Space Shuttle Main Engine – Thirty Years Of Innovation

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Abstract

The Space Shuttle Main Engine is the first reusable, liquid booster engine designed for human space flight. This paper chronicles the 30-year history and achievements of the SSME from authority to proceed up to the latest flight configuration – the Block II SSME.

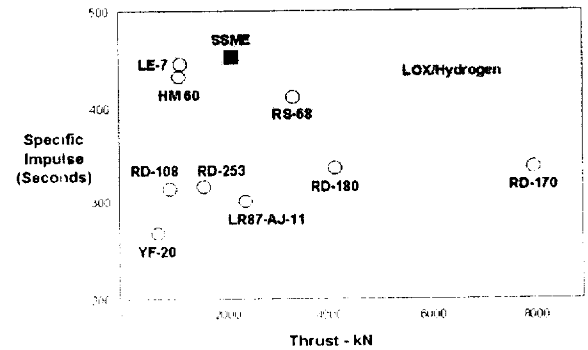
Space Shuttle Requirements

In January of 1969, NASA awarded four $300,000 awards to General Dynamics, Lockheed, McDonnell Douglas and North American Rockwell to initiate Phase A Space Shuttle Development studies. The system studies yielded a two-stage-to-orbit vehicle that required the liquid oxygen and liquid hydrogen main engines to perform substantially beyond then available state-of-the-art propulsion. A year later in April, three awards were given to Aerojet, Pratt & Whitney and Rocketdyne to initiate the Phase B Engine studies for the Shuttle's main engine.

Rocketdyne was given the go-ahead in 1972 to initiate the design and development of the Space Shuttle Main Engine (SSME) under contract to the NASA Marshall Space Flight Center. The engine design required a 55-mission life before overhaul with a total duration of 27,000 seconds (or 7.5 hours). The 2,200 kilo-newton thrust class SSME used a staged combustion cycle configuration to achieve high performance, developing a vacuum specific impulse in excess of 450 seconds. Even by current standards, SSME performance is unsurpassed compared to its world peers.

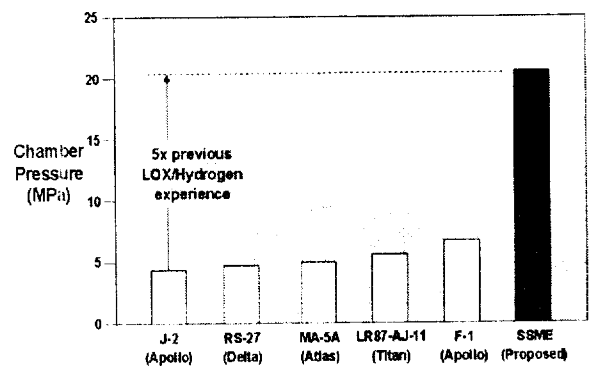
Vacuum nominal thrust	2,190 kN
Sea level nominal thrust	1,770 kN
Vacuum specific impulse	452 sec
Sea level specific impulse	366 sec
Area ratio	69:1
Mixture ratio	6.0:1 o/f
Weight	3,530 kg

SSME Nominal Characteristics



Global Liquid Booster Engine Vacuum Performance

The weight and envelope requirements yielded a compact design with a nominal chamber pressure of 20 MPa, about 5 times it's J-2 predecessor in the Apollo/Saturn program.



US Liquid Booster Engine Chamber Pressure - circa 1960s

A dual-preburner powerhead configuration was chosen to provide precise mixture ratio excursion and throttling control between 50% to 109% power levels. All engine functions and self diagnostic of it's fail-operate, fail-safe, redundant control systems would be continuously monitored and controlled by an on-board digital Main Engine Controller (MEC), a first for booster engines.

Design Challenges

The staged combustion cycle chosen for high efficiency yielded a technologically advanced and complex engine that required hydrogen and oxygen operating pressures beyond known experience. Emphasis on fatigue capability, strength, ease of assembly and disassembly, inspectability, and materials compatibility were all major considerations in achieving a fully reusable design.

High strength alloys needed to be developed to meet the severe operating environments. These included INCO-718, NARloy-Z, cast titanium, Mar-M, and IN-100. Advanced non-metallic applications were also later developed. Oxygen compatibility was a major concern due to reaction and ignition under the high pressures. Mechanical impact testing had begun as early as 1950's and vastly expanded in the 1970's to accommodate the SSME's operating envelope. This led to a new class of LOX reaction testing up to 69 MPa.

