PART III. SPACE SHUTTLE MAIN ENGINE

Introduction

The Space Shuttle Main Engine (SSME) was the first and only fully reusable, high performance, liquid rocket engine in the world rated for human spaceflight. The staged combustion engine burned a mixture of LO2 and LH2 to lift the vehicle into space. The ET provided the fuel and oxidizer for the three SSMEs, which worked in tandem with the twin SRBs during the first two minutes of powered flight. The engines operated for an approximate total eight-and-one-half minutes from ignition to MECO, and burned over 1.6 million pounds (approximately 528,000 gallons) of propellant. The SSMEs powered the Shuttle with more than 1.2 million pounds of thrust.

The SSME staged combustion cycle burned the fuel in a two-step process. First, the dual preburners burned most of the hydrogen and part of the oxygen from the turbopumps, producing hydrogen-rich gas at high pressure and limited temperature. The flow of hot gas drove the turbines in the high-pressure turbopumps. The turbine exhaust flowed into the main combustion chamber, where the fuel was completely burned, producing hydrogen-rich gas at high pressure and high temperature. The exhaust from the main combustion chamber expanded through the nozzle to produce thrust. At sea level, the propellants provided each engine thrust levels of approximately 380,000 pounds at rated power level (RPL) or 100 percent thrust; 390,000 pounds nominal power level (NPL) or 104.5 percent RPL; and 420,000 pounds at full power level (FPL) or 109 percent RPL (or approximately 470,000 pounds, 490,000 pounds, and 512,000 pounds, respectively, in a vacuum).

The engines were throttleable in one-percent increments over a thrust range of 67 to 109 percent RPL. All three main engines received the same throttle command at the same time. This provided for a high thrust level during liftoff and initial ascent, but allowed thrust to be reduced during the final ascent phase. The engines were gimbaled to control pitch, yaw and roll during the ascent.

The SSME operated at greater temperature extremes than any mechanical system in common use today. Before ignition, the LH2, the second coldest liquid on Earth, was minus 423 degrees F. The combustion chamber reached 6,000 degrees F following ignition, which was hotter than the boiling point of iron. To meet the demands of the severe operating environments, exotic alloys were developed, such as NARloy-Z (Rocketdyne) and Inconel Alloy 718 (Special Metals Corporation).[1036] The latter, a nickel-based superalloy, was used in approximately 1,500 engine components and comprised roughly 51 percent of the SSME, by weight.

[1036] R.P. Jewett and J.A. Halchak, “The Use of Alloy 718 in the Space Shuttle Main Engine,” in *Superalloys 718, 625 and Various Derivatives*, ed. Edward A. Loria (The Minerals, Metals & Materials Society, 1991), 749-760.

The three engines, almost interchangeable in the launch position, were referred to as the center (Engine 1), left (Engine 2), and right (Engine 3). The only difference among the three positions on the orbiter was that different areas of the nozzles required thermal protection from the external environment depending on orbiter position.[1037]

The nozzle, main combustion chamber, powerhead, low-pressure turbopumps, valve assemblies, and ducts were manufactured by Pratt & Whitney Rocketdyne[1038] in Canoga Park, California. The high-pressure turbomachinery for the last engine configuration flown on the Shuttle, the Block II SSME, was produced at the Pratt & Whitney Rocketdyne facility in West Palm Beach, Florida. The first flight for the high-pressure liquid oxidizer turbopumps occurred in 1995, and in 2001 for the high-pressure fuel turbopumps. Major SSME subcontractors were HR Textron (also known as Woodward HR Textron and Hydraulic Research, Inc.) in Valencia, California, for engine valve actuators and Honeywell, Inc. in Clearwater, Florida, for the main engine controller. Historically, more than thirty-five subcontractors in about twelve states contributed to the SSME project.[1039]

The SSME program was managed by NASA's Space Shuttle Project Office located at MSFC. Engines and engine components were tested at NASA's SSC in Mississippi. Over the course of the SSP, the SSMEs accumulated more than fifty-seven hours of flight time and another 246.7 hours of ground testing.[1040] Originally, the main engines were designed for fifty-five starts and 27,000 seconds of run time before needing replacement.[1041]

Reporting on the SSME program status as of October 1992, in response to a request from the House of Representatives' Committee on Science, Space and Technology, the SSME Assessment Team concluded that, "By all accounts, the SSME is a marvel of engineering achievement."[1042]

[1037] Katherine P. VanHooser, personal communication with James M. Ellis, MSFC, August 23, 2011.

[1038] Pratt & Whitney Rocketdyne, headquartered in Canoga Park, California, is a division of Pratt & Whitney, a wholly owned subsidiary of the United Technologies Corporation. The company was formed by North American Aviation (NAA). In 1967, NAA and Rocketdyne merged with the Rockwell Corporation to form North American Rockwell, later part of Rockwell International. The aerospace entities of Rockwell International, including the former NAA, and Rocketdyne, were sold to Boeing in 1996. In 2005, Boeing sold what was then called Rocketdyne Propulsion and Power to United Technologies Corporation, which they subsequently combined with their Pratt & Whitney Space Propulsion Division. The name of the corporate entity at the time of the relevant historical event is used throughout this section of the narrative.

[1039] NASA MSFC, Transition Project Office, "STS Stack" Recordation Data Package, June 15, 2009, Tab D: MSFC STS Element Major Hardware Suppliers.

[1040] Pratt & Whitney, "Pratt & Whitney Rocketdyne's Space Shuttle Main Engines Power Final Flight to International Space Station," P&W Press Release, July 8, 2011, http://www.pw.utc.com/media_center/ press_release/2011/ 07_jul/7-8-2011_00001.asp.

[1041] Originally, the main engines were contractually required to operate for 27,000 seconds consisting of fifty-five starts at eight minutes per flight. Jenkins, *Space Shuttle*, 412.

[1042] NASA, *Report of the SSME Assessment Team*, January 1993, i, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930012456.pdf.

Historical Overview

Early Engine Studies

Before the close of 1969, the STS had been generally defined as a two-stage, fully reusable spacecraft having high performance engines using LH2 and LO2.[1043] The engine would have a two-position bell nozzle, would be throttleable from 73 to 100 percent of rated power, and would operate at a 10 percent thrust level during on-orbit operations. The capability to run the engines at more than their maximum thrust rating also was specified.[1044]

A few months after the award of contracts for Phase A Shuttle feasibility studies, MSFC issued a RFP for SSME preliminary design studies. On April 30, 1970, NASA awarded parallel one year Phase B contracts to Aerojet General, Pratt & Whitney, and North American Rockwell/Rocketdyne to define SSME requirements.[1045] Each company received $6 million to study engine concepts and to produce prototype hardware, under the management of NASA's MSFC. The Phase B engine definition and preliminary design competition, which lasted almost one year, occurred at roughly the same time as the Phase B Space Shuttle studies by North American Rockwell and McDonnell Douglas, as well as the Phase A Alternate Space Shuttle studies.[1046] The SSME was considered the "pacing component of the Shuttle," and its development proceeded in tandem with that of the orbiter.[1047]

All three aerospace company competitors designed their engines for very high chamber pressure.[1048] Rocketdyne spent its own money to build a full-scale test version of the SSME that "could demonstrate a thrust of 415,000 pounds, stable combustion, a chamber pressure of 3,000 psi, and adequate cooling."[1049] This prototype SSME thrust chamber (partial engine) was fired successfully at the company's Nevada Field Laboratory near Reno during late 1970 and early 1971.[1050] As noted by Frank Stewart, a former deputy in the Engine Project Office, this "probably gave them the leg up" toward award of the later engine manufacturing contract.[1051]

[1043] Dunar and Waring, *Power to Explore*, 277-279.
[1044] Jenkins, *Space Shuttle*, 225.
[1045] Bob Biggs, "Space Shuttle Main Engine Development History," May 11, 2006, Pratt & Whitney Rocketdyne, Inc., presentation materials.
[1046] Dunar and Waring, *Power to Explore,* 288.
[1047] Dunar and Waring, *Power to Explore,* 284.
[1048] Baker, *Manual*, 96.
[1049] Jenkins, *Space Shuttle*, 110.
[1050] The Nevada Field Laboratory closed in March 1971 after nine years of operation, following completion of space shuttle engine tests. Archaeological Consultants, Inc. (ACI) and Weitze Research, *Historic Resources Survey and Assessment of the NASA Facility at Santa Susana Field Laboratory, Ventura County, California* (survey report, NASA MSFC, 2008).
[1051] Frank Stewart, interview by Jessie Whalen, Oral Interviews: Space Shuttle History Project Transcripts Collection, Report No. MHR-16 (Huntsville, AL: MSFC History Office, December 1988), February 4, 1988, 63; T. A. Heppenheimer, *History of the Space Shuttle* , vol. 1, *The Space Shuttle Decision: NASA's Search for a Reusable Space Vehicle* (Washington, DC: Smithsonian Institution Press, 2002), 102, 132.

NASA changed the baseline requirements for the SSME in January 1971, by raising the planned sea level thrust from 415,000 to 550,000 pounds. This was done to accommodate the DoD needs for increased payload capacity. The SSME Phase C/D RFP to build and test the SSME prototypes (Phase C) and to perform final design and manufacture (Phase D) was issued by MSFC on March 1, 1971. The shuttle configuration baseline in the RFP was a two-stage vehicle with both a manned fly-back booster and a piggy-back mounted orbiter. NASA specified that a single powerhead would serve for both the booster engine and the orbiter engine. The only clearly defined engine feature noted in the RFP was the bell-type nozzle.[1052] The three recipients of the Phase B engine definition contracts submitted proposals in April 1971, in response to the RFP.

At the time the RFP was let, the original concept of the Space Shuttle was undergoing redefinition. In order to lower costs and complexity, in May 1971, NASA decided that both the LO2 and LH2 propellants would be put in external propellant tanks. Further refinements and budget cutbacks followed, and in early 1972, the fly-back booster concept was abandoned in favor of reusable solid rocket boosters and a three-engine fly-back orbiter.[1053] The SSME was no longer required to be both a booster and an orbiter engine. The engine rated thrust level was reduced to 470,000 pounds (vacuum) with 109 percent emergency power level capacity.[1054]

Contract Awards

NASA's MSFC announced the selection of the Rocketdyne Division of North American Rockwell for the Phase C/D contract in July 1971.[1055] One month later, Pratt & Whitney contested this decision and filed an official protest with the U.S. Government's General Accounting Office (GAO).[1056] As a result, Rocketdyne's contract was put on hold until after a decision in the case was reached. On March 31, 1972, the GAO ruled in favor of Rocketdyne, and in May 1972, the SSME contract with Rocketdyne was confirmed.

While NASA began determining the final design requirements, the actual definition of "the physical, electrical, and functional interfaces" of the STS could not begin until after July 26, 1972, when the orbiter contractor was selected. Following the issuance of interim contracts to initiate work on SSME development and production, a definitive contract was signed on August 14, 1972. This SSME contract predated the awarding of the Shuttle orbiter contract.[1057] The SSME DDT&E contract (NASA No. NAS8-27980) called for ten development engines and three

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[1052] Robert E. Biggs, "Space Shuttle Main Engine, The First Ten Years," in *History of Liquid Rocket Engine Development in the United States, 1955-1980*, ed. Stephen E. Doyle (American Aeronautical Society History Series, Volume 13, 1992), 5.
[1053] Dunar and Waring, *Power to Explore*, 284.
[1054] Biggs, "The First Ten Years," 5.
[1055] Dunar and Waring, *Power to Explore*, 288.
[1056] Biggs, "The First Ten Years," 69-122.
[1057] "Space Shuttle Main Engine Contract Signed with NAR," *Marshall Star*, August 23, 1972, 1-2.

flight engines for OV-102, with delivery of the first flight engines by 1977.[1058] It was not until early 1973 that MSFC provided Rocketdyne with specifications for the main engine, as described in the Interface Control Document (ICD), released in February, and the Contract End Item Specification (CEI), released in May. The ICD and CEI "contributed to development of detailed Design Verification Specifications, for the engine as a whole as well as for turbopumps and other components."[1059]

Rocketdyne designated their Canoga Park, California, facility as the manufacturing location for the engine, with engine system development testing to be conducted at the Mississippi Test Facility (MTF) near Bay St. Louis, Mississippi.[1060] Funding was provided for facilities changes needed at the Canoga Park manufacturing plant.[1061] NASA also made available $15.4 million in additional monies to Rocketdyne for modifying the Coca Area test stands (Coca I and IV) at their SSFL in California.[1062] These stands would accommodate static firings of individual SSME components, such as turbopumps and combustion devices, and combined SSME components.

