearings resulted in a rotor assembly that is very tolerable to damage/unbalance.

The turbine sections design has focused on achieving long life with the parts in the hot section. Blade life is also enhanced with thin thermally compliant airfoils that can accept the rapid thermal transients at ignition and shutdown. Operability improvements included the elimination of bearing drying time constraints and use of liquid air insulation materials common with the low pressure fuel pump. The engine redline is simplified by deleting the coolant liner feature used on earlier configurations.

## Current SSME Capabilities

The Block II configuration has met the primary goals defined (Ref. 1) for the 1990's evolution of the SSME. The safety and reliability of the SSME and the shuttle has been enhanced. The component redesigns have greatly reduced the number of creditable failure modes classified as criticality one. Design features that eliminated known problem areas have also increased the operating margins.

The Quantative Risk Assessment (QRA) is one metric that the Shuttle program uses for risk management of flight hardware and reliability predictions for new hardware (Ref 2). The SSME application of QRA to ascent risk includes the following steps:

1. Identify initiating events, i.e., critical failure modes/causes.
2. Develop event sequence diagrams that define how component failures could propagate through the system loading to an end state.
3. Determine the probability of failure due to the initiating event.
4. Aggregate the probabilities of all initiating events to obtain the probability of catastrophic failure at the mode, component, system and vehicle level.

The application of the QRA to the SSME configurations is presented in **Figure 3.** Each of the block changes has been significant in reducing the predicted engine ascent risk from 1 in 404 missions to 1 in 1283 missions.

Increased reusability has greatly reduced the recurring cost of the SSME. Flight usage is based on demonstrated life capability and the overhaul requirements derived from ground tests. An extensive ground test program of approximately 800,000 seconds has established fleet leaders for each component. A component fleet leader is a unit that has the highest time without a failure or the lowest time to failure. Safe life for flight components is one half of the fleet leader when there are six units that have demonstrated life greater than 50% fleet leader. If there are less than six units with demonstrated life greater than 50% fleet leader, the safe life for flight units is 25% of fleet leader. The component hot fire history presented **Table 1** shows that the HPFTP/AT is the only component with demonstrated life less than the 60 mission design requirement. The demonstrated life of the HPFTP/AT will increase as reliability testing proceeds.

The Block II engine requires significantly less maintenance than earlier configuration. Inspection requirements for the high pressure turbopumps can be satisfied by borescope and torque checks of the rotor. Therefore, the Block II engine has no requirement for removal of the turbopumps for inspection between scheduled overhauls. When the capability of the new fuel pump upgrade is fully realized the engine will be capable of ten flights without refurbishment or removal (except for removal of internal inspection ports).

Abort Thrust Level: While the SSME was being evolved to the Block II configuration, the power level was baselined at 104.5% rated thrust for nominal and intact abort conditions. In-tact abort is the partial or complete loss of thrust from one SSME. The Block II SSME has been certified for flight operation up to 106% rated thrust. The SSME has been designed for 109% rated thrust and has extensive hot fire experience at thrust levels up to 111% power as shown in **Figure 4**.

Operability: The SSME shop maintenance has been reduced as reusability has been implemented. However, the SSME ground operability/turnaround requirements have not been changed to utilize the Block II engine capabilities. The aft compartment has a high work load between flights. Earlier engine configurations were removed to allow parallel processing of the engines and the orbiter. Also earlier engine configurations required component removal for life limit inspection to maintain safe life. Engine removal provided accessibility for the inspections. Engine removal between flights is not required for a Block II engine.

The SSME post flight turnaround time is about **60** day as contrasted to a six shift turnaround for the Block II certification test program. The SSME ground test experience utilizes a similar regiment of inspections as for flight. Engine flight operation turnaround flow is shown in **Figure 5** along with projected improvements after full implementation and maturity of the Block II engine. The faster turnaround has not been pursued due to the relative low flight rate of the shuttle.

## Future Evaluation Paths

NASA and its industry partners developed an upgrade program in 1999 to significantly improve shuttle system safety. The SSME focus was to, (a) improved component safety by eliminating creditable catastrophic failure modes, (b) higher thrust for abort scenarios, (c) increased operability and improved life margin. Producability and supportability improvement to extend the SSME usage past 2012 were also included.

Improved Component Safety Path: In order to reduce the ascent risk of the SSME the mitigation must address the catastrophic failure risk drivers show in **Figure 6**. Redesign of the higher risk components and the implementation of improved real-time health management system were to be applied. Health management approaches are applied to impending component or system failures that can be identified such that shutdown of the engine can be accomplished prior to catastrophic failure. Vibration monitoring of turbopumps is an example. The technical aspects of the health management system (HMS) upgrades are not discussed in this paper. The predicted ascent risk values with the application of the HMS and potential redesign of the MCC and nozzle are shown in **Figure 7**. Nozzle and MCC upgrade considerations are discussed below.