The long-term behavior to hydrogen effects also needed to be understood to achieve full reusability. Thus a whole field of materials testing evolved to understand the behavior of hydrogen charging on all affected materials. The Shuttle program today can boast having the world's most extensive materials database for propulsion.

Engineering design tools advanced along with the digital age as analysis migrated from the mainframe platform to workstations and desktop personal computers. Cycle time for finite element models, computer aided design and manufacturing, and computational fluid dynamic analysis dropped from days to hours to minutes. Today, near real-time engine performance analysis are conducted during ground testing.

Development Testing

The first engine level test of the SSME, called the Integrated Subsystem Test Bed (ISTB), occurred in May 1975 at the NASA National Space Technology Laboratory (NSTL) in Mississippi, since renamed the Stennis Space Center (SSC). Component level testing began one year earlier at Rocketdyne's Santa Susana Field Laboratory (SSFL) on the outskirts of Los Angeles.

The first 100,000 seconds of development test time was reached in 5 years and 7 months, requiring an aggressive test schedule at both NSTL and SSFL. The A-2 and B-1 test stands at NSTL verified operation at altitude conditions while the A-1 stand demonstrated the rigors of sea level performance and engine gimballing for thrust vector control. SSFL's A-3 stand supplemented sea level testing as well as deep throttling by using a low expansion ratio nozzle. The testing was crucial in identifying problems related to the initial designs of the high-pressure turbopumps, powerhead, valves and nozzles. These issues were resolved through the dedication of a national team of talented civil, industrial and academic members.

Further confidence in the design was provided through extensive margin testing beyond the normal flight envelope, including high power extended duration tests, and near-depleted inlet propellant conditions to simulate zero-g effects. The robustness of key components were subjected to a full series of design verification tests, some with intentional hardware defects, to validate safety margins should they develop undetected flaws during operation.

Testing was also performed to replicate the three engine cluster interactions with the Orbiter. The Main Propulsion Test Article (MPTA) consisted of an Orbiter aft-fuselage complete with full thrust structure, main propulsion electrical and system plumbing, External Tank, and three SSMEs. A total of 18 tests were completed at the NSTL by January 1981 to validate the Main Propulsion System (MPS) was ready for launch.

The completion of the SSME Preliminary Flight Certification (PFC) in March 1981 marked a major milestone in clearing the initial flights at 100% Rated Power Level (RPL).

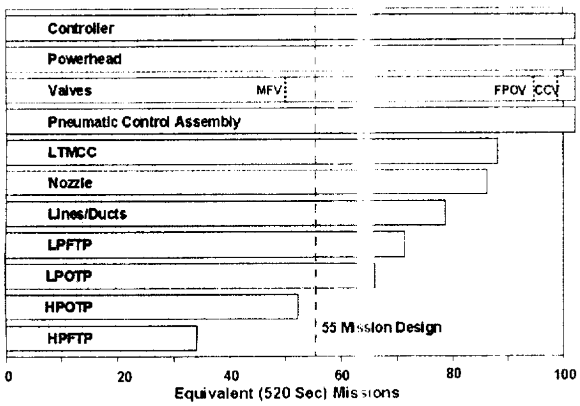
Flight History

On April 12, 1981 the Orbiter Columbia lifted off launch pad 39A from the NASA Kennedy Space Center (KSC) on its maiden voyage STS-1. The first flight configuration engines were aptly named the First Manned Orbital Flight (FMOF) SSME. These engines were flown during the initial 5 STS development missions at 100% RPL thrust. The ability to perform routine Orbiter turnaround was validated with the SSMEs remaining installed. Only the heat shield needed removal to gain access to checkout and drying ports.

The development of a Full Power Level (FPL) 109% RPL SSME was initiated with the successful flight of STS-1. A higher thrust capability was needed to support a multitude of NASA, commercial and DOD payloads, especially if launched from the west coast. However, by 1983 test failures demonstrated the basic engine lacked margin to continuously operate at 109% thrust. FPL development was halted while continuing life improvements were implemented into the Phase II SSME and later certified to 104% RPL.

The 1986 Challenger accident provoked major fundamental changes to the Space Shuttle program. Improvements to the Phase II SSME were implemented and an additional 90,241 seconds of engine testing was accrued during the recovery period, including re-certification to 104% RPL as part of return-to-flight.

The Space Shuttle has flown a total of 109 flights (as of STS-110 on April 2002) using a total of 41 engines. SSME Engine 2019 is the flight fleet leader having flown 19 times. The on-going ground test program continues to advance the fleet leader concept by ensuring the design's reusability through reliability testing.

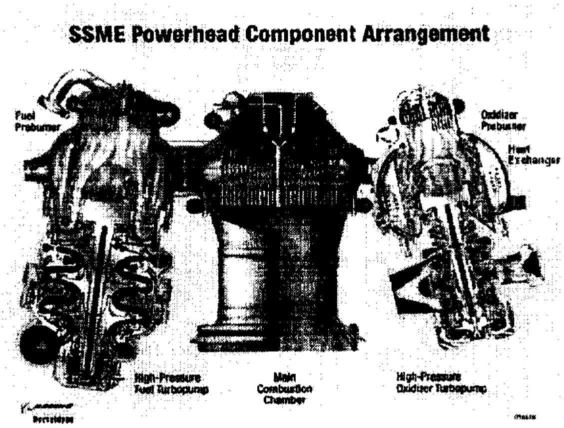


SSME Component Fleet Leaders

Product Improvements

The Phase II SSME continued to become the workhorse configuration for Shuttle launches up to the late 1990's while additional improvements envisioned during the 1980's were undergoing development and flight certification for later incorporation. Five major components were targeted for advanced development to further enhance safety and reliability, lower recurring costs, and increase performance capability:

- Powerhead
- Heat Exchanger (HEX)
- Main Combustion Chamber (MCC)
- High Pressure Oxidizer TurboPump (HPOTP)
- High Pressure Fuel TurboPump (HPFTP)



SSME Powerhead Components

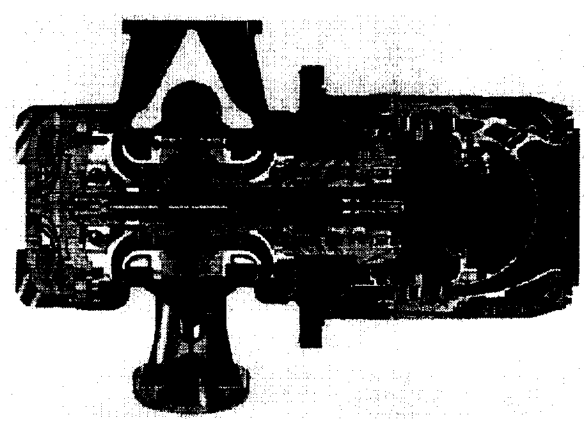
These major changes would later be divided into two Block configuration upgrades with Rocketdyne tasked to improve the Powerhead, HEX and MCC while Pratt & Whitney was selected to design, develop and produce the HPOTP and HPFTP.

Block I

The first flight of the Block I SSME occurred on STS-70 in July 1995. The configuration included a redesigned two-duct transfer tube powerhead, Single Tube Heat Exchanger (STHEX), and the new high-pressure oxidizer turbopump. These components utilized new design and production processes to eliminate failure causes, increase the inherent reliability and operating margin, and reduce production cycle time and costs.

The powerhead redesign was less risky and was chosen to proceed ahead of the main combustion chamber. The Two-duct powerhead eliminated over 74 welds and had 52 fewer detail parts. The improved design led to production simplification and a 40% cost reduction compared to the previous three-duct configuration. The STHEX eliminated all inter-propellant welds and its wall thickness was increased by 25% for added margin against penetration.

The new HPOTP eliminated 293 welds, added improved suction performance, introduced a stiff single disk/shaft configuration and thin-cast turbine airfoils. Initial component level testing occurred at the E-8 test facility of Pratt & Whitney in West Palm Beach, Florida and later graduated to engine-level development, certification and acceptance testing at SSC.



SSME Block II High Pressure Oxidizer Turbopump

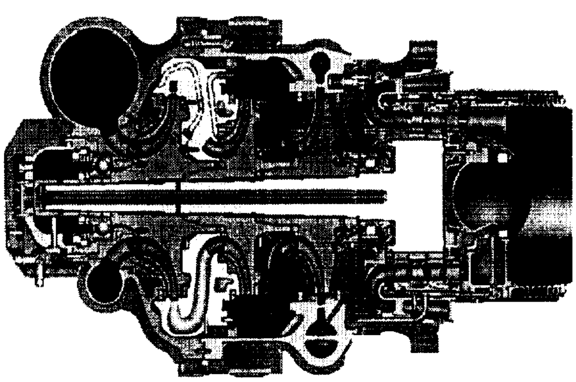
Block II

The Large Throat Main Combustion Chamber (LTMCC) began prototype testing at SSFL in 1988 but it was not until 1992 after a series of combustion stability 'bomb' tests at the MSFC Technology Test Bed (TTB) that all concerns regarding combustion stability were put to rest. The Block II would also incorporate the new high-pressure fuel turbopump, modified low-pressure turbopumps, software operability enhancements, and other miscellaneous component changes.

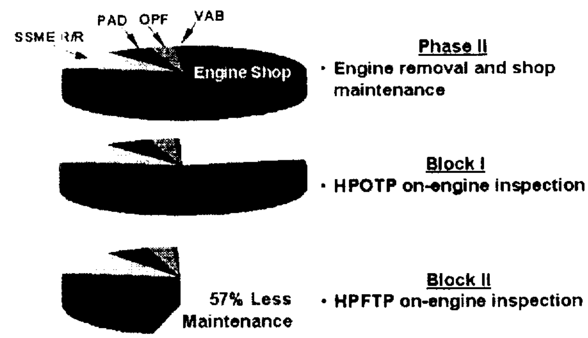
The primary mission for the Block II was support for critical International Space Station (ISS) launches with its heavy payload manifest beginning in 1998. As Block II development testing progressed, the LTMCC had matured more rapidly than the HPFTP. By February 1997, NASA decided to go forward with an interim configuration called the Block IIA. This configuration, using the existing flight proven high-pressure fuel pump, would allow earliest implementation of the LTMCC to support ISS launches.

The LTMCC would become one of the most significant safety improvements for the SSME by effectively reducing operating pressures and temperatures up to 10% for all subsystems. The engine components would essentially be operating in a 'de-rated' environment. The LTMCC large throat design also incorporated improved cooling capability for longer life and utilized high strength castings eliminating 50 welds.

By the time the first Block IIA flew on STS-89 in January 1998, the LTMCC design had accumulated in excess of 100,000 seconds. The last Block IIA mission occurred on STS-109 in March 2002 after supporting 49 engine flights.


SSME Block II High Pressure Fuel Turbopump

By late 1999, the Block II HPFTP had progressed into certification testing. The HPFTP design philosophy mirrored those proven in the HPOTP, namely 387 welds were eliminated, incorporation of a stiff single-piece disk/shaft thin-cast turbine airfoils and a cast pump inlet that improved the suction performance and robustness against pressure surges. As with the HPOTP, the HPFTP turbine inlet did not require off-engine inspections, which contributed significantly to achieving an engine turnaround manpower reduction of 57%. The HPFTP also demonstrated that a turbine blade failure would result in a contained, safe engine shutdown. By introducing the added operational margin of the LTMCC with the new turbopumps, the Block II SSME was twice as safe as the Phase II SSME.



SSME Turnaround Operability

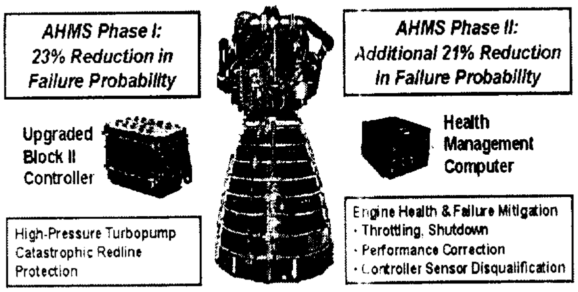
The first two single-engine flights of the Block II occurred on STS-104 and STS-109 in July 2001 and March 2002, respectively, followed by the first 3-engine cluster flight on STS-110 in April 2002. The HPFTP had accumulated 150,843 seconds of engine test maturity at the time of the first flight and is continuing a reliability demonstration test program to validate the 10 mission between overhaul goal.

Overall, the SSME program is projected to reach the 1 million seconds hot-fire milestone by early 2003. This unprecedented level of testing has established the SSME as the world's most reliable booster engine, demonstrating a single engine reliability in excess of 0.9995.

Shuttle Upgrades

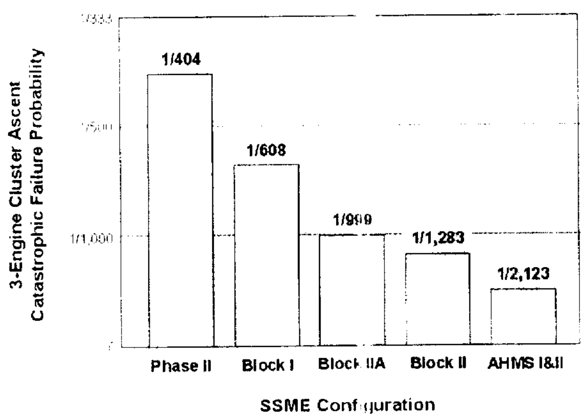
The Space Shuttle, having flown only a quarter of its design life, will continue to be NASA's reusable space transportation system workhorse. But the SSME continues to adapt new technology and processes to meet evolving program needs.

Upgrades to the Space Shuttle are defined into two broad categories: safety and supportability. The current upgrade plan calls for high priority safety upgrades to significantly reduce the risk of a catastrophic loss of a vehicle. Significantly is the SSME Advanced Health Management System (AHMS). The AHMS improves real time monitoring of engine performance, provides health advisories to the crew and ground operations, improves engine malfunction responses, and streamlines ground turnaround operations. The Quantitative Risk Assessment System (QRAS) analysis shows implementation of both Phase I and II of AHMS reduces SSME ascent risk by over 40% to 1 in 2,123 flights.



SSME Advanced Health Management System

The data acquisition system for real-time vibration monitoring flew on STS-96, advancing AHMS maturity.



QRAS SSME Ascent Risk Reduction

Technology Demonstrations

The SSME, by virtue of being the only reusable booster engine, has shown to be an adaptive test bed for advanced technologies supporting both NASA and the Air Force.

The SSME test program pioneered the use of plume emission spectrometry beginning in 1986 as a non-intrusive means to characterize rocket engine health. This diagnostic tool has proven to be highly accurate at detecting abnormal engine wear not recorded on other engine measurements.

Early 'bomb' combustion stability testing of the LTMCC prototype as well as the first high-pressure turbopump hydrostatic bearing tests was conducted on NASA's Technology Test Bed Engine 3001. TTB also supported X-33/RLV studies by demonstrating operation beyond the STS envelope: deep throttling to 10% thrust, abbreviated chill-downs, reduced propellant inlet pressures and temperatures, and mixture ratio excursions up to 6.9.

The low cost Universal Main Combustion Chamber (UMCC) prototype tests with NASA's Advanced Space Transportation Program provided valuable design data for the XRS-2100 aerospike engine and the Delta IV RS-68 engine.

Boeing utilized the robustness and reusability of the SSME in a recoverable propulsion module concept as their entry into the 1995 Air Force EELV competition. SSME Engine 2107, protected by an inflatable water shield, was dropped into the Mississippi River, recovered, dried and inspected, and hot-fire tested to prove concept viability.

Summary

The SSME embodies the relentless pursuit to set liquid propulsion standards for safety, reliability, reusability and performance. Through constant innovation of technology and processes, the ascent risk has been reduced by a factor of 2 with an additional factor of 2 potential from future upgrades. The implementation of Block I and II into the fleet marks an operational era where meeting the manifest and supportability are met by system robustness through added margin and failure elimination, cost effective producible designs, and streamlined turnaround operations. The SSME continues to push the reusability envelope by extending fleet leaders and overhaul intervals, backed by nearly 1 million seconds of hot fire experience. Future improvements are envisioned to assure the capability of the SSME fully support the Space Transportation System well into the 21st century.

References

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Block II SSME Operability Improvements, B. Beckman, J. Chilton and F. Jue, AIAA 97-2819, 33rd AIAA Joint Propulsion Conference