In September 1974, the Shuttle Projects Office at MSFC assigned James L. Splawn as the NASA resident manager of the SSME office at Rocketdyne in Canoga Park, where he headed an on-site group of twenty-three MSFC employees.[1063] MSFC, working with Rocketdyne, designed each SSME for fifty-five flights and "an accumulative run time of 7.5 hours before overhaul."[1064] During the development and testing of the engine, MSFC conducted quarterly SSME reviews, and also established an SSME Hardware Simulation Laboratory (HSL) at the center in late 1974.[1065]

In May 1978, NASA purchased nine additional main engines from Rocketdyne under terms of a letter amendment to the original contract.[1066] Rocketdyne was authorized to manufacture and test an additional twelve SSMEs in November 1979, under the terms of a $365.7 million contract amendment.[1067] Seven years later, the company was awarded the Development, Flight &

[1058] "NASA Awards Contract for Shuttle Engine," *Marshall Star*, April 19, 1972, 2.

[1059] Heppenheimer, *The Space Shuttle Decision*, 133.

[1060] When first established in 1961, the MTF was known as the Mississippi Test Operations; it became the MTF in 1965. It retained this name until 1974, when it was renamed the National Space Technology Laboratories (NSTL). The facility became the John C. Stennis Space Center (SSC) in 1988, by Executive Order of President Ronald Reagan. SSC was responsible for flight green run testing of the SSME, as well as assembly and refurbishment of development engines. For ease of reference, the establishment will be referred to as SSC throughout the remainder of the document. NASA SSC, "John C. Stennis Space Center History, Chronology of Significant Events," October 5, 2007, http://www.nassa.gov/centers/stennis/about/history/chronology /chronology.html.

[1061] "Shuttle Facility Funds Provided," *Marshall Star*, October 25, 1972, 2.

[1062] Beginning in 1948, the SSFL in Ventura County, California, was used as a rocket engine testing facility; it is no longer in use. The Coca Area at SSFL supported the SSP from 1971 through 1988. ACI and Weitze, *Santa Susana Field Laboratory*.

[1063] "West Coast Marshall Employees Doing Essential Shuttle Work," *Marshall Star*, November 28, 1976, 1, 3.

[1064] "SSME: Powerful, Efficient, Reusable," *Marshall Star*, October 11, 1978, 3-4.

[1065] "SSME Simulation Facility Being Prepared at MSFC," *Marshall Star*, October 9, 1974, 1-2.

[1066] "NASA Buying 9 Additional Main Engines," *Marshall Star*, May 31, 1978, 3.

[1067] J. Mitchell, ed., *Thirty-Five Years in Power for America* (Canoga Park, California: Rockwell International, Technology Test Bed contract (No. NAS8-40000), which was retroactive to May 1977, and extended until November 1996. The value at the end of this contract was $5.883 billion. Rocketdyne also was awarded the $1.5 billion SSME Recycle, Flight Support, and Block I and Block II Enhancements contract No. NAS8-45000 in June 1986. The period of performance was retroactive to September 1985, and extended through December 2001.

Additionally, NASA awarded a $1.07 billion DDT&E contract (No. NAS8-36801) to United Technologies/Pratt & Whitney in West Palm Beach for the alternate SSME high-pressure fuel and oxidizer turbopumps. The contract called for five production verification units of each type; the period of performance was from August 18, 1986, through September 30, 2005. Upon expiration, this contract was subsumed into contract No. NAS8-01140.[1068]

In May 2002, Boeing was awarded the SSME support contract (No. NAS8-01140) valued at $2.181 billion (as of Mod 114). The period of performance, retroactive to January 2002, extended through September 30, 2010. In April 2011, NASA executed a $36.9 million contract modification with Pratt & Whitney Rocketdyne to provide continued SSME prelaunch and launch support from April 1 through July 31, 2011. This modification to the original 2002 contract No. NAS8-01140 supported the SSME operations until the end of the SSP.[1069]

SSME Test Programs

> *"One thing that surprises a lot of people about the SSME is that each of those engines burns 1,000 pounds of propellants a second. When you combust hydrogen and oxygen, the exhaust is water vapor. So when they run a test, there'll be a big cloud of exhausted water vapor. If the wind conditions were right, and the cloud vapor floated over you, it would condense because it was cooler in the atmosphere than the exhaust, and it would pour down rain on you. We got wet once in a while."*
>
> \- George D. Hopson, SSME Project Manager, MSFC [1070]

The SSME was developed and improved through decades of testing. All serialized parts for use in flight were limited to a maximum of 50% of the starts and seconds accrued on the fleet leader (similar non-flight part that had the highest number of starts or seconds).[1071] Under the leadership of J.R. Thompson, SSME Project Manager, deliberate flaws were introduced into the test

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Rocketdyne Division, 1990), 30.

[1068] NASA MSFC, "STS Stack," Tab C.

[1069] "NASA Awards Space Shuttle Main Engine Contract Modification," April 03, 2011, http://www.aero-news.net/index.cfm?printable=1&ContentBlockID=1042 c1c3- fb8f-4777-03April2011.

[1070] George D. Hopson, interview by Jennifer Ross-Nazzal, *NASA STS Recordation Oral History Project*, July 20, 2010, http://www.jsc.nasa.gov/history/oral_histories/STS-R/HopsonGD/HopsonGD_7-20-10.htm.

[1071] Katherine P. Van Hooser and Douglas P. Bradley, "AIAA-2011-7159 Space Shuttle Main Engine – The Relentless Pursuit of Improvement," paper presented at the American Instutute of Aeronautics and Astronautics Space 2011 Conference, Long Beach, CA, September 2011.

engines. While this approach unnerved the senior management at NASA Headquarters, if such a flawed engine could successfully run the full duration test, it would demonstrate that the SSME was clear to fly.[1072]

At the inception of engine development, NASA's requirement was for 100 percent rated power level, referred to as RPL. RPL is equivalent to a sea level thrust of approximately 380,000 pounds and vacuum thrust of 470,000 pounds. One hundred and nine (109) percent power, originally called emergency power level, ultimately became referred to as Full Power Level or FPL. The original objective of certifying the SSME for operation at FPL was deferred because of development difficulties and delays. Instead, certification at 100 percent RPL became the objective for the baseline First Manned Orbital Flight (FMOF) engine.[1073]

Components Testing

The SSMEs manufactured at Rocketdyne's plant in Canoga Park were tested at both SSFL in California, and SSC in Mississippi. Collectively, these facilities evaluated the performance of every engine and engine component. Beginning with components and subsystems, then complete engines, the entire SSME development program entailed thousands of laboratory and hot fire tests.[1074] Initially, NASA's general approach was to test every component on its own, develop it, and have a certain maturity before the component went into an engine.[1075]

The Coca Area test stands at SSFL were selected for components testing (Figure Nos. C-1 through C-3). Coca I had separate test stands for oxygen and hydrogen turbopumps, while the Coca IV stand had two test positions used for igniters and preburners, respectively.[1076] The Coca Area had been inactive since late 1968, and work to prepare the test stands for the SSME was plagued by cost overruns and delays.[1077] Nevertheless, a SSME test program milestone was reached on April 15, 1974, with the first hot firing at the Coca I stand. This successful thirty-four second-run of a preburner assembly predated by one year the start of engine level tests.[1078] However, NASA's original plan to conduct turbopump component-level development tests was hampered by difficulties in manufacturing components on schedule, as well as by major facility failures.[1079] As a result, within a few years, the plan to test every component separately was

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[1072] Smith, interview.
[1073] NASA, *SSME Assessment*, i.
[1074] Heppenheimer, *The Space Shuttle Decision*, 133.
[1075] Otto K. Goetz, interview by Jennifer Ross-Nazzal, *NASA STS Recordation Oral History Project*, July 20, 2010, http://www.jsc.nasa.gov/history/oral_histories/STS-R/GoetzOK/GoetzOK_7-20-10.htm.
[1076] Heppenheimer, *The Space Shuttle Decision*, 137.
[1077] Rockwell International, "SSME Facilities Review Meeting," SHHDC-260 (Huntsville, AL: MSFC History Office, February 20, 1974).
[1078] "Rocket Test Firings to Resume at NSTL," *Marshall Star*, April 24, 1975, 2; "Rocketdyne is SSME builder," *Rockwell News* (April 1981), 3; Royce E. Mitchell, interview by Jennifer Ross-Nazzal, *NASA STS Recordation Oral History Project*, June 30, 2010, http://www.jsc.nasa.gov/history/oral_histories/STS-R/MitchellRE/MitchellRE_6-30-10.htm; Bob Biggs, "The First Ten Years," 1.
[1079] NASA, *SSME Assessment*, i.

abandoned in favor of testing the engine itself.[1080] The A-1 and A-2 test stands at SSC, previously used to test the Apollo/Saturn V boosters, became the site for sea level static (stationary) firings of single engines. By 1974, engineers were busy converting the stands to test the SSME.[1081] In retrospective, J.R. Thompson observed that abandoning component testing and "going directly to the engine, running head-on with the problems that had to be solved," was very satisfactory.[1082]

The Coca test stands continued to be used, but typically only on smaller components. However, component testing of preburners, valves, nozzles, main combustions chambers, and controllers at SSFL made only modest progress. Following a fire on Coca I in February 1976, Rocketdyne discontinued separate testing of the oxygen turbopumps; these components were tested as part of complete engines at SSC instead. Fuel turbopump testing continued at Coca I until September 1977, when further testing was halted. After twenty-seven months, only three oxygen turbopump assemblies had run a total of twenty-four times for a cumulative time of 161 seconds. During the same period, six fuel turbopump assemblies were tested twenty-seven times for a cumulative run time of 111 seconds.[1083]

Engine-Level Test Program

The prototype development main engine, SSME 0001, alternately known as the Integrated Subsystem Test Bed (ISTB) engine, was completed by Rocketdyne at the Canoga Park facility in March 1975, then delivered to SSC for static firing tests about one month ahead of schedule.[1084] Larger and heavier than a flight-type engine, the ISTB engine was "primarily a tool to develop the engine start sequence and the engine shutdown sequence."[1085] It included turbopumps, combustion devices, controls, and a shortened nozzle. Since the controller was not yet ready for use, the ISTB used a rack-mounted laboratory computer, located remotely.

The first ISTB test, without ignition, took place on May 19, 1975, followed by the first main chamber ignition test on June 24, 1975.[1086] After ignition tests were completed, subsequent firings were targeted for higher thrust levels to evaluate engine starting characteristics and performance.[1087] The first mainstage[1088] test of the ISTB, a 3.38-second firing on Test Stand A-1, was a program milestone as the engine reached and stabilized at 50 percent of rated thrust, the

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[1080] Goetz, interview.

[1081] "SSC plays vital role in history of NASA space flight," *Lagniappe*, January 2004: 5.

[1082] J.R. Thompson, interview by Jennifer Ross-Nazzal, *NASA STS Recordation Oral History Project*, May 13, 2011, http://www.jsc.nasa.gov/history/oral_histories/STS-R/ThompsonJR/ThompsonJR_5-13-11.htm.

[1083] Heppenheimer, *Development of the Space Shuttle*, 156.

[1084] "First Shuttle Main Engine Completed a Month Early," *Marshall Star*, March 26, 1975, 1, 4.

[1085] Goetz, interview.

[1086] "First Shuttle Engine Ignited," *Marshall Star*, June 11, 1975, 4; "Space Shuttle Main Engine reaches milestone," *Lagniappe*, January 2004: 1, 5.

[1087] "Major Milestone Reached in Space Shuttle Program," *Marshall Star*, July 2, 1975, 1, 4.

[1088] During mainstage testing, all engine components operated at a thrust level in the normal flight range of the shuttle orbiter. Mitchell, interview.

minimum power level.[1089] Testing of the ISTB engine was "stuck at low power" for almost one year due to problems with the fuel turbopump, which delayed the attainment of 100 percent power level.[1090] First identified in March 1976, the fuel turbopump's subsynchronous whirl problem involved violent rotor instability, which caused failure of the turbine end bearings. According to J.R. Thompson, the whirl problem was solved by inserting a small paddle, which allowed for adequate cooling of the bearings.[1091] Engineers stiffened the shaft and bearing supports, and new dampening seals around the carriers of the bearings in the turbopumps were installed.[1092]

Testing of the second and third development engines was started in 1976. On March 12, 1976, one engine successfully demonstrated a 65 percent power level for 42.5 seconds.[1093] Following the critical design review in September 1976, the SSME was approved for production. Early 1977 marked the first testing of the development engines at RPL. Development engine SSME 0002, fitted with a flight-configuration nozzle, was fired successfully using the altitude test position on Test Stand A-2 in March 1977. An objective of this test was to verify throttle capabilities from 50 percent to 109 percent of the 470,000 pounds thrust level at altitude.[1094] Engine 0003 was tested in the A-1 Stand, at the sea level test position at rated thrust conditions for sixty seconds of the total eighty-second test duration.[1095] On March 24, 1977, during testing of Engine 0003, failure of a lift off seal in the high-pressure oxidizer turbopump resulted in a fire. Replacement of the seal by a KEL-F labyrinth seal solved the problem. Later, this modification became a permanent design change.[1096]

By the end of March 1977, more than 150 engine firings had been conducted at SSC since initiation of the test program in May 1975, and more than 3,500 seconds of firing time had been accumulated (see Figure Nos. C-4 through C-15 for a pictorial representation of the testing process).[1097] Future tests were designed for longer-duration firings at rated conditions, as well as long-duration firings at various thrust levels, to demonstrate satisfactory engine operation simulating the anticipated mission thrust profiles.

Notwithstanding the successes, individual engine testing proceeded slowly due to a variety of technical problems, mostly in the high-pressure fuel turbopump. These problems, primarily mechanical in nature and materials, included deteriorating bearings, faulty seals, and turbine blade dampers. According to Heppenheimer, three issues stood out: "unbalance in the turbine rotor, inadequate cooling of the turbine bearings, and poor load distribution and load-carrying

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[1089] "First SSME Mainstage Test Fired at NSTL," *Marshall Star*, February 11, 1976, 1.
[1090] Goetz, interview.
[1091] Thompson, interview.
[1092] Goetz, interview.
[1093] Jenkins, *Space Shuttle*, 225.
[1094] "High Altitude SSME Tests Start at NSLT," *Marshall Star*, January 12, 1977, 2.
[1095] "SSME Fired 60 Seconds At Rated Thrust Conditions," *Marshall Star*, March 16, 1977, 1.
[1096] Biggs, "Development History," 19.
[1097] "Space Shuttle Main Engine Is Throttled Successfully," *Marshall Star*, March 30, 1977, 1, 4.

capacity of both sets of bearings."[1098] Other significant challenges included start sequence problems, high-pressure oxidizer turbopump explosions, fuel preburner burn through, and nozzle steerhorn failures.[1099]

As recalled by Otto Goetz, SSME Chief Engineer and Project Manager, cracks in the turbine blades in the high-pressure fuel turbopumps were a big challenge. The fuel turbopump contained a total of 122 turbine blades, each measuring 1"-long x 0.5"-wide. At full power, these generated 600 horsepower (hp). The blades were cast from a nickel-based super alloy developed by Martin Metals.[1100] The first turbine blade failures were identified in mid-November 1977, and were attributed to blade fatigue and insufficient damping. According to Rocketdyne's manager of SSME development and chief project engineer Robert (Bob) Biggs, "a rigidly locked blade array . . . led to fatigue failures in the blade airfoil close to the root. The first blade failure would cascade to multiple blades." In one test, "the rotor seized stopping the fuel flow and resulting in significant erosion of the hot gas system."[1101] The design solution was the addition of lightweight precision-tolerance dampers. Other solutions to the turbine blade problem entailed replacement of the original blade material. To prevent cracking resulting from the 2,000 degree temperature difference between the core and exterior blade temperatures at the start sequence of the SSME, insulating material was added as a coating to the exterior of the turbine blades.[1102]

Biggs related that the SSME start sequence was difficult to develop due to very low inertia turbopumps, very high power densities, and a lack of auxiliary start power.[1103] Forty-two tests were required to complete the first start sequence. The engine also was very sensitive to small errors, such that a one-tenth of a second timing error could cause major damage.

Many of the engine components required redesign, which added time for required testing. As a result, by the beginning of 1978, NASA's cumulative test time was short of the targeted goal. "The original test plan of 1973 had called for cumulative run time to reach 38,000 seconds by the end of 1977. The actual total, 13,507 seconds, was barely one-third of this mark."[1104] Further, less than five percent of the total accumulated run time had been at the 100 percent RPL for 520 seconds, and no test had achieved 109 percent RPL.

On February 15, 1978, Dr. Myron (Mike) Malkin, NASA Headquarters Shuttle Program Director, instituted a moratorium on testing at 109 percent RPL until after STS-1. This ban was imposed by NASA management, "concerned that new problems at the high power level would

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[1098] Heppenheimer, *Development of the Space Shuttle,* 150.
[1099] Biggs, "Development History," 10.
[1100] Heppenheimer, *Development of the Space Shuttle,* 152.
[1101] Biggs, "Development History," 24.
[1102] Goetz, interview.
[1103] Biggs, "Development History," 13.
[1104] Heppenheimer, *Development of the Space Shuttle,* 154.

detract from the effort required to support the first flight at rated power level."[1105] Engine 2004, used for 109 percent RPL abort certification, was exempted from the moratorium.

Several program milestones were reached during 1978. On May 10, Engine 0005 became the first to run at RPL for the full flight duration of 520 seconds. By August, this engine had accumulated more than 5,000 seconds of operation within a six week period, of which more than 4,500 seconds were at or above 100 percent of RPL.[1106] On September 7, 9, and 11, three test firings, each of 520-second duration, were completed at 100 percent of RPL. In a thirty-day period, ending September 11, the main engine logged twenty-two tests totaling 5,470 seconds of run time.[1107] In October, a static firing for more than thirteen minutes demonstrated the engine's capability to return the orbiter to its landing site in case of a mission abort during launch.[1108]

NASA's overall objective was to boost the accumulated firing time to meet their goal of 80,000 seconds, which was viewed as a necessary testing milestone prior to the first orbital flight of the SSP. To achieve this goal, Rocketdyne reactivated a test stand at SSFL. NASA contracted with Bechtel Corporation's Industrial Projects Group to modify the Coca I test stand, carried out in October and November 1978; this facility was renamed Test Stand A-3. The initial firing on November 7, 1978, was performed to check out the test stand, as well as to test the rebuilt SSME 0201. This engine, originally designed as Engine 0001, had previously completed sixty-seven tests on Test Stand A-1 and fifteen altitude tests on A-2 at SSC.[1109] Thirty-five consecutive firings, all at the scheduled duration, were made at SSFL during 1979 and 1980, in a prelude to the certification of individual engines for flight. Overall, the full-scale SSME firings at Test Stand A-3, which supplemented the sea level testing at SSC, were "crucial in identifying problems related to the initial designs of the high-pressure turbopumps, powerhead, valves, and nozzles."[1110] Also, initial trials of new modifications to the engine were run. Rocketdyne added personnel and ran the Coca A-3 test stand "around the clock, with a two-shift firing crew and a third shift for maintenance."[1111]

At the end of 1978, the SSME test program had accumulated 34,810 seconds in 394 firings. The total accumulated run time included 10,624 seconds at RPL, of which 3,521 seconds were for the full 520-second duration. As a result of an aggressive test schedule at both SSFL and SSC, the first 100,000 seconds of development test time were reached in five years and seven months

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[1105] Biggs, "Development History," 32.

[1106] Engine 2005 was retired from service in November 1978 with more than 12,000 seconds of accumulated run time. Heppenheimer, *Development of the Space Shuttle,* 162; "SSME Runs Flight Duration at 100%," *Marshall Star*, May 17, 1978, 1.

[1107] "SSME Completes Three RPL Firings for Full Duration," *Marshall Star*, September 13, 1978, 1.

[1108] "SSME Passes Launch Abort Test at NSTL," *Marshall Star*, November 8, 1978,1.

[1109] "Engine Test Position," *Marshall Star*, October 25, 1978, 3; "First Checkout," *Marshall Star*, November 15, 1978, 4.

[1110] Fred Jue, "Space Shuttle Main Engine – Thirty Years of Innovation," (Canoga Park, California: The Boeing Company, Rocketdyne Propulsion & Power, no date), http://www.engineeringboeing.com/dataresources/SpaceShuttleMainEngineThirtyYearsofInnovation.doc.

[1111] Heppenheimer, *Development of the Space Shuttle,* 164.

following the start of the SSME test program in 1974.[1112] Among other significant accomplishments, the engine testing program validated the design changes within the oxygen turbopump, and also confirmed the value of the improvements to the turbine blades.[1113]

Main Propulsion Test Program (1978-1981)

Static testing of individual engines at SSC and SSFL ran in parallel with tests of the Main Propulsion Test (MPT) Program, which was not part of the formal SSME development program.[1114] The purpose of this program was to evaluate the performance of the complete propulsion system and to certify it for operation prior to the first manned orbital flight of the shuttle. The Main Propulsion Test Article, or MPTA (also known as the Orbiter Boattail Simulator), built by Rockwell's Space Division, was comprised of three main engines plus a simulated orbiter midbody and a flight-weight aft fuselage to which the engines were fitted. LO2 and LH2 were fed to the engines from a 154' flight-type external tank. The orbiter simulator was delivered to SSC on June 24, 1977. The engines and external tank followed in July and September of 1977, respectively.[1115] The MPT Program was active between April 21, 1978, and January 17, 1981. During this time, a series of eighteen tests was completed, of which six lasted 520 seconds; the last test was the longest at 625 seconds.[1116] At its conclusion, the program accumulated a total run time of 3,775 seconds.[1117]

A one-second ignition test marked the first MPT Program test. Scheduled for a total run time of 2.35 seconds, an anomaly resulted in early termination.[1118] On May 19, 1978, a fifteen-second run marked the first major test firing of the Shuttle's main propulsion system. Over the next several months, additional tests were run to increase the duration of firing and the engine thrust levels until they were fixed at 109 percent RPL for about eight minutes at a time, which would simulate the conditions of an actual mission.[1119]

The MPT Program was beset with problems and delays, much like the component and single engine tests. On December 27, 1978, fire destroyed one of the three engines, halting further testing until May 1979. Rupture of a hydrogen line on an engine nozzle occurred in November

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[1112] Jue, "Thirty Years."

[1113] Heppenheimer, *Development of the Space Shuttle,* 162.

[1114] The MPT hot firings were treated as tests of the orbiter, and did not count as part of the testing for SSME qualification. Heppenheimer, *Development of the Space Shuttle,* 459.

[1115] Orville Driver, interview by Jessie Whalen and Sarah McKinley, December 14, 1987, Oral Interviews: Space Shuttle History Project Transcripts Collection, Report No. MHR-16 (Huntsville, AL: MSFC History Office, December 1988), 5.

[1116] "MPT Firing Friday 'Very Successful' in 15-Second Run," *Marshall Star*, May 24, 1978, 1; "MPTA Series is Completed," *Marshall Star*, August 2, 1978, 1, 3; Karen J. Weitze, *Historical Assessment for the Equipment Boneyards, Marshall Space Flight Center* (survey report, NASA MSFC, 2004), 15-29.