The current nozzle is a component with failure modes that can result in near instantaneous LOX rich failure conditions. The rapid progression of these failures necessitates redesign to eliminate rather rather than use of HMS. Failure of a liquid hydrogen feedline or a series of nozzle tubes is a criticality one-failure mode. The feedlines transfer 6000 psi cryogenic liquid hydrogen coolant to the nozzle as shown in **Figure 8.** The nozzle's feedlines and aft manifold are subjected to large dynamic stresses due to pressure perturbations upstream of the exit plane before the flow in the nozzle is fully developed. During startup transients the nozzle's exit diameter and aft manifold can flex several inches resulting in high loads in the feedlines.

The nozzle receives a high level of attention to manage potential failure modes and to preclude excessive coolant leakage from the cold and hot sides of the wall. Maintenance leak checks and inspections are required between each hot fire ground test. While the inspections are maintaining the saftey of the fleet, the risk of human error is inherently present. Therefore, the elimination of the failure mode has been considered as a more robust approach for achieving a safer engine.

MCC redesign allows the consideration of other safety or performance options. A larger throat option would further derates the engine to improve reliability for nominal missions and abort condition. The larger throat would support intact aborts or potential shuttle crew escape options, i.e. help offset increases to orbiter weight. **Figure 9** shows the potential thrust range improvements. The larger the throat the greater the available thrust since the engine can be throttled up to higher chamber pressure levels if needed. However, the larger throat has the penalty of reduced Isp as also shown in **Figure 9.** MCC redesign would also allow improvement of the MCC/nozzle interface joint, which has no seal redundancy. Adding seal redundancy would reduce the probability of hydrogen coolant leakage to the orbiter aft compartment (a potentially catastrophic event). Therefore, Nozzle and MCC component improvements become a programmatic trade. The parameters to be traded are:

a. Additional improvement in ascent risk
b. Increased thrust for:
    1. Safer in-flight abort options
    2. Potential crew escape design options

c. Slight decreases in Isp and payload capability

Higher Abort Thrust Capability: Many shuttle system studies have assessed methods to provide increased crew safety for an intact abort. Intact abort is the partial or complete loss of thrust from one SSME. The intact abort options vary with flight time as show in **Figure 10**. The first option, return to launch site, is considered to be the highest risk. Therefore, early availability of the transatlantic landing (TAL) option is a priority consideration. Earlier TAL options needs higher thrust from the SSME and/or the solid rocket booster. Engine system studies have indicated that operating the SSME at thrust levels up to 115% for intact aborts is feasible. Engine operation at the higher thrust has not been demonstrated with ground testing. Shuttle flight trajectory studies show that new guidance software and increased SSME thrust has the potential to make the TAL option available at lift-off.

Another option being studies by the shuttle program is the feasibility of crew escape systems. Modifications to incorporate this type of system can increase the weight of the orbiter significantly, lowering payload capability. Additional thrust from the SSME could potentially offset or minimize the weight impact from a crew escape system.

## Summary/Conclusion

The SSME is a high performance liquid hydrogen/liquid oxygen engine with an exceptional flight success history. Its capabilities have been enhanced by the block changes introduced since 1995. The missions that deploy and sustain the International Space Station will necessitate that the Space Shuttle be operational well into the next decade. The challenge for the SSME project is to evolve its capabilities to the missions of the next decade. The primary focus will be higher reliability, more robust abort capability, reduced maintenance, and improved operability.

## References


1. R.D. Paster and S.L. Stohler, "SSME Evolution", AIAA, 1989
2. C.R. Hoffman, R. Pugh, F.M. Safie, "Methods and Techniques For Risk Assessment Predictions Of Space Shuttle Upgrades", AIAA, 1998

# Table 1. Component Fleet Leader Summary

| Component(s) | Demonstrated Ground Test Fleet Leader (F/L) | | | |
|---|---|---|---|---|
| Description | Equivalent Missions (520 Sec) | 50% F/L | # of Units > 50% F/L | Flight Leader |
| Lines & Ducts | 79 | 37 | 4 | 8 |
| Powerhead and Hex | 114 | 60 | 4 | 11 |
| Large Throat MCC | 89 | 43 | 5 | 8 |
| Nozzle | 87 | 55 | 15 | 16 |
| HPFTP/AT | 24 | 11 | 3 | 1 |
| HPOTP/AT | 51 | 23 | 7 | 9 |
| LPFTP | 71 | 45 | 7 | 8 |
| LPOTP | 65 | 31 | 5 | 8 |
| Pneumatic Control Assy | 103 | 68 | 17 | 34 |
| Controller | 154 | 90 | 13 | 35 |
| Main Fuel Valve | 51 | 36 | 2 | 25 |
| Main Oxidizer Valve | 104 | 83 | 11 | 31 |
| Fuel Preburner Oxid Valve | 95 | 67 | 21 | 32 |
| Oxid Preburner Oxid Valve | 127 | 81 | 15 | 28 |
| Coolant Control Valve | 98 | 85 | 13 | 34 |

