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Space Shuttle Main Engine Off-Nominal Low Power Level Operation

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SSME OFF-NOMINAL LOW POWER LEVEL OPERATION

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ABSTRACT

This paper describes Rocketdyne's successful analysis and demonstration of the Space Shuttle Main Engine (SSME) operation at off-nominal power levels during Reusable Launch Vehicle (RLV) evaluation tests. The nominal power level range for the SSME is from 65% rated power level (RPL) to 109% RPL. Off-nominal power levels incrementally demonstrated were: 17% RPL, 22% RPL, 27% RPL, 40% RPL, 45% RPL, and 50% RPL. Additional achievements during low power operation included: use of a hydrostatic bearing High Pressure Oxidizer Turbopump (HPOTP), nominal High Pressure Fuel Turbopump (HPFTP) first rotor critical speed operation, combustion stability at low power levels, and refined definition of nozzle flow separation heat loads.

INTRODUCTION

The SSME is a staged combustion cycle engine which burns liquid hydrogen and liquid oxygen, both cryogenic. Two preburners burn a fuel rich mixture to power the high pressure fuel and oxidizer turbopump turbines. This fuel rich mixture is combined with additional oxidizer and fuel (used for coolant) and burned in the main combustion chamber at a mixture ratio of 6 lbs of oxidizer to 1 lb of fuel, (see Figure-1). The SSME is rated at 470,000 pounds thrust at rated power level, with a main combustion chamber (MCC) pressure of 3006 psia (Figure 2). Throttling and power level operation is achieved by varying the fuel preburner oxidizer valve (FPOV) for mixture ratio control and the oxidizer preburner oxidizer valve (OPOV) for power level control.

BACKGROUND

The RLV program has a demonstrator phase entitled X-33. The X-33 phase had three vehicle contractors competing for downselect. Two of the contractors, Rockwell Space Division and McDonnell Douglas, had selected the SSME for the X-33 propulsion system. Based on the expected mission profiles a test program was designed to demonstrate expected key X-33 RLV SSME operating characteristics. Under contract NCC8-45, a joint Rocketdyne/NASA-Marshall Space Flight Center (MSFC) Cooperative Agreement, an SSME Dual Use Test program was set up to define a test plan and conduct testing on engine 3001. This engine is highly instrumented and is also referred to as the Technology Test Bed (TTB) engine. The team worked extensively with the vehicle primes to best use resources available to the program. Key objectives included operation at off-nominal low power level and with reduced engine inlet pressures. A team was created to determine and assess all technical issues, determine overall system risk, and perform all necessary steps to run the tests in a timely and safe manner. The tests at TTB were performed based on analysis completed by a team of Rocketdyne and MSFC personnel working all issues closely together with final test approval from NASA and Rocketdyne management. The tests completed at SSC had a full Rocketdyne team and a few key individuals from MSFC and Stennis Space Center (SSC) with Rocketdyne management providing final approval for test.

The SSME engine used in this test series is a Phase II engine. It has a three-duct powerhead and standard throat MCC. The HPOTP unit no. 4404 is a hydrostatic bearing pump. All hardware was Rocketdyne Phase II hardware in the eight tests completed for RLV demonstration.

DISCUSSION OF RESULTS

Low Power Level Operation

A total of four tests were completed. The first two tests at MSFC were 'dwell' tests at very low power levels from 27% RPL down to 17% RPL. The last two tests were at SSC with an exhaust driven diffuser and were longer duration throttled tests above 40% RPL and less than 100% RPL.

The SSME digital transient model (DTM) was used to predict first time operation at low power levels (<27% RPL) with great success. The initial set of tests on TTB 801-062 and 801-065 were used to demonstrate very low power level operation. Both tests were run in open loop operation.

After low power level data was obtained during Test 902-639 using SSME DTM predictions, the power balance model (PBM) was anchored to the data and used to make predictions for 902-641, also with great success.

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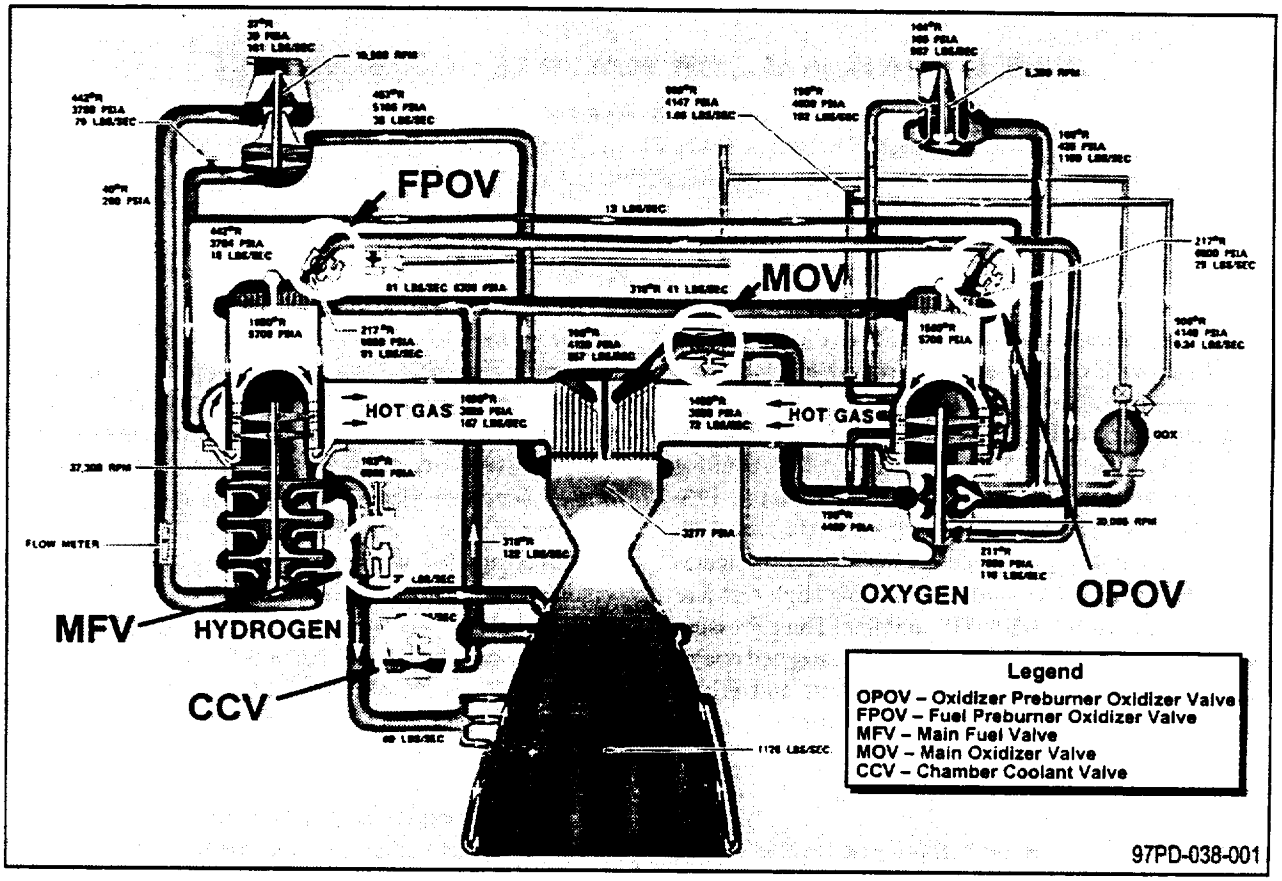

Figure 1. SSME Propellant Flow Schematic

- Rated power level (RPL) 100% — 470,000 lbs
- Rated chamber pressure — 3006 psia
- Specific impulse at altitude — 453.5 seconds
- Throttle range — 65 to 109%
- Propellants — Oxygen/hydrogen
- Weight — 7000 lbs
- Design life — 27,000 seconds, 55 starts

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Figure 2. The SSME is the First Reusable Large, Liquid Rocket Engine

Test 801-062 (Figure-3) ran a programmed duration of 7.5 seconds with five seconds at 27% RPL with nominal operation. This test was an extension of the nominal 'plateau point' at 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. Prior to test, there was concern about icing in the oxygen preburner (OPB) (a critical failure mode), due to low temperatures (<490 R) if the predicted high pressure oxidizer turbopump (HPOTP) turbine discharge temperature of 800 R was high. The higher than predicted nozzle separation heat load combined with the CCV modification resulted in satisfactory temperatures and eliminated the icing concern. Engine thermal stabilization, hardware differences, the CCV modification effect, and mainly nozzle heat transfer due to separation, caused slight variation from the predicted balance. Turbine temperatures were 150 R higher than prediction and engine power was 2% higher than predicted. The model was updated to reflect test data.

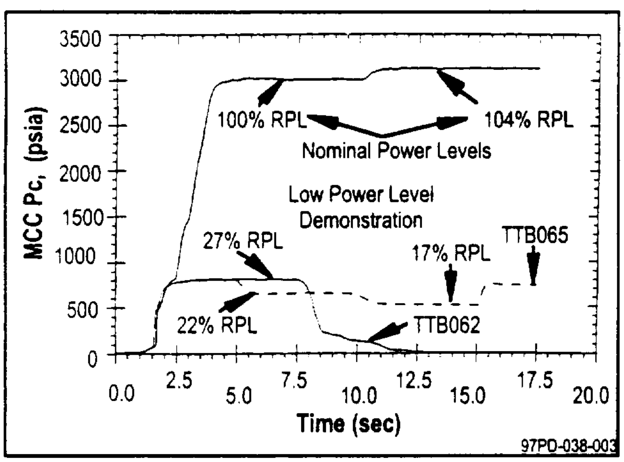

Figure-3. SSME Low Power Levels TTB-062/065

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. There were no surprises and operation was very near prediction (Figures 4 and 5).

The very low mixture ratio (MR) operation on tests 801-062 and 801-065 (the "dwell" tests) were under open loop control. The MR values between 3.0 and 4.0 on those tests was necessary to ensure a safe margin from the high pressure fuel turbopump (HPFTP) boilout point and to achieve adequate cooling of the MCC at the low power level conditions. HPFTP boilout (stall) was the most significant issue which drove the engine system operating point balance. Adequate fuel flow was mandatory to guard against boilout but since the oxidizer preburner oxidizer valve (OPOV) (LOX control) was running at minimum area, the fuel preburner oxidizer valve (FPOV) (fuel control) had to be used to further reduce engine power at the risk of HPFTP boilout. The main oxidizer valve which controls LOX flow to the (MCC) was also used to reduce power but in turn increases turbine pressure ratios and forces turbine LOX flow up so it was decided to minimize its use. A redline was set up which would cut the test if the HPFTP pump flow divided by speed (Q/N) dipped below 0.24. The predicted boilout point based on pump maps is 0.1, but that number is analytical, and due to the criticality of the failure mode required, a robust margin of safety. As test data, revealed the HPFTP flow coefficient was as predicted at .286 at 17% RPL (Figure-6). In the future if very low power levels are desired, a pump flow test program is needed to establish safe operating lower Q/N limits in order to increase MR. Overall engine operation was nominal.

Test 902-638 (Figure 7) ran 148 seconds of a programmed 160 seconds, and shutdown prematurely due to a 12 lb/sec nozzle leak leading (unrelated to test objectives) to excessively high HPOTP turbine discharge temperatures and violating a 1760 R redline. A post-test PBM data reduction run was used to back out performance with the nozzle leak removed. This revealed operation would have been very near prediction. Operation included 50 seconds at 80% RPL, 50 seconds at 50% RPL, 20 seconds at 45% RPL and 8 seconds at 40% RPL.

Slight preburner boost pump (PBP) bi-stability was observed at 50% RPL operation. The PBP flow coefficient is affected by main oxidizer valve (MOV) position and could move up or down based on the MOV setting at constant power level. The SSME digital transient model predicted a HPOTP turbine discharge temperature undershoot would occur when throttling from 80% RPL to 50% RPL. This occurs when throttling the MOV and commanding a power level change at the same time. Normally, the FPOV responds to OPOV crossfeed gain to reduce MR error. Required movement of the FPOV due to OPOV crossfeed gain is insufficient because the MOV when throttled closed reduces MCC Pc and does not require as much normal OPOV movement to produce a power level change. This situation will cause MR variations leading to overshoots and undershoots as predicted. The solution to this problem is to add an additional crossfeed gain from MOV to FPOV during MOV throttling. and is not considered an issue for future operation. Shutdown from 40% RPL was nominal as predicted by the SSME digital transient model.

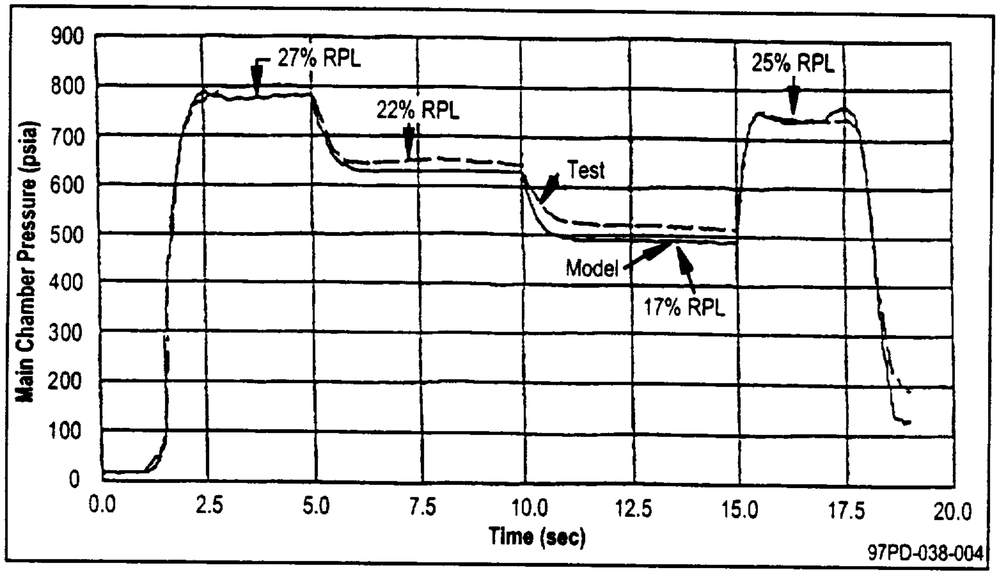

Figure-4. SSME Digital Transient Model Results - TTB-065

Figure 5. Low Power Level Predictions versus Actuals at 17 to 27% RPL

	TTB-062/65 27%RPL	**TTB-065 22%RPL**	**TTB-065 17%RPL**
Parameter	Actual	Pred/**Actual**	Pred/**Actual**
MCC Pc	810/805	645-665/**650**	470/**520**
Engine MR	4.0/3.8	3.0/**3.5**	2.4/**3.0**
Nozzle coolant flow	~27/26	21-23/**21**	15-20/**17.3**
Preburner fuel supply temp.,	410/420	407/**467**	400/**468**
MCC Coolant flow	12/11.4	12/**10.3**	11/**9.5**
MCC coolant discharge temp.	330/341	293/**324**	235/**275**
OPOV position	45.0	44.5	44.0
FPOV position	50.7	47.6	44.6
MOV position	59.3	54.0	49.5
MFV position	100	100	100
CCV position	40	42	44
PBP discharge PR (psia)	2800/2752	2878/**2700**	2940/**2750**
HPOTP discharge PR	1800/1740	1865/**1770**	1980/**1830**
HPOTP speed (rpm)	15900/15000	16200	16400
HPOTP in PR	295/287	300/**300**	290/**310**
OPB Pc	1300/1183	1124/**990**	977/**835**
LPOP speed	3400/3308	3470/**3340**	3450/**3380**
LPFP speed	11000/10861	11150/**10000**	10600/**9400**
HPFTP discharge PR	1870/1874	1625/**1520**	1370/**1280**
HPFTP speed	18700/18600	17400/**16700**	15800/**15300**
HPFTP in PR	175/175	176/**160**	164/**146**
FPB PC	1150/1129	956/**880**	730/**720**
HPOTP turbine discharge temp.	980/970	1030/**1130-1190**	1040/**1230-1300**
HPFTP turbine discharge temp.	930/920	807/**790-890**	660/**670-760**
HPFTP Q/N GPM/RPM	.31/.31	.29-.30/**.29**	.28-.30/**.286**
DTM accuracy 10/10 for 100% on key predictions (within +/- 3σ)			

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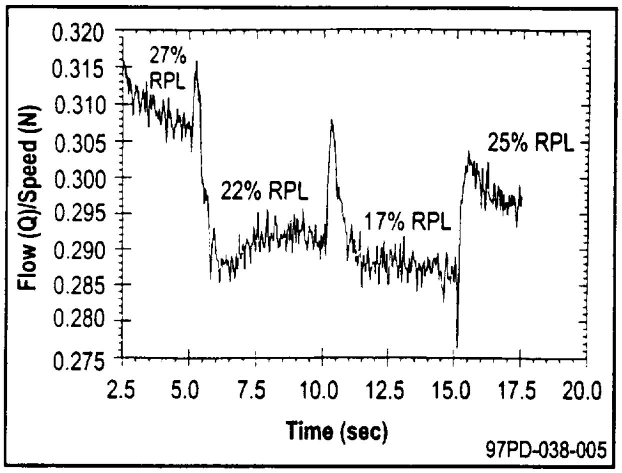

Figure-6. HPFTP Flow Coefficient

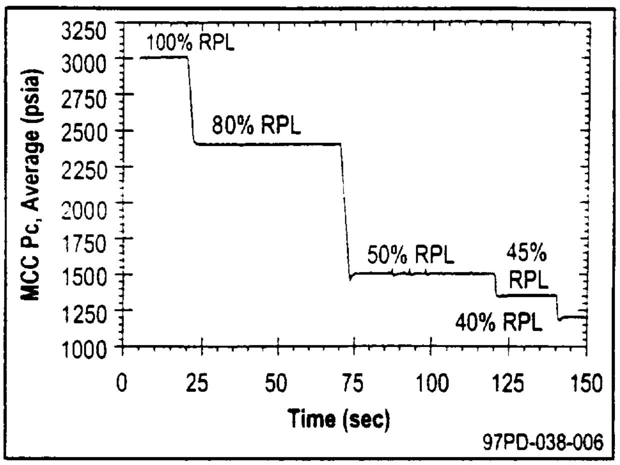

Figure 7. Engine 3001 Test 902-638 Low Power Level Operation

Test 902-641 (Figure 8) 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. As expected HPOTP discharge temperature overshoots and undershoots were observed during throttling. Nozzle leakage was less than 1 lb/sec. and predictions were very close to observed data (Figure 9). Shutdown from 80% RPL was nominal as predicted by the SSME digital transient model. Overall operation was nominal.

ADDITIONAL ACHIEVEMENTS/KEY INFORMATION

Turbomachinery Operation

A host of concerns were raised at the beginning of this effort about the ability of the Rocketdyne SSME turbopumps to handle running successfully at low power levels. This is understandable since the turbopumps had never run at mainstage low power levels. Some of the

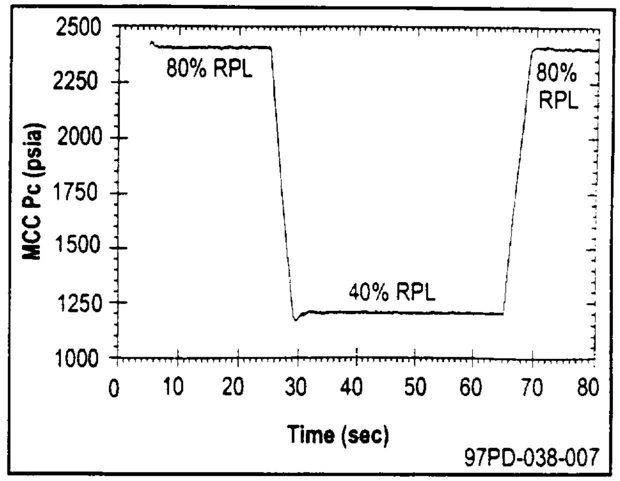

Figure 8. Test 902-641 Low Power Level Operation

issues raised were: the rotordynamic stability of the turbopumps, the ability of the high pressure turbopumps to run at speeds close to the shaft critical speed, The ability of the HPFTP thrust bearing to lift-off at the low Q/N and not cause rotordynamic problems, the ability of the hydrostatic bearing HPOTP to run in the stall region, the possibility of freezing in the high pressure turbopumps turbines which would destabilize the axial thrust and cause the turbine to fail, the turbopumps axial thrust balance at the low power levels, the bi-stability of the HPOTP boost pump, and the performance of the turbopumps at the low Q/N exhibited at the low power levels. Rocketdyne's hydrostatic bearing HPOTP operation was flawless. Slight preburner pump bi-stability was noted at 50% RPL. The HPFTP operated without any problems on top of 1st rotor critical speed (Figure 10). All pump concerns were alleviated by successful operation (Figures 11 to 13)

Combustion Stability at Low Power Level

Engine 3001 has several special pressure measurements that allow for measurement of the pressure drops across the preburner injectors for both fuel and LOX. For the dwell test conditions the injector pressure drops are small due to the small flowrates in the preburners. The fuel flow ΔPs shown in the data reduction printouts were verified from the special pressures available and are in good agreement with the injector modeling used for engine performance predictions. The LOX ΔPs are so small that the measurement resolution of the sensors for those pressure drops don't allow for good verification of the ΔP magnitudes from the test data.

The injector ΔPs for the LOX injectors during the dwell tests generally fall below the standard DP/Pc of 10% which is used as a rule of thumb for adequate protection

Figure 9. Low Power Level Predictions versus Actuals at 40% RPL

Parameter	1-sigma (σ) eng-eng	Pretest Pred	Actual Site	Delta	# of σ
LPOTP speed	61	3555	3480	-75	-1.2
HPOTP speed	374	16710	16575	-135	-0.4
LPFTP speed	319	10560	10635	75	0.2
HPFTP speed	309	20540	20915	375	1.2
HPOT discharge temp. A	51.9	1235	1250	15	0.3
HPOT discharge temp. B	51.9	1265	1260	-5	-0.1
HPFT discharge temp. A	58.7	1245	1295	50	0.9
HPFT discharge temp. B	58.7	1250	1275	25	0.4
OPOV Pos (%)	2.28	51.6	51.2	-0.4	-0.2
FPOV Pos (%)	1.29	56.4	57.1	0.7	0.5
Mixture ratio		5.930	5.910	-0.020	
EFFM speed		1350	1350	0	

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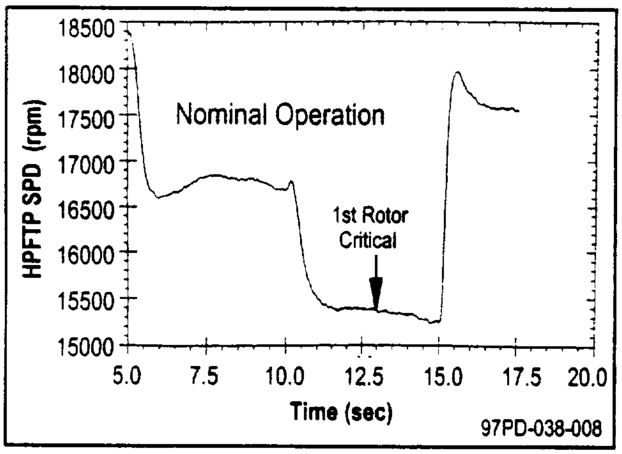

Figure 10. HPFTP First Rotor Critical Speed Operation

against chugging. High frequency data from the test did not show any evidence of chugging or combustion stability problems even with the low ΔP/Pc values. 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 dwell tests are large and help to verify protection against chugging on the SSME at low power levels.

Nozzle Separation Heat Load

Nozzle separation heat load was higher by a factor of two than predicted by the model. Updating the SSME digital transient model allowed better understanding of transient separation heat load observed during engine start and shutdown and is an aid to general SSME operation.

Nozzle Sideloads

Nozzle sideloads caused by separation in the nozzle cause damage during start and shutdown (Figures 14 and 15). Prior to test, justifiable concerns were raised about dwelling at low power level with the high sideloads. Analysis based on strain data predicted damage from the low power level tests is equivalent to four normal start and shutdown transients. During testing, sideloads were experienced with minimal damage as predicted.

SSME Margin Demonstration Testing

This testing served as SSME margin testing in a number of areas. The 0.5 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 operation was observed with a 12 lb/sec nozzle leak, the largest in SSME history. The FPB was operated at 700 R (avg.) the lowest mainstage temperature in the SSME database. The HPFTP mainstage flow coefficient was 0.286, the lowest in the mainstage SSME database. Prior to this, the lowest was 0.33 during mainstage.

CONCLUSION

The SSME is a versatile, proven rocket engine.. This test program demonstrated the ability of the SSME to accommodate wide variation in safe operating ranges. The demonstrated prediction capability of the SSME

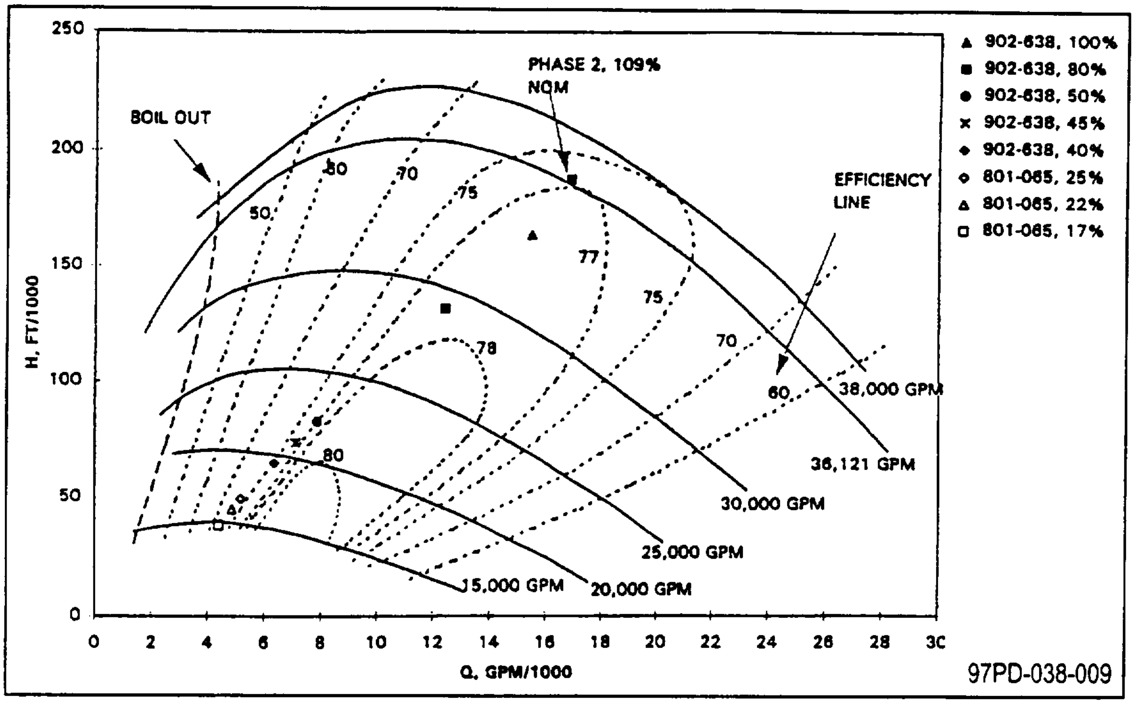

Figure 11. SSME HPFTP Performance

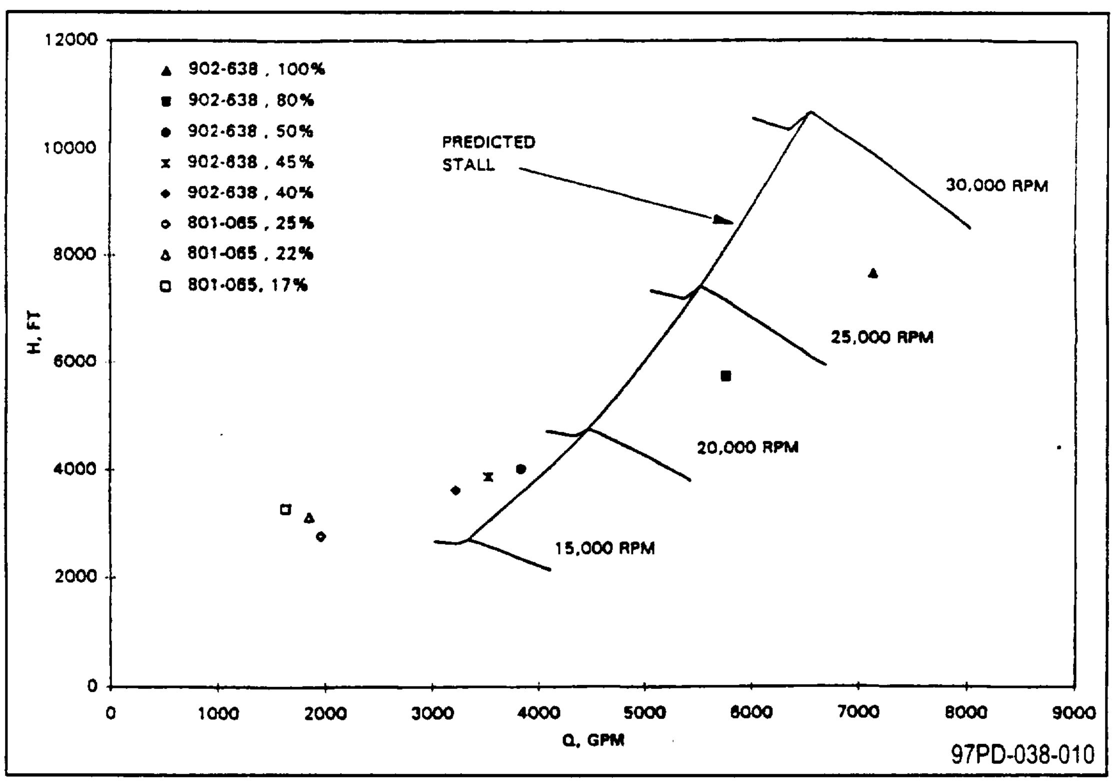

Figure 12. SSME HPOTP Main Pump Performance

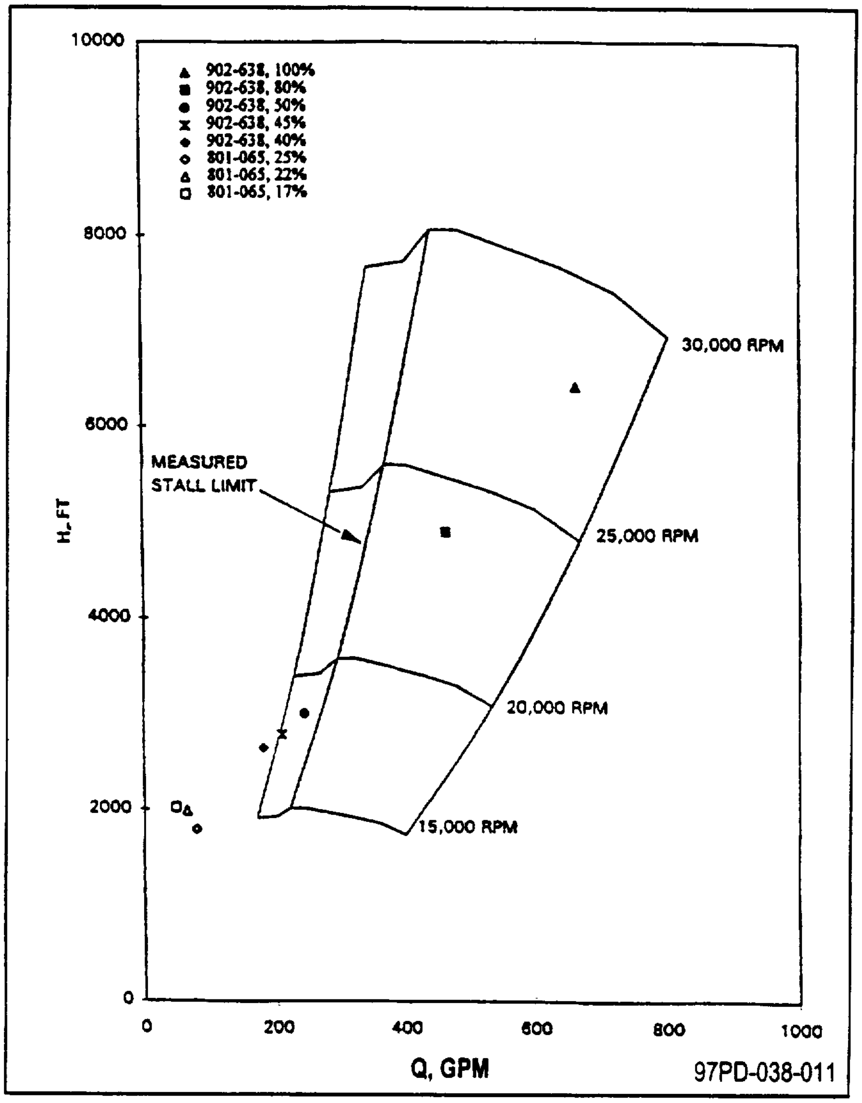

Figure 13. SSME HPOTP Preburner Pump Performance

DTM and the PBM was quite impressive. The benefits of this test program will have an impact on SSME operation in general far into the future. In closing, the as-advertised X-33/RLV successful operating potential of the SSME was demonstrated in test without error and with great success.

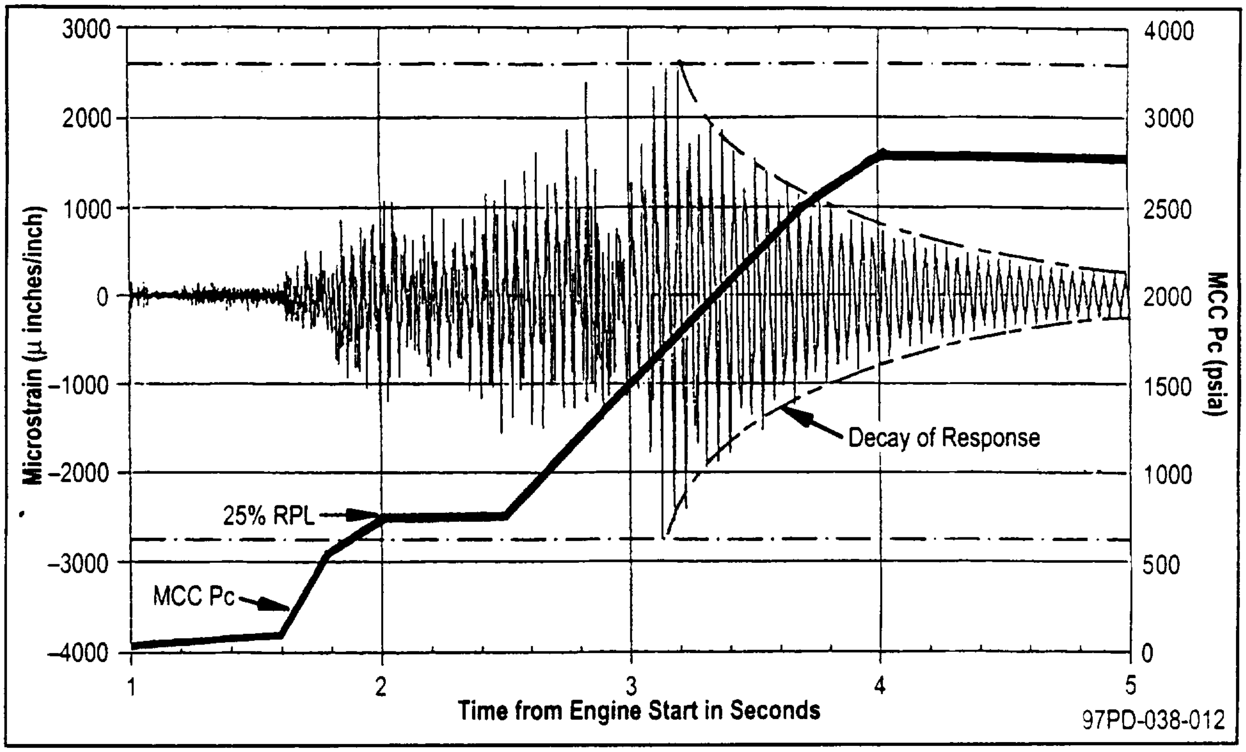

Figure 14. Test 801-041 SG #11 - 104% RPL Start Location: Nozzle Aft Manifold Stubout

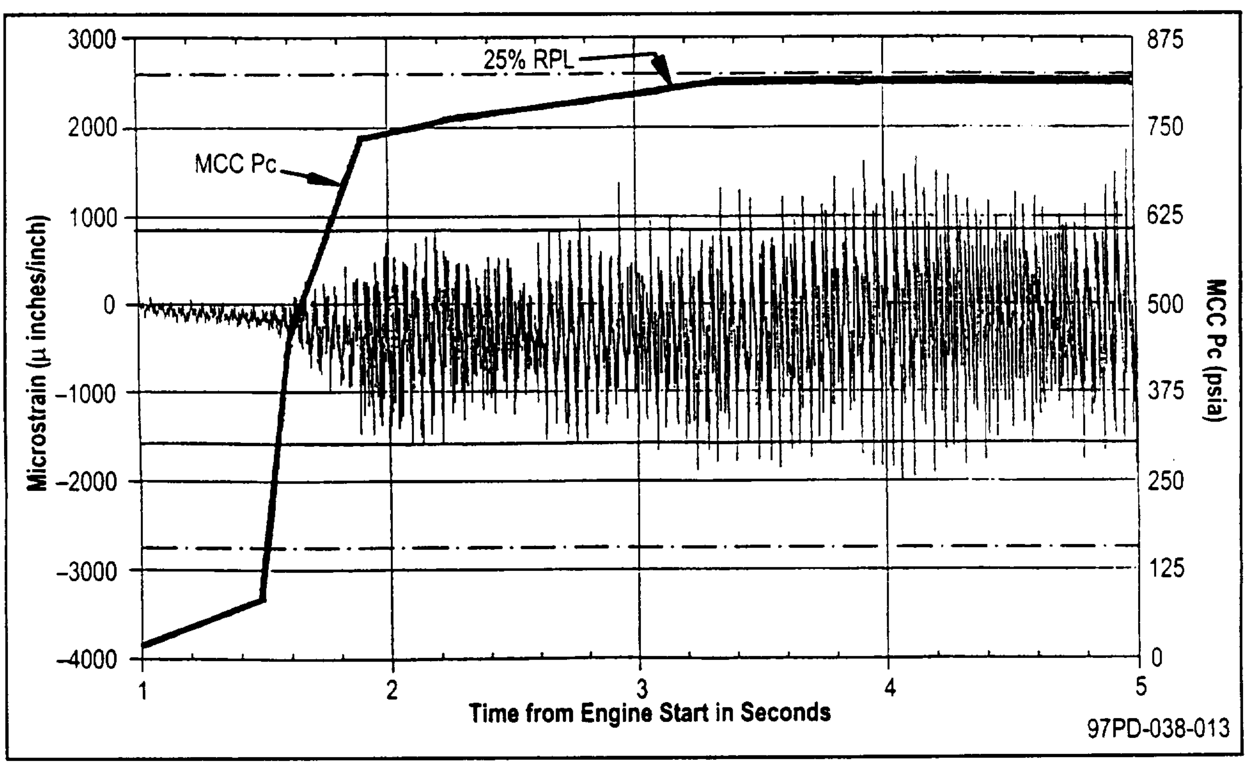

Figure 15. Test 801-062 SG #3 - 25% RPL Start Location: Nozzle Aft Manifold Stubout