[1117] NASA SSC, *Shuttle Survey Historic Eligibility Report for Stennis Space Center, Hancock County, Mississippi* (survey report, NASA SSC, 2007, 23.

[1118] "All Engines Fire in 1st MPTA Test," *Marshall Star*, April 26, 1978, 1.

[1119] "MPT Firing Friday," 1.

1979. After automatic engine cutoff, Rocketdyne shipped the damaged engine back to Canoga Park for analysis. Investigators from MSFC and Rocketdyne checked out all welds to determine how to correct the engine problem.[1120] The event further delayed the launch preparations for STS-1.

A milestone was reached in December 1979, with the first full duration run of the MPTA, lasting 550 seconds. On March 20, 1980, in the eighth test of the Shuttle's main propulsion system, the three SSMEs were static fired for 535 seconds. For the first time during the MPT program, the engines were gimbaled while a pogo effect was deliberately induced.[1121] The test was planned to demonstrate the engine accumulator system's capability to prevent pogo during flight. Additionally, for the first time, a thrust vector control (TVC) failure simulation was run to test whether redundant systems would perform properly in such an event during launch.[1122]

The test on May 29, 1980, used stub nozzles which were designed to allow the engines to be run at less than 90 percent of RPL at sea level. In this test, the three flight-type engines were throttled in stages from 100 percent rated thrust to 65 percent. Engine No. 3 was cut off at 530 seconds, Engine No. 2 at 545 seconds, and Engine No. 1 was kept firing at 65 percent until cutoff at 574 seconds. The July 1980, hot firing called for flight nozzles, which were not intended for use at less than 90 percent. This run was the first time the engine cluster achieved 102 percent of rated power.[1123] During the test, a burn-through occurred in the preburner chamber wall of Engine 0006. This engine was returned to Canoga Park for repair prior to the next test, scheduled for November 1980.[1124]

The November 3, 1980, test of the MPTA was automatically terminated at 21.74 seconds into the planned 581-second static firing. This occurred when sensors indicated that the high-pressure fuel turbopump turbine discharge temperature in the No. 2 engine exceeded acceptable limits. Initial inspection of the hardware revealed an irregular-shaped hole in the nozzle, caused by structural failure in the braze joint between the nozzle coolant tubes and the aft manifold.[1125]

The 596-second MPTA test on December 4, 1980, successfully achieved one of the major objectives of the program, to test the sensor which detects fuel depletion in the hydrogen tank and cuts off the engines. The test profile called for the three engines to begin at 100 percent RPL then be throttled briefly to 65 percent and then ramped up to 102 percent. During the test, Engine No. 1 ran for 590.69 seconds; Engine No. 2 was purposefully cut off at 442.01 seconds, and Engine No. 3 ran for 590.69 seconds. All three engines were gimbaled for approximately 300

[1120] "MPT Firing Ended After Nine Seconds," *Marshall Star*, November 7, 1979, 1-2; "MPT Failure Cause: Weak Weld Metal," *Marshall Star*, November 21, 1979, 3.

[1121] Pogo is a phenomenon involving low-frequency flow oscillations. Cf., Jenkins, *Space Shuttle*, 416.

[1122] "Eighth Main Propulsion Test is Successful," *Marshall Star*, March 26, 1980, 1.

[1123] "MPT Firing Conducted 'Without A Hitch," *Lagniappe*, June 18, 1980: 1, 6.

[1124] "Engine Returned to Support MPT," *Marshall Star*, October 1, 1980, 4.

[1125] "Two MPTA Firings Set for December," *Lagniappe*, November 26, 1980: 5.

seconds.[1126] The static firing brought the total test time on the main propulsion system to fifty-three minutes, seventeen seconds. This was in addition to the more than twenty-four hours of single engine tests conducted at SSC. Collectively, the accumulated firing time completed the certification requirements for the first Shuttle launch. The last test of the MPT Program occurred on January 17, 1981. Complete with simulated abort profiles, this 625-second firing was the program's longest test and the first at 102 percent of RPL using the flight-type nozzle.[1127] Orville Driver, MPT Deputy Manager at NSTL from 1977 to 1986, related that although some engines were certified for 109 percent of RPL, no three-engine cluster was ever tested at 109 percent.[1128]

Preliminary Flight Certification

Starting in 1979, the focus of the SSME test program shifted from proving that the design met the specified requirements to demonstrating the engine's reliability for flight, including the ability to handle abort missions. The Preliminary Flight Certification (PFC) test program entailed a series of tests called "cycles." Each cycle consisted of thirteen tests and 5,000 seconds of test exposure. All of the tests in each cycle had to be completely successful, and every engine component had to successfully complete the certification program.[1129] If there was a failure, the cycle needed to be restarted. Two PFC cycles on each of two engines of the flight configuration were required to certify that configuration for ten missions.[1130] The certification tests included evaluation of the start sequence; calibration tests to verify compatibility between hardware and software; firings at rated power at 520 seconds, plus with abort simulations at 665 (abort to orbit) and 823 seconds (return to launch site abort); as well as a 425-second run above RPL. Each redesign required certification, with each change run on one engine for 5,000 seconds, roughly the equivalent of ten flights.[1131]

The engines used for certification were not the ones scheduled to fly, since this test program "used up much of their life."[1132] Production Engine 2004 went through the first cycle between March 27 and June 27, 1979, and the second cycle from September 2, 1979 to February 8, 1980.[1133] Engine 0009, the flight spare for the orbiter *Columbia*, completed the first cycle in late August 1980, and the second in December 1980. The second cycle ended with accomplishment of an 823-second structural margin test designed to test distressed ball bearings in the liquid

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[1126] "MPTA Static Firing Goes Exactly as Planned," *Lagniappe*, December 17, 1980: 3; "Two MPTA Firings," 1, 5.
[1127] Two of the three engines completed the 625-second duration; the engine in the No. 1 position shut down at 239 seconds. Jenkins, *Space Shuttle*, 227.
[1128] Driver, interview, 7.
[1129] Hopson, interview.
[1130] Jenkins, *Space Shuttle*, 227.
[1131] Bob Marshall, interview by Jessie Whalen and Sarah McKinley, April 22, 1988, Oral Interviews: Space Shuttle History Project Transcripts Collection, Report No. MHR-16 (Huntsville: AL: MSFC History Office, December 1988), 136.
[1132] Heppenheimer, *Development of the Space Shuttle*,166.
[1133] "Third Shuttle Main Engine On Its Way To Mississippi," *Marshall Star*, April 4, 1979, 1; "SSME Update," *Marshall Star*, June 27, 1979, 1.

oxygen turbopump.[1134] With this accomplishment, the FMOF configuration SSME was qualified for flight. In total, eight PFC cycles were completed prior to STS-1.

On March 13, 1980, the first full power test (109 percent of RPL) of the SSME was completed. Of the 125-second run on a single engine, ten seconds were at 109 percent of RPL, and twenty-six seconds were above the normal RPL. This milestone was a major step towards certification of the engine for FPL abort capability.[1135] Additionally, a goal of 65,000 seconds had been established by John Yardley, NASA Headquarters Associate Administrator for Manned Space Flight, as representing engine flight worthiness. This requirement for total accumulated test duration of a single engine was achieved on March 24, 1980, during a test on Engine 2004.

Acceptance Testing

Every engine that went on the orbiter was acceptance tested. Unless there was a rebuild, which would trigger the need for a new acceptance or green run test, testing was done once for each engine.[1136] If the engine passed, it was put into the flight pool.[1137] Engine 2005, earmarked for the first orbital flight of the SSP, was the first of the three-engine cluster to be delivered to SSC, in April 1979, for acceptance testing.[1138] Engines 2006 and 2007 followed. The acceptance test protocol at this point in the program included a 1.5-second start verification, a 100-second calibration firing, and a 520-second flight demonstration test. Engine 2007 was the first to complete the acceptance test requirements, and to qualify as the first flight engine for the SSP.[1139] Following successful completion of the test series, the three engines were shipped to KSC for installation on *Columbia*.[1140]

In preparation for STS-1, twenty-one engines had been tested, including the three scheduled to fly on *Columbia*. Approximately 575 single-engine tests had been conducted, totaling more than 77,000 seconds of run time.[1141]

[1134] "Space Shuttle Main Engine 0009 to Complete PFC Test Series," *Lagniappe* , August 22, 1980: 1, 3.

[1135] A malfunction of one engine could require thrust levels in excess of rated power from the other two engines to enable the Shuttle to achieve orbit or return for safe landing. "SSME Tested at Full Power," *Marshall Star*, March 19, 1980, 1.

[1136] Marshall, interview, 138.

[1137] Hopson, interview. Rocketydyne's contract with NASA stipulated that twelve flight-ready engines would be at KSC at all times.

[1138] "Third Shuttle Main Engine," 1.

[1139] Mitchell, interview.

[1140] "Columbia's Engines Complete Checks," *Lagniappe*, June 18, 1980, 1, 4; "Main Engine Recertification Tests Started," *Marshall Star*, June 4, 1980, 2.

[1141] D.J. Sanchini and H.I. Colbo, "Space Shuttle Main Engine Development," Microfiche No. SHHDC-3542 (Huntsville, AL: MSFC History Office).

Engine Testing Since 1981

Within one month of the launch of STS-1, 109 percent RPL certification testing was initiated. This series required two testing cycles each on two engines. Each cycle entailed a minimum of thirteen tests and 5,000 seconds, including 3,000 seconds at FPL, 380 seconds at 105 percent RPL, and 380 seconds at 111 percent RPL. Nine different normal and emergency test power level profiles were specified.[1142] Engines 2010 and 2013 were selected for FPL certification. The first cycle testing of Engine 2010 began on December 14, 1981, and concluded on February 9, 1982; the second cycle was run between February 19, 1982 and June 6, 1982. Overall, twenty-eight tests made up the first two series, resulting in 10,331 total seconds of which 6,650 seconds were at FPL.[1143] Testing of Engine 2013, begun on March 7, 1982, was prematurely concluded as the result of a catastrophic high-pressure fuel turbopump failure.[1144] As a result, Engine 2014 replaced Engine 2013 as the second FPL certification engine, requiring a fresh start. The first cycle began on May 15, 1982; the second cycle concluded on April 23, 1983. All tests were completed successfully with all requirements met. However, frequent replacement of the high-pressure oxidizer and fuel turbopumps was required. The two test cycles for Engine 2010 required a total of seven oxidizer and eleven fuel turbopump removals for repair, parts replacement, or configuration upgrade. Similarly, Engine 2014 required ten oxidizer and eight fuel turbopump replacements during its two testing cycles.[1145]

The December 18, 1982, flight readiness firing of the new orbiter *Challenger* included the new FPL configuration SSME Engines 2011, 2015, and 2012. The initial test indicated a large hydrogen leak. A follow-up test run on January 25, 1983, traced the leak to the main combustion chamber of Engine 2011. The problem had been caused by a crack in the coolant outlet elbow of the chamber, which resulted from a previous major repair. Engine 2011 was removed and replaced with Engine 2017, after spare Engine 2016 was found to be unacceptable for flight due to a heat exchanger leak.[1146]

Given the repeated major engine failures, in February 1983, NASA ordered an immediate halt to all FPL testing. This second moratorium closely followed the discovery of the small leak in Engine 2016’s heat exchanger primary tube. In August 1983, the moratorium was rescinded when the SSME program was restructured into two separate and equal programs, Development and Flight. The Development program was charged with developing turbopumps for FPL (Phase II).[1147] However, it was not until the introduction of the Block II engine in 2001 that “109 percent became available on a routine basis.”[1148] However, 109 percent remained reserved for

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[1142] Biggs, “Development History,” 43.
[1143] “Rocketdyne’s SSMEs complete second series of full power tests,” *Rockwell News*, June 25, 1982, 2.
[1144] Biggs, “Development History,” 44.
[1145] Biggs, “Development History,” 49.
[1146] Biggs, “Development History,” 53-54.
[1147] Biggs, “Development History,” 57.
[1148] Jenkins, *Space Shuttle*, 227.

contingency use only, in accordance with NSTS 12820 Space Shuttle Operational Flight Rule A4-53, "Use of Maximum Throttles."

Following eighteen problem-free launches, in July 1985, during *Challenger's* eighth mission (STS-51F), one of the SSMEs experienced premature shutdown, causing the vehicle to abort to orbit. Analysis indicated that the shutdown was due to faulty temperature sensors. Work on redesigned sensors had begun prior to STS-51F, and the new sensors were incorporated before the next flight. The only other instances in which flight engines were prematurely shutdown while on a vehicle were during five on-pad aborts which occurred before missions STS-41D, STS-51F, STS-55, STS-51, and STS-68 between 1984 and 1994. After each on-pad abort, the conditions causing the anomaly were understood and the engines were inspected or replaced prior to launch.

No engine tests were conducted for five months during the SSP stand down in the aftermath of the *Challenger* accident on January 28, 1986. As part of NASA's recovery efforts, the SSME program underwent a two-year review of requirements. Included in the design review were structural audits, thousands of weld assessments, and examination of 10,000 problem reports.[1149] As a result, a total of seventy-one engine design changes were identified.

On August 18, 1986, the Development and Flight SSME programs were reunited as one program. Around this time, MSFC awarded a contract to Pratt & Whitney in West Palm Beach, Florida, to design and develop the alternate high-pressure oxidizer turbopump and the high-pressure fuel turbopump for the SSME.

Prior to 1985, engine tests were conducted at a rate of approximately 33,000 seconds per year. Starting in 1987, the rate increased to about 43,000 seconds per year.[1150] The first SSME static firing following the *Challenger* accident was on June 26, 1986. During the test, Engine 2106 was ignited for 1.5 seconds on Test Stand A-2 at SSC. This was the first test in a series leading to a full-duration static test of 520 seconds on July 25, 1986. During 1987 and 1988, static firings of the SSMEs reached an "all time peak with a record firing of 1,040 seconds, the longest shuttle engine test ever conducted."[1151] This record was later broken by two test firings of 2,017 seconds each, performed just weeks before the RTF launch of *Discovery* on September 29, 1988.

Test Stand E-8 at Pratt & Whitney's facility in West Palm Beach supported development testing of the SSME alternate turbopumps, beginning in 1988. Thereafter, with the activation of the B-1 test stand on March 30, 1988, all SSME testing was consolidated at NASA's SSC. Test Stand B-1 began service with the ignition test of Engine 2206, followed by a twenty-five-second firing on April 9.

[1149] Biggs, "Development History," 62.

[1150] NASA, *SSME Assessment*, 11.

[1151] Mack R. Herring, *Way Station to Space: A History of the John C. Stennis Space Center* (Washington, DC: NASA Headquarters, 1997), 331-332.

Many milestones were achieved during the SSME testing program. The 500th engine test occurred on November 26, 1980.[1152] This achievement was doubled on February 25, 1988, with the 1,000th test firing of a SSME, and doubled again four years later, on July 24, 1992, with the 2,000th test firing. The ground test program for the Block II high-pressure fuel turbopump, started in late 1999, had accrued a total of 251 starts and 143,596 seconds of hot fire experience by March 2002. According to George Hopson, this hot fire accrual was comparable to the test time of 268 starts and 129,222 seconds for the Block I high-pressure oxidizer turbopumps.[1153] The SSME reached one million seconds of test and flight operations during a test firing at SSC on January 21, 2004.[1154]

In other program milestones unrelated to engine testing, in August 2003, the first overhaul of a Pratt & Whitney high-pressure oxidizer turbopump flight unit was completed. Refurbishment followed completion of the turbopump's first seven years of service, during which time it underwent five ground tests and flew on six missions. The fifteen-month overhaul and repair process entailed complete disassembly, inspection, and refurbishment, plus upgrade or replacement of components. Most major parts were reused. Pratt and Whitney's specified service duration before required overhaul for the LO2 turbopump was equivalent to eleven shuttle missions.[1155]

SSME Nozzle 5016, shipped in June 2011, was the last engine component delivered to KSC to support the SSP. All other parts had been made, and were refurbished as needed.

Phased Engine Development

Design improvements made throughout SSME's history significantly improved reliability, reusability, and maintenance. Significant changes to major components were introduced in groups in "block upgrades." The implementation of the Advanced Health Management System discussed below was the last major change to the engine. It culminated in a four-fold reduction in the probability of a catastrophic failure due to a SSME. Useable life on many components also increased significantly throughout the history of the project. Many major components were tested in excess of one hundred times. With the increases in reliability and durability of components, maintenance was significantly reduced. The time required to inspect and prepare an engine between flights over the course of the SSP was reduced by 57%.[1156]

[1152] "500th SSME Test Conducted at NSTL," *Lagniappe,* November 26, 1980, 1, 5.

[1153] George D. Hopson, "Atlantis STS-110 Space Shuttle Program SSME Flight Readiness Review," March 26, 2002, http://www.jsc.nasa.gov/news/columbia/frr/sts-110/11_ssme.pdf.

[1154] NASA SSC, "Chronology of Significant Events."

[1155] Pratt & Whitney, "Pratt & Whitney Delivers First Overhauled Space Shuttle Oxidizer Turbopump," August 2003, http://www.pw.utc.com/media_center/press_releases/2003/08_aug/8-22-2003_7412429.asp.

[1156] Van Hooser and Bradley, "Space Shuttle Main Engine."

According to Dewayne Collins, SSME Transition Manager, the alternate turbopumps represented the main technological improvement over the past two decades.[1157] Other noteworthy changes were the two-duct powerhead (Block I), the single-coil heat exchanger (Block I), and the large-throat main combustion chamber (Block IIA).

First Manned Orbital Flight SSME and Full Power Level SSME

The baseline, or FMOF, engine flew on the first five Shuttle missions at 100 percent RPL.[1158] Subsequently, the first improvement program, the Full Power Level SSME, was first flown on *Challenger's* mission STS-6, launched on April 4, 1983. This upgrade to the baseline configuration engine incorporated changes to the hot gas manifold fuel bowl liner, the fuel preburner, and the flowmeter. In the high-pressure fuel turbopump, the interstage seals were replaced and the turbine blade to tip seal clearance was increased. The housing material of the high-pressure oxidizer turbopump was changed to INCO 903. The blocking area of the low-pressure fuel turbopump was revised, and the turbine discharge turning vane in the low-pressure oxidizer turbopump was modified. Also, the tube wall thickness of the nozzle was increased, and a steam loop was added to the nozzle.[1159]

Phase II Engine

In 1983, NASA began the Phase II engine development program (Figure No. C-16). "The most significant improvements in the Phase II engine were in turbopump components and new and improved sensors."[1160] The latter included an improved hot gas temperature sensor, and the addition of a skin temperature sensor to the anti-flood valve. In addition, the pressure sensor cavity was modified and structural improvements were made to the spark igniter case. The Phase II engine first flew on *Discovery's* RTF mission, STS-26, launched on September 29, 1988.

Block I and Block II Engines

The next major step in engine advancement was replacement of the high-pressure turbopumps in order to meet NASA's goal of increasing the period of time between overhauls by flying ten times without removing the turbopumps. Pratt & Whitney was selected to provide redesigned alternate turbopumps. The primary objective for the turbopump redesign was to eliminate failure modes and vulnerablitlities in the heritage design. Some of the turbopump parts were originally built by welding together forged segments. These welds were expensive and time-consuming, and caused a lot of problems. Accordingly, elimination of the welds was a key specification in the Block I and II SSME design. Otto Goetz believed this was a major achievement, which

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[1157] Dewayne Collins, interview with Joan Deming and Patricia Slovinac, April 8, 2010, MSFC.
[1158] Jue, "Thirty Years."
[1159] Fred Jue and Fritz Kuck, "Space Shuttle Main Engine (SSME) Options for the Future Shuttle," The Boeing Company (American Institute of Aeronautics and Astronautics, Inc., AIAA 2002-3758, 2002), 2.
[1160] Jue and Kuck, "Options for the Future," 1-2.

increased the reliability of the engine.[1161] Additionally, he considered the change to a different material for the Block I and II turbine blades, which eliminated the need for any coating on the airfoils, another significant improvement.[1162]

The **Block I** SSME was comprised of the Phase II base engine with the addition of an improved powerhead, single-coil heat exchanger, and a new high-pressure oxidizer turbopump made by Pratt & Whitney. The new two-duct powerhead, which replaced the three-duct design, improved the distribution of the fuel flow and reduced the pressure and temperature in the engine. It eliminated over seventy-four welds and had fifty-two fewer detail parts. The two-duct powerhead also featured new improved main injector and both preburner injectors, as well as a heat exchanger with no inter-propellant welds.[1163] The redesigned single-coil heat exchanger featured thicker walls, increased by 25 percent. The new high-pressure oxidizer turbopump included new ball bearings made of silicon nitride, a ceramic material 30 percent harder and 40 percent lighter than steel. This material greatly improved the wear performance and fatigue life of the turbopump bearings.[1164] The casting process used to produce the new high-pressure oxidizer turbopump eliminated all but seven of the 300 welds of the previous turbopump.[1165] The new turbopump also introduced a stiff single disk/shaft configuration and thin-cast turbine airfoils.

Certification testing on the new Block I configuration SSME was completed at SSC in March 1995 (Figure No. C-17). The new turbopump was designed for a life of sixty missions, and certified for ten flights without inspection, overhaul or maintenance.[1166] The first Block I flight engine (Engine 2036) was flown on *Discovery* (STS-70), launched on July 13, 1995; it flew in the center (No. 1) position.[1167] The same engine flew in the No. 3 position on *Endeavour* during mission STS-72, launched on January 10, 1996. On May 19, 1996, *Endeavour* (STS-77) was the first shuttle to fly with the full complement of three Block I SSMEs. The last flight of the Block I engine was STS-88 in December 1998.

The succeeding configuration, the **Block IIA** SSME, featured a new large throat main combustion chamber. The new chamber design increased throat diameter by 6 percent and decreased chamber pressure by 9 percent. Welded forgings were replaced by integral castings, resulting in the elimination of forty-eight welds.[1168] It also incorporated improved cooling

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[1161] Goetz, interview.
[1162] Goetz, interview.
[1163] Biggs, “Development History,” 63.
[1164] Jue, “Thirty Years.”
[1165] NASA MSFC, “Space Shuttle Main Engine (SSME) Enhancements,” NASA Facts, March 2002, http://www.nasa.gov/centers/marshall/ pdf/174534 main_ssme.pdf.
[1166] “Discovery lifts off with upgraded SSME; crew deploys TDRS-G,” *Aerospace Daily,* Microfiche No. SHHDC-5884 (Huntsville, AL: MSFC History Office, July 14, 1995).
[1167] “Shuttle Flies With Block 1,” *Aviation Week & Space Technology*, Microfiche No. SHHDC-5878 (Huntsville, AL: MSFC History Office, July 17, 1995).
[1168] Biggs, “Development History,” 63.

capability for longer life. Overall, the throat of the new chamber was about 10 percent larger, which allowed the high-pressure turbopumps to operate at lower turbine temperatures and pressures.[1169] Royce Mitchell, former Deputy Manager for the SSME program, noted that this configuration was a significant step in safety and reliability. The large throat "reduced the pressure in the chamber, which meant all the pumps and all the rotating machinery and all the flow upstream of the reduced chamber could be relaxed, could be lower-pressure, lower rpm, and the safety of the main engine took a quantum leap when the Block II came along."[1170] The Block IIA SSME was first flown on *Endeavour* (STS-89) in January 1998; its last flight was STS-109 in March 2002.

The **Block II** configuration added a more robust high-pressure fuel turbopump developed by Pratt & Whitney and incorporated the changes made in the Block I and Block IIA engines. The design of the high-pressure fuel turbopump mirrored that of the high-pressure oxidizer turbopump. Welded sheet metal was replaced by precision investment castings, thus eliminating 387 welds for the housing. The alternate turbopump incorporated a stiff single-piece shaft/disk with thin-walled turbine blades. The new design also incorporated silicon nitride bearing elements similar to the upgraded high-pressure oxidizer turbopump, and eliminated the need for special airfoil coatings.[1171] The unique casting made the turbopump stronger and increased the number of flights between major overhauls. Although the new turbopump added 240 pounds of weight to the Shuttle, the engine was safer and more reliable because of increased turbopump robustness.[1172] Compared with the Phase II SSME, the Block II engine was twice as safe and required 57 percent less maintenance.[1173] It was designed for a life span of sixty starts.[1174]

Certification testing for the Block II high-pressure fuel turbopump began in late 1999 (Figure No. C-18). The first Block II engine (Engine 2051) flew on *Atlantis* (STS-104) in July 2001; the second was flown on *Endeavour* (STS-108) in December 2001.[1175] In April 2002, *Atlantis* (STS-110) was the first Shuttle to incorporate three Block II engines (Engines 2048, 2051 and 2045), which included the first full Pratt & Whitney suite of six high-pressure turbopumps. By this time, thirteen Block II high-pressure fuel turbopumps had been manufactured and delivered, and twelve units completed acceptance tests at SSC. A total of nineteen units had been scheduled for completion through manufacture by September 2002.[1176]

[1169] NASA MSFC, *Space Shuttle Main Engine Turbopump*, NASA Facts (Huntsville, AL: Marshall Space Flight Center, April 2005), http://www.nasa.gov/centers/marshall/pdf/113012main_shuttle_turbopump.pdf.
[1170] Mitchell, interview.
[1171] NASA MSFC, "Turbopump."
[1172] NASA MSFC, "Enhancements."
[1173] Jue, "Thirty Years."
[1174] Jenkins, *Space Shuttle*, 412.
[1175] One Block II configuration engine and two Block IIA engines flew on mission STS-104. "New main engine promises even safer shuttle ride," NASA News Release, April 26, 2001, http://spaceflight.nasa.gov/spacenews/releases/2001/H01-79.html.
[1176] Hopson, "Atlantis STS-110."

Advanced Health Management System

In 2000, NASA's MSFC began development of the **Advanced Health Management System** (AHMS), a modification of the existing Block II main engine controller. The AHMS became active on mission STS-117 in June 2007. This final enhancement of the SSME included the addition of advanced digital signal processors, radiation-hardened memory, and new software. These changes to the main engine controller provided the capability of monitoring the vibrations of the high-pressure turbopumps in such a way that made it possible "to analyze and discriminate true rotor unbalance from erroneous sensor readings."[1177] They could detect and track a very subtle shift in the engine's vibration levels in a split second, allowing the engine to be safely shut down.

SSME Physical and Functional Descriptions

SSMEs by the Numbers

With the final mission of the SSP, forty-six engines were flown in 135 launches for a total of 405 engine missions. Of the total engine missions, 273 were completed with the FMOF, Phase II, or Block I configuration engines; forty-nine were with the Block IIA configuration containing the new large throat main combustion chamber; and eighty-three were Block II configuration featuring both the large throat main combustion chamber and the new high-pressure fuel turbopump.[1178] Typically, existing engines were modified to incorporate the newest design. All seven newly manufactured Block I configuration engines (Engines 2036 through 2042) were upgraded, and all fourteen Block IIA configuration engines were modified to Block II when the new high-pressure fuel turbopump became available. Many components from the earlier Phase II and Block I engines were used for the upgraded engines.[1179] Two original FMOF engines, 2007 and 2015, each underwent two successive rebuilds to the Phase II and Block I configurations. Engine 2007 began service with STS-1, and flew on *Columbia's* initial five missions. It ended service with STS-52, launched in October 1992, its thirteenth flight.

The SSP lost six engines as the result of the *Challenger* and *Columbia* accidents. Of the three SSMEs lost on Challenger, Engines 2020, 2021, and 2023, Engines 2020 and 2021 had flown together on four of their five previous flights. Engines 2049, 2053, and 2055 were lost with *Columbia*. This had been the maiden flight of Engine 2055.

[1177] NASA MSFC, *Space Shuttle Main Engine Advanced Health Management System,* NASA Facts, (Huntsville, AL: George C. Marshall Space Flight Center, August 2007), http://www.nasa.gov/centers/marshall/pdf/186582main_REV_B_AHMS_Fact_Sheet_STS-118.pdf; Jue and Kuck, "Options for the Future," 2.

[1178] Pratt & Whitney Rocketdyne, Inc., "Space Shuttle Main Engine KSC Processing Nominal Flow (Landing to Launch)," no date, 26, presentation materials provided to Joan Deming and Patricia Slovinac, KSC, June 2010.

[1179] Jenkins, *Space Shuttle*, 420.

The SSP ended with fourteen SSMEs in the active fleet. All were Block II engines with a two-duct powerhead. In the heyday of the program, twelve engines were kept flight-ready. At any time, an average of two to three engines were out of service, and there were always six engines ready, including three on the orbiter vehicle and three ready to be swapped out, if needed.

Engine 2019 was the fleet leader during the SSP. It flew nineteen missions, beginning with the launch of STS-9 (*Columbia*) on November 28, 1983, and completed its service with the landing of STS-93 (*Columbia*) on July 27, 1999. The newest addition to the SSME fleet, Engine 2061, arrived at KSC on December 19, 2008.[1180] It flew only two missions, STS-130, launched on February 8, 2010, and STS-134, launched on May 16, 2011. Engines 2045, 2047, and 2060 were the last to fly out the program on STS-135 (*Atlantis*). Of these, Engines 2045 and 2047 were both veterans of fourteen previous missions. Engine 2017 was the only unmodified engine to fly on all five orbiters, on flights dating from STS-6 (*Challenger*) in April 1983, through STS-75 (*Columbia*) in February 1996.

General Description

Each SSME measured approximately 14' in length and 7.5' in diameter at the exit of the nozzle, and weighed approximately 7,775 pounds. The engine powerhead, the portion located above the nozzle, included the two high-pressure turbopumps and the main combustion chamber, plus the main injector and the two preburner injectors.

SSME Major Components

The SSME contained approximately 50,000 parts, of which 7,000 were tracked periodically for replacement.[1181] The major components included the low-pressure fuel turbopump, the high-pressure fuel turbopump, the low-pressure oxidizer turbopump, the high-pressure oxidizer turbopump, the hot gas manifold, the oxidizer and fuel preburners, the main combustion chamber, the oxidizer heat exchanger, the nozzle, and five propellant valves. Physical and functional descriptions of each major Block II engine component follow.

Low- Pressure and High-Pressure Turbopumps

Each SSME had two high-pressure turbopumps that supplied LO2 and LH2 to the engine's main combustion chamber. A turbopump is a single unit consisting of a pump, driven by a turbine, that boosts the pressure of the propellant. The low-pressure oxidizer and low-pressure fuel turbopumps were mounted 180 degrees apart on the engine. The ducts from the low-pressure

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[1180] Helen Lewin, "SSME Planned Assignments Including Performance Impacts," Pratt & Whitney Rocketdyne, September 17, 2009, 20, http://rkdn.ksc.nasa.gov. Engine 2062 was also finished, but never acceptance tested. VanHooser, personal communication.

[1181] NASA KSC, *Space Shuttle Main Engine Processing Facility*, NASA Facts (Florida: Kennedy Space Center, 2006), http://www.nasa.gov/centers/kennedy/pdf/ 167449main_SSMEPF-06.pdf.

turbopumps to the high-pressure turbopumps contained flexible bellows that enabled them to flex when loads were applied.[1182]

The **Low-Pressure Oxidizer Turbopump** (Figure No. C-19) contained an axial-flow inducer driven by a six-stage hydraulic turbine. It boosted the LO2 pressure from 100 psia to 422 psia. The flow was supplied to the high-pressure oxidizer turbopump to permit it to operate at higher speeds without cavitating.[1183] The low-pressure oxidizer turbopump operated at approximately 5,150 rpm. It measured approximately 18” x 18”, and was flange-mounted to the orbiter propellant ducting.[1184] A triple-redundant, magnetic-type, speed transducer was located on the turbine end.

The **Low-Pressure Fuel Turbopump** (Figure No. C-20) contained an axial-flow inducer driven by a two-stage, axial-flow turbine powered with gaseous hydrogen. It boosted LH2 pressure from 30 psia to 276 psia and supplied the high-pressure fuel turbopump. During engine operation, this pressure increase allowed the high-pressure fuel turbopump to operate at high speeds without cavitating. The low-pressure fuel turbopump operated at approximately 16,185 rpm. It measured approximately 18” x 24”, and was flange-mounted to the SSME at the inlet to the low-pressure fuel duct.[1185] Foam insulation encased in a Kevlar jacket covered the pump housing.

The **High-Pressure Oxidizer Turbopump** (Figure No. C-21), which debuted in July 1995, contained a mainstage pump for all of the oxidizer flow and another for a portion of the oxidizer flow used to supply the preburners. The mainstage pump was a double entry centrifugal impeller flanked by two inducers. The preburner pump was a single centrifugal impeller. The turbopump had a common shaft and was driven by a three-stage, hot gas turbine. The main pump boosted LO2 pressure from 422 psia to 4,300 psia while operating at approximately 28,120 rpm. The turbopump provided 970 pounds of LO2 per second.

The high-pressure oxidizer turbopump discharge flow split into several paths, one of which was routed to drive the low-pressure oxidizer turbopump turbine. Another path was routed through the main oxidizer valve and entered the main combustion chamber. Another small path was tapped off and sent to the oxidizer heat exchanger, where it was vaporized and then used to pressurize the external tank. The final path entered the preburner impeller to raise the LO2’s pressure from 4,300 psia to 7,420 psia for use in both preburners. The high-pressure oxidizer turbopump measured approximately 24” x 36”, and was flange-mounted to the hot gas manifold.[1186]

[1182] USA, *Crew Operations*, 2.16-6.
[1183] Cavitation occurs when cavities of gas develop and collapse in liquid fuels.
[1184] USA, *Crew Operations*, 2.16-5.
[1185] USA, *Crew Operations*, 2.16-4.
[1186] USA, *Crew Operations*, 2.16-5, 2.16-6.

The **High-Pressure Fuel Turbopump** (Figure No. C-22), which debuted in July 2001, was the most complex component of the SSME. The three-stage centrifugal pump was driven by a two-stage, hot gas turbine. It supplied 162 pounds of LH2 fuel per second, boosted LH2 pressure from 276 psia to 6,515 psia, and operated at a speed of approximately 36,000 rpm, or 600 times per second. Because of the centrifugal force at this speed, the turbine blades, which normally weigh 13 ounces each, weighed the equivalent of 14 tons.[1187] The high-pressure fuel turbopump generated 70 hp for each pound of its weight, compared with an automobile engine, which generates about 0.5 hp for each pound of its weight. It measured approximately 22" x 44", and was flange-mounted to the hot gas manifold.

The discharge flow from the high-pressure fuel turbopump was routed through the main fuel valve and then split into three flow paths. One path was through slots in the jacket of the main combustion chamber, where the hydrogen was used to cool the chamber walls, and then delivered to the low-pressure fuel turbopump to drive its turbine. The second flow path, through the chamber coolant valve, supplied LH2 to the preburner combustion chamber and also cooled the hot gas manifold. The third hydrogen flow path was used to cool the engine nozzle. It then joined the second flow path from the chamber coolant valve.[1188]

Hot Gas Manifold

The hot gas manifold, the central component of the powerhead, was considered the structural backbone of the engine. It tied together and structurally supported the major components and almost all of the engine weight. Hot gas generated by the preburners, after driving the high-pressure turbopumps, passed through the hot gas manifold on the way to the main combustion chamber.[1189]

The hot gas manifold was manufactured in two halves which were joined together by electron-beam welding. The structural outer walls consisted of an alloy 903 sheet metal liner, with a space between the liner and wall cooled by hydrogen gas to reduce the outer wall temperature.[1190] The main injector was located in the center of the hot gas manifold. It included 600 coaxial elements which injected LO2 through their center posts. Flow shields, bolted to the outer row of elements, helped to protect them from damage and erosion from the high-velocity gas.

The redesigned two-duct hot gas manifold, first flown in July 1995, replaced the three small fuel ducts with two enlarged ducts. This modification significantly improved fluid flows in the system, decreased pressure and turbulence, and lowered temperatures in the engine during operation. As a result, the overall performance of the engine was enhanced and maintenance was reduced.

[1187] Goetz, interview.
[1188] USA, *Crew Operations*, 2.16-4, 2.16-5.
[1189] USA, *Crew Operations*, 2.16-7.
[1190] Jewett and Halchak, "Alloy 718," 754.

Preburners

Both the fuel preburner and oxidizer preburner were welded to the hot gas manifold. The first stage of combustion took place in the two preburners, where LO2 and LH2 were partially burned. The preburners produced hot gas that passed through the turbines to generate the power to drive the high-pressure pumps.[1191] The hot gas then passed through the hot gas manifold on the way to the main combustion chamber. Here, the addition of LO2 resulted in further combustion.

The structural body and inlet manifold of each preburner were machined from Inconel alloy 718 forgings and preformed sheet metal. These were joined by electron-beam and gas tungsten welding. The fuel preburner had an internal diameter of 10.43" and a combuster length of 4.37". The injector was made up of 264 coaxial elements, arranged in a concentric row pattern. Twenty-four of the elements supported and cooled three baffles that helped to stabilize combustion. An augmented spark ignition chamber was located in the center of the injector. The oxidizer preburner had an internal diameter of approximately 7.5" and a combuster length of 4.25". The injector was comprised of 120 coaxial elements, arranged in a concentric row pattern. Fifteen of the elements supported and cooled the three baffles. Of similar configuration to the fuel preburner, it contained a spark ignition chamber in the center of the injector. [1192]

Main Combustion Chamber

The main combustion chamber (Figure No. C-23), bolted to the hot gas manifold, was where the LH2 and LO2 from the fuel and oxidizer preburners were mixed and burned to provide thrust.

The main combustion chamber had to tolerate hot gases at temperatures up to 6,000 degrees F. It also had to contain the internal pressure of 3,000 psi. To meet these demands, Rocketdyne developed NARloy-Z, a high conductivity copper-based alloy that contained silver and zirconium. The exterior of the liner was made from structural nickel which was applied by an electroforming process. The support jacket of the main combustion chamber was made from Inconel alloy 718. The main combustion chamber was cooled by super-cold hydrogen, which flowed through 430 channels machined into the liner inner wall.

A small augmented spark igniter chamber was located in the center of the main combustion chamber's injector. The main injector measured approximately 17.7" in diameter at the end, and featured a barrel-shaped collection of 600 identical, non-baffle injector elements, arranged in concentric rings.[1193] Each element was a hollow cylindrical post through which hot gases flowed. The dual-redundant igniter was used during the engine start sequence to initiate combustion. The

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[1191] USA, *Crew Operations*, 2.16-7.

[1192] Baker, *Manual*, 104.

[1193] Steven J. Wofford, personal communication with James M. Ellis, MSFC, August 31, 2011.

igniter was turned off after approximately three seconds because the combustion process was self-sustaining.[1194]

Heat Exchanger

Mounted in the oxidizer side of the hot gas manifold, the single-coil heat exchanger was made from a continuous piece of coiled stainless steel alloy tubing measuring 41' in length, and with an outer diameter of 0.50". It drew on engine heat from the turbine discharge flow from the high-pressure oxidizer turbopump to produce a flow of GO2 that pressurized the ET oxygen tank. Until mid-1995, the heat exchanger featured seven welds. The redesigned exchanger eliminated all seven welds and tripled the wall thickness of the tube. The increased thickness, to 0.032 inches compared with as thin as 0.0125 inches previously, served to reduce wear, and thus make catastrophic failures less likely. Maintenance time and post-flight inspections also were minimized.

Nozzle

The engine nozzle (Figure No. C-24) extended below the main combustion chamber. The velocity of the combustion gas was governed by the nozzle area ratio.[1195] The SSME nozzle measured 10.3" in diameter at the throat, and 90.7" at the nozzle exit. Total length of the nozzle was 121". The throat area measured approximately 93 square inches and the nozzle area was 50.265 square feet. The nozzle configuration underwent a number of successive design changes to meet requirements specifying an area ratio of 77.5:1 and a length equal to 80 percent of a fifteen degree conical nozzle.[1196] At 100 percent power level, propellants flowed through the nozzle at a rate of 1,035 pounds per second. "The nozzle accelerates the combustion products to 17,000 feet per second at the nozzle exit, generating 470,000 pounds of thrust at vacuum."[1197]

Coolant feed lines were located at the aft end of the nozzle. The inside wall of the nozzle was lined with 1,080, 1/8" stainless steel cooling tubes that carried hydrogen. The tubes were brazed to the surrounding structural jacket. During flight, a portion of the fuel was first circulated through the tubes before it was directed to the combustion chamber. Nine hatbands were welded around the jacket for hoop strength, and a hydrogen feed line ("steerhorn") measuring 1.625" in diameter also was attached to the nozzle exterior. Coolant manifolds were welded to the top and bottom of the nozzle, along with three fuel transfer ducts and six drain lines.

A support ring welded to the throat of the nozzle was the attach point for the engine heat shield. For protection from the high temperatures during the launch, ascent, on-orbit, and entry phases,

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[1194] USA, *Crew Operations*, 2.16-7.

[1195] The nozzle area ratio is derived by dividing the nozzle exit area by the throat area. R.A. O'Leary and J.E. Beck, "Nozzle Design,"1992, http//:www.engineeringatboeing.com.

[1196] O'Leary and Beck, "Nozzle Design."

[1197] O'Leary and Beck, "Nozzle Design."

portions of the nozzle were insulated with four layers of metallic batting covered with a metallic foil (Nichrome) acting as a thermal shield, and closed out by a layer of fine weave Nichrome screen.[1198]

Propellant Valves

Each engine had five major valves: the oxidizer preburner oxidizer valve, the fuel preburner oxidizer valve, the main oxidizer valve, the main fuel valve, and the chamber coolant valve. These valves were hydraulically actuated and controlled by electrical signals from the engine controller.

The **oxidizer preburner oxidizer valve** and the **fuel preburner oxidizer valve** were used to control the thrust level of the engine. The speeds of the high-pressure oxidizer turbopump and high-pressure fuel turbopump depended on the position of these two valves. The valves increased or decreased the LO2 flow into the preburners, thereby increasing or decreasing preburner chamber pressure and high-pressure oxidizer turbopump and high-pressure fuel turbopump speed. This directly affected LO2 and gaseous hydrogen flow into the main combustion chamber, which in turn increased or decreased engine thrust. The fuel preburner oxidizer valve was used to maintain a constant six-to-one propellant mixture ratio.[1199]

The **main oxidizer valve** controlled LO2 flow into the engine combustion chamber. The **main fuel valve** controlled the total LH2 flow into the engine cooling circuit, the preburner supply lines, and the low pressure fuel turbopump turbine. When the engine was operating, the main valves were fully open. A **chamber coolant valve** was located on each engine combustion chamber coolant bypass duct. It regulated the amount of gaseous hydrogen allowed to bypass the nozzle coolant loop to control engine temperature.[1200]

Other SSME Components and Systems

Main Engine Controller

Each SSME had its own on-board digital computer, which monitored and controlled all engine functions and diagnostics. It could shut an engine down if it detected a problem. Instructions to the engine control elements were updated 50 times per second, or every twenty milliseconds. The pressurized, thermally conditioned controller, manufactured by Honeywell, was attached to the thrust chamber and nozzle coolant outlet manifolds on the low-pressure fuel turbopump side of the engine. Each controller contained two redundant digital computer units, and each Block II computer used Motorola 68000 32-bit microprocessors. The double-redundant system contained a total of four processors per controller. All the sensors and actuators were connected directly to

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[1198] USA, *Crew Operations*, 2.16-7.
[1199] USA, *Crew Operations*, 2.16-8.
[1200] USA, *Crew Operations*, 2.16-8.

the controller. The microprocessors operated in "lock-step" within the dual central processing units (A and B). Prior to replacement by the Motorola processors, the controller used two redundant Honeywell HDC-601 computers.

The controller, operating in conjunction with the engine sensors, valves, actuators, and spark igniters, formed a self-contained system for engine control, checkout, and monitoring. It provided "engine flight readiness verification, engine start and shutdown sequencing, closed-loop thrust and propellant mixture ratio control, sensor excitation, valve actuator and spark igniter control signals, engine performance limit monitoring, and performance and maintenance data," as well as "onboard engine checkout, response to vehicle commands, and transmission of engine status." [1201]

The SSME controller processed four critical engine operating parameters and closely monitored them to see whether they remained within the specified limits (or "redlines"). A redline violation sensed by the controller caused it to automatically shut down the engine.[1202] In-flight parameters included:

- The high-pressure fuel turbopump's turbine discharge temperature not to exceed 1,860 degrees Rankine (R)[1203]
- The high-pressure oxidizer turbopump's turbine discharge temperature not to exceed 1,660 degrees R or fall below 720 degrees R.
- The high-pressure oxidizer turbopump's intermediate seal purge pressure not to fall below 159 psia.
- During steady state operation, the main combustion chamber's pressure not to fall more than 200 psia (400 psia, during throttling) below the reference chamber pressure.

Additional parameters were monitored on the ground prior to engine start, or following engine start but prior to SRB ignition. Exceedance of specified values for these parameters could also initiate a shutdown or inhibit engine start.

Bleed Valves

Two bleed valves were contained in each SSME, including one LH2 bleed valve and one LO2 bleed valve. The **liquid hydrogen bleed valves** were used to circulate LH2 through the engines

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[1201] USA, *Crew Operations,* 2.16-9, 2.16-10.

[1202] USA, *Crew Operations,* 2.16-26. Redlines were designed to avert catastrophic failure by initiating engine shutdown. Synchronous vibration redlines were later added, with the incorporation of AHMS, for the high-pressure oxidizer turbopump and high-pressure fuel turbopump, bringing the total of active, in-flight redlines to six. The Phase II and earlier SSMEs had two more redlines. These were a secondary seal redline on the high-pressure oxidizer turbopump seal package, and a coolant liner redline on the high-pressure fuel turbopump. Wofford, personal communication; Jon D. Reding, personal communication.

[1203] Rankine is a temperature measurement unit equal to one Fahrenheit degree, and zero on this scale is an absolute zero. Under the standard atmospheric pressure 0 Rankine equals -459.67 Fahrenheit. This scale does not have any temperature below zero; Aqua-Calc. "What is Rankine," http://www.aqua-calc.com.

during prelaunch thermal conditioning. They also served to dump the LH2 trapped in the engines after MECO. The **liquid oxygen bleed valves** connected the engine internal LO2 lines to an overboard port. They were used only during prelaunch thermal conditioning.

Helium System

Helium was used to pneumatically close the five main hydraulically-actuated valves in the propellant lines should a hydraulic failure occur. The helium system also was used to purge the high-pressure oxidizer turbopump intermediate seals. Helium was injected between the seals to keep the hydrogen used to cool the turbine-end bearings from mixing with the LO2 in the pump end.[1204]

Pneumatic Control Assembly

Each SSME had one pneumatic control assembly. The assembly contained solenoid valves which were energized by commands from the SSME controller to control and perform various functions. These functions included "the high-pressure oxidizer turbopump intermediate seal cavity and preburner oxidizer dome purge, pogo system postcharge, and pneumatic shutdown."[1205]

Thrust Vector Control Actuators

Two main engine TVC actuators were connected to the powerhead of each SSME. One was for yaw and the other for pitch. The pitch actuator could move the engine 10.5 degrees up or down and the yaw actuator a maximum of 8.5 degrees up or down.[1206] Each actuator had its own hydraulic switching valve and received hydraulic pressure from the orbiter hydraulic systems.[1207] The actuators provided attitude control and trajectory shaping by gimbaling both the SSMEs and SRBs during first-stage and the SSMEs alone during second-stage. They changed each main engine's thrust vector direction as needed during the flight sequence.

SSME Process Flow

Since the arrival of the first SSME at KSC in 1979, Pratt & Whitney Rocketdyne was responsible for SSME processing. Historically, the engines were built and assembled at Rocketdyne's facility in Canoga Park, California (Figure Nos. C-25 through C-30), with flight inspections performed at KSC. With the completion of the Space Shuttle Main Engine

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[1204] Mark Kirkman, "Space Shuttle Systems 101 – More Than You Ever Needed To Know About the Space Shuttle Main Engines," *InterSpace News*, July 27, 2008, 4, http://www.interspacenews.com/ FeatureArticle/tabid/130/ Default.aspx?id=2130.
[1205] USA, *Crew Operations*, 2.16-24.
[1206] Baker, *Manual*, 105.
[1207] USA, *Crew Operations*, 2.16-25.

Processing Facility (SSMEPF) in June 1998, both the SSME assembly and flight inspection functions were consolidated at KSC. The SSMEPF was designed specifically for processing the main engines in support of Shuttle flight operations. The specifications for the facility were developed by representatives from Pratt & Whitney Rocketdyne, NASA Design Engineering, and United Space Alliance (USA).[1208] The facility provided the capabilities for post-flight inspections, maintenance, and functional checkout of all engine systems prior to installation in the orbiter. Before completion of this facility, these operations were conducted in the VAB. Engine 2058 was the first to be fully assembled in the SSMEPF. Processing and assembly work began in February 2004.[1209] This engine was first flown on STS-115, launched on September 9, 2006.

Assembly Sequence of Major Hardware

The assembly of SSME major hardware followed a number of sequential steps, beginning with the attachment of the large-throat main combustion chamber to the nozzle (Figure No. C-31). Next, the powerhead was attached to the main combustion chamber (Figure No. C-32), followed by the high-pressure oxidizer turbopump (Figure No. C-33) and high-pressure fuel turbopump (Figure No. C-34) attachments to the powerhead. The attachment of engine ducts and lines followed (Figure No. C-35). Next, both the low-pressure oxidizer turbopump (Figure No. C-36) and the low-pressure fuel turbopump were attached to the powerhead, followed by the addition of the main fuel valve and main fuel valve assembly (Figure No. C-37). The fuel pump oxidizer valve and valve assembly followed (Figure No. C-38). The assembly process for major hardware was completed with the attachment of the main engine controller (Figure No. C-39).[1210]

Landing to Launch

The flow for the engines supported the larger vehicle flow, which began with the Shuttle landing and ended with the next launch. All aspects of the SSME flow were handled at KSC.[1211] Following the *Challenger* accident, new maintenance requirements mandated that all three engines be removed after each flight. Routine operational SSME turnaround involved three primary activities: 1) post-landing safety inspection; 2) processing for reuse; and 3) launch preparation.[1212]

[1208] NASA KSC, “Engine Processing Facility.”

[1209] “KSC completes first full Shuttle main engine,” *Spaceport News,* August 13, 2004, 8.

[1210] Jerry Cook, et al., “SSME Historical Recordation,” presentation materials provided to Joan Deming and Trish Slovinac, June 12, 2009, MSFC.

[1211] “SSME Post flight to launch processing,” June 12, 2009, in NASA MSFC, “STS Stack,” Tab K, 19.

[1212] Rockwell International, Rocketdyne Division, “Space Shuttle Main Engine Turnaround Maintenance and Activities,” Microfiche No. SHHDC-5576 (Huntsville, AL: MSFC History Office, March 3, 1982), 2.

Post-landing Safety Inspection

After the Shuttle landed, an initial safety inspection was carried out at the KSC SLF prior to towing to the OPF. Safing was limited to a visual inspection to verify that the engines were secure for transport. Inspectors looked at exposed portions of the engines to detect any damage from the flight or landing, and to determine if the engines appeared structurally sound and firmly secured to the orbiter structure.[1213] Bearing drying purges were also connected at this time.

Processing for Reuse

After safing operations, the orbiter was towed to an OPF High Bay for initial processing, which took approximately fourteen working days.[1214] Here, the SSMEs were removed from the vehicle. Engine removal entailed the de-pinning of the TVC actuators, the de-foaming of the interface, removal of the heat shields, disconnection of the interface joints, and installation of interface ground support equipment (GSE). The three engines were removed in the order of 2 (left), 3 (right), and 1 (center) [they were installed in the reverse order, 1-3-2], and subsequently transported to the SSMEPF.

At the SSMEPF, all scheduled and corrective engine maintenance was performed. Routine maintenance after each flight included automatic checkout (accomplished by the engine controller), external and internal inspections, and limited leak checks of critical components, such as seals and other elements that could compromise launch pad safety or vehicle operation. External inspection included the detection and evaluation of structural failures (cracks, broken brackets and clamps, deformation, loss of clearance); local erosion and overheating (combustion chamber and preburner bodies, hot gas manifold and hot gas ducts); and damage from non-engine causes. Internal inspections focused on the components that experienced the most extreme temperature, pressures, and speeds during engine operation. Borescopes allowed inspections to be conducted with minimum engine disassembly.[1215]

The workflow in the SSMEPF began with an initial pre-processing leak check of the nozzle tubes as well as the fuel, hot gas, and liquid oxygen internals. Then, after system drying, post-flight leak checks of the main combustion chamber liner and heat exchanger were carried out prior to disassembly and inspection. Line replacement units (LRUs) were removed, and the powerhead and turbopumps were inspected.[1216] Next, the LRUs were installed, and joints and electrical connections were secured. A retest and checkout followed the preparations for installation of the SSMEs. Overall, processing in the SSMEPF took about eighty days for the three-engine set.[1217]

[1213] Rockwell International, “Turnaround Maintenance,” 2.

[1214] Cook, et al., “SSME Historical Recordation.”

[1215] Rockwell International, “Turnaround Maintenance,” 3-4.

[1216] LRU applies to engine parts that can be replaced in the turnaround area while the engine is installed in the vehicle. Rockwell International, “Turnaround Maintenance,” 5.

[1217] Cook, et al., “SSME Historical Recordation.”

The high-pressure turbopumps were removed after the first flight of a new engine for a more thorough inspection for debris. If the engine had flown previously, the turbopumps remained installed and were inspected using borescopes. In addition, the powerhead was inspected, and, as needed, repairs were made to the major components, including turbopumps, the main engine controller, nozzle, valves, actuators, and ducts. New or overhauled components were integrated into the flight engines. Leak checks, valve flow checks, and flight readiness tests were performed, and the nozzle TPS was installed.

Pratt & Whitney provided refurbishment for its high-pressure oxidizer and fuel turbopumps at each overhaul, scheduled after approximately ten flights. After refurbishment at the West Palm Beach facility, each turbopump was acceptance tested at SSC and then returned to service for an additional ten missions. Each turbopump was designed for a minimum service life of sixty missions.[1218]

Following the completion of work in the SSMEPF, the engines were returned to the OPF for installation into the orbiter and for pre-flight operations. (See Figure Nos. C-40 through C-46 for a pictorial representation showing the process of SSME installation into the orbiter.) These activities took approximately seven days. Work in the flow included the connection of interface joints, removal of GSE, turbopump torques, interface leak checks, connection of the TVC system, application of foam to the interfaces, installation of heat shields, and gimbal clearance checks.[1219] A final closeout inspection was made to detect any damage caused by maintenance activities. Engine nozzle covers were installed before transport to the VAB High Bay.

Launch

While the Shuttle was in the VAB, the SSMEs underwent one day of further leak checks, checkout, and rollout preparations. Pre-rollout activities included checkout of the orbiter/ET and orbiter/MLP interfaces, removal of the engine nozzle covers, and activation and deactivation of the trickle purge.

Following rollout and arrival at the launch pad, work included a helium signature test, ball seal leak checks, and main combustion chamber polishing. The helium fuel system purge was started at T-6.5 hours, and at T-6 hours the propellant bleed valves were opened to allow for thermal conditioning. At T-5 hours 50 minutes, the launch processing system initiated the SSME LH2 chill-down sequence in preparation for LH2 loading.

At T-4 minutes, the fuel system purge began. It was followed at T-3 minutes 25 seconds by the beginning of the engine gimbal tests. If all actuators functioned satisfactorily, the engines were gimbaled to a predefined position at T-2 minutes 15 seconds. The engines remained in this

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[1218] Pratt & Whitney, “Shuttle Atlantis Flies With Three New P&W Fuel Turbopumps,” press release, April 8, 2002, http://www.pw.utc.com.media_center/press _releases/2002/04_apr/4-8-2002_5712178.asp.

[1219] Cook, et al., “SSME Historical Recordation.”

position until engine ignition. At approximately T-3 minutes, the ET LO2 tank was pressurized to 221 psi, and almost one minute later, the LH2 tank was pressurized to 42 psi. At T- 90 seconds, the engines were declared ready when all thermal and pressure conditions for engine start were met. At T-10 seconds, the hydrogen burn-off flares fired underneath the engine nozzles. They helped to burn off excess hydrogen gas that had accumulated near the engines. At T-9.5 seconds, the engine chill-down sequence was complete.[1220]

At approximately T-6 seconds, the engines were started, one at a time. The starting of the engines was staggered in 120 millisecond intervals to minimize shock loads.[1221] Between engine start and MECO, LH2 and LO2 flowed out of the ET through the disconnect valves, into the feedline manifolds, and then was distributed to the engines.

If all three SSMEs reached 90 percent of their rated thrust by T-3 seconds, then at T-0, the computers issued the commands to ignite the SRBs and to detonate the eight hold-down bolts so liftoff could occur. If one or more of the three main engines did not reach 90 percent of their rated thrust at T-3 seconds, all SSMEs were shut down. The SSME controller operated and controlled the engine, and the hydraulic actuators controlled the main propellant valves. An on-board computer automatically controlled the start-up of the engine; shutdown was commanded by the vehicle, usually when the specified velocity had been obtained.[1222]

Beginning at T-0, the SSME gimbal actuators were commanded to their null positions and then allowed to operate as needed for thrust vector control. About seven seconds after liftoff, the Shuttle was clear of the launch tower and traveling approximately 87 miles per hour. The SSMEs throttled down to reduce stress during the period of maximum dynamic pressure. At approximately 65 seconds mission elapsed time (MET), the engines were again throttled up to 104.5 percent RPL and remained at that setting for a normal mission until approximately 7 minutes 40 seconds MET, when the engines were throttled down to limit vehicle acceleration to no more than three times normal Earth gravity (3-g). About 6 seconds before MECO, the engines were throttled back to 67 percent in preparation for shutdown. After approximately 8 minutes 30 seconds MET, the engines were commanded to shut down.[1223]

After ET separation, approximately 1,700 pounds of propellant were still trapped in the SSMEs. This residual LO2 and LH2 made the orbiter tail-heavy and unstable, and therefore, was removed. Dumping of these propellants occurred simultaneously, beginning at MECO plus 2 minutes, 2 seconds. The LO2 trapped in the feedline manifolds was expelled under pressure from the helium subsystem through the SSME nozzles. The pressurized LO2 dump continued for ninety seconds. The LH2 was expelled overboard without pressure from the helium subsystem. It flowed through the fill and drain valves and the topping valve for two minutes. After the

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[1220] USA, *Crew Operations*, 2.16-30.
[1221] Kirkman, “Space Shuttle Systems 101.”
[1222] USA, *Crew Operations*, 2.16-30.
[1223] USA, *Crew Operations*, 2.16-31.

propellant dump was completed, the SSMEs were gimbaled to their entry stow position, with the engine nozzles moved inward (toward one another) to reduce aerodynamic heating. They remained in this position until the orbiter was towed back to the designated OPF High Bay after landing.[1224]

[1224] USA, *Crew Operations*, 2.16-33, 2.16-34.