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

[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

[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

[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.