Figure 1. History of SSME Flight Configurations

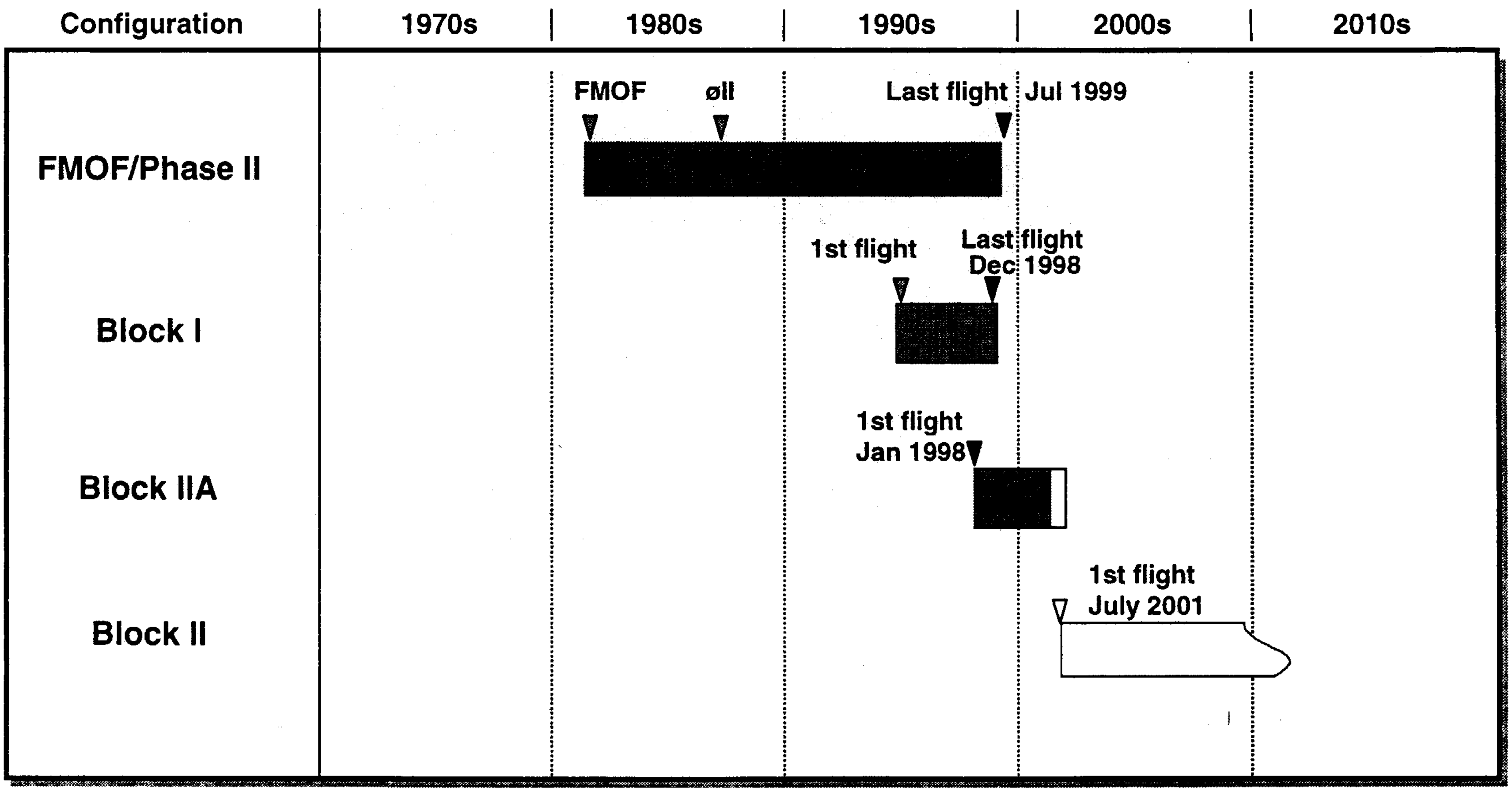
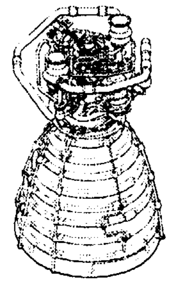


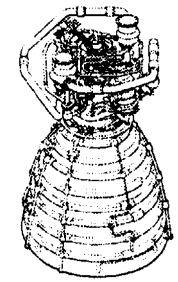
Figure 2. SSME Major Upgrades

**STS-70**
**(Block I)**



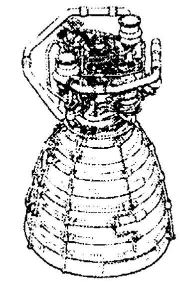
- Two Duct Power Head
  - Injector Life
  - Liner Life
  - No Baffles
  - Injector Isp Mod
- Single Tube HEX
  - No Welds
  - FOD Tolerant
- HPOTP/AT
  - Weld Elimination
  - Robust Bearings
  - Blade Life
  - Robust Margins
- Hot Gas Temp Sensor
  - Reliability

**STS-89**
**(Block IIA)**



- Large Throat MCC
  - P&T Reduction
  - Increase Cooling
  - Weld Elimination
- Block II LPOTP
  - Performance
  - Robust Bearing
- Block II LPFTP
  - Performance
  - Robust LAI
- Software Operability
- Purge Check Valve
- HPFTP
  - Blade Life
  - Weld Reduction
  - Rotor Balance

**STS-104**
**(Block II)**



- HPFTP/AT
  - Weld Elimination
  - Robust Bearings
  - Robust Margins
  - Blade Life
  - FOD/DOD Tolerant

Figure 3. Predicted Catastrophic Ascent Risk

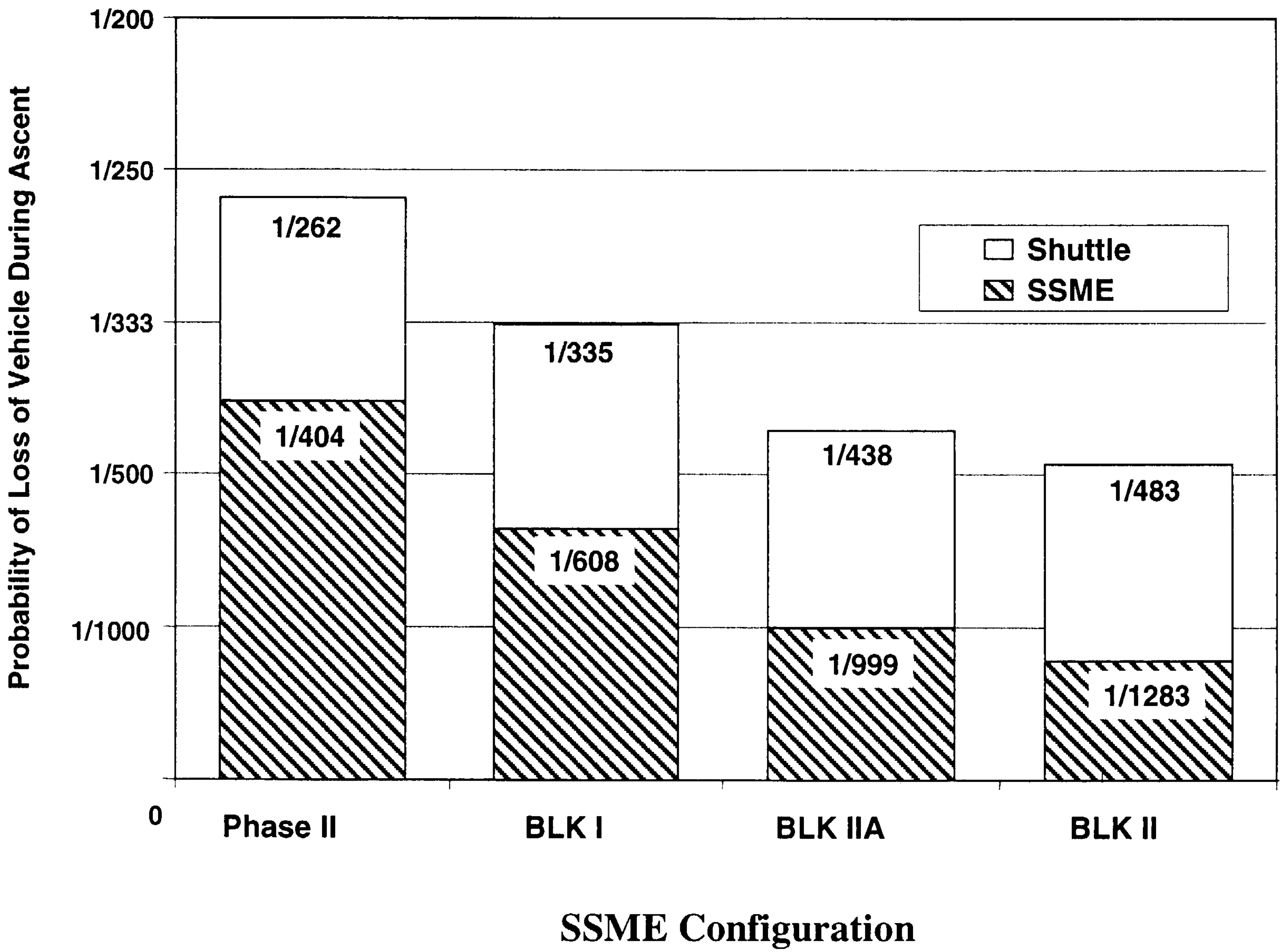


Figure 4. Block II Test Time at Various Power Levels

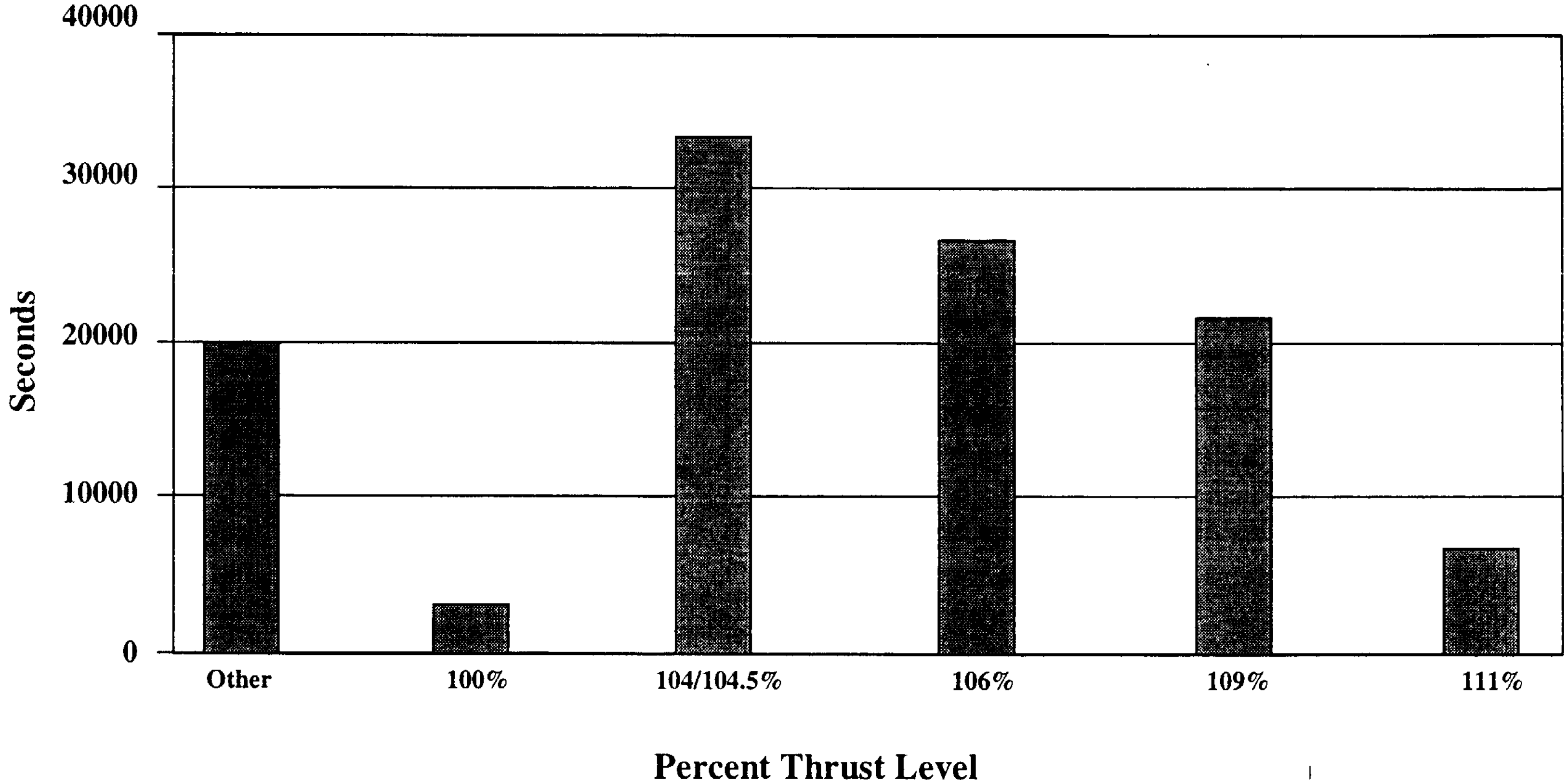


Figure 5. Launch Processing Flow Improvements With Block II SSME

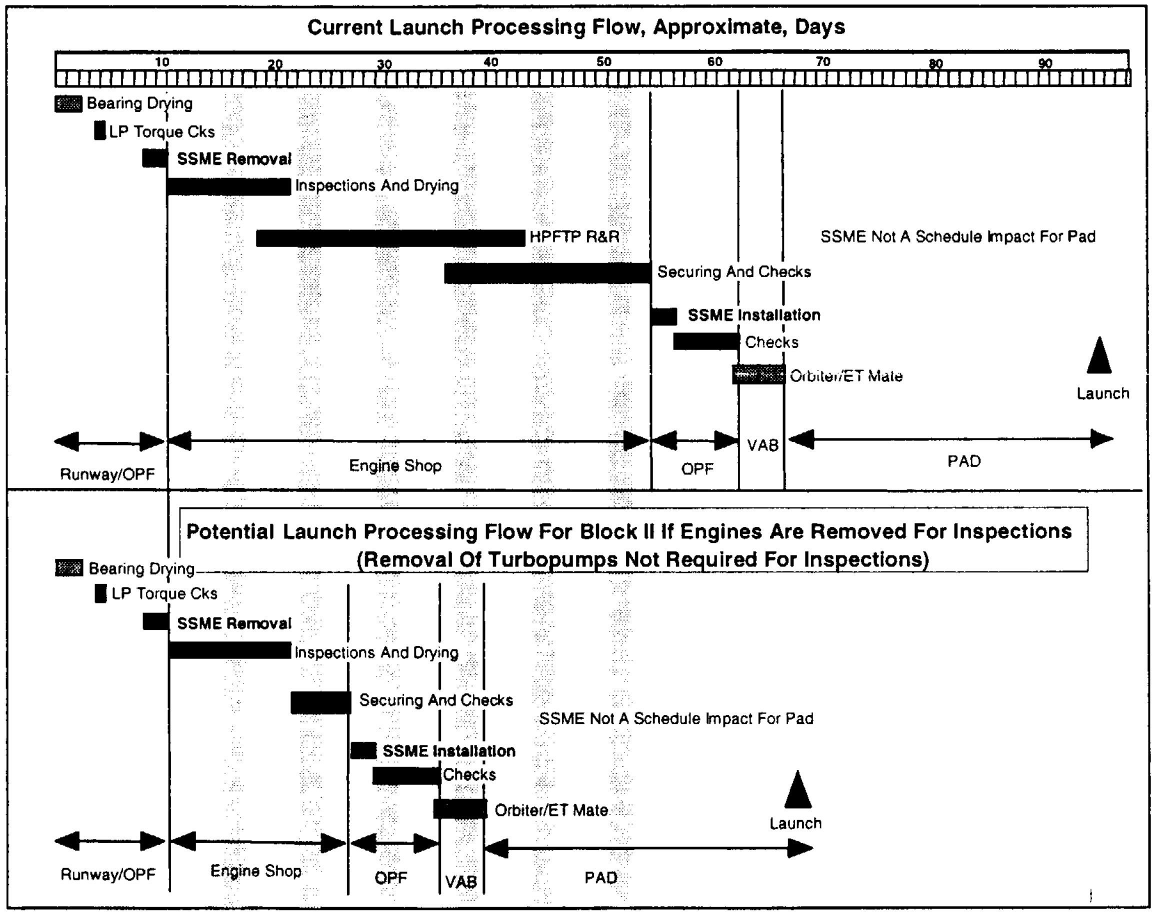


Figure 6. SSME Block II Component Reliability

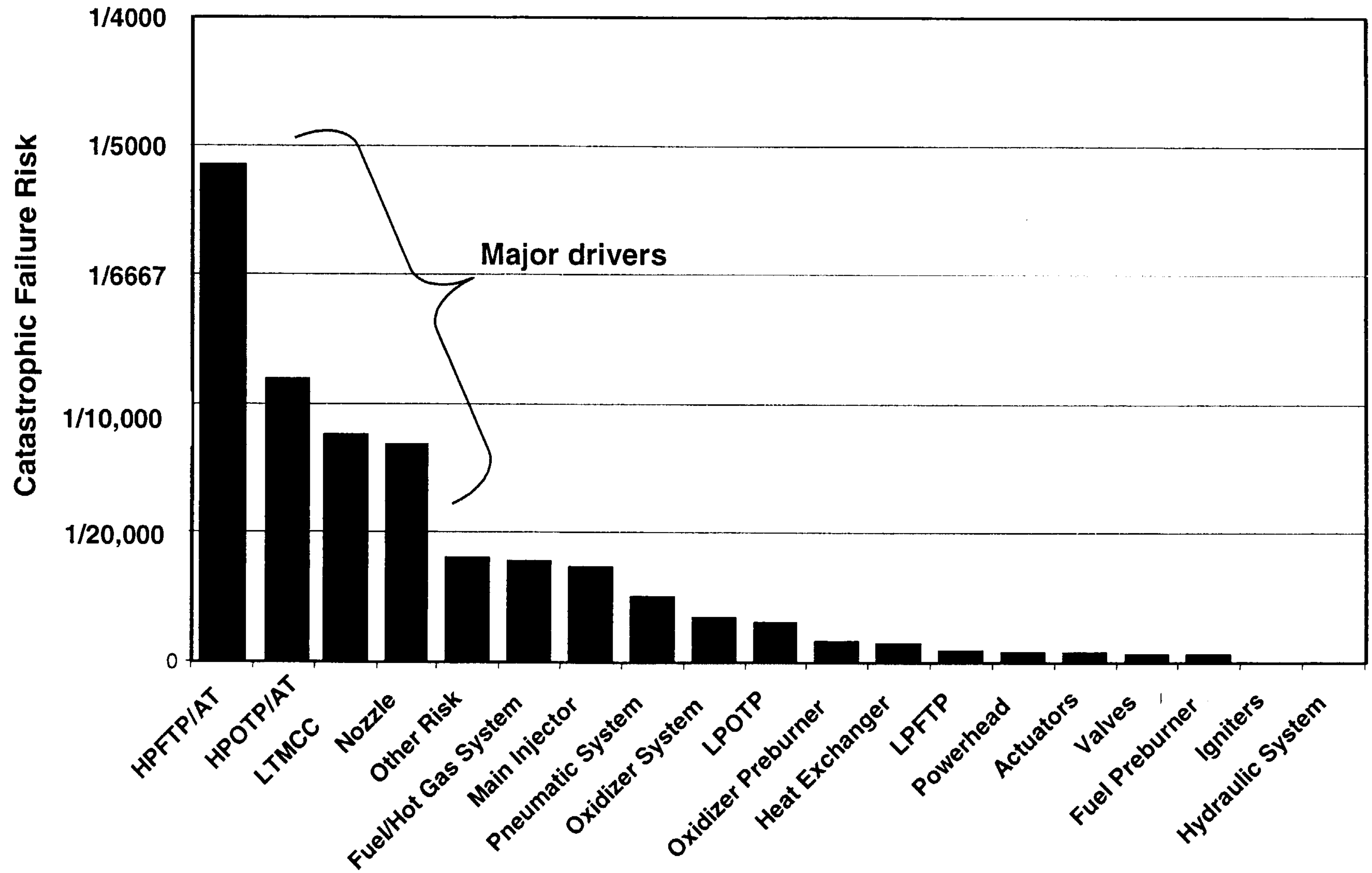
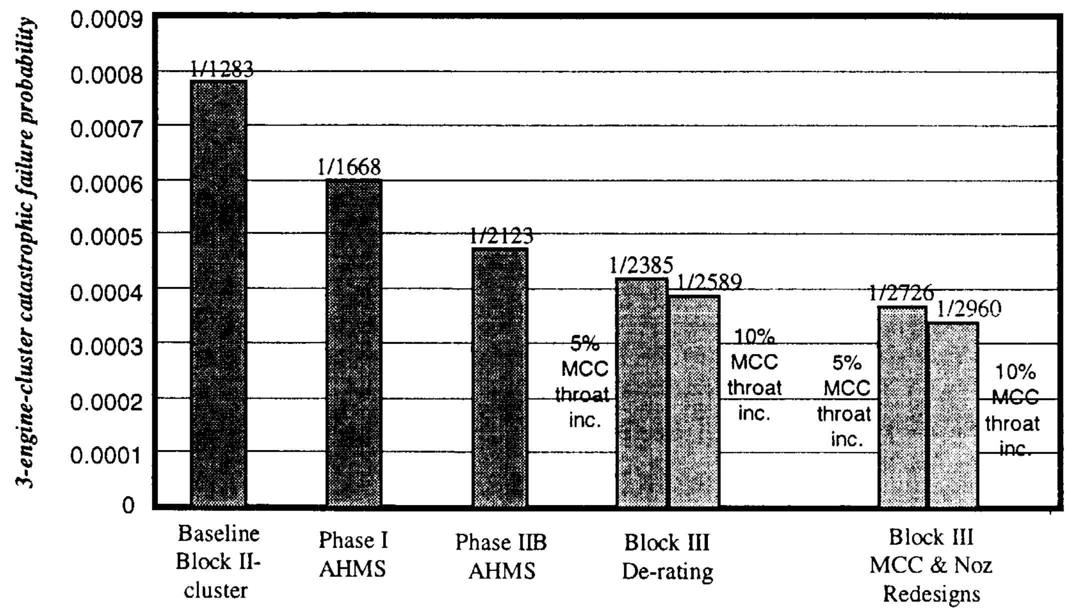


Figure 7. Predicted Catastrophic Ascent Risk With Potential Upgrades



# Figure 8. Nozzle Coolant Flow And Feedlines

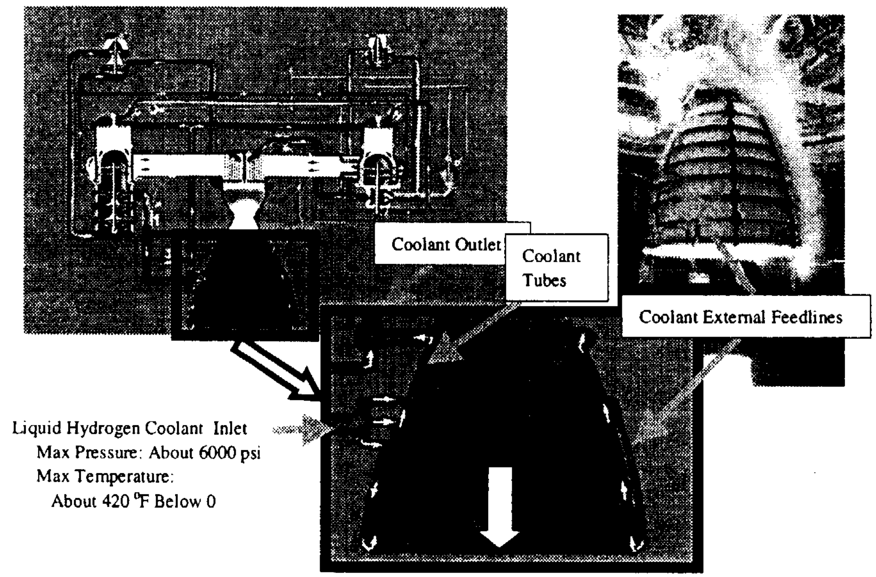


Figure 9. Contingency Thurst Options With MCC Area Changes

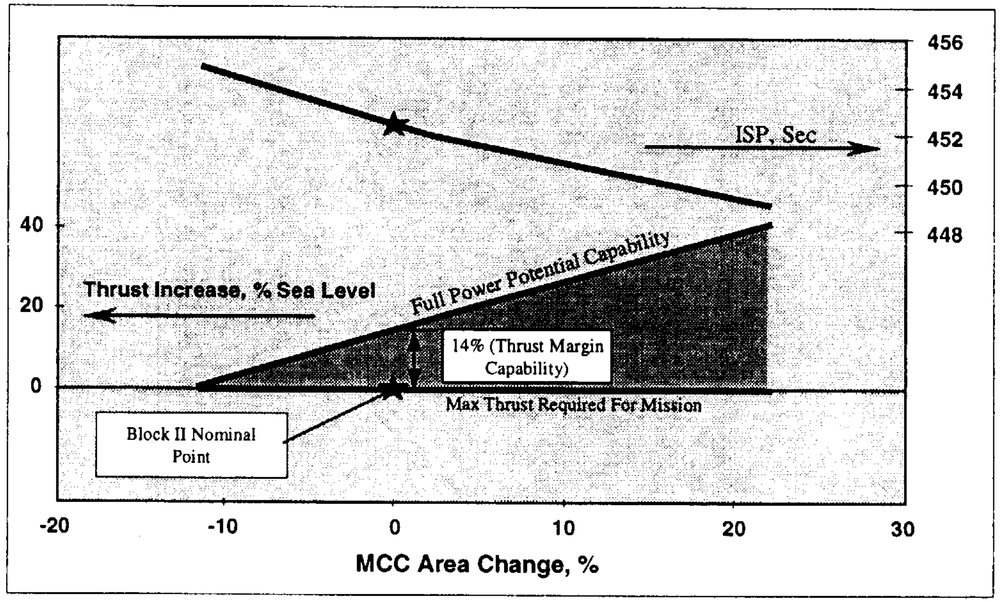


Figure 10. Intact Abort Mode Boundaries