2.16 MAIN PROPULSION SYSTEM (MPS)

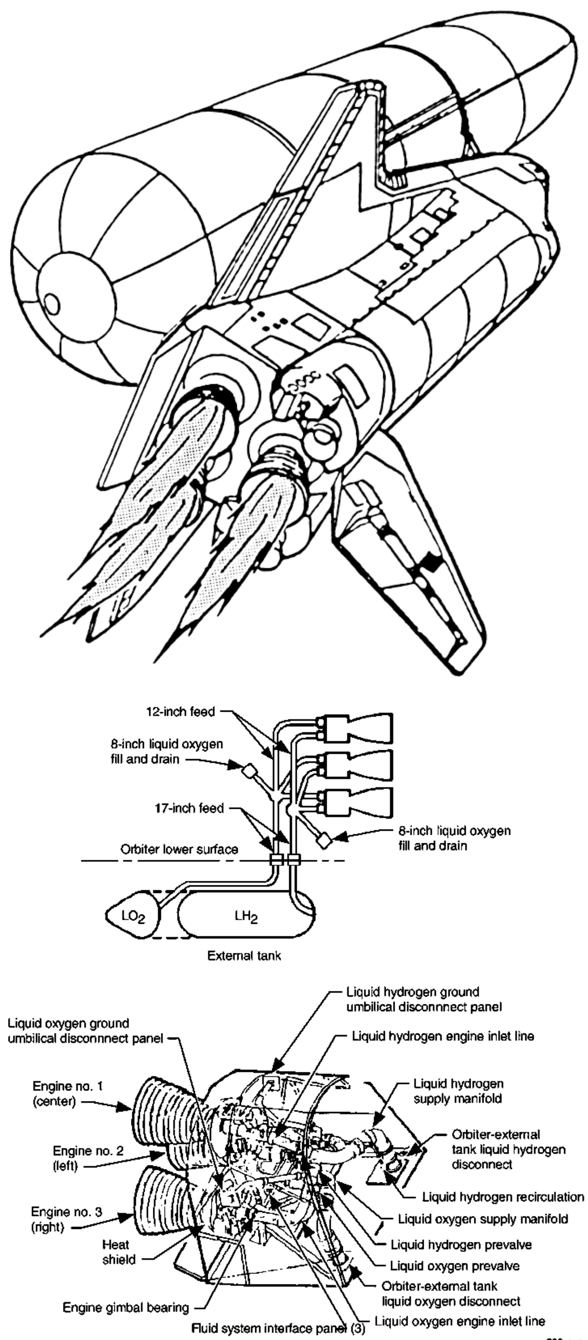
CONTENTS

Description

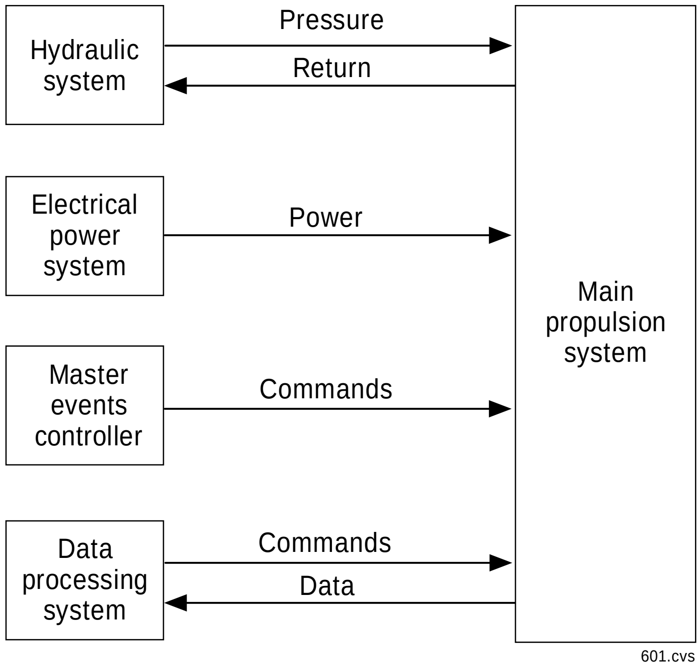
The space shuttle main engines (SSMEs), assisted by two solid rocket motors during the initial phases of the ascent trajectory, provide vehicle acceleration from lift-off to main engine cutoff (MECO) at a predetermined velocity.

The MPS has critical interfaces with the orbiter hydraulic system, electrical power system, master events controller, and data processing system. The hydraulic system supplies hydraulic pressure to operate the main engine valves and gimbal actuators. The electrical power system furnishes ac power to operate the main engine controllers and dc power to operate the valves and transducers in the propellant management and helium systems. The master events controller initiates firings of pyrotechnic devices for separating the solid rocket boosters from the external tank and the external tank from the orbiter. The data processing system controls most of the MPS functions during ascent and entry.

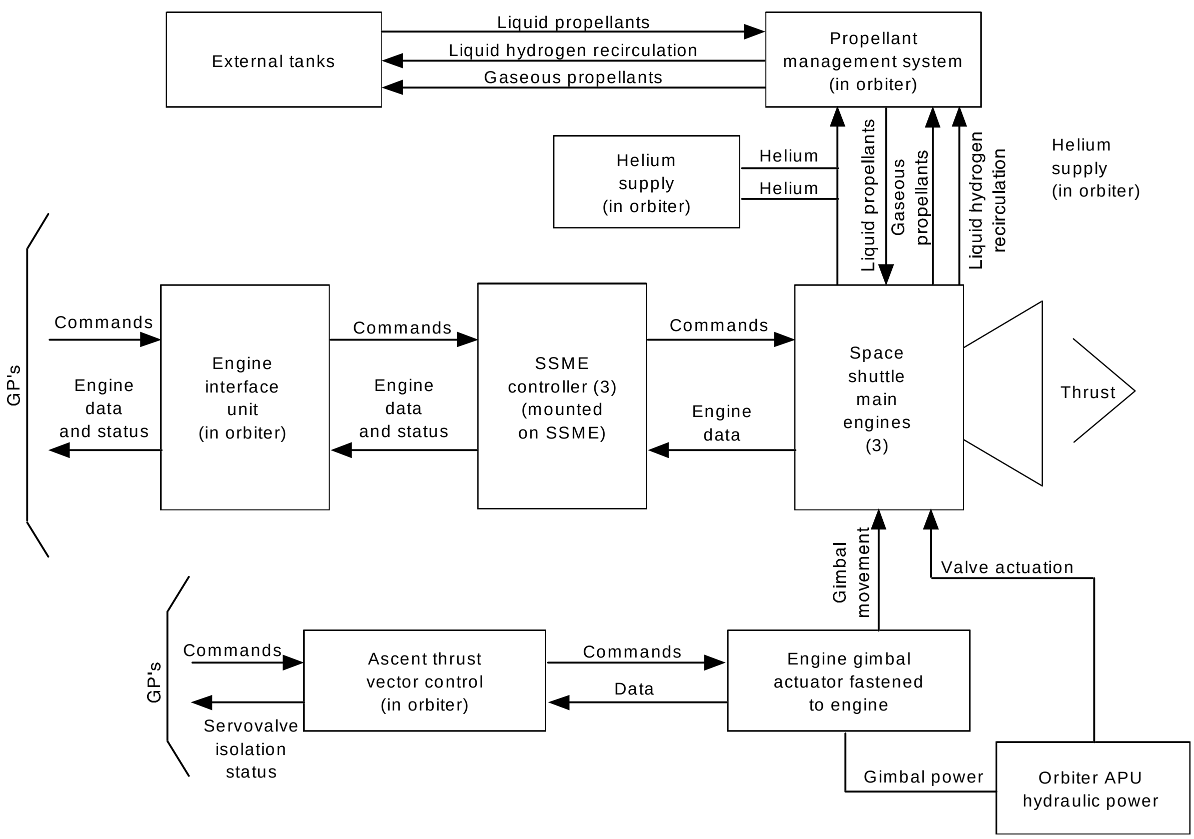
The MPS has three SSMEs, three SSME controllers, the external tank, the orbiter MPS propellant management system and helium subsystem, four ascent thrust vector control units, and six SSME hydraulic TVC servo-actuators. (The external tank is described in detail in Section 1.3.) Most of the MPS is located in the aft fuselage beneath the vertical stabilizer.



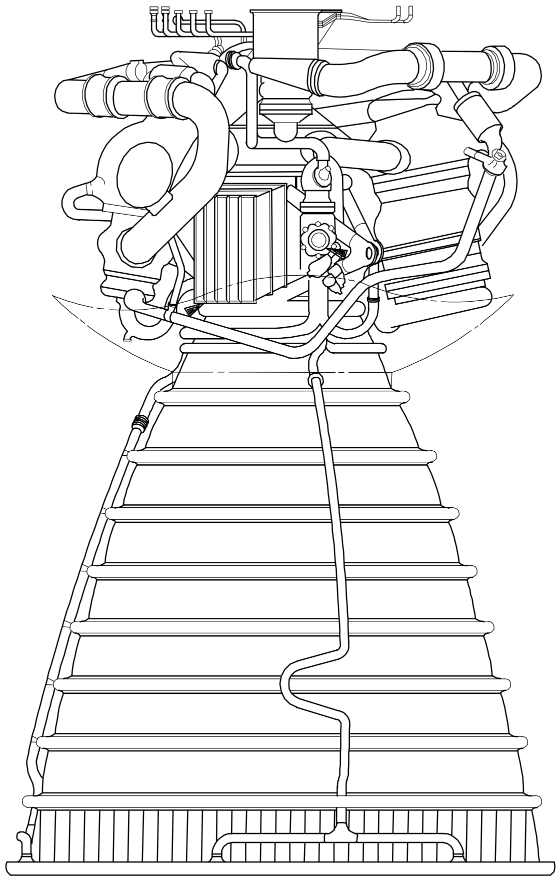
Main Propulsion System



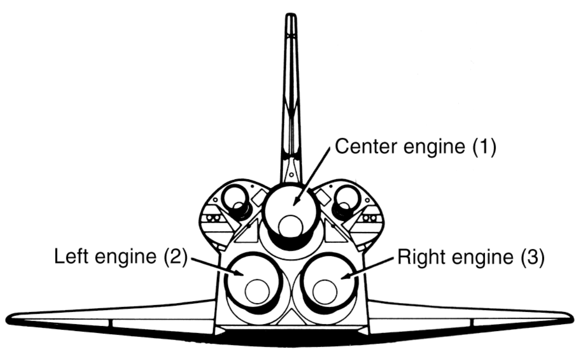
Critical Interfaces with the Main Propulsion System



Main Propulsion System Subsystem



Space Shuttle Main Engine



Main Engine Numbering System

Space Shuttle Main Engines (SSMEs)

The three SSMEs are reusable, high-performance, liquid propellant rocket engines with variable thrust. The engines use liquid hydrogen for fuel and cooling and liquid oxygen as an oxidizer. The propellant is carried in separate tanks within the external tank and is supplied to the main engines under pressure. Using a staged combustion cycle, the propellants are partially burned at high pressure and relatively low temperature in two preburners, then completely burned at high pressure and high temperature in the main combustion chamber.

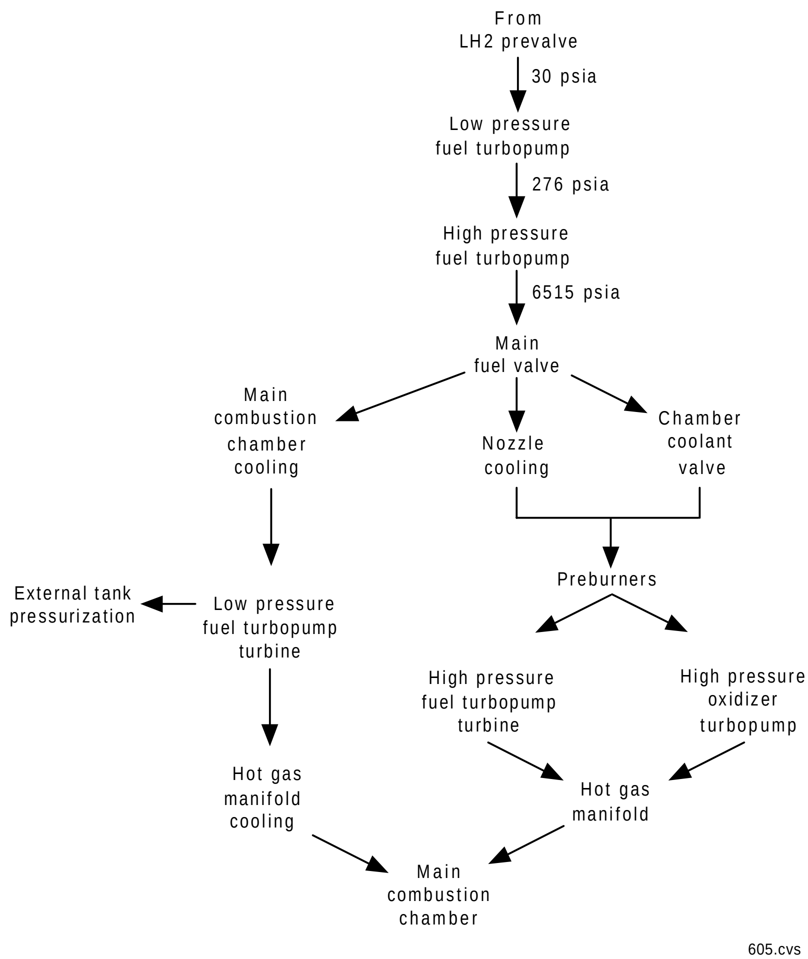
The engines are generally referred to as the center (engine 1), left (engine 2), and right (engine 3). Each engine is designed for 15,000 seconds of operation over a life span of 30 starts. Throughout the throttling range, the ratio of the liquid oxygen to liquid hydrogen mixture is 6:1. Each nozzle area ratio is 77.5:1. The engines are 14 feet long and 7.5 feet in diameter at the nozzle exit. Overall, a space shuttle main engine weighs approximately 7,000 pounds.

The main engines can be throttled over a range of 67 to 109 percent of their rated power level in 1-percent increments. A value of 100 percent corresponds to a thrust level of 375,000 pounds at sea level and 470,000 pounds in a vacuum; 104 percent corresponds to 393,800 pounds at sea level and 488,800 pounds in a vacuum; 109 percent corresponds to 417,300 pounds at sea level and 513,250 pounds in a vacuum.

At sea level, flow separation in the nozzle reduces the engine throttling range, prohibiting operation of the engine at its minimum 67-percent throttle setting. All three main engines receive the same throttle command at the same time. Normally, these come automatically from the orbiter general-purpose computers (GPCs) through the engine controllers. During certain contingency situations, engine throttling may be controlled manually through the pilot's speedbrake/thrust controller. SSME throttling reduces vehicle loads during maximum aerodynamic pressure and limits vehicle acceleration to a maximum of 3 g's during ascent.

Hydraulically powered gimbal actuators allow each engine to be gimbaled in the pitch and yaw axes for thrust vector control.

The SSME major components are the fuel and oxidizer turbopumps, preburners, a hot gas manifold, main combustion chamber, nozzle, oxidizer heat exchanger, and propellant valves.



Main Engine Fuel Flow

Phase II, Block I, and Block II SSMEs

Currently there are two types of SSMEs in fleet, Phase II and Block I. The Phase II SSME has been flying since the STS-26 mission. The Block I SSME is a modification to the older Phase II SSME and has been flying with the Phase I SSME since the STS-70 mission.

The modifications to the Phase II SSMEs are designed to improve the safety and reliability of the engine. The modifications to the Block II SSME include a new high-pressure oxidizer turbopump (HPOT), a two-duct powerhead, and a single coil heat exchanger. The thrust and specific impulse for the Phase II and Block I SSMEs are approximately equal.

Design and testing are also underway on the Block II SSME. The Block II engine will incorporate all of the improvements of the Block I engine, plus a new high-pressure fuel turbopump (HPFT) and a large throat main combustion chamber. The first flight of the Block II SSME is scheduled for 1997.

Fuel Turbopumps

Low-Pressure Fuel Turbopump

The low-pressure fuel turbopump is an axial-flow pump driven by a two-stage axial flow turbine powered by gaseous hydrogen. It boosts liquid hydrogen pressure from 30 psia to 276 psia and supplies the high-pressure fuel turbopump. During engine operation, this pressure increase allows the high-pressure fuel turbopump to operate at high speeds without cavitating. The low-pressure fuel turbopump operates at approximately 16,185 rpm, measures approximately 18 by 24 inches, and is flange-mounted to the SSME at the inlet to the low-pressure fuel duct.

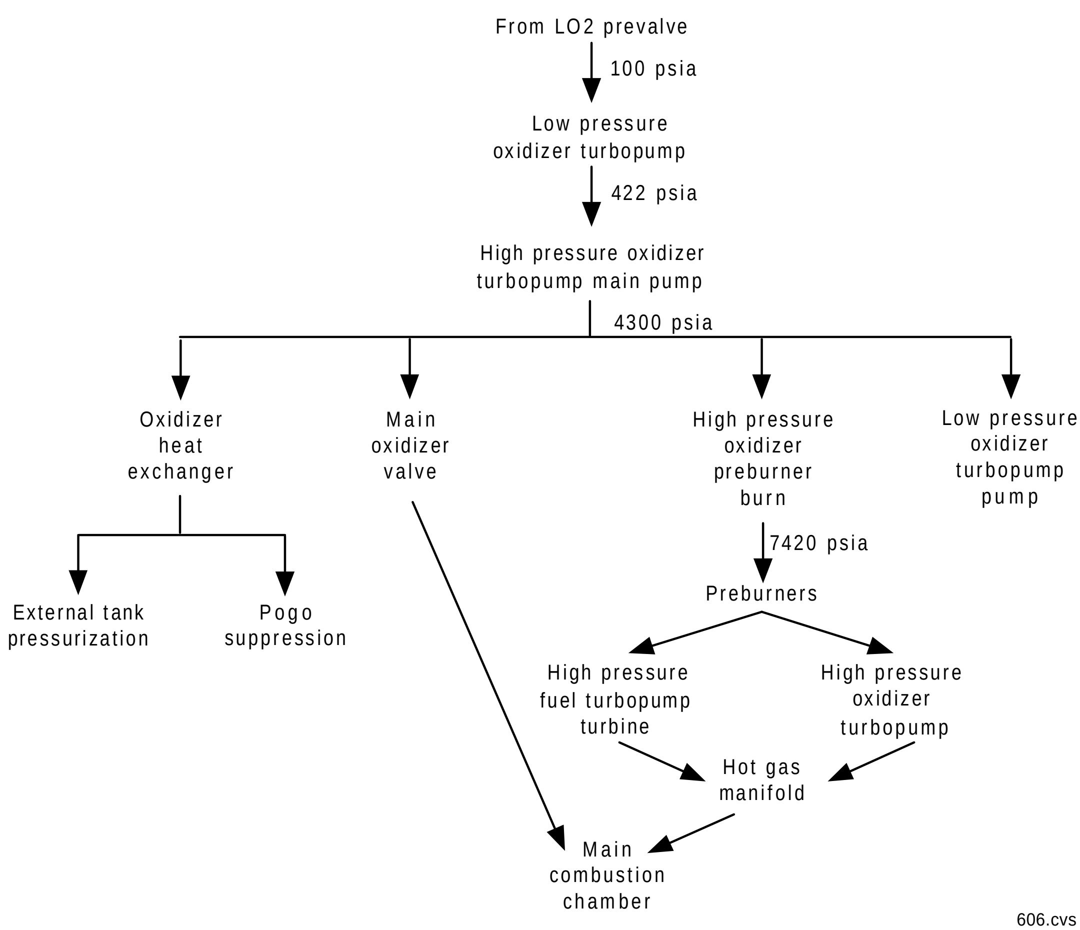
High-Pressure Fuel Turbopump

The high-pressure fuel turbopump, a three-stage centrifugal pump driven by a two-stage, hot-gas turbine, boosts liquid hydrogen pressure from 276 psia to 6,515 psia. It operates at approximately 35,360 rpm. The discharge flow from the high-pressure turbopump is routed through the main fuel valve and then splits into three flow paths. One path is through the jacket of the main combustion chamber, where the hydrogen is used to cool the chamber walls, and then to the low-pressure fuel turbopump to drive its turbine. The second flow path, through the chamber coolant valve, supplies liquid hydrogen to the preburner combustion chambers and also cools the hot gas manifold. The third hydrogen flow path is used to cool the engine nozzle. It then joins the second flow path from the chamber coolant valve. The high-pressure fuel turbopump is approximately 22 by 44 inches and is flanged to the hot-gas manifold.

Oxidizer Turbopumps

Low-Pressure Oxidizer Turbopump

The low-pressure oxidizer turbopump is an axial-flow pump driven by a six-stage turbine powered by liquid oxygen. It boosts the liquid oxygen pressure from 100 psia to 422 psia. The flow is supplied to the high-pressure oxidizer turbopump to permit it to operate at high speeds without cavitating. The low-pressure oxidizer turbopump operates at approximately 5,150 rpm, measures approximately 18 by 18 inches, and is flange-mounted to the orbiter propellant ducting.



Main Engine Oxidizer Flow

High-Pressure Oxidizer Turbopump

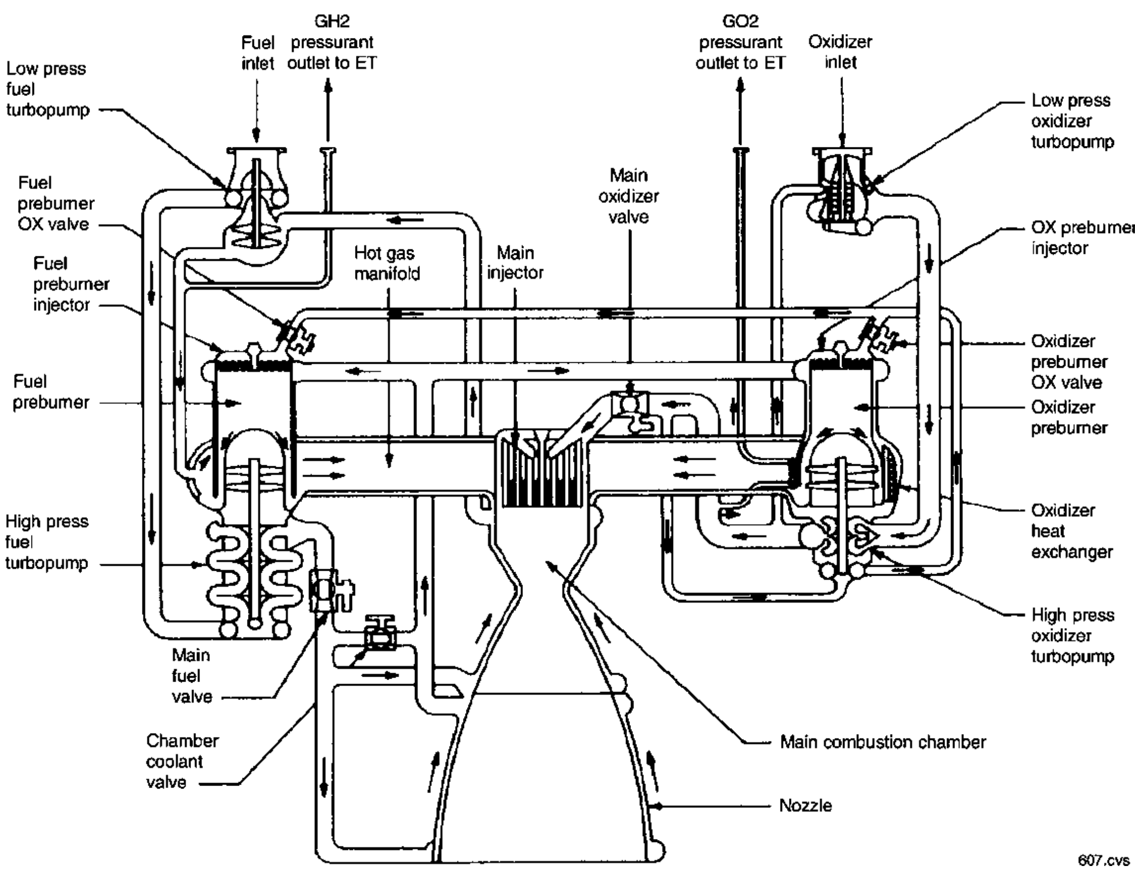
The high-pressure oxidizer turbopump consists of two single-stage centrifugal pumps (a main pump and a preburner pump) mounted on a common shaft and driven by a two-stage, hot-gas turbine. The main pump boosts liquid oxygen pressure from 422 psia to 4,300 psia while operating at approximately 28,120 rpm. The high-pressure oxidizer turbopump discharge flow splits into several paths, one of which is routed to drive the low-pressure oxidizer turbopump turbine. Another path is routed through the main oxidizer valve and enters the main combustion chamber. Another small flow path is tapped off and sent to the oxidizer heat exchanger, where it is vaporized and then used to pressurize the external tank. The final path enters the preburner boost pump to raise the liquid oxygen's pressure from 4,300 psia to 7,420 psia at the inlet to the liquid oxygen preburner. The high-pressure oxidizer turbopump measures approximately 24 by 36 inches. It is flanged to the hot-gas manifold.

Bellows

The low-pressure oxygen and low-pressure fuel turbopumps are mounted 180° apart on the engine. The lines from the low-pressure turbopumps to the high-pressure turbopumps contain flexible bellows that enable them to flex when loads are applied. This prevents them from cracking during engine operations.

Helium Purge

Because the high-pressure oxidizer turbopump turbine and pumps are mounted on a common shaft, mixing the fuel-rich hot gas in the turbine section and the liquid oxygen in the main pump could create a hazard. To prevent this, the two sections are separated by a cavity that is continuously purged by the MPS engine helium supply during engine operation. Two seals, one located between the turbine section and the cavity, and the other between the pump section and cavity, minimize leakage into the cavity.



Main Engine Schematic

WARNING

Depletion of the MPS helium supply or closure of both MPS isolation valves will cause loss of helium pressure in the cavity separating the fuel-rich hot gas and the liquid oxygen in the main pump. This condition results in an automatic engine shutdown if limits are enabled. If limits are inhibited, leakage through one or both of the seals and mixing of the propellants could result in uncontained engine damage when helium pressure is lost.

Hot Gas Manifold

The hot-gas manifold is the structural backbone of the engine. It supports the two preburners, the high-pressure turbopumps, and the main combustion chamber. Hot gas generated by the preburners, after driving the high-pressure turbopumps, passes through the hot-gas manifold on the way to the main combustion chamber.

Preburners

The oxidizer and fuel preburners are welded to the hot-gas manifold. Liquid hydrogen and liquid oxygen from the high-pressure turbopumps enter the preburners and are mixed so that efficient combustion can occur. The preburners produce the fuel-rich hot gas that passes through the turbines to generate the power to operate the high-pressure turbopumps. The oxidizer preburner's outflow drives a turbine that is connected to the high-pressure oxidizer turbopump and the oxidizer preburner boost pump. The fuel preburner's outflow drives a turbine connected to the high-pressure fuel turbopump.

Main Combustion Chamber

Each engine main combustion chamber receives fuel-rich hot gas from the fuel and oxidizer preburners. The high pressure oxidizer turbopump supplies liquid oxygen to the combustion chamber where it is mixed with fuel-rich gas by the main injector. A small augmented spark igniter chamber is located in the center of the injector. The dual-redundant igniter is used during the engine start sequence to initiate combustion. The igniters are turned off after approximately 3 seconds because the combustion process is self-sustaining. The main injector and dome assembly are welded to the hot-gas manifold. The main combustion chamber is bolted to the hot-gas manifold. The combustion chamber, as well as the nozzle, is cooled by gaseous hydrogen flowing through coolant passages.

The nozzle assembly is bolted to the main combustion chamber. The nozzle is 113 inches long, with an exit plane of 94 inches. The physical dimension of the nozzle creates a 77.5:1 expansion ratio. A support ring welded to the forward end of the nozzle is the engine attach point to the engine heat shield. Thermal protection is provided for the nozzles to protect them from the high heating rates experienced during the launch, ascent, on-orbit, and entry phases. The insulation consists of four layers of metallic batting covered with a metallic foil and screening.

Oxidizer Heat Exchanger

The oxidizer heat exchanger converts liquid oxygen to gaseous oxygen for tank pressurization and pogo suppression. The heat exchanger receives its liquid oxygen from the high-pressure oxidizer turbopump discharge flow.

Pogo Suppression System

A pogo suppression system prevents the transmission of low-frequency flow oscillations into the high-pressure oxidizer turbopump and, ultimately, prevents main combustion chamber pressure (engine thrust) oscillation. Flow oscillations transmitted from the vehicle are suppressed by a partially filled gas accumulator, which is attached by flanges to the high-pressure oxidizer turbopump's inlet duct.

The system consists of a 0.6-cubic-foot accumulator with an internal standpipe, helium precharge valve package, gaseous oxygen supply valve package, and four recirculation isolation valves.

During engine start, the accumulator is charged with helium 2.4 seconds after the start command to provide pogo protection until the engine heat exchanger is operational, and gaseous oxygen is available. The accumulator is partially chilled by liquid oxygen during the engine chill-down operation. It fills to the overflow standpipe line inlet level, which is sufficient to preclude gas ingestion at engine start. During engine operation, the accumulator is charged with a continuous gaseous oxygen flow.

The liquid level in the accumulator is controlled by an internal overflow standpipe, which is orificed to regulate the gaseous oxygen overflow at varying engine power levels. The system is sized to provide sufficient supply of gaseous oxygen at the minimum flow rate and to permit sufficient gaseous oxygen overflow at the maximum pressure transient in the low-pressure oxidizer turbopump discharge duct. Under all other conditions, excess gaseous and liquid oxygen are recirculated to the low-pressure oxidizer turbopump inlet through the engine oxidizer bleed duct. The pogo accumulator is also pressurized at engine shutdown to provide a positive pressure at the high-pressure oxidizer turbopump inlet. The post-charge prevents turbine overspeed in the zero-gravity environment.

CAUTION

Insufficient helium supply for engine shutdown could result in engine damage during shutdown. A pre-MECO manual shutdown may be required if a leak develops in the helium system.

Valves

Each engine has five propellant valves (oxidizer preburner oxidizer, fuel preburner oxidizer, main oxidizer, main fuel, and chamber coolant) that are hydraulically actuated and controlled by electrical signals from the engine controller. They can be fully closed by using the MPS engine helium supply system as a backup actuation system.

High-pressure oxidizer turbopump and high-pressure fuel turbopump turbine speed depends on the position of the oxidizer and fuel preburner oxidizer valves. The engine controller uses the preburner oxidizer valves to control engine thrust by regulating the flow of liquid oxygen to the preburners. The oxidizer and fuel preburner oxidizer valves increase or decrease the liquid oxygen flow into the preburner, thereby increasing or decreasing preburner chamber pressure and high-pressure oxidizer turbopump and high-pressure fuel turbopump turbine speed. This directly affects liquid oxygen and gaseous hydrogen flow into the main combustion chamber, which in turn can increase or decrease engine thrust. The fuel preburner oxidizer valve is used to maintain a constant 6:1 propellant mixture ratio.

The main oxidizer valve controls liquid oxygen flow into the engine combustion chamber. The main fuel valve controls the total liquid hydrogen flow into the engine cooling circuit, the preburner supply lines, and the low-pressure fuel turbopump turbine. When the engine is operating, the main valves are fully open.

A chamber coolant valve on each engine combustion chamber coolant bypass duct regulates the amount of gaseous hydrogen allowed to bypass the nozzle coolant loop to control engine temperature. The chamber coolant valve is 100 percent open before engine start, and at power levels between 100 and 109 percent. For power levels between 67 and 100 percent, the valve's position will range from 68.3 to 100 percent open.

Propellant Dump

The main oxidizer valve is opened to allow residual liquid oxygen to be dumped overboard through the engine nozzle after engine shutdown. Both liquid hydrogen fill/drain valves, as well as the fuel bleed valve, are opened after engine shutdown to allow residual liquid hydrogen to drain overboard.

Space Shuttle Main Engine Controllers

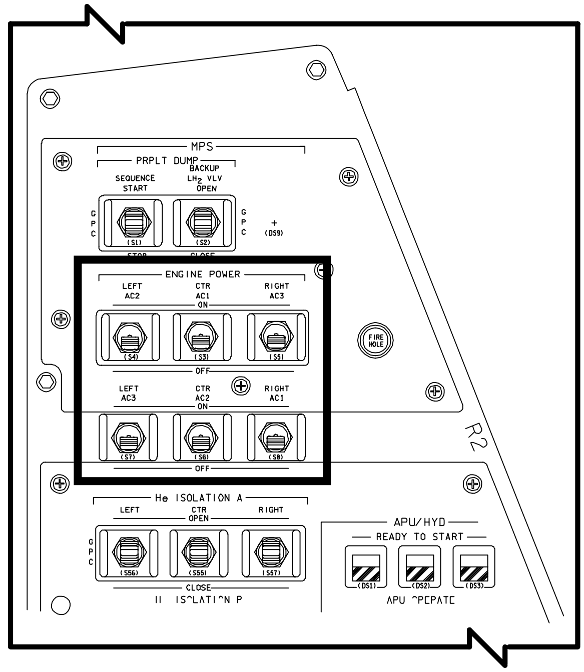
The controller is a pressurized, thermally conditioned electronics package attached to the thrust chamber and nozzle coolant outlet manifolds on the low-pressure fuel turbopump side of the engine. Each controller contains two redundant digital computer units, referred to as units A and B. Normally, A is in control, and unit B electronics are active, but not in control. Instructions to the engine control elements are updated 50 times per second (every 20 milliseconds). Engine reliability is enhanced by a dual-redundant system that allows normal digital computer unit operation after the first failure and a fail-safe shutdown after a second failure. High-reliability electronic parts are used throughout the controller. The digital computer is programmable, allowing engine control equations and constants to be modified by changing the software.

The controller is packaged in a sealed, pressurized chassis and is cooled by convection heat transfer through pin fins as part of the main chassis. The electronics are distributed on functional modules with special thermal and vibration protection.

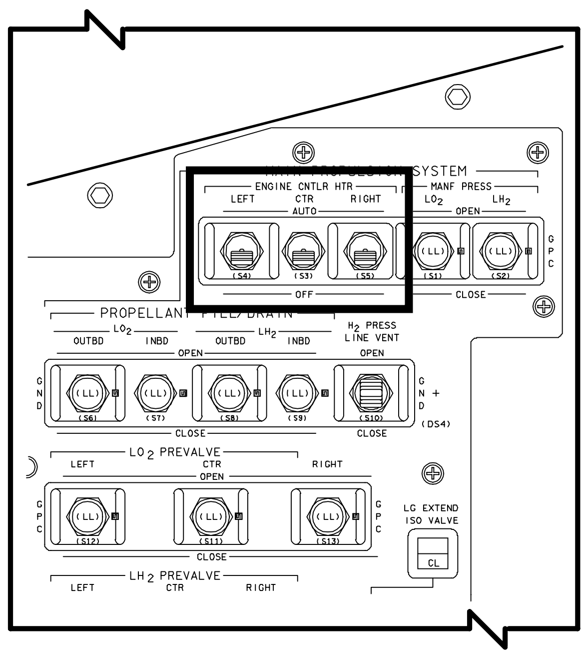
Operating in conjunction with engine sensors, valves, actuators, and spark igniters, the controllers form a self-contained system for engine control, checkout, and monitoring. The controller provides engine flight readiness verification, engine start and shutdown sequencing, closed-loop thrust and propellant mixture ratio control, sensor excitation, valve actuator and spark igniter control signals, engine performance limit monitoring, and performance and maintenance data. The controller also provides onboard engine checkout, response to vehicle commands, and transmission of engine status.

Controller power is supplied by the three ac buses in a manner that protects their redundancy. Each computer unit within a controller receives its power from a different bus. The buses are distributed among the three controllers such that the loss of any two buses will result in the loss of only one engine. The digital computer units require all three phases of an ac bus to operate. There are two MPS ENGINE POWER switches on panel R2 for each engine controller (LEFT, CTR, RIGHT); the top switch is for digital computer unit A, and the bottom switch is for digital computer unit B. Cycling an MPS ENGINE POWER switch to OFF and back to ON will cause the affected digital computer unit to stop processing.

The MAIN PROPULSION SYSTEM ENGINE CNTLR HTR LEFT, CTR, RIGHT switches on panel R4 are non-functional. The heaters were not installed in Block II controllers due to analysis that showed the Block I heaters were not required.



MPS ENGINE POWER Switches on Panel R2



MAIN PROPLSION SYSTEM ENGINE CNTLR HTR Switches on Panel R4

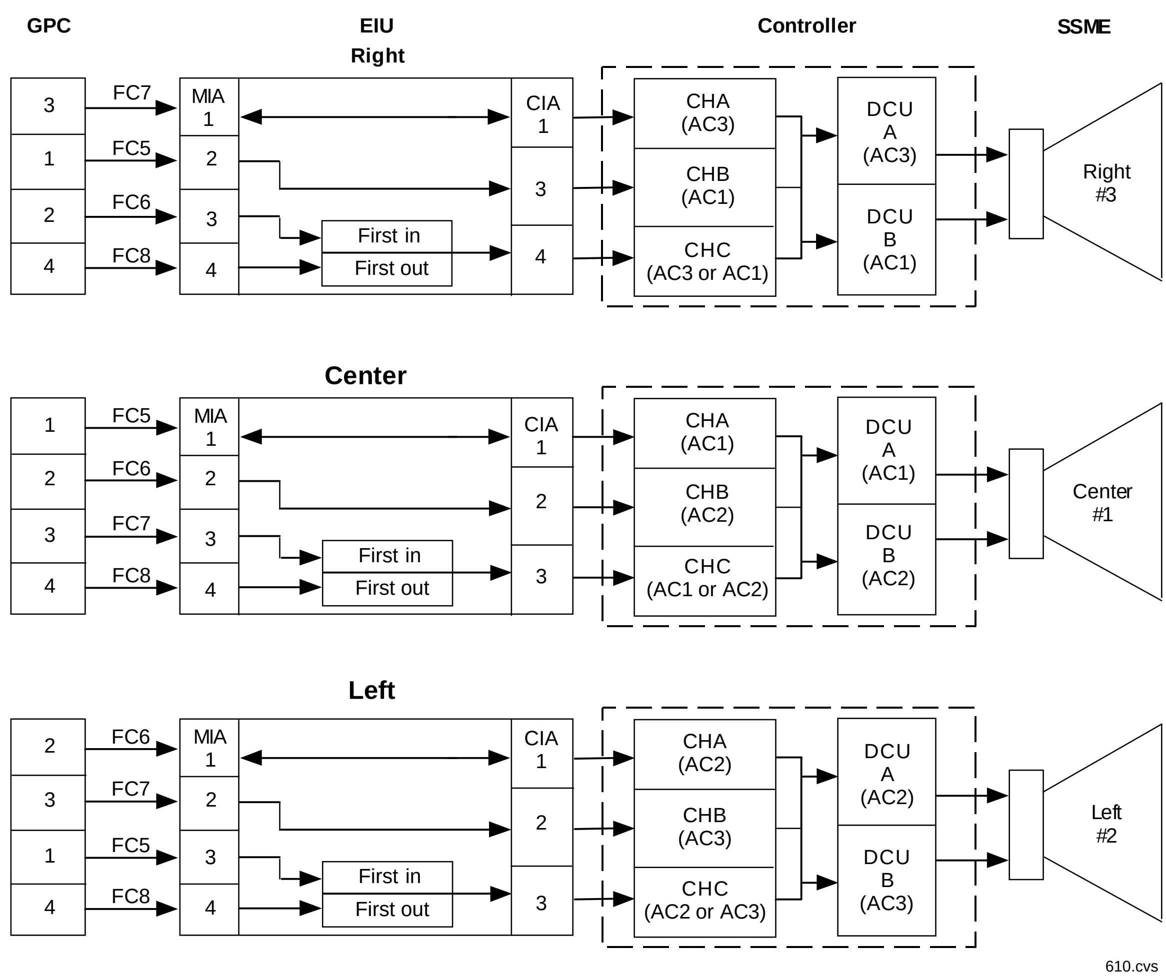
Command and Data Flow

Command Flow

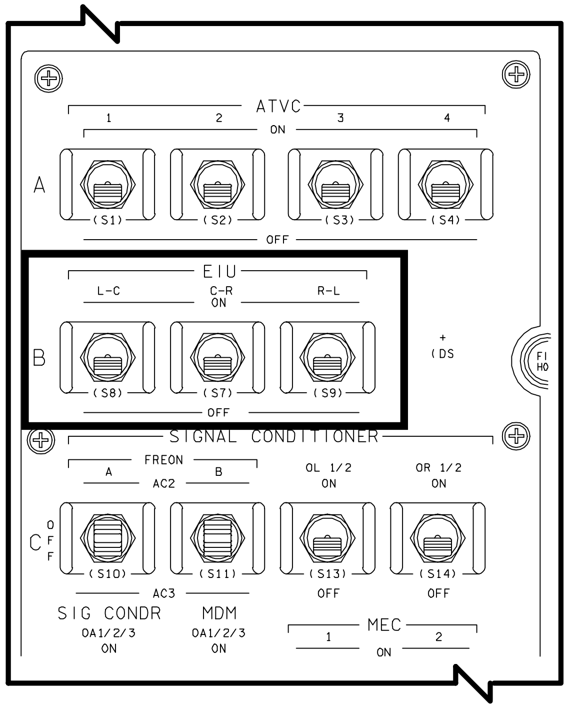
Each controller receives commands transmitted by the GPCs through its own engine interface unit (EIU), a specialized multiplexer/demultiplexer (MDM) that interfaces with the GPCs and with the engine controller. When engine commands are received by the unit, the data are held in a buffer until the GPCs request data; the unit then sends the data to each GPC. Each engine interface unit is dedicated to one SSME and communicates only with the engine controller that controls its SSME. The three units have no interface with each other.

The engine interface units are powered through the EIU switches on panel O17. If a unit loses power, its corresponding engine cannot receive any throttle, shut down, or dump commands, and will not be able to communicate with the GPCs. As a result, the controller will maintain the last valid command until it is shut down manually via the MPS ENGINE POWER switches on panel R2.

Each orbiter GPC, operating in a redundant set, issues engine commands from resident SSME subsystem operating programs to the EIUs for transmission to their corresponding engine controllers. Engine commands are output over the GPC's assigned flight-critical data bus (a total of four GPCs outputting over four flight-critical data buses). Therefore, each EIU will receive four commands. The nominal ascent configuration has GPCs 1, 2, 3, and 4 outputting on flight-critical data buses 5, 6, 7, and 8, respectively. Each data bus is connected to one multiplexer interface adapter in each EIU.



Main Engine Command Flow



EIU Switches on Panel O17

The EIU checks the received engine commands for transmission errors. If there are none, the EIU passes the validated engine commands on to the controller interface assemblies, which output the validated engine commands to the engine controller. An engine command that does not pass validation is not sent to the controller interface assembly. Instead, it is dead-ended in the multiplexer interface adapter. Commands that come through multiplex interface adapters 1 and 2 are sent to controller interface assemblies 1 and 2 respectively. Commands that come to multiplex interface adapters 3 and 4 pass through controller interface assembly 3 data-select logic. This logic outputs the command that arrives at the interface first. The other command is dead-ended. The selected command is output through controller interface assembly 3. In this manner, the EIU reduces the four input commands to three output commands.

The engine controller vehicle interface electronics receive the three engine commands, check for transmission errors (hardware validation), and send controller hardware-validated engine commands to the controller channel A and B electronics. Normally, channel A electronics are in control, with channel B electronics active, but not in control. If channel A fails, channel B will assume control. If channel B subsequently fails, the engine controller will pneumatically shut the engine down. If two or three commands pass voting, the engine controller will issue its own commands to accomplish the function requested by the orbiter GPCs. If command voting fails, and two or all three commands fail, the engine controller will maintain the last command that passed voting, and the GPC will issue an MPS CMD C (L, R) fault message (PASS CRT only pre-BFS engage) and light the yellow MAIN ENGINE STATUS light on panel F7.

The backup flight system (BFS) computer, GPC 5, contains SSME hardware interface program applications software. When the four primary GPCs are in control, GPC 5 does no commanding. When GPC 5 is in control, the BFS sends commands to, and requests data from, the engine interface unit; in this configuration, the four primary GPCs neither command nor listen. The BFS, when engaged, allows GPC 5 to command flight-critical buses 5, 6, 7, and 8 for main engine control through the SSME hardware interface program, which performs the same main engine command functions as the SSME subsystem operating program. The command flow through the engine interface units and engine controllers is the same when GPC 5 is engaged as for the four-GPC redundant set.

Data Flow

The engine controller provides all the main engine data to the GPCs. Sensors in the engine supply pressures, temperatures, flow rates, turbopump speeds, valve positions, and engine servovalve actuator positions to the engine controller. The engine controller assembles these data into a vehicle data table and adds other status data. The vehicle data tables output via channels A and B to the vehicle interface electronics for transmission to the engine interface units. The vehicle interface electronics output data over both the primary and secondary data paths.

The vehicle data table is sent by the controller to the engine interface unit. There are only two data paths versus three command paths between the engine controller and the engine interface unit. The data path that interfaces with controller interface assembly 1 is called primary data. Primary data consist of the first 32 words of the SSME vehicle data table. Secondary data is the path that interfaces with controller interface assembly 2. Secondary data consist of the first six words of the vehicle data table. Primary and secondary data are held in buffers until the GPCs send a primary and secondary data request command to the engine interface units. Primary data are output only through multiplex interface adapter 1 on each engine interface unit. Secondary data are output only through multiplex interface adapter 4 on each engine interface unit.

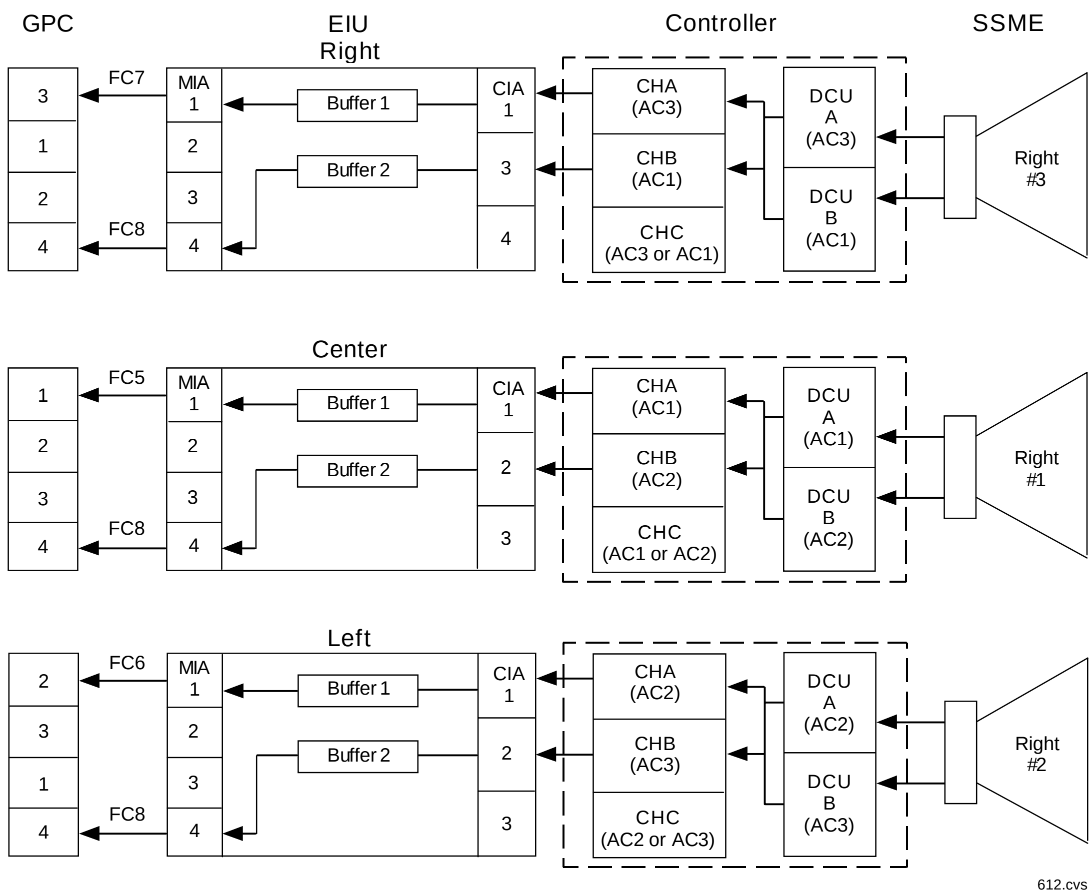
At T minus zero, the orbiter GPCs request both primary and secondary data from each engine interface unit. For no failures, only primary data are looked at. If there is a loss of primary data (which can occur between the engine controller channel A electronics and the SSME subsystem operating procedure), only the secondary data are transmitted to the GPCs.

NOTE

Prelaunch loss of either primary or secondary data will result in data path failure and either an engine ignition inhibit or a launch pad shutdown of all three main engines. Post-launch, loss of both is required for a data path failure. A data path failure will cause the GPCs to issue an MPS DATA C (L, R) fault message and light the appropriate yellow MAIN ENGINE STATUS light on panel F7.

Controller Software

The two primary engine controller programs are the flight operational program and the test operational program. The flight operational program is a real-time, process-control program that processes inputs from engine sensors, controls the operation of the engine servovalves, actuators, solenoids, and spark igniters, accepts and processes vehicle commands, provides and



Main Engine Data Flow

transmits data to the vehicle, and provides checkout and monitoring capabilities.

The test operational program supports engine testing prior to launch. Functionally, it is similar to the flight operational program but differs in implementation. The programs are modular and are defined as computer program components. Each consists of a data base organized into tables. During application of the computer program components, the programs perform data processing for failure detection and status of the vehicle. As system operation progresses through an operating phase, combinations of control functions are operative at different times. These combinations within a phase are defined as operating modes.

The checkout phase initiates active control monitoring or checkout. The standby mode in this phase puts the controller on pause while active control sequence operations are in process. Monitoring functions that do not affect engine hardware status are continually active during this mode. Such functions include processing vehicle commands, updating engine status, and self-testing the controller. During checkout, data and instructions can be loaded into the engine controller's computer memory, permitting updates to the software and data as necessary to proceed with engine-firing or checkout operations. Component checkout is also performed during this mode.

The start preparation phase consists of system purges and propellant conditioning in preparation for engine start. Purge sequence 1 mode is the first. It includes oxidizer system and intermediate seal purge operation. Purge sequence 2 mode is the second purge sequence, including fuel system purge operation and the continuation of purges initiated during purge sequence 1. Purge sequence 3 mode includes propellant recirculation (bleed valve operation). Purge sequence 4 mode includes fuel system purges and indicates that the engine is ready to enter the start phase. The engine-ready mode occurs when proper engine thermal conditions for start have been attained, and other criteria for start have been satisfied, including a continuation of the purge sequence 4 mode.

The start phase covers engine ignition operations and scheduled open-loop operation of the propellant valves. The start initiation mode includes all functions before ignition confirm and the closing of the thrust control loop. During thrust buildup, the main combustion chamber pressure is monitored to verify closed-loop sequencing is in progress.

Main stage is automatically entered upon successful completion of the start phase. Mixture ratio control and thrust control are active.

The shutdown phase covers operations to reduce main combustion chamber pressure and drive all valves closed to effect full engine shutdown.

The post-shutdown phase is entered upon completion of SSME shutdown. During the terminate sequence, all propellant valves are closed, and all solenoid and torque motor valves are de-energized.

Propellant Management System (PMS)

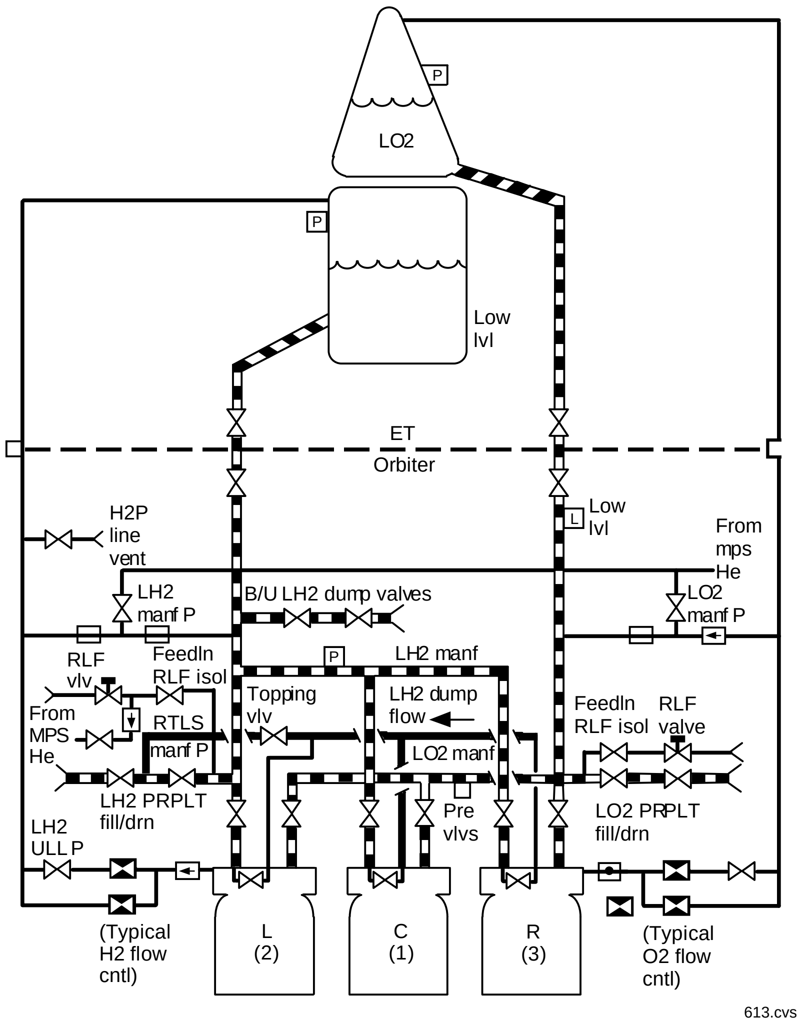
Liquid hydrogen and liquid oxygen pass from the ET to the propellant management system. The PMS consists of manifolds, distribution lines, and valves. It also contains lines needed to transport gases from the engines to the external tank for pressurization.

During prelaunch activities, this subsystem is used to load liquid oxygen and liquid hydrogen into the external tank. After MECO, the PMS is used to complete a liquid oxygen and liquid hydrogen dump and vacuum inerting. It is also used for manifold repressurization during entry.

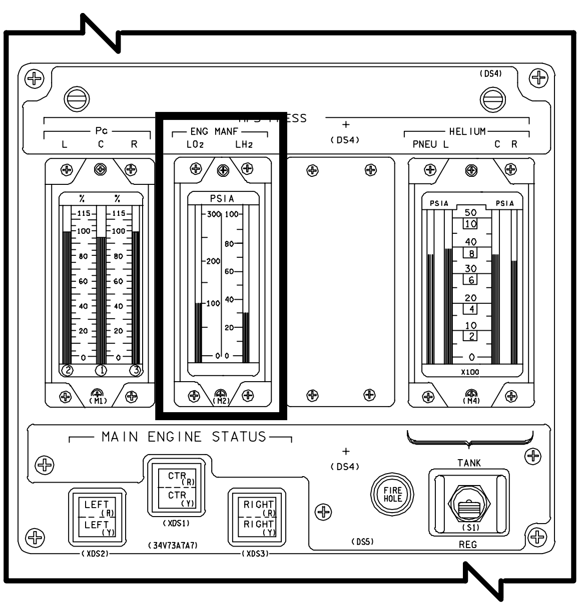
Propellant Manifolds

Two 17-inch-diameter MPS propellant feedline manifolds are located in the orbiter aft fuselage, one for liquid oxygen and one for liquid hydrogen. Each manifold interfaces with its respective line on the ET. Both manifolds interface with an 8-inch fill/drain line containing an inboard and outboard fill/drain valve in series. Inside the orbiter, the manifolds diverge into three 12-inch SSME feedlines, one for each engine.

Fluid pressures within the oxygen and hydrogen feedline manifolds can be monitored on the two MPS PRESS ENG MANF meters on panel F7 or on the BFS GNC SYS SUMM 1 display (MANF P LH2, LO2).



MPS Propellant Management System Schematic from the Ascent Pocket Checklist



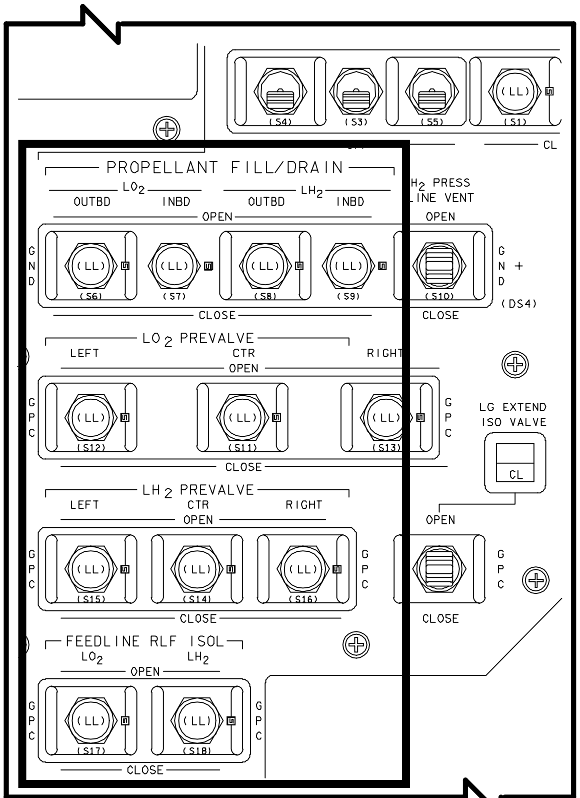
MPS PRESS ENG MANF Meters on Panel F7

Feedline Disconnect Valves

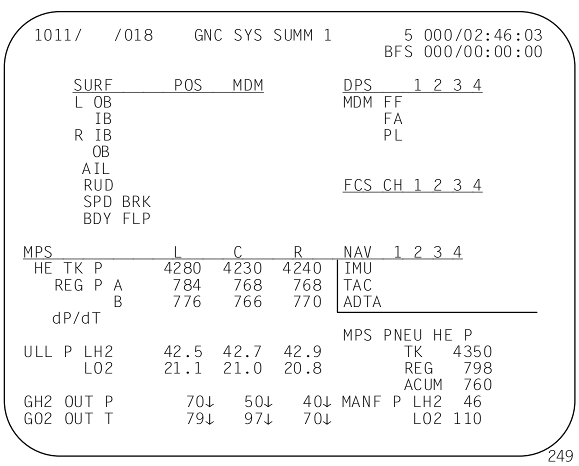
Two disconnect valves are found in each feedline where the orbiter meets the external tank. One is on the orbiter side of the manifold, and the other is on the external tank side. All four are closed automatically prior to external tank separation.

Fill/Drain Valves

Two (outboard and inboard) 8-inch-diameter liquid oxygen and liquid hydrogen fill/drain valves are connected in series. They are used to load the external tank before launch and to vacuum inert the feedline manifolds after the post-MECO MPS propellant dump. The valves can be manually controlled by the PROPELLANT FILL/DRAIN LO_2, LH_2 OUTBD, INBD switches on panel R4. Each switch has OPEN, GND, and CLOSE positions.



PROPELLANT FILL/DRAIN, REVALVE and FEEDLINE RLF ISOL Switches on Panel R4



GNC SYSTEM SUMMARY 1

Relief Valves

Each 8-inch liquid hydrogen and liquid oxygen manifold has a 1-inch-diameter line that is routed to a feedline relief isolation valve and then to a feedline relief valve. When the feedline relief isolation valve is opened automatically after MECO, the corresponding manifold can relieve excessive pressure overboard through its relief valve. The relief isolation valves can also be manually controlled by the MAIN PROPULSION SYSTEM FEEDLINE RLF ISOL LO_2 and LH_2 switches on panel R4. The switches have OPEN, GPC, and CLOSE positions.

Backup Liquid Hydrogen Dump Valves

The backup liquid hydrogen dump line connects the feedline manifold to an overboard port above the left wing of the orbiter. The line, designed primarily for a post-MECO liquid hydrogen dump during a return-to-launch site abort, is also used to vent the liquid hydrogen manifold after a nominal MECO. Since liquid hydrogen evaporates quickly, this vent is used to prevent pressure buildup in the hydrogen manifold from repeatedly cycling the relief valve before the propellant dump begins.

Flow through the lines is controlled by two valves in series, which are normally commanded by the GPCs. However, during OPS 1, they can be manually controlled by the MPS PRPLT DUMP BACKUP LH_2 VLV switch on panel R2, which has OPEN, GPC, and CLOSE positions. In an RTLS abort dump, liquid hydrogen is dumped overboard through a port at the outer aft fuselage's left side between the orbital maneuvering system/reaction control system pod and the upper surface of the wing. These valves are also known as the LH2 RTLS Dump valves.

Topping Valve

This valve controls the flow of liquid hydrogen through the tank topping manifold, which is used for prelaunch liquid hydrogen tank topping and thermal conditioning. During thermal conditioning, propellants flow through the engine components to cool them for engine start.

Liquid hydrogen is loaded through the outboard fill/drain valve, circulates through the topping valve to the engines for thermal conditioning, and is pumped into the external tank for tank topping. (The part of the topping recirculation line that goes to the external tank is not shown on the pocket checklist schematic.) The topping valve can be controlled indirectly by the crew via the LH2 inboard

FILL DRAIN switch on panel R4. When this switch is taken to OPEN, both the LH2 inboard fill drain and topping valves open.

There is no topping valve for liquid oxygen. Since liquid oxygen is harmless in the atmosphere, it is not circulated back to the external tank during thermal conditioning. Rather, it is dumped overboard through the engine liquid oxygen bleed valves and out the overboard bleed valve.

Liquid Hydrogen and Liquid Oxygen Bleed Valves

Three liquid hydrogen bleed valves, one in each engine, connect the engine internal liquid hydrogen line to the topping valve manifold. The valves are used to route liquid hydrogen through the engines during prelaunch thermal conditioning and to dump the liquid hydrogen trapped in the engines post-MECO.

There are also three liquid oxygen bleed valves that are not shown on the pocket checklist schematic. They connect the engine internal liquid oxygen lines to an overboard port and are used only during prelaunch thermal conditioning.

Prevalves

The prevalve in each of the three 12-inch feedlines to each engine isolates liquid oxygen and liquid hydrogen from each engine or permits liquid oxygen and liquid hydrogen to flow to each engine. Most of the prevalve functions are automatic, but they can also be controlled by the LO_2 and LH_2 PREVALVE, LEFT, CTR, RIGHT switches on panel R4. Each switch has OPEN, GPC, and CLOSE positions.

Ullage Pressure System

Ullage refers to the space in each tank not occupied by propellants. The ullage pressure system consists of the sensors, lines, and valves needed to route gaseous propellants from the three main engines and supply them to the external tank to maintain propellant tank pressure during engine operation.

There are two external tank pressurization manifolds, one for gaseous oxygen and one for gaseous hydrogen. During prelaunch, the manifolds are used to supply ground support pressurization of the ET using helium routed through the T-0 umbilical. Self-sealing quick disconnects are provided at the T-0 umbilical for separation at lift-off.

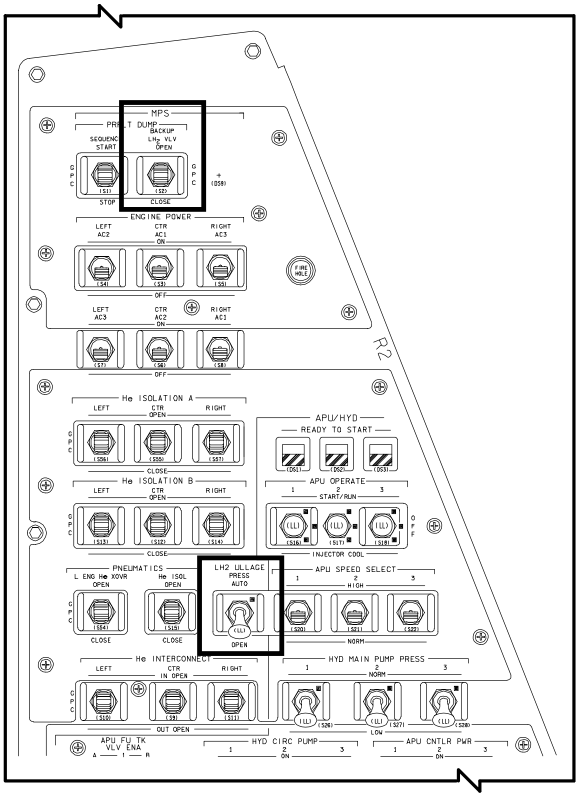
Each manifold contains three 0.63-inch-diameter pressurization lines, one from each engine. The three lines join in a common manifold prior to entering the ET.

In each SSME, a small portion of liquid oxygen from the high-pressure oxidizer turbopump main pump is diverted into the engine's oxidizer heat exchanger. The heat generated by the engine's high-pressure oxidizer turbopump converts the liquid oxygen into gaseous oxygen and directs it through a check valve to a fixed orifice and then to the ET. During ascent, the liquid oxygen tank pressure is maintained between 20 and 25 psig by the fixed orifice. If the tank pressure is greater than 30 psig, it is relieved through the liquid oxygen tank's vent and relief valve.

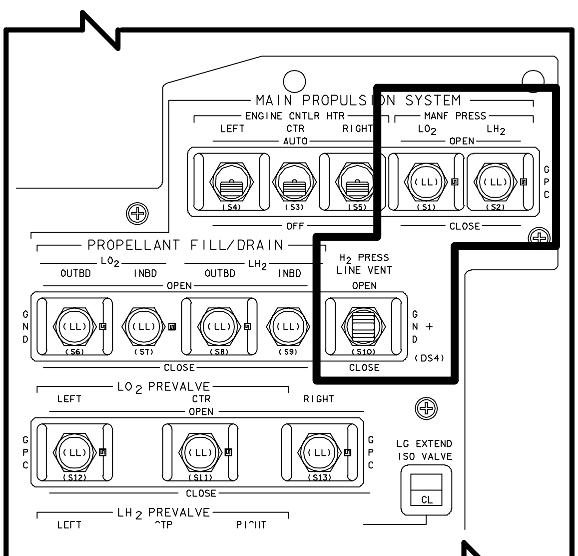
In each SSME, a small portion of gaseous hydrogen from the low-pressure fuel turbopump is directed through two check valves, two orifices, and a flow control valve before entering the ET. During ascent, the liquid hydrogen tank's pressure is maintained between 32 and 34 psia using both a variable and a fixed orifice in each SSME supply system. The active flow control valve is controlled by one of three liquid hydrogen pressure transducers. When the tank pressure decreases below 32 psia, the valve opens; when the tank pressure increases to 33 psia, the valve closes. If the tank pressure exceeds 35 psia, the pressure is relieved through the liquid hydrogen tank's vent and relief valve. If the pressure falls below 32 psia, the LH2 ULLAGE PRESS switch on panel R2 is positioned from AUTO to OPEN, causing all three flow control valves to go to full open.

The three liquid hydrogen and three liquid oxygen ullage pressures are displayed on the BFS GNC SYS SUMM 1 display (ULL P).

The SSME/ET liquid hydrogen pressurization system also contains a line that is used to vent the liquid hydrogen pressurization manifold during inerting. It is controlled by the H_2 PRESS LINE VENT switch on panel R4. This valve is normally closed, but is positioned open during vacuum inerting for a 1-minute period. The GND position allows the launch processing system to control the valve during ground operations.



MPS PRPLT DUMP BACKUP LH$_2$VLV Switch and LH$_2$ULLAGE PRESS Switch on Panel R2



MAIN PORPULSION SYSTEM MANF PRESS and H2 PRESS LINE VENT Switches on Panel R4

Manifold Repress Valves

The liquid hydrogen and liquid oxygen manifold repress valves route helium from the MPS helium system into the feedline manifolds. The helium pressure is used to expel propellants during the MPS propellant dump and to repressurize the propellant lines during entry. The valves can be controlled manually using the MAIN PROPULSION SYSTEM MANF PRESS switches on panel R4.

MPS Valve Types

All the valves in the MPS are either electrically or pneumatically operated. Pneumatic valves are used where large loads are encountered, such as in the control of liquid propellant flows. Electrical valves are used for lighter loads, such as the control of gaseous propellant flows.

The pneumatically actuated valves are divided into two types: type 1, which requires pneumatic pressure to open and close the valve, and type 2, which is spring-loaded to one position and requires pneumatic pressure to move to the other position.

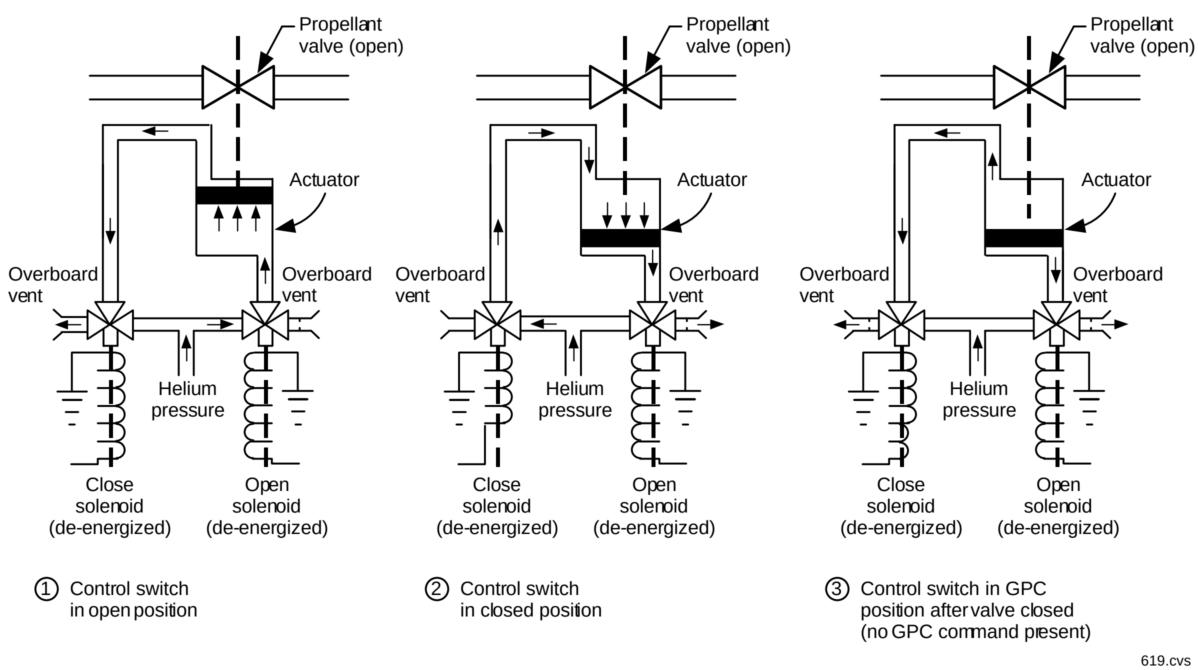
Each type 1 valve actuator is equipped with two electrically actuated solenoid valves, which control helium pressure to an "open" or "close" port on the actuator. Energizing the solenoid valve on the open port allows helium pressure to open the pneumatic valve. Energizing the solenoid on the close port allows helium pressure to close the pneumatic valve. Removing power from a solenoid valve removes helium pressure from the corresponding port of the pneumatic actuator and allows the helium pressure trapped in that side of the actuator to vent into the aft compartment. Removing power from both solenoids allows the pneumatic valve to remain in the last commanded position. This is known as a bi-stable valve.

Type 1 valves are used for the liquid oxygen and liquid hydrogen feedline 17-inch umbilical disconnect valves, the liquid oxygen and liquid hydrogen prevalves, the liquid hydrogen and liquid oxygen inboard and outboard fill and drain valves, and the liquid hydrogen 4-inch recirculation disconnect valves.

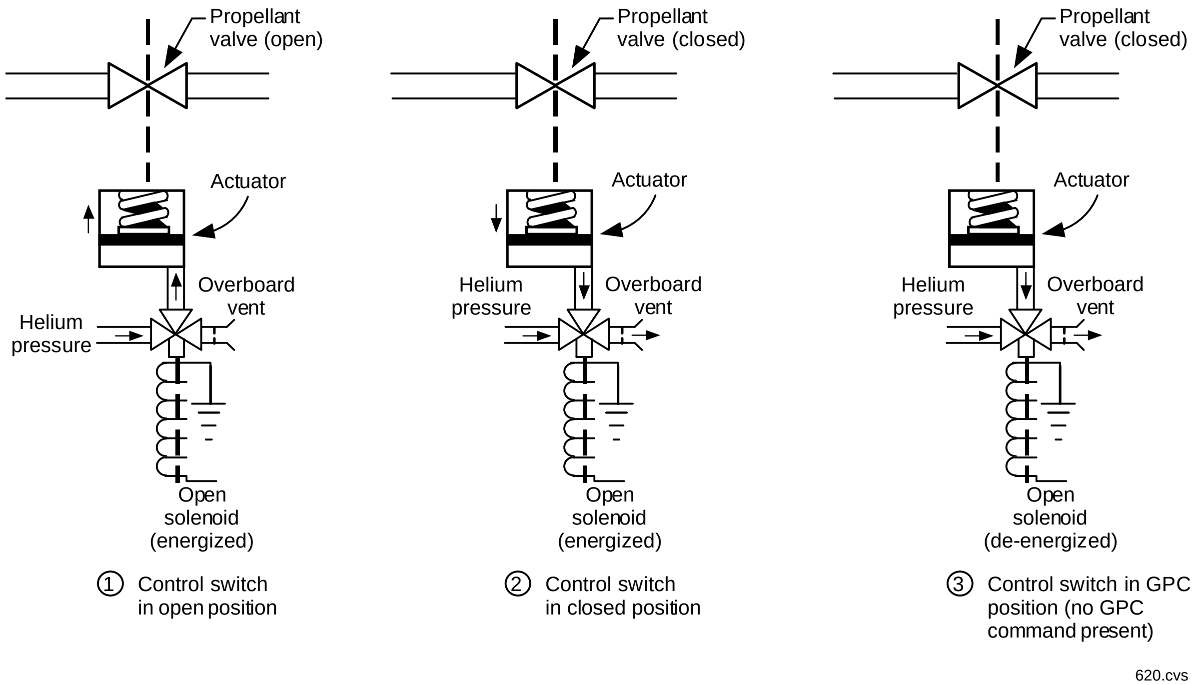
Each type 2 valve is a single electrically actuated solenoid valve that controls helium pressure to either an open or a close port on the actuator. Removing power from the solenoid valve removes helium pressure from the corresponding port of the pneumatic actuator and allows helium pressure trapped in that side of the actuator to vent overboard. Spring force takes over and drives the valve to the opposite position. If the spring force drives the valve to the open position, the valve is referred to as a normally open (NO) valve. If the spring force drives the valve to a closed position, the valve is referred to as a normally closed (NC) valve.

Type 2 pneumatic valves are used for the liquid hydrogen RTLS inboard dump valve (NC), the liquid hydrogen RTLS outboard dump valve (NC), the liquid hydrogen feedline relief shutoff valve (NO), the liquid oxygen feedline relief shutoff valve (NO), the three liquid hydrogen engine recirculation valves (NC), the two liquid oxygen pogo recirculation valves (NO), the liquid hydrogen topping valve (NC), the liquid hydrogen high-point bleed valve (NC), and the liquid oxygen overboard bleed valve (NO).

The electrically actuated solenoid valves are spring-loaded to one position and move to the other position when electrical power is applied. These valves also are referred to as either normally open or normally closed, depending on their position in the de-energized state. Electrically actuated solenoid valves are the gaseous hydrogen pressurization line vent valve (NC), the three gaseous hydrogen pressurization flow control valves (NO), and the three gaseous oxygen pressurization flow control valves (NO).



Propellant Management Subsystem Typical Type 1 Pneumatically Actuated Propellant Valve



Propellant Management Subsystem Typical Type 2
Pneumatically Actuated Propellant Valve Helium System

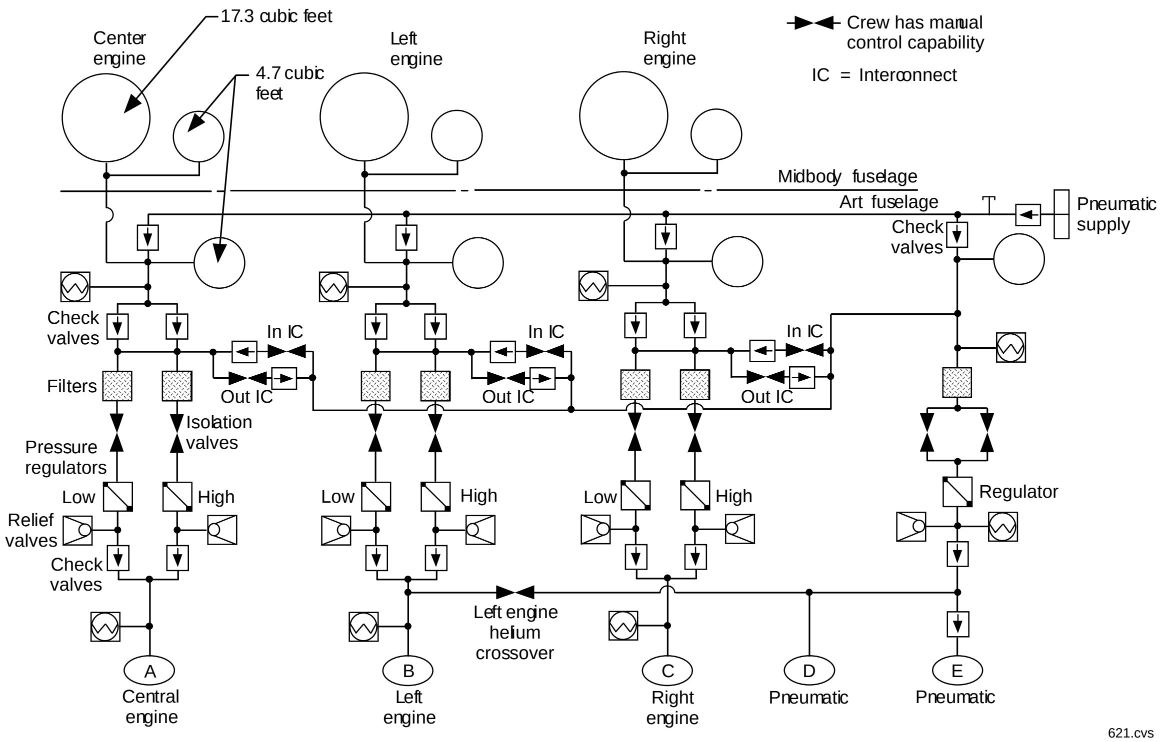
Helium System

The MPS helium system consists of seven 4.7-cubic-foot helium supply tanks, three 17.3-cubic-foot helium supply tanks, and associated regulators, check valves, distribution lines, and control valves.

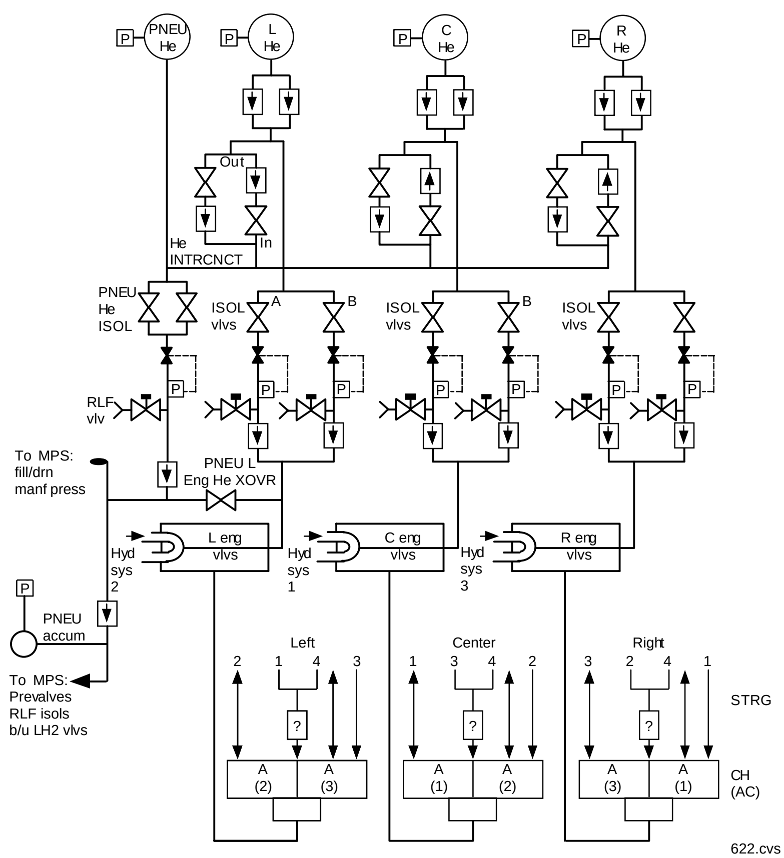
The MPS helium system is used for in-flight purges within the engines, and it provides pressure for actuating engine valves during emergency pneumatic shutdowns. It also supplies pressure to actuate the pneumatically operated valves within the propellant management system. During entry, the remaining helium is used for the entry purge and repressurization. (Unlike the orbital maneuvering system and reaction control system, the MPS does not use helium to pressurize propellant tanks.)

The MPS helium supply system is divided into four separate subsystems, one for each of the three main engines and a fourth pneumatic system to operate the propellant valves.

All the valves in the helium subsystem are spring-loaded to one position and electrically actuated to the other position. The supply tank isolation valves are spring-loaded to the closed position and pneumatically actuated to the open position. Valve position is controlled via electrical signals either generated by the onboard GPCs or manually by the flight crew. All the valves can be controlled automatically by the GPCs, and the flight crew can control some of the valves.



Helium System Storage and Supply



Main Propulsion System Helium Schematic from the Ascent Pocket Checklist

Helium Tanks

The tanks are composite structures consisting of a titanium liner with a fiberglass structural overwrap. The large tanks are 40.3 inches in diameter and have a dry weight of 272 pounds. The smaller tanks are 26 inches in diameter and have a dry weight of 73 pounds. The tanks are serviced before lift-off to a pressure of 4,100 to 4,500 psi.

Four of the 4.7-cubic-foot helium supply tanks are located in the aft fuselage, and the other three are located below the payload bay in the midfuselage. The three 17.3-cubic-foot helium supply tanks are also located below the payload bay in the midfuselage.

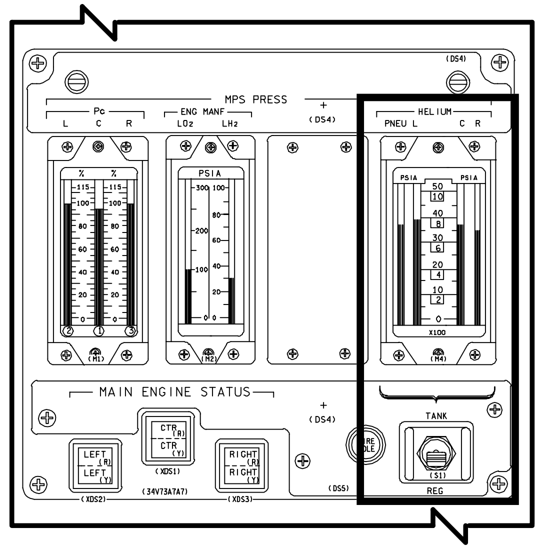
Each of the larger supply tanks is plumbed to two of the smaller supply tanks (one in the mid-body, the other in the aft body), forming three clusters of three tanks. Each set of tanks normally provides helium to only one engine and is commonly referred to as left, center, or right engine helium, depending on the engine serviced. Each set normally provides helium to its designated engine for in-flight purges and provides pressure for actuating engine valves during emergency pneumatic shutdown.

The remaining 4.7-cubic-foot helium tank is referred to as the pneumatic helium supply tank. It provides pressure to actuate all the pneumatically operated valves in the propellant management subsystem.

The helium pressure of the pneumatic, left, center, and right supply systems can be monitored on the MPS PRESS HELIUM, PNEU, L, C, R meters on panel F7 by positioning the switch below the meters to TANK. Left, center, right, and pneumatic tank pressures can be monitored on the BFS GNC SYS SUMM 1 display (MPS L, C, R HE TK P and MPS PNEU HE P TK).

Helium Isolation Valves

Eight helium supply tank isolation valves grouped in pairs control the flow of helium from the tanks. One pair of valves is connected to each of the three tank clusters, and one pair is connected to the pneumatic supply tank. In the engine helium supply tank system, each pair of isolation valves is connected in parallel, with each valve in the pair controlling helium flow through one leg of a dual-redundant helium supply circuit. Each helium supply circuit contains two check valves, a filter, an isolation valve, a regulator, and a relief valve.



MPS PRESS HELIUM Meters and Switch on Panel F7

The two isolation valves connected to the pneumatic supply tanks are also connected in parallel. The rest of the pneumatic supply system consists of a filter, the two isolation valves, a regulator, a relief valve, and a single check valve.

Each engine helium supply isolation valve can be individually controlled by the He ISOLATION A LEFT, CTR, RIGHT, and He ISOLATION B LEFT, CTR, RIGHT switches on panel R2. The switches have OPEN, GPC, and CLOSE positions. The two pneumatic helium supply isolation valves are controlled by a single PNEUMATICS He ISOL switch on panel R2, which also has OPEN, GPC, and CLOSE positions.

Helium Pressure Regulators

Each engine helium supply tank has two pressure regulators operating in parallel. Each regulator controls pressure to within 730 to 785 psia in one leg of a dual-redundant helium supply circuit and is capable of providing all the helium needed by the main engines.

The pressure regulator for the pneumatic helium supply system is not redundant and regulates outlet pressure between 715 to 770 psig. Downstream of the pneumatic regulator are the liquid hydrogen manifold pressure regulator and the liquid oxygen manifold pressure regulator. These regulators are used only during MPS propellant dumps and manifold pressurization. Both regulators are set to provide outlet pressure between 20 and 25 psig. Flow through the regulators is controlled by the appropriate set of two normally closed manifold pressurization valves.

Downstream of each pressure regulator, with the exception of the two manifold repressurization regulators, is a relief valve. The valve protects the downstream helium distribution lines from overpressurization if the associated regulator fails fully open. The two relief valves in each engine helium supply are set to relieve at 790 to 850 psig and reseat at 785 psig.

The regulated pressure of the left, center, right, and pneumatic systems can be monitored on the BFS GNC SYS SUMM 1 display (MPS L, C, R REG P and MPS PNEU REG). They can also be displayed on the MPS PRESS HELIUM PNEU, L, C, and R meters on panel F7 by placing the switch below the meters to REG. The meters however, only display the A reg pressure. B reg pressure can only be seen on BFS GNC SYS SUMM 1.

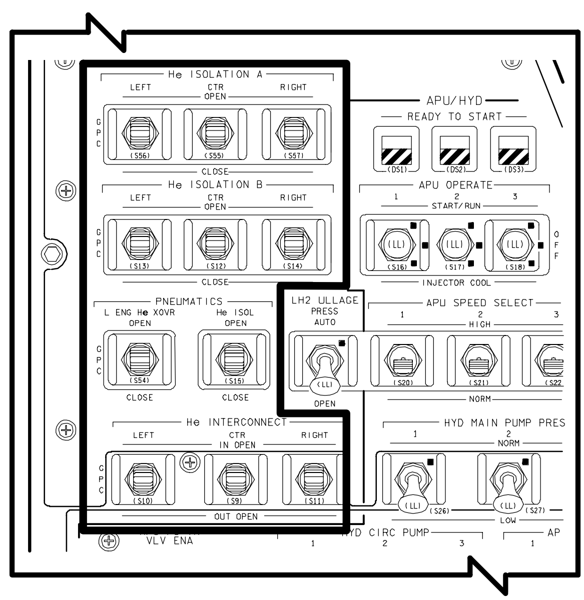
Pneumatic Left Engine Helium Crossover Valve

The crossover valve between the pneumatic and left engine helium systems serves as a backup for the nonredundant pneumatic pressure regulator system. In the event of a pneumatic helium regulator failure or a leak in the pneumatic helium system, the left engine helium system can provide regulated helium through the crossover valve to the pneumatic helium distribution system. The PNEUMATICS L ENG He XOVR switch is on panel R2.

Helium Interconnect Valves

Normally, each of the four helium supply systems operates independently until after MECO. Each engine helium supply has two interconnect (crossover) valves associated with it, and each valve in the pair of interconnect valves is connected in series with a check valve. The check valves allow helium to flow through the interconnect valves in one direction only. One check valve associated with one interconnect valve controls helium flow in one direction, and the other interconnect valve and its associated check valve permit helium flow in the opposite direction. The in/open interconnect valve controls helium flow into the associated engine helium distribution system from the pneumatic distribution system. The out/open interconnect valve controls helium flow out of the associated engine helium supply system to the pneumatic distribution system.

Each pair of interconnect valves is controlled by a single switch on panel R2. Each He INTERCONNECT LEFT, CTR, RIGHT switch has three positions: IN OPEN, GPC, and OUT OPEN. With the switch in the IN OPEN position, the in/open interconnect valve is open, and the out/open interconnect valve is closed. The OUT OPEN position does the reverse. With the switch in GPC, the valves are controlled by the orbiter software.



He ISOLATION, PNEUMATICS L ENG He XOVR and He ISOL, and He INTERCONNECT Switches on Panel R2

Manifold Pressurization

Manifold pressurization valves, located downstream of the pneumatic helium pressure regulator, are used to control the flow of helium to the LO2 propellant manifold for a nominal

LO2 propellant dump and for LH2 and LO2 manifold repressurization on entry. There are four of these valves grouped in pairs. One pair controls helium pressure to the liquid oxygen propellant manifold, and the other pair controls helium pressure to the liquid hydrogen propellant manifold.

There are additional regulators just past the manifold repress valves that regulate the pneumatic helium from the normally regulated pressure of 750 psi to a lower, usable pressure. The LH2 manifolds are pressurized to 17 to 30 psig and the LO2 manifolds are pressurized to 20 to 25 psig during the MPS dump and entry manifold repressurization.

Additionally, on the LH2 propellant manifold, there are RTLS manifold pressurization valves that open on the RTLS and TAL propellant dumps to assist in removing LH2 from the manifold.

Pneumatic Control Assemblies

There is one pneumatic control assembly on each SSME. The assembly is essentially a manifold pressurized by one of the engine helium supply systems and contains solenoid valves to control and direct pressure to perform various essential functions. The valves are energized by discrete ON/OFF commands from the output electronics of the SSME controller. Functions controlled by the pneumatic control assembly include the high-pressure oxidizer turbopump intermediate seal cavity and preburner oxidizer dome purge, pogo system postcharge, and pneumatic shutdown.

MPS Hydraulic Systems

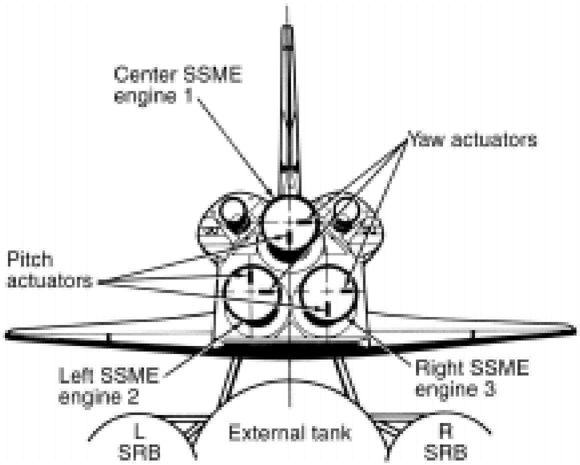
Hydraulic System Operation

The three orbiter hydraulic systems (see Section 2.1 for details on the hydraulic system) supply hydraulic pressure to the SSME to provide thrust vector control and actuate engine valves on each SSME. The three hydraulic supply systems are distributed to the thrust vector control (TVC) valves. These valves are controlled by HYDRAULICS MPS/TVC ISOL VLV switches (one for each of the three hydraulic systems) on panel R4. A valve is opened by positioning its switch to OPEN. The talkback indicator above each switch indicates OP when the valve is open and CL when it is closed.

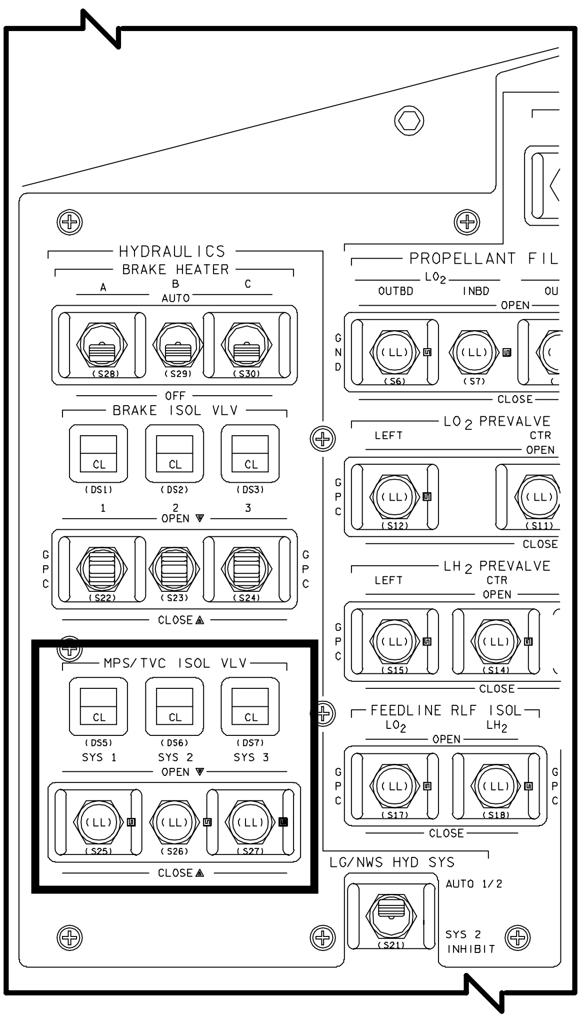
When the three MPS TVC hydraulic isolation valves are opened, hydraulic pressure is applied to the five hydraulically actuated engine valves. These valves are the main fuel valve, the main oxidizer valve, the fuel preburner oxidizer valve, the oxidizer preburner oxidizer valve, and the chamber coolant valve. All hydraulically actuated engine valves on an engine receive hydraulic pressure from the same hydraulic system. The left engine valves are actuated by hydraulic system 2, the center engine valves are actuated by hydraulic system 1, and the right engine valves are actuated by hydraulic system 3. Each engine valve actuator is controlled by dual-redundant signals: channel A/engine servovalve 1 and channel B/engine servovalve 2 from that engine's controller electronics. As a backup, all the hydraulically actuated engine valves on an engine are supplied with helium pressure from the helium subsystem left, center, and right engine helium tank supply system.

Hydraulic Lockup

Hydraulic lockup is a condition in which all the propellant valves on an engine are hydraulically locked in a fixed position. This is a built-in protective response of the SSME valve actuator/control circuit. It takes effect any time low hydraulic pressure or loss of control of one or more of the five hydraulically actuated main engine valves renders closed-loop control of engine thrust or propellant mixture ratio impossible. Hydraulic lockup allows an engine to continue to burn in a safe condition. The affected engine will continue to operate at the approximate power level in effect at the time hydraulic lockup occurred. Once an engine is in a hydraulic lockup, any subsequent shutoff commands, whether nominal or premature, will cause a pneumatic engine shutdown. Hydraulic lockup does not affect the capability of the engine controller to monitor critical operating parameters or issue an automatic shutdown if an operating limit is out of tolerance, but the engine shutdown would be accomplished pneumatically.



Main Engine Gimbal Actuators



MPS/TVC ISOL VLV Switches and Talkbacks on Panel R4

Thrust Vector Control

The three MPS thrust vector control valves must also be opened to supply hydraulic pressure to the six main engine TVC actuators. There are two servoactuators per SSME: one for yaw and one for pitch. Each actuator is fastened to the orbiter thrust structure and to the powerheads of the three SSMEs.

Two actuators per engine provide attitude control and trajectory shaping by gimbaling the SSMEs in conjunction with the solid rocket boosters during first-stage and without the solid rocket boosters during second-stage ascent. Each SSME servoactuator receives hydraulic pressure from two of the three orbiter hydraulic systems; one system is the primary system, and the other is a standby system. Each servoactuator has its own hydraulic switching valve. The switching valve receives hydraulic pressure from two of the three orbiter hydraulic systems and provides a single source to the actuator.

Normally, the primary hydraulic supply is directed to the actuator; however, if the primary system were to fail and lose hydraulic pressure, the switching valve would automatically switch over to the standby system, and the actuator would continue to function. The left engine's pitch actuator uses hydraulic system 2 as the primary and hydraulic system 1 as the standby. The engine's yaw actuator uses hydraulic system 1 as the primary and hydraulic system 2 as the standby. The center engine's pitch actuator uses hydraulic system 1 as the primary and hydraulic system 3 as the standby, and the yaw actuator uses hydraulic system 3 as the primary and hydraulic system 1 as the standby. The right engine's pitch actuator uses hydraulic system 3 as the primary and hydraulic system 2 as the standby. Its yaw actuator uses hydraulic system 2 as the primary and hydraulic system 3 as the standby.

The SSME servoactuators change each main engine's thrust vector direction as needed during the flight sequence. The three pitch actuators gimbal the engine up or down a maximum of 10.5° from the installed null position. The three yaw actuators gimbal the engine left or right a maximum of 8.5° from the installed position. The installed null position for the left and right main engines is 10° up from the X axis in a negative Z direction and 3.5° outboard from the engine centerline parallel to the X axis. The center engine's installed null position is 16° above the X axis for pitch and on the X axis for yaw. When any engine is installed in the null position, the other engines do not come in contact with it.

There are three actuator sizes for the main engines. The piston area of the center engine upper pitch actuator is 24.8 square inches, its stroke is 10.8 inches, it has a peak flow of 50 gallons per minute, and it weighs 265 pounds. The piston area of the two lower pitch actuators is 20 square inches, their stroke is 10.8 inches, their peak flow is 45 gallons per minute, and they weigh 245 pounds. All three yaw actuators have a piston area of 20 square inches, a stroke of 8.8 inches, a peak flow of 45 gallons per minute, and weigh 240 pounds. The minimum gimbal rate is 10° per second; the maximum rate is 20° per second.

Detailed information about ascent thrust vector control is provided in Section 2.13.

Hydraulic System Isolation On Orbit

The HYDRAULICS MPS/TVC ISOL VLV SYS 1, SYS 2, and SYS 3 switches on panel R4 are positioned to CLOSE during on-orbit operations to protect against hydraulic leaks downstream of the isolation valves. In addition, there is no requirement to gimbal the main engines from the stow position. During on-orbit operations when the MPS TVC valves are closed, the hydraulic pressure supply and return lines within each MPS TVC component are interconnected to enable hydraulic fluid to circulate for thermal conditioning.

Malfunction Detection

There are three separate means of detecting malfunctions within the MPS: the engine controllers, the hardware caution and warning system, and the software C/W system.

The SSME controller, through its network of sensors, has access to numerous engine operating parameters. A group of these parameters has been designated critical operating parameters, and special limits defined for these parameters are monitored by the main engine controller. Several MPS parameters are monitored by hardware and software. If a violation of any hardware limit is detected, the caution and warning system will illuminate the red MPS caution and warning light on panel F7. The light will be illuminated if any of the following conditions are sensed by the hardware C/W system:

- "MPS LH2/02 MANF" -MPS liquid oxygen manifold pressure is above 249 psia or the liquid hydrogen manifold pressure is above 65 psia
- "MPS HE P C(L,R)" - MPS regulated (A leg only) left, center, or right helium pressure is less than 680 or greater than 810 psia
- "MPS HE P C(L,R) - MPS center, left, or right tank pressure is less than 1,150 psia

In addition to the MPS light, the Backup C&W light on panel F7 will also illuminate. The limits for the backup C&W system are identical to the hardware C&W. The backup C&W is what generates the applicable C&W message.

The flight crew can monitor the MPS PRESS HELIUM PNEU, L, C, R meter on panel F7 when the switch below the meter is placed in the TANK or REG position. However, the meters only display the "A" regulator pressure when in the REG position. Pressure is also shown on the BFS GNC SYS SUMM 1 display. The MPS PRESS ENG MANF LO_2, LH_2 meter can also be monitored on panel F7. A number of conditions will require crew action. For example, an ET ullage pressure low message will require the flight crew to pressurize the external liquid hydrogen tank by setting the LH_2 ULLAGE PRESS switch on panel R2 to OPEN. A low helium tank pressure may require the flight crew to interconnect the pneumatic helium tank to an engine supply using the MPS He INTERCONNECT LEFT, CTR, and RIGHT switches on panel R2.

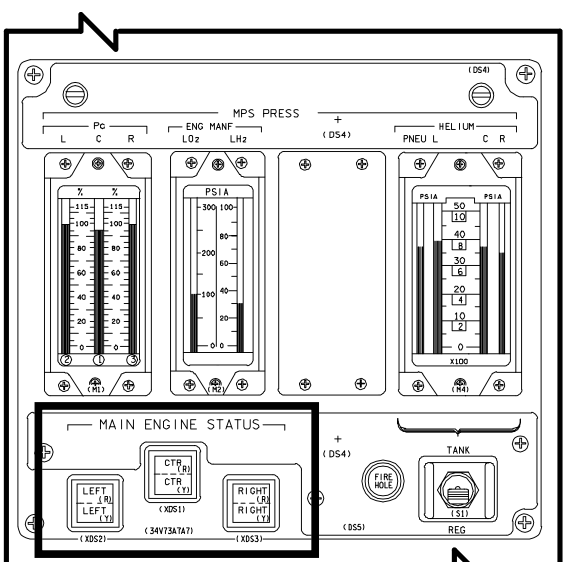
MAIN ENGINE STATUS LEFT, CTR, RIGHT lights on panel F7 are divided into two parts: the top half lights red and the bottom half lights yellow . The top half is illuminated for SSME shutdown and redline exceedances.

The yellow bottom half of the MAIN ENGINE STATUS light will be illuminated by the following failures:

- Electrical lockup
- Hydraulic lockup
- Command path failure (loss of two or more command channels or command reject between the GPCs and the SSME controller)
- Data path failure (loss of both primary and secondary data from the SSME controller)

In an electrical lockup for the affected SSME, loss of data from fuel flow rate sensors or the chamber pressure sensors will result in the propellant valve actuators being maintained electronically in the positions existing at the time the last sensor failed. For both sensors to be considered failed, it is only necessary for one sensor to actually fail. In hydraulic lockup, electrical lockup, or command path failure all engine-throttling capability for the affected engine is lost; subsequent throttling commands to that engine will not change the thrust level.

Biased sensors will affect main engine performance. During engine mainstage operation, measurements of the combustion chamber pressure and fuel flow rate are used by the controller to closely control power level and mixture ratio.



MAIN ENGINE STATUS Lights on Panel F7

There are two chamber pressure transducers on each SSME (an "A" and a "B"). Each consists of two bridges (Wheatstone-type strain gauges) for a total of four controller measurements (an A1, A2 pair and a B1, B2 pair). Each of these measurements is monitored for reasonableness before being used by the controller.

The fuel flow meter is located in the duct between the low and high pressure liquid hydrogen pumps. Four measurements (A1, A2 and B1, B2) come from the flow meter for use by the controller after each passes reasonableness checks.

Biases of either the flow meter or chamber pressure transducers can cause off-nominal engine operation. Essentially, the crew has no insight into this type of failure and must rely on Mission Control for assistance. The controller will adjust the engine valves to maintain the commanded power level as seen by the chamber pressure transducers, and this is what is displayed to the crew.

The red upper half of the MAIN ENGINE STATUS LEFT, CTR, RIGHT lights on panel F7 will be illuminated for an engine in shutdown or post-shutdown phase or for the following redline exceedances with limits inhibited:

- The high-pressure fuel turbopump's discharge temperature is above 1960° R
- The high-pressure oxidizer turbopump's discharge temperature is above 1760° R or below 720° R
- The high-pressure oxidizer turbopump's intermediate seal purge pressure is below 170 psia (Phase II SSME) or 159 psia (Block I and Block II SSMEs)
- The high-pressure oxidizer turbopump's secondary seal purge pressure is above 100 psia (Phase II SSME only)
- The high-pressure fuel turbopump's coolant liner pressure is greater than the controller-calculated limit (~3675 psig at 104%)
- The main combustion chamber's pressure is 400 psig below the reference chamber pressure

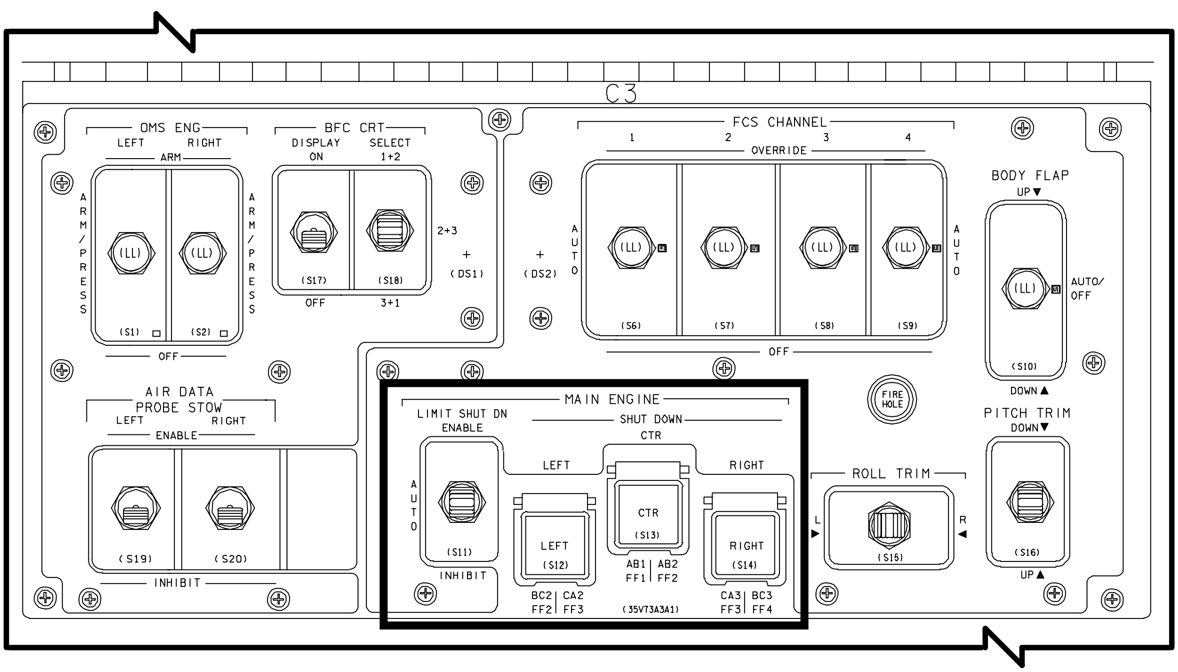
Because of the rapidity with which it is possible to exceed these limits, the engine controller has been programmed to sense the limits and automatically shut down the engine if the limits are exceeded. Although a shutdown as a result of violating operating limits is normally automatic, the flight crew can, if necessary, inhibit an automatic shutdown by using the MAIN ENGINE LIMIT SHUT DN switch on panel C3. The switch has three positions: ENABLE, AUTO, and INHIBIT. The ENABLE position allows any engine that violates operating limits to be shut down automatically. The AUTO position allows only the first engine that violates operating limits to be shut down automatically. If either of the two remaining engines subsequently violates operating limits, it would be inhibited from automatically shutting down. Should a remaining engine violate operating limits, it will not be shut down automatically unless the switch is manually taken to ENABLE and then to AUTO. The INHIBIT position inhibits all automatic shutdowns. The MAIN ENGINE SHUT DOWN LEFT, CTR, RIGHT pushbuttons on panel C3 have spring-loaded covers (guards). When the guard is raised, and the pushbutton is depressed, the corresponding engine shuts down immediately, provided the engine command is operational.

> **WARNING**
>
> Failure of an engine with limit shutdown inhibited will probably result in engine and controller damage, which will prevent detection of the engine failure by the GPCs.

The software caution and warning processing of the orbiter GPC's can detect certain specified out-of-limit or fault conditions of the MPS. Th SM alert light on panel F7 is illuminated, a fault message appears on the PASS and/or BFS CRT displays, and an audio tone sounds if:

PASS and BFS generated fault messages

- "MPS DATA C(L,R)" - Data path failures occur due to loss of both primary and secondary data from the main engine controller
- "MPS CMD C(L,R)" - Command path failures occur due to loss or rejection of GPC commands to the main engine controller (PASS only pre-engage)
- "MPS HYD C(L,R)" - Hydraulic lockups occur due to the failure of any one of the five hydraulically actuated valves from achieving its commanded position



MAIN ENGINE LIMIT SHUT DN Switch and MAIN ENGINE SHUT DOWN Pushbuttons on Panel C3

- "MPS ELEC C(L,R)" Electric lockups occur due to the loss of all Pc data or all fuel flow rate data from the engine

- "ET SEP-INH" - ET separation inhibits occur due to feedline disconnect failures or excessive vehicle rates(>0.7 deg/sec in any axis)

- "SSME FAIL C(L,R)" - Premature main engine shutdown (backup C&W light and master alarm only, no MPS light)

PASS only generated fault messages

- "ET SEP-MAN" or "ET SEP SEP-AUT" - ET separation switch failures (PASS annunciated only) occur when the GPCs can't determine the position of the ET SEPARATION switch on panel C3

- "ME SHDN SW C(L,R)" - Main engine pushbutton failures (PASS annunciated only occur when there is a failure of one of the two contacts on an SSME shutdown pushbutton resulting in a switch dilemma)

BFS only generated fault messages

- "MPS LH2/O2 ULL" - ET liquid hydrogen ullage pressure is less than 31.6 or greater than 46.0 psia or the liquid oxygen ullage pressure is less than 0 or more than 29.0 psig

- "MPS HE P C(L,R)" - MPS regulated (A&B leg) left, center, or right helium pressure is less than 679 or more than 810 psi

- "MPS HE P C(L,R)" - Helium system pressure change over time is greater than 20 psi for 3 seconds

- "MPS PNEU P TK" - MPS pneumatic tank pressure is less than 3800 psi

- "MPS PNEU P REG" - MPS pneumatic regulator pressure is less than 700 psia or greater than 810 psia

- "MPS PNEU P ACUM" - MPS pneumatic accumulator pressure is less than 700 psia

- "MPS H2 OUT P C(L,R)" - SSME GH_2 outlet pressure less than 1050 psia (engine failure)

- "MPS O2 OUT T C(L,R)" - SSME GO_2 outlet temperature less than 125° F (engine failure)

These failures have messages that are annunciated in OPS 1 and 6. Also, the BFS does all processing of the MPS helium and ullage pressure systems. In OPS 3, the MPS parameters on the BFS SYS SUMM 1 will be blanked, except for helium REG A and B pressure. In OPS 2 there is no software caution and warning for the MPS. Therefore, if either manifold pressure (LO2 or LH2) violates limits while on orbit, the only indication the crew will see is hardware caution and warning (MPS light and master alarm.) There will be no message on the CRT.

Operations

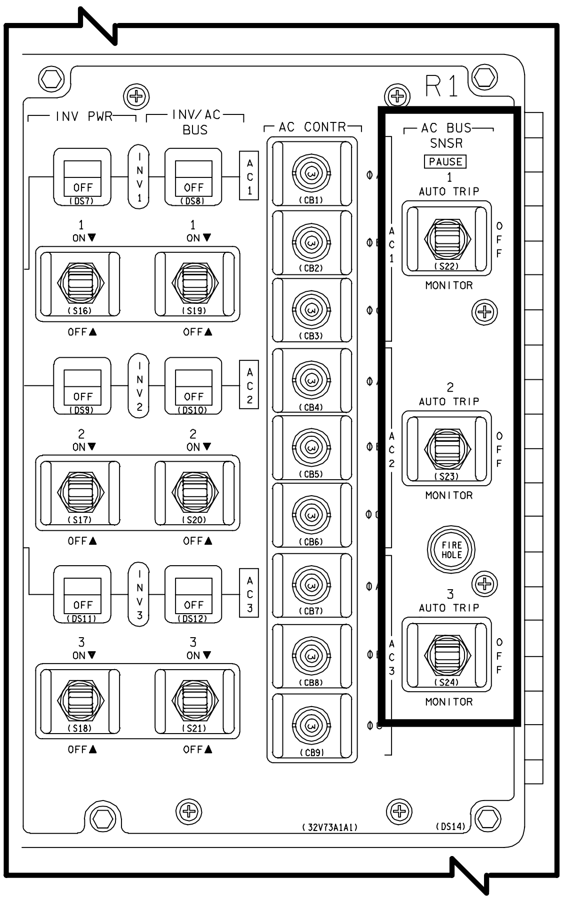
Prelaunch

At T minus 5 hours 50 minutes, the launch processing system initiates the SSME liquid hydrogen chill-down sequence in preparation for liquid hydrogen loading. At T minus 5 hours 15 minutes, the fast-fill portion of the liquid oxygen and liquid hydrogen loading sequence begins, and the liquid hydrogen recirculation pumps are started shortly thereafter. At T minus 3 hours 45 seconds, the fast fill of the liquid hydrogen tank to 98 percent is complete, and a slow topping off process that stabilizes to 100 percent begins. At T minus 3 hours 30 minutes, the liquid oxygen fast fill is complete. At T minus 3 hours 15 minutes, liquid hydrogen replenishment begins, and liquid oxygen replenishment begins at T minus 3 hours 10 minutes.

During prelaunch, the pneumatic helium supply provides pressure to operate the liquid oxygen and hydrogen prevalves and outboard and inboard fill and drain valves. The three engine helium supply systems are used to provide anti-icing purges.

The MPS helium tanks are pressurized from 2,000 psi to their full pressure at T minus 3 hours 20 minutes. This process is gradual to prevent excessive heat buildup in the supply tank. Regulated helium pressure is between 715 and 775 psi.

At this time, the MPS He ISOLATION A and B switches, the MPS PNEUMATICS L ENG He XOVR and He ISOL switches, and the MPS He INTERCONNECT LEFT, CTR, RIGHT switches on panel R2 are in the GPC position. With the switches in this position, the eight helium isolation valves are open, and the left engine crossover and the six helium interconnect valves are closed.



AC BUS SNSR Switches on Panel R1

At T minus 16 minutes, one of the first actions by the flight crew (the pilot) is to place the six MPS He ISOLATION A and B switches and the MPS PNEUMATICS He ISOL switch on panel R2 in the OPEN position. This procedure will not change the position of the helium isolation valves, which were already open, but it inhibits launch processing system control of valve position.

During prelaunch, liquid oxygen from ground support equipment is loaded through the ground support equipment liquid oxygen T-0 umbilical and passes through the liquid oxygen outboard fill and drain valve, the liquid oxygen inboard fill and drain valve, and the orbiter liquid oxygen feedline manifold. The liquid oxygen exits the orbiter at the liquid oxygen feedline umbilical disconnect and enters the liquid oxygen tank in the external tank.

During loading, the liquid oxygen tank's vent and relief valves are open to prevent pressure buildup in the tank due to liquid oxygen loading. The MAIN PROPULSION SYSTEM PROPELLANT FILL/DRAIN LO_2 OUTBD and INBD switches on panel R4 are in the GND (ground) position, which allows the launch processing system to control the positions of these valves. Just prior to lift-off, the launch processing system will first command the liquid oxygen inboard fill and drain valve to close. The liquid oxygen in the line between the inboard and outboard fill and drain valves is then allowed to drain back into the ground support equipment, and the launch processing system commands the outboard fill and drain valve to close.

Also during prelaunch, liquid hydrogen supplied through the ground support equipment liquid hydrogen T-0 umbilical passes through the liquid hydrogen outboard fill and drain valve, the liquid hydrogen inboard fill and drain valve, and the liquid hydrogen feedline manifold. The liquid hydrogen then exits the orbiter at the liquid hydrogen feedline umbilical disconnect and enters the liquid hydrogen tank in the external tank. During loading, the liquid hydrogen tank's vent valve is left open to prevent pressure buildup in the tank due to boiloff. The MAIN PROPULSION SYSTEM PROPELLANT FILL/DRAIN LH_2 OUTBD and INBD switches on panel R4 are in the GND position, which allows the launch processing system to control the position of these valves.

During the T minus 3 hour hold the pilot positions the three AC BUS SNSR switches on panel R1 to MONITOR. These sensors are not part of the MPS, but the procedure protects the SSMEs. Each engine controller is powered by two of the three ac buses, one for each digital computer unit. Therefore, the loss of one bus will result in a loss of controller redundancy on two engines, and the loss of any two buses will cause the associated engine to shut down. With the switches positioned to MONITOR, the sensors will provide caution and warning for an over/undervoltage or overload condition, but they will not trip a bus off line.

Engine Start

At T minus 4 minutes, the fuel system purge begins. It is followed at T minus 3 minutes 25 seconds by the beginning of the engine gimbal tests, during which each gimbal actuator is operated through a canned profile of extensions and retractions. If all actuators function satisfactorily, the engines are gimbaled to a predefined position at T minus 2 minutes 15 seconds. The engines remain in this position until engine ignition.

At T minus 2 minutes 55 seconds, the launch processing system closes the liquid oxygen tank vent valve, and the tank is pressurized to 21 psig with ground support equipment-supplied helium. The liquid oxygen tank's pressure can be monitored on the BFS GNC SYS SUMM 1 CRT (MANF P LO2). The 21-psig pressure corresponds to a liquid oxygen engine manifold pressure of 105 psia.

At T minus 1 minute 57 seconds, the launch processing system closes the liquid hydrogen tank's vent valve, and the tank is pressurized to 42 psig with ground support equipment-supplied helium. The pressure is monitored on the BFS GNC SYS SUMM 1 CRT display (MANF P LH2).

At T minus 31 seconds, the onboard redundant set launch sequence is enabled by the launch processing system. From this point on, all sequencing is performed by the orbiter GPCs in the redundant set, based on the onboard clock time. The GPCs still respond, however, to hold, resume count, and recycle commands from the launch processing system.

At T minus 16 seconds, the GPCs begin to issue arming commands for the solid rocket booster ignition pyro initiator controllers, the hold-down release pyro initiator controllers, and the T-0 umbilical release pyro initiator controllers.

At T minus 9.5 seconds, the engine chill-down sequence is complete, and the GPCs command the liquid hydrogen prevalves to open (the liquid oxygen prevalves are open during loading to permit engine chill-down). The MAIN PROPULSION SYSTEM LO_2 and LH_2 PREVALVE LEFT, CTR, RIGHT switches on panel R4 are in the GPC position.

At T minus 6.6 seconds, the GPCs issue the engine start command, and the main fuel valve in each engine opens. Between the opening of the main fuel valve and MECO, liquid hydrogen flows out of the external tank/orbiter liquid hydrogen disconnect valves into the liquid hydrogen feedline manifold. From this manifold, liquid hydrogen is distributed to the engines through the three engine liquid hydrogen feedlines. In each line, liquid hydrogen passes through the prevalve and enters the main engine at the inlet to the low-pressure fuel turbopump.

When the GPCs issue the engine start command, the main oxidizer valve in each engine also opens. Between the opening of the main engine oxidizer valve and MECO, liquid oxygen flows out of the external tank and through the external tank/orbiter liquid oxygen umbilical disconnect valves into the liquid oxygen feedline manifold. From this manifold, liquid oxygen is distributed to the engines through the three engine liquid oxygen feedlines. In each line, liquid oxygen passes through the prevalve and enters the main engine at the inlet to the low-pressure oxidizer turbopump.

If all three SSMEs reach 90 percent of their rated thrust by T minus 3 seconds, then at T minus 0, the GPCs will issue the commands to fire the solid rocket booster ignition pyro initiator controllers, the hold-down release pyro initiator controllers, and the T- 0 umbilical release pyro initiator controllers. Lift-off occurs almost immediately because of the extremely rapid thrust buildup of the solid rocket boosters. The 3 seconds to T minus zero allow the vehicle base bending loads to return to minimum by T minus 0.

If one or more of the three main engines do not reach 90 percent of their rated thrust at T minus 3 seconds, all SSMEs are shut down, the solid rocket boosters are not ignited, and a pad abort condition exists.

Ascent

Beginning at T minus 0, the SSME gimbal actuators, which were locked in their special preignition position, are first commanded to their null positions for solid rocket booster start and then are allowed to operate as needed for thrust vector control.

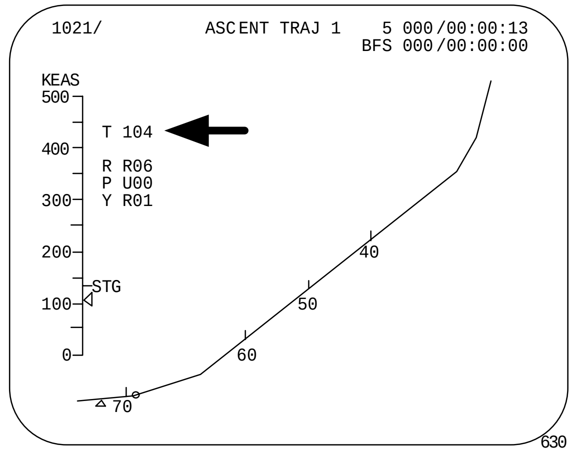
Between lift-off and MECO, as long as the SSMEs perform nominally, all MPS sequencing and control functions are executed automatically by the GPCs. During this period, the flight crew monitors MPS performance, backs up automatic functions, if required, and provides manual inputs in the event of MPS malfunctions.

During ascent, the liquid hydrogen tank's pressure is maintained between 32 and 34 psig by the orifices in the two lines and the action of the flow control valve.

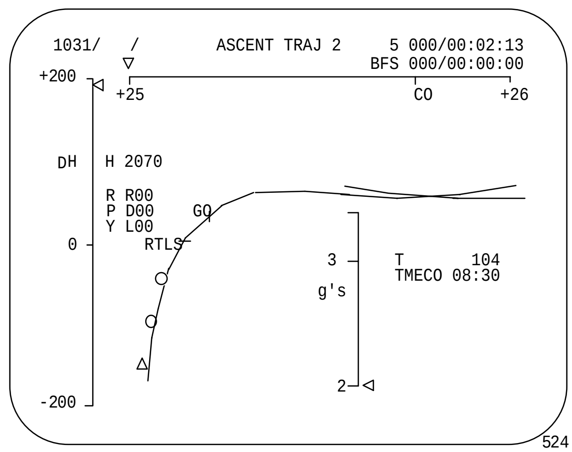
The liquid oxygen tank's pressure is maintained between 20 and 25 psig by fixed orifices in the ET to SSME pressurization lines. A pressure greater than 30 psig will cause the tank to relieve through its vent and relief valve.

The SSME thrust level depends on the flight: it is usually 104 percent, but the maximum setting of 109 percent may be required for emergency situations. This is known as max throttle. Percent of thrust that would be commanded (T) by the BFS is displayed on the BFS ASCENT TRAJ 1 and 2 displays, and actual thrust levels are read on the three MPS PRESS P_c meters on panel F7. As dynamic pressure rises, the GPCs throttle the engines to a lower power level (minimum 67 percent) to minimize structural loading while the orbiter is passing through the region of maximum aerodynamic pressure. This is called the "thrust bucket" because of the way the thrust plot appears on the graph. Although the bucket duration and thrust level vary, a typical bucket runs from about 30 to 65 seconds, mission elapsed time (MET). The solid rocket booster propellant is also shaped to reduce thrust. At approximately 65 seconds MET, the engines are once again throttled up to the appropriate power level (104 percent) and remain at that setting for a normal mission until 3-g throttling is initiated.

SRB separation is the next major event on ascent. The SRBs burn out after about two minutes of flight. Appearance of an overbright "Pc < 50" (chamber pressure in the SRBs in psi) on the trajectory display indicates to the crew that the SRB separation sequence has begun. Actual separation occurs about five seconds later to allow for SRB thrust tailoff.



BFS ASCENT TRAJ 1 DISPLAY
(percent of thrust commanded by the BFS)



BFS ASCENT TRAJ 2 DISPLAY

Liquid oxygen manifold pressure is greatly affected by acceleration from the SRBs, but because of its low density, liquid hydrogen is not. At SRB separation, the liquid oxygen manifold pressure will drop from well over 100 psia to approximately 50 psia. Pressure rises again as the vehicle approaches 3 g's. The crew can monitor the manifold pressures on the BFS GNC SYS SUMM 1 display (MANF P) and on the MPS PRESS ENG MANF meters on panel F7.

Beginning at approximately 7 minutes 40 seconds MET, the engines are throttled back to maintain vehicle acceleration at 3 g's or less. Three g's is an operational limit devised to prevent excessive physical stress on the flight crew and vehicle. Approximately 6 seconds before main engine cutoff, the engines are throttled back to 67 percent in preparation for shutdown.

Main Engine Cutoff (MECO)

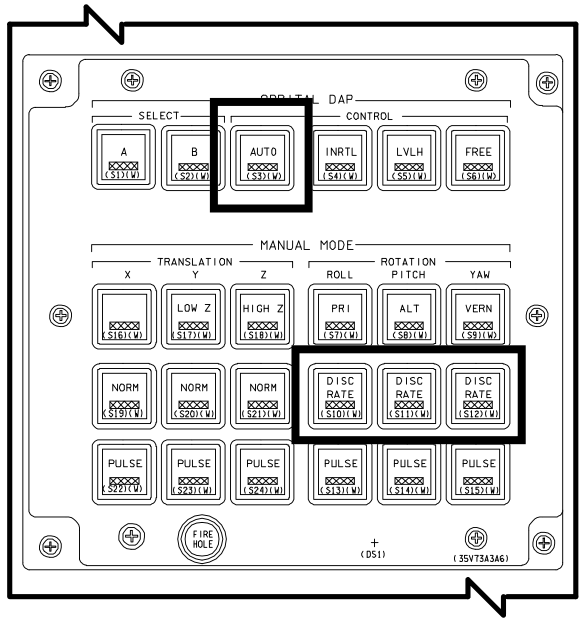
Although MECO is based on the attainment of a specified velocity, the engines can also be shut down due to the depletion of liquid oxygen or liquid hydrogen before the specified velocity of MECO is reached. Liquid oxygen depletion is sensed by four sensors in the orbiter liquid oxygen feedline manifold. Liquid hydrogen depletion is sensed by four sensors in the bottom of the liquid hydrogen tank. If any two of the four sensors in either system indicate a dry condition, the GPCs will issue a MECO command to the engine controller (provided they go dry after the arming mass is reached).

Once MECO has been confirmed at approximately 8 minutes 30 seconds MET, the GPCs execute the external tank separation sequence. The sequence takes approximately 18 seconds to complete and includes opening the feedline relief isolation valves, arming the external tank separation pyro initiator controllers, closing the liquid hydrogen and liquid oxygen feedline 17-inch disconnect valves, turning the external tank signal conditioners' power off (deadfacing), firing the umbilical unlatch pyrotechnics, retracting the umbilical plates hydraulically, and gimbaling the SSMEs to the MPS dump sequence position.

At this point, the computers check for external tank separation inhibits. If the vehicle's pitch, roll, and yaw rates are greater than 0.7 degree per second, or the feedline disconnect valves fail to close, automatic external tank separation is inhibited. If these inhibit conditions are met, the GPCs issue the commands to the external tank separation pyrotechnics. As with the SRBs, the crew has the capability to override the external tank separation with the ET SEPARATION switch located on panel C3. In crew-initiated external tank separation or RTLS aborts, the inhibits are overridden.

At orbiter/external tank separation, the gaseous oxygen and gaseous hydrogen feedlines are sealed at the umbilicals by self-sealing quick disconnects.

In the cockpit, the crew observes MECO through the illumination of the three red MAIN ENGINE STATUS lights on panel F7. In addition, the Pc meters on panel F7 drop to 0 percent. Four of the ORBITAL DAP pushbutton lights on panel C3 illuminate when the MECO CONFIRMED software flag has been set. This flag must be set to enter the ET separation sequence. Remember, the DAP lights will not illuminate on an RTLS abort since the trans DAP is not entered at MECO as it is uphill or on a TAL abort.



ORBITAL DAP CONTROL AUTO Light on Panel C3

Post-MECO

Ten seconds after main engine cutoff, the backup liquid hydrogen dump valves are opened for 2 minutes to ensure that the liquid hydrogen manifold pressure does not result in operation of the liquid hydrogen feedline relief valve.

After MECO confirmed plus 20 seconds, the GPCs interconnect the pneumatic helium and engine helium supply system by opening the center and right out/open interconnect valves and the left in/open interconnect valve if the MPS He INTERCONNECT LEFT, CTR, RIGHT switches on panel R2 are in the GPC position. This connects all 10 helium supply tanks to a common manifold, and it ensures that sufficient helium is available to perform the liquid oxygen and liquid hydrogen propellant dumps.

After external tank separation, approximately 1,700 pounds of propellant are still trapped in the SSMEs, and an additional 3,700 pounds of propellant remain trapped in the orbiter's MPS feedlines. This 5,400 pounds of propellant represents an overall center-of-gravity shift for the orbiter of approximately 7 inches. Non-nominal center-of-gravity locations can create major guidance problems during entry. The residual liquid oxygen, by far the heavier of the two propellants, poses the greatest impact on center-of-gravity travel.

A hazard from the trapped liquid hydrogen occurs during entry, when any liquid or gaseous hydrogen remaining in the propellant lines may combine with atmospheric oxygen to form a potentially explosive mixture. In addition, if the trapped propellants are not dumped overboard, they will sporadically outgas through the orbiter liquid oxygen and liquid hydrogen feedline relief valves, causing slight vehicle accelerations.

The MPS propellent dumps (LO2 and LH2) occur simultaneously. Both dumps are completely automatic. The helium subsystem is used during the MPS dump to help expel the liquid oxygen from the LO2 manifold. To support this, the GPCs command the center and right helium interconnects to out/open and the left interconnect to in/open at MECO plus 20 seconds. This occurs provided the helium interconnects are in the GPC position.

The MPS dump starts automatically at MECO plus 2 minutes. The MPS dump may be started manually by taking the MPS PRPLT DUMP SEQUENCE switch to START. The earliest that the manual MPS dump can be performed is MECO plus 20 seconds. The only reason that the crew may need to start the dump prior to MECO plus 2 minutes is if the LO2 or LH2 manifold pressure rises unexpectedly. The MPS dump will start automatically prior to MECO plus 2 minutes if the LH2 manifold pressure is greater than 60 psi. The dump takes 2 minutes to complete. The STOP position of the MPS PRPLT DUMP SEQUENCE switch is used to prevent the automatic dump from starting during the ET separation sequence if it is delayed by an RCS leak or feedline disconnect valve failure.

For the LO2 dump, the GPCs command the two liquid oxygen manifold repressurization valves to open (the MAIN PROPULSION SYSTEM MANF PRESS LO2 switch on panel R4 must be in the GPC position), command each engine controller to open its SSME main oxidizer valve (MOV), and command the three liquid oxygen prevalves to open (the LO2 PREVALVE LEFT, CTR, RIGHT switches on panel R4 must be in the GPC position). The liquid oxygen trapped in the feedline manifolds is expelled under pressure from the helium subsystem through the nozzles of the SSMEs. This is propulsive and typically provides about 9-11 feet-per-second of delta V.

The pressurized liquid oxygen dump continues for 90 seconds. At the end of this period, the GPCs automatically terminate the dump by closing the two liquid oxygen manifold repressurization valves, wait 30 seconds, and then command the engine controllers to close their SSME main oxidizer valve. The three liquid oxygen prevalves remain open during the orbit phase of the flight.

Concurrent with the liquid oxygen dump, the GPCs automatically initiate the MPS liquid hydrogen dump. The GPCs command the two liquid hydrogen fill and drain valves (inboard and outboard) to open, the topping valve to open, and the three LH2 prevalves to open.

The liquid hydrogen trapped in the orbiter feedline manifold is expelled overboard without pressure from the helium subsystem. The liquid hydrogen flows overboard through the inboard and outboard fill and drain valves, and the topping valve for 2 minutes. The GPCs automatically stop the dump by closing the liquid hydrogen outboard fill and drain valve and the topping valve.

At the end of the liquid oxygen and liquid hydrogen dumps, the GPCs close the helium out/open and in/open interconnect valves, provided the He INTERCONNECT LEFT, CTR, RIGHT switches on panel R2 are in the GPC position. After the MPS dump is complete, the SSMEs are gimballed to their entry stow position with the engine nozzles moved inward (toward one another) to reduce aerodynamic heating. Although the gimbals move to an MPS dump position during the external tank separation, the I-loads are currently the same as the entry stow position. At this time, the BODY FLAP lights on panel F2 and F4 turn off. This is the crew's indication that the MPS dump is complete.

In the post OMS-1 procedures, the pilot positions all six MPS ENGINE POWER switches on panel R2 to OFF, which removes all power to the main engine controllers. Once power is removed from the controllers, the main oxidizer valves, which are necessary for the liquid oxygen portion of the dump, can no longer be operated.

The pilot also positions the six He ISOLATION switches and the PNEUMATIC He ISOLATION switch to GPC at this time. When this is done, the helium isolation valves automatically close, but the pneumatic helium isