



## **AIAA 97-2686 SSME Key Operations Demonstration**

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# SSME KEY OPERATIONS DEMONSTRATION

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## ABSTRACT

A Space Shuttle Main Engine (SSME) test program was conducted between August 1995 and May 1996 using the Technology Test Bed (TTB) Engine. SSTO vehicle studies have indicated that increases in the propulsion system operating range can save significant weight and cost at the vehicle level. This test program demonstrated the ability of the SSME to accommodate wide variation in safe operating ranges and therefore it's applicability to the SSTO mission.

A total of eight tests were completed with four at Marshall Space Flight Center's Advanced Engine Test Facility and four at the Stennis Space Center (SSC) A-2 altitude test stand. Key demonstration objectives were: 1) Mainstage operation at 5.4 to 6.9 mixture ratio; 2) Nominal engine start with significantly reduced engine inlet pressures of 50 psia LOX and 38 psia fuel; and 3) Low power level operation at 17%, 22%, 27%, 40%, 45%, and 50% of Rated Power Level. Use of the highly instrumented TTB engine for this test series has afforded the opportunity to study in great detail engine system operation not possible with a standard SSME and has significantly contributed to a greater understanding of the capabilities of the SSME and liquid rocket engines in general.

## INTRODUCTION

Single stage to orbit (SSTO) launch vehicles require low vehicle dry weight in order to achieve the high propellant mass fraction (about 90%) required to accomplish the SSTO mission. This requires minimum vehicle structure weight as well as high propulsion system thrust-to-weight (T/W). The following SSTO design parameters assist in achieving the desired vehicle mass:

- a) Low pressure propellant tanks would allow reduced tank dry weight through reduced wall thickness. This low tank pressure provides lower inlet pressures to the engine and therefore drive engine tank head start requirements.
- b) Reduced temperature propellants (also referred to as 'subcooled' or 'densified' propellants) would allow

reduction in tank volume and therefore structure weight. The engine inlet temperature may be similarly reduced, which can impact engine start characteristics.

- c) Vehicle ascent trajectory is controlled through engine thrust vector control (TVC) and engine throttling. The engine throttle limits are driven by vehicle gross lift off weight (GLOW) and acceleration limits (payload and/or vehicle structural limits as the vehicle continues to accelerate due to propellant consumption). Typical payload and crew acceleration limits are three times the acceleration due to gravity. Typical SSTO study propulsion system throttle ranges are 50 to 100% thrust (vertical landers can require significantly greater throttle ranges). A wide throttle range impacts pressures, temperatures and flowrates throughout the engine system. Combustion stability can also be adversely impacted.
- d) Wide engine propellant Mixture Ratio (MR) operating range would allow improved tailoring of engine performance to desired vehicle ascent trajectories. This can be accomplished by propellant utilization control (to minimize tank residual propellant mass at engine cutoff) or increased thrust at low altitude using increased MR and increased specific impulse (Isp) at high altitude using reduced MR. A broader MR operating range can impact engine turbine temperatures and coolant supply flowrates.
- e) Reduced engine prestart cryogenic propellant system chill requirements would improve prelaunch operability and either reduce the duration or the amount of prechill flow required to recover from an unplanned launch countdown hold.

An SSTO propulsion system would be required to operate acceptably within the above vehicle design parameters, which are outside of the typical operating range for most liquid rocket engines. Significant analyses and engine test demonstrations were conducted by Rocketdyne and NASA-MSFC using a highly instrumented SSME in support of Reusable Launch Vehicle (RLV) Phase A studies and preliminary vehicle designs. These efforts demonstrated mature liquid rocket engine operational capability currently exists and is applicable to the SSTO mission goals. This paper discusses eight SSME demonstration tests, conducted in 1995 and 1996, and their applicability to SSTO goals.<sup>1</sup> Table 1 illustrates the SSTO benefits of the objectives demonstrated during these tests.

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Table 1. SSTO Benefits from Improved Engine Operability

Test Objective	SSTO Benefits
<ul style="list-style-type: none"> <li>✓ 6.5 – 6.9 mixture ratio operation</li> <li>✓ Subcooled propellant</li> <li>✓ Throttling                             <ul style="list-style-type: none"> <li>✓ 80%, 50%, 45%, 40%</li> <li>✓ 25% dwell</li> <li>✓ 10:1 thrust</li> </ul> </li> <li>✓ Extend hydrostatic bearing experience base</li> <li>✓ Low start box pressures                             <ul style="list-style-type: none"> <li>✓ 40 psia H<sub>2</sub>/80 psia LOX</li> <li>✓ 40 psia H<sub>2</sub>/65 psia LOX</li> <li>✓ 38 psia H<sub>2</sub>/57 psia LOX</li> <li>✓ 38 psia H<sub>2</sub>/50 psia LOX</li> </ul> </li> <li>* One-day turnaround</li> <li>✓ Minimize engine prechill time</li> </ul>	<ul style="list-style-type: none"> <li>Minimize vehicle dry weight</li> <li>Improve operability/minimize vehicle dry weight</li> <li>SSTO mission mainstage requirements</li> <li>SSTO mission abort/restart option</li> <li>Restart option</li> <li>Improved engine life and operability</li> <li>SSTO thin-walled tanks, shorter vehicle, aft LOX tanks</li> <li>Improved operability</li> <li>Improved operability</li> </ul>
<ul style="list-style-type: none"> <li>✓ Test completed</li> <li>* Nozzle repair work prevented running last test and lengthened engine drying time.</li> </ul>	

97PD-037-001

### SUMMARY OF OBJECTIVES DEMONSTRATED

The TTB engine test 902-641, conducted on May 4, 1996, concluded a highly successful eight-test series designed to demonstrate the versatility of the SSME for key SSTO objectives. A summary of the eight tests and results is shown in Table 2. Key objectives demonstrated during the test series were:

- Mainstage operation between at 5.4 to 6.9 mixture ratio (standard MR = 6.0);
- Nominal engine start with engine inlet pressures of 50 psia LOX and 38 psia fuel (standard LOX = 103 to 111 psia, fuel = 43 to 47 psia), and LOX inlet temperature subcooled to 160°R (standard = 170.5 to 178°R);
- Nominal operation at low power levels of 17% RPL, 22% RPL, 27% RPL, 40% RPL, 45% RPL, 50% RPL, and 80% RPL (standard power level operation = 65% RPL to 109% RPL); and
- Satisfactory engine LOX chill at 50 psia (standard chill = 85 psia).

Additional achievements include: expanded hydrostatic bearing high pressure oxidizer turbopump (HPOTP) experience base, nominal high pressure fuel turbopump (HPFTP) operation at first rotor critical speed, demonstrated combustion stability at low power level, enhanced power balance and transient model capability due to new operating data points, improved definition of nozzle flow separation heat loads, and expanded margin demonstration testing for nominal SSME operation, including dem-

onstrated safe operation with a 12 lb/sec nozzle fuel leak.

Use of the highly instrumented TTB engine (S/N 3001) for this test series has afforded the opportunity to study in great detail engine system operation not possible with a standard SSME and has significantly contributed to a greater understanding of the capabilities of the SSME and liquid rocket engines in general.

### TEST PROGRAM PLANNING

Based on the expected SSTO/RLV mission profiles, a test program was designed to demonstrate key SSME operating characteristics. A joint NASA/Rocketdyne team was established to define a test plan and conduct testing on the TTB engine. The team worked extensively with the RLV program office and vehicle contractors to best use resources available to the program. Test objectives, benefits, and priorities were derived jointly and are summarized in Table 1. The program schedule is shown in Figure 1.

Another joint team responsibility was to determine and assess all technical issues and overall system risk, and perform all necessary steps to run the tests in a timely and safe manner. The tests at MSFC were performed based on analysis completed by a team of Rocketdyne and MSFC personnel working all issues closely together with NASA as the lead for final test approval. The tests completed at SSC had a full Rocketdyne team and key individuals from NASA. Rocketdyne acted as lead for final SSC test approval.

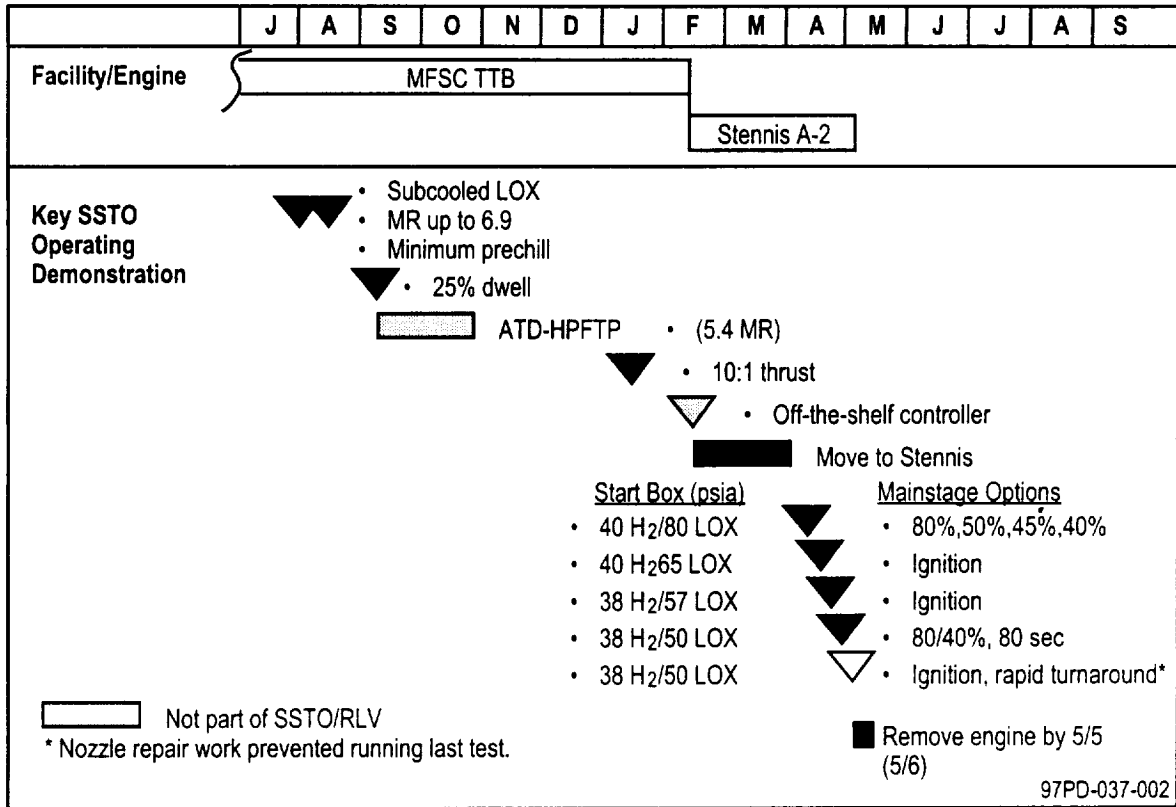


Figure 1. SSME Demonstration Test Plan and Schedule

Table 2. Completed SSME Demonstration Test Matrix

Test Variables	Flight Engine	Test Number TT801-XXX				Stennis 902-XXX			
		060	061	062	065	638	639	640	641
• Test Duration, sec	-	130	110 Planned 59.4 Actual	7.5	17.5	160 Planned 148 Actual	1.9	1.9	80
• Power Level	104%	90%	100%	27%	17%	40%	-	-	40%
• Abbreviated Chilldown (min)	90	78	41	30	-	-	-	-	-
• Reduced LOX Inlet Temps (°R)	170	166.4	161	-	-	164	163.5	161	160.5
• High MR	6.011	6.94	6.86	-	-	6.0	-	-	6.0
• Reduced Prop. Inlet Press. (psia)	45/105 (fuel/LOX)	-	-	-	-	40/80	40/65	38/57	38/50
• Hydrostatic Bearings (starts)	N/A	8	9	10	13	15	16	17	18
Test Completion Date		8/4/95	8/25/95	9/15/95	1/17/96	4/22/96	4/25/96	4/29/96	5/4/96

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### DISCUSSION OF TEST RESULTS

The SSME engine used in this test series is a Phase II engine. It has a three-duct powerhead and standard throat main combustion chamber (MCC). The HPOTP unit no. 4404 is a hydrostatic bearing pump. All additional hard-

ware was Phase II for the eight tests completed for RLV demonstration. Test 801-064 is included as additional data which demonstrates mixture ratio operation at 5.4. Test 801-064 was not part of the RLV demonstration testing but demonstrated an objective applicable to RLV. Test 801-064 used an alternate HPFTP.

The first four tests were conducted at MSFC's Advanced Engine Test Facility (AETF) with MSFC test personnel conducting the readiness reviews, tests and data reviews. Engine 3001 was then transferred to Stennis Space Center for the remaining four tests. The A-2 test stand was selected because of the availability of the diffuser for altitude simulation. This allowed engine operation at low power levels, which without a diffuser would produce high nozzle sideloads.

### High/Low Mixture Ratio Demonstration

The engine operating mixture ratio for SSTO missions may be different than the standard MR of 6.0 as is used in the Space Shuttle program today. Higher MR values can be beneficial from a payload standpoint and various SSTO concepts have been studied with engine MR values up to seven. At high altitudes, it may be advantageous to lower MR (5.4) to obtain higher Isp performance. Engine 3001 was run at both high and low MR operating conditions at the TTB test stand at MSFC to demonstrate the SSME mixture ratio capability (Figure 2). The nominal SSME MR during shuttle flights is 6.0. The data provided an excellent opportunity to anchor prediction models and expand component performance databases.

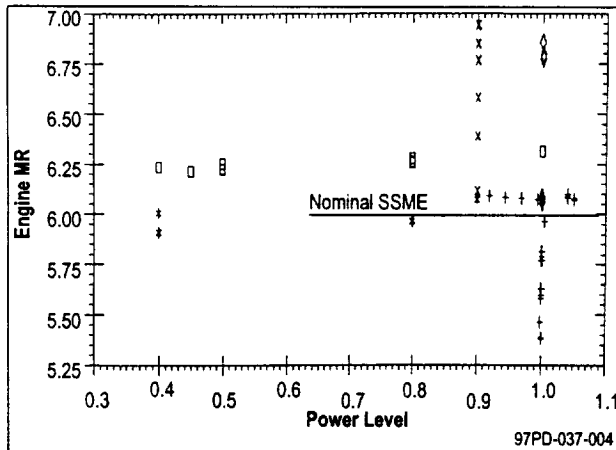


Figure 2. SSME Demonstration of Mixture Ratio Range

Tests 801-060 and -061 involved high mixture ratio operation with Engine 3001 at constant power level conditions. Test 801-060 was conducted at 90% power level, with varied MR from 6.0 up to 6.95 in incremental steps during the test. Test 801-061 was conducted at 100% power level, with MR varied from 6.0 to 6.86. The engine showed stable transition between MR values.

The test results from the TTB test series demonstrated mixture ratio control capability and turbomachinery operation at the off nominal MR. Test 801-061 was terminated prematurely due to a high oxidizer turbopump turbine discharge temperature at a MR of 6.86 and 100% power level. The high temperature operation of the HPOTP turbine was primarily due to the "balancing" of the fuel flow to the high pressure turbines being targeted for a 6.0 MR with today's SSME configuration. By rebalancing the fuel flow to the high pressure turbines and incorporating a Block II SSME large throat MCC, the HPOTP can be run at cooler operating temperatures during high MR conditions. This approach could be used for an SSTO application to obtain higher power levels and/or provide longer hardware life.

Although not part of this program, low mixture ratio operation at 5.4 was demonstrated on test 801-064 at 100% power level. This test was part of the development testing of the SSME alternate HPFTP. Engine 3001 showed stable, successful transition between 6.0 and 5.4 MR in 0.2 MR steps. Turbomachinery and control system performance were as expected.

### Low Engine Inlet Pressure Demonstration

In order to reduce vehicle tank weights, it was desired to demonstrate that the SSME can start at reduced engine inlet pressures. Since the SSME utilizes a tank head start, reductions in tank pressure reduce engine inlet pressure available to establish engine start flowrates. The goal was to demonstrate an acceptable start with a LOX inlet pressure of 50 psia and a fuel inlet pressure of 38 psia with a LOX inlet temperature of 161 R (subcooled propellant). This was accomplished with nominal engine transients during Test 902-641, and the engine was ramped into mainstage successfully. Standard SSME conditions are a LOX inlet pressure of 103 to 111 psia, a fuel inlet pressure of 43 to 47 psia, and a LOX inlet temperature of 178°R. It was decided to reduce the inlet pressures incrementally during the four test series to minimize the possibility of engine damage. Tests 902-638 to 902-641 had LOX inlet pressures of 80, 65, 57, and 50 psia, fuel inlet pressures of 40, 40, 38, and 38 psia, and LOX inlet temperatures of 164, 163.5, 161, and 160.5°R respectively, all with nominal operation. Tests 902-639 and 640 were 1.9 second ignition tests.

Key issues which drove the modifications necessary to conduct a nominal start at reduced pressure were HPFTP pump boilout, igniter operation, and the HPFTP turbine thermal environment. Reductions in engine inlet pressure reduce engine flowrates, and therefore engine

power and transient buildup characteristics. Start transients were kept similar to the SSME database buildup characteristics.

Fuel preburner oxidizer valve (FPOV) and oxidizer preburner oxidizer valve (OPOV) flow area increases were used to compensate for the reduced LOX inlet pressure. It was decided not to compensate for the reduced fuel inlet pressure. This was assessed as unnecessary and the start was allowed to slow down with reduced fuel inlet pressure. The final family of reduced inlet pressure transients are slightly slower than previous experience because no attempt was made to compensate for the reduced fuel flow. The digital transient model (DTM) was used to determine the valve sequences for the FPOV, OPOV, and main oxidizer valve (MOV). Model predictions of the start transients were very close to actuals with nominal operation during the entire start series. Modeling was performed by MSFC with technical input from Rocketdyne.

The HPFTP turbine thermal profile was satisfactory and within the nominal SSME database. HPFTP unit number 2604 has an instrumented turbine which allowed for detailed verification of the turbine environment. Posttest inspections also revealed no turbine degradation.

### Subcooled Propellant Start Effect

As predicted, using the SSME DTM, injector prime times and engine start transients are faster in buildup with reductions in LOX inlet temperature. An improved correlation between LOX inlet temperature and injector prime times was determined based on reductions in inlet temperature during tests 801-060 and -061. Overall start transients were nominal with subcooled LOX as predicted. No concern has been found with the effect of subcooled propellants on start transients.

### Low Power Level Operation

A total of four tests were completed. The first two tests at MSFC were conducted at very low power levels from 27% RPL down to 17% RPL. The last two tests at SSC, using an exhaust driven diffuser, were longer duration tests at power levels between 40% RPL and 100% RPL.

The SSME DTM was used to predict first time operation at very low power levels (<27% RPL) with great success.<sup>2,3</sup> The initial tests on TTB 801-062 and -065 were used to demonstrate very low power level operation. Both tests were run in open loop control operation. Again, MSFC performed the modeling with technical input from

Rocketdyne, with eventual dual modeling to double check results and facilitate quick analysis and retest. After low power level data was obtained during test 902-639, the power balance model (PBM) was anchored to the data and used to make predictions for 902-641, also with great success.<sup>4</sup>

Test 801-062 (Figure 3) ran a programmed duration of 7.5 seconds, including five seconds at 27% RPL, with nominal operation. This test was an extension of the nominal 'plateau point' at engine start plus two seconds which the SSME dwells at for 0.5 seconds during every start. The chamber coolant valve (CCV), which would nominally run at 70% open, was run at 40% open to increase turbine temperatures in order to prevent turbine icing at low combustion temperatures.

Test 801-065 (Figure 3) ran a programmed duration of 17.5 seconds which included five seconds at 22% RPL and five seconds at 17% RPL with nominal operation. The 17% RPL demonstrated an RLV-equivalent sea-level thrust of 12.6% for a large throat SSME with a 14:1 expansion ratio nozzle. There were no surprises and operation was very near predictions. The HPFTP operated at the first rotor critical speed at 17% RPL with nominal operation.

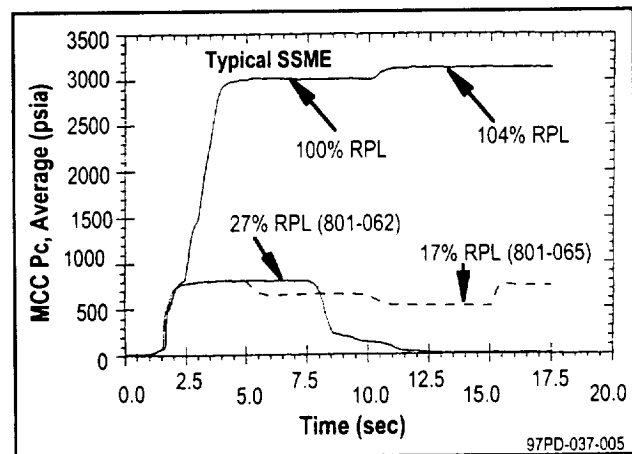


Figure 3. Low Power Level Test Demonstrations

The very low MR operation on tests 801-062 and 801-065 was under open loop control which was necessary to ensure a safe margin from the HPFTP boilout point and to achieve adequate cooling of the MCC at the low power level conditions. MRs were 3.9, 3.6 and 3.0, at 25%, 22% and 17% RPL, respectively as shown in Figure 4.

HPFTP pump boilout was the most significant issue which drove the engine system operating point balance.

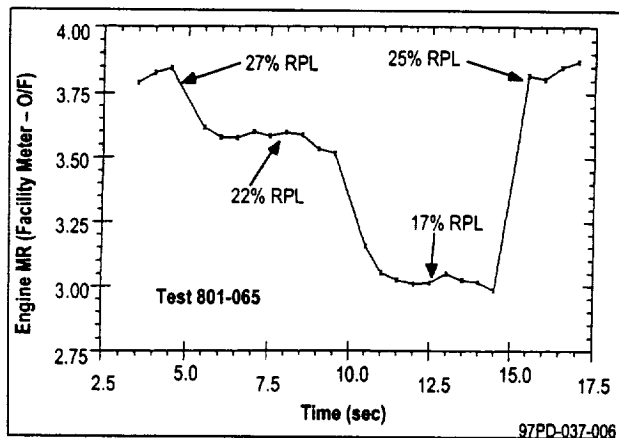


Figure 4. Open Loop Mixture Ratio Control at Very Low Throttle

Adequate fuel flow was mandatory to guard against boilout but since the OPOV (oxidizer control) was running at minimum flow area, the FPOV (fuel control) had to be used to further reduce engine power at the risk of HPFTP boilout. The main oxidizer valve which controls oxidizer flow to the main chamber was also used to reduce power but in turn increases turbine pressure ratios and forces turbine oxidizer flow up, so it was decided to minimize its use. A redline was set up which would terminate the test safely if the HPFTP flow divided by speed ( $Q/N$ ) dipped below 0.24. The predicted boilout point based on pump performance maps is 0.1, but that number is analytical and, due to the criticality of the failure mode, required a robust margin of safety. The test data revealed the HPFTP flow coefficient was as predicted; 0.286 at 17% RPL. In the future, if very low power levels with higher MR ( $>3.0$ ) are desired, a pump flow test is needed to establish safe operating lower  $Q/N$  limits.

The second series of low power tests were run with a diffuser at A-2 test stand at SSC. SSTO studies indicated throttling below 50% RPL may be required. An evaluation of the facility diffuser performance indicated capability of running the SSME as low as 33% RPL with sufficient diffuser margin.

Test 902-638 (Figure 5) ran 148 seconds of a programmed 160 seconds and shutdown prematurely due to a 12 lb/sec nozzle fuel leak leading to excessively high HPOTP turbine discharge temperatures and violation of the 1760°R turbine redline. A post-test PBM data reduction run was used to back out performance with the nozzle leak removed. The analysis revealed operation would have been very near DTM predictions without the nozzle leak. This test included 50 seconds at 80% RPL, 50 seconds at 50% RPL, 20 seconds at 45% RPL and eight seconds at 40% RPL.

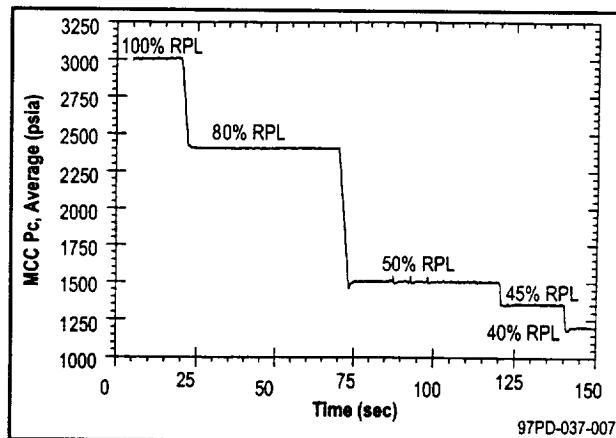


Figure 5. Test 902-638 Low Throttle Demonstration

Test 902-641 ran a programmed duration of 80 seconds. This test was started to 80% RPL and ramped to 40% RPL at 25 seconds and ramped back to 80% RPL at 65 seconds, with shutdown at 80 seconds. Pretest predictions were made with the PBM which was anchored to low power level data after 902-638. Nozzle leakage was less than 1 lb/sec (after nozzle leak repairs) and predictions were very close to observed data. Shutdown from 80% RPL was nominal as predicted by the SSME digital transient model. Overall operation was nominal.

### Engine Chill

In 1993, a study was initiated at MSFC to investigate the chilldown characteristics of the SSME prior to engine start. The current requirement for chilldown duration is 90 minutes of continuous flow in the oxidizer and fuel systems. The intent of the study was to provide justification for abbreviating the required time to chill the engine. Engine 3001, with highly instrumented high pressure oxidizer and fuel pumps, was used to characterize the thermal response of the engine and subsystems. Temperatures on all the major component housings and individual piece parts were reviewed to determine the minimum required chill duration to achieve thermal equilibrium.

Based on this study, a minimum chilldown duration of 30 minutes was recommended for use on the SSME. To demonstrate the results of the study, three tests were planned to reduce the LOX chilldown duration in steps. The first test, 801-060, reduced the chilldown duration from 90 minutes to 78 minutes, the second, 801-061, reduced the chilldown duration to 41 minutes, and the third test, 801-062, reduced the chilldown duration to 30 minutes. Post-test data review and hardware inspections indicated no anomalous conditions.



These tests demonstrated the current SSME requirement for engine chilldown of 90 minutes could be abbreviated to 30 minutes without any effect on engine operation or performance. This result could be used to shorten pretest operations and reduce the recycle time required due to a stop flow condition during pre-launch operations.

The above MSFC chilldown tests were at nominal inlet chilldown pressures. An additional series of tests at SSC were conducted to evaluate the impact of lower chilldown pressures. Lower start pressures due to SSTO tank structural constraints require engine chilldown inlet pressures that do not exceed the planned tank pressures. A series of four LOX system chill tests were conducted during the four SSC tests. A LOX system chill at 50 psia engine inlet pressure was achieved on test 902-641.

LOX was introduced into the engine at tank head pressure (approximately 43 psia) for 45 minutes to chill the engine hardware to the equivalent saturation temperature. Then the inlet pressure was increased to 50 psia, raising the flowrate and the saturation temperature. After approximately five minutes, the facility engine inlet bleed was opened to lower the temperature of the LOX entering the engine. The combination of the increased flow, increased saturation temp. and reduced engine inlet temperature caused the oxygen throughout the engine to change from two phase to liquid. The temperatures throughout the engine stabilized 1500 to 2000 seconds later. The total time to achieve a satisfactory chill was approximately 85 minutes. Throughout this chill procedure the facility LOX bleed back pressure valve was kept fully open. It was found crucial during the chilldown to maintain LOX pump inlet temperature at the subcooled 161°R temperature. Additional propellant feedline insulation was required to minimize heat loss and was added prior to test 902-640.

Based on test 902-641 data, it is possible to shorten the chill time by;

- a) Reducing the 45 minutes at tank head chill to 30 minutes.
- b) Lowering the inlet temperature (by opening the inlet bleeds) immediately instead of waiting five minutes.

### **Rapid Engine Test Turnaround**

A one-day rapid turnaround test had been planned for the end of this test series to demonstrate engine operability. The engine pre-test chill and post-test drying time reductions were important elements of the quick turnaround goal.

The previously discussed nozzle tube leakage caused great difficulty in achieving engine dryness requirements within even the standard eight-hour requirement. As a result, the one-day turnaround testing was not conducted. Efforts were in work to prepare a replacement nozzle. However the SSC A-2 test stand schedule necessitated the removal of the instrumented engine 3001 to support shuttle flight program needs (acceptance test of a flight engine).

### **Additional Achievements**

A number of additional achievements, listed below, were accomplished during demonstration testing.

#### **Hydrostatic Bearing HPOTP**

The rotordynamic performance of the hydrostatic bearing HPOTP 4404 during the SSTO test series was consistent and stable during all power levels and engine conditions. The hydrostatic bearing provided excellent rotor support under all load conditions with no degradation during the test series. The bearing rotordynamic performance was evaluated based mainly on the proximity probe data from the two sensors which monitored the hydrostatic bearing journal.

The condition of the bearing does not indicate any noticeable degradation over the 18 starts accumulated on the hydrostatic bearing. Satisfactory bearing performance has been demonstrated at key power levels between 17% RPL and 109% RPL. Satisfactory rotordynamic performance was achieved over this same range with no excessive or unstable vibration response or any subsynchronous vibrations of the turbopump.

#### **HPFTP Critical Speed Operation**

During test 801-065 at 17% RPL, the HPFTP operated at the first rotor critical speed with nominal operation and very low vibration levels as predicted, due to high damping of the turbopump shaft. First rotor critical speed is calculated to be 14,900 RPM. The HPFTP operated at a minimum of 15,300 rpm during test 801-065.

#### **Combustion Stability at Low Power Level**

Engine 3001 has several special pressure measurements that allow measurement of the pressure drops across the preburner injectors. The fuel flow pressure drops were verified from the special pressures available and are in good agreement with the injector modeling used for engine performance predictions.

High frequency sensors did not show any evidence of combustion stability problems. The close coupling of the OPOV and FPOV control valves to the injectors protects against chugging. The pressure drops across the control valves during the tests are large and provide protection against chugging on the SSME at low power levels.

#### Nozzle Operation During Flow Separation

Nozzle steady state loads were obtained under flow separation conditions at low power level operation during tests 801-062 and -065. Nozzle separation heatload was higher by a factor of two than predicted by the model. (Heat load under separation conditions is difficult to model. The pretest estimate was conservative.) Updating the SSME DTM with actual test data allowed better understanding of transient separation heatload observed during engine start and shutdown and is an aid to general SSME operation.

#### SSME Margin Demonstration Testing

This testing served as SSME margin testing in a number of areas. The one-half second dwell at the plateau during start was run nominally for five seconds and indicates the plateau is a very stable operating point. Turbomachinery operation at very reduced speeds and pressures indicates the robust operating characteristics of the hardware. Safe engine operation was observed with a 12 lb/sec nozzle leak, the largest in SSME history. The fuel preburner was operated at 700°R (average), the lowest mainstage temperature in the SSME database. The HPFTP mainstage flow coefficient was 0.286. The lowest flow coefficient in the mainstage SSME database prior to this was 0.33.

#### General Engine Performance

Generally speaking, Engine 3001 can be classified as a lower performing Phase II engine within the SSME family, with lower performing high pressure pumps. The powerhead and MCC have well known pre-existing performance degradations including: seven deactivated injector posts, 36 widened BLC holes, and 3.2 lbm/sec MCC coolant leakage at 100% RPL (3006 psia chamber pressure). These contribute to warmer turbine temperatures and higher propellant consumption for Engine 3001. Isp is approximately four seconds lower (at 100% RPL) for Engine 3001 due to these degradations.

Engine 3001 had been tested 40 times prior to this eight-test series. The design life for this specially instrumented engine was 25 tests and most of the major compo-

nents were not new at engine assembly. At the last test of this series (there were three intervening non-SSTO tests), Engine 3001 had been tested 51 times. The powerhead had 92 tests, the main combustion chamber had 92 tests, and the nozzle had 54 tests.

On top of the known degradations, the nozzle suffered six tube ruptures during test 902-638 along with numerous locations of smaller “blowing” leaks. This caused an estimated 12 lbm/sec nozzle fuel leak. The large increase in demand for oxygen to maintain chamber pressure (dictated by the onboard controller) caused the oxygen system to power up. The excessive oxygen demand drove HPOTP turbine temperatures to redline values (1760°R) during 100% RPL operation.

This nozzle is a high time nozzle with numerous prior tube leaks which were a known risk to test duration. Unfortunately, it was the only nozzle available in the short test window to support testing and had to be used. All objectives were met despite the performance of this nozzle.

#### CONCLUSION

The SSME is a proven, versatile rocket engine. This test program demonstrated the ability of the SSME to accommodate wide variation in operating ranges as illustrated in *Figure 6*. The test program also advanced liquid rocket engine modeling and analysis in general with the utilization of the highly instrumented TTB engine. The demonstrated prediction capability of the SSME Digital Transient Model and the Power Balance Model was excellent. The close teamwork of Rocketdyne and MSFC was quite rewarding and sets the stage with high confidence for future demonstration testing. The results of these tests will have a beneficial impact on future SSME operation in general. As a result of this successful test program, the space shuttle program is currently considering implementation of expanded SSME operability.

#### RECOMMENDATIONS

Technical issues and lessons learned for future SSME tests of this nature:

##### High Mixture Ratio

High mixture ratios up to 6.9 should be achievable with the current Block II SSME engine with a minor orifice modification for fuel distribution to the preburners to reduce HPOTP turbine temperatures and achieve component life/margin requirements.

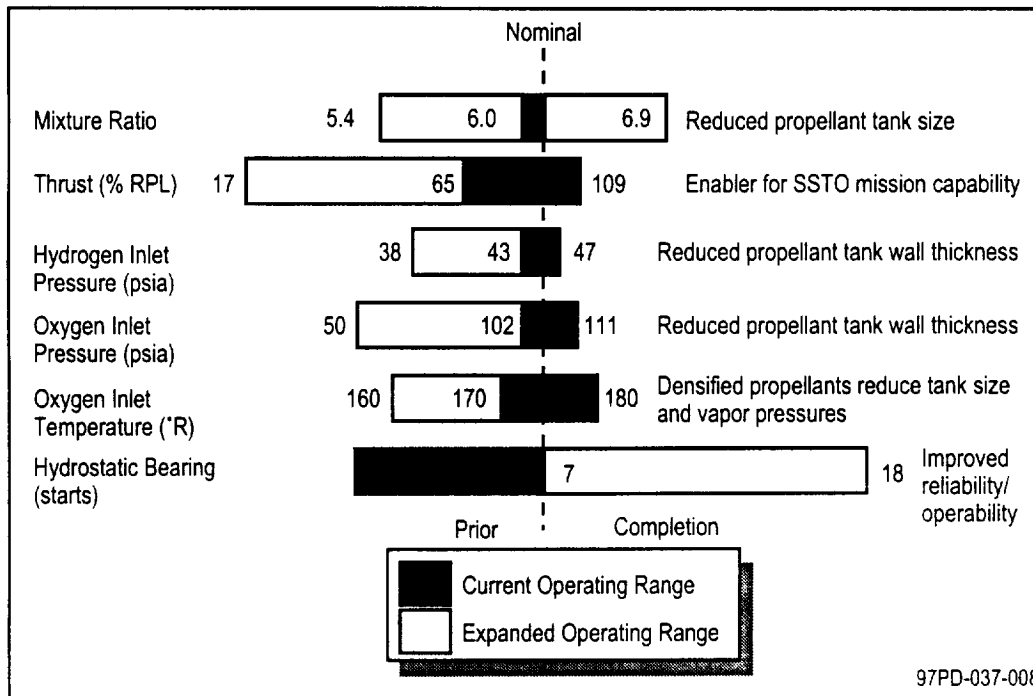


Figure 6. Expanded SSME Operating Range

### Low Start Pressures

There is high confidence the engines can start reliably for inlet pressures as low as 38 psia hydrogen and 50 psia LOX.

### Subcooled LOX

No issues were identified with running subcooled LOX to conditions as low as 160°R. It is recommended that temperature sensors be added to the facility propellant tanks to verify bulk temperatures for information purposes.

### Throttling

Throttling to as low as 40% RPL is feasible with no hardware modifications.<sup>§</sup>

Throttling as low as 17% RPL is feasible but a development program would be required to achieve higher mixture ratios. This includes:

- 1) Recommend FPOV and OPOV valves that have control below the current leakage band at very low flowrates. This will allow closed loop control operation below 40% RPL.

<sup>§</sup> It is assumed that a nozzle specifically suited to SSTO vehicle requirements will be designed.

- 2) HPFTP flow tests are needed to anchor the pump boilout region at low flow conditions.

### Chill

LOX chilldown time can be reduced from 90 to 30 minutes at current engine inlet conditions. Chilldown can be achieved at inlet pressures as low as 50 psia but will require correspondingly lower inlet temperatures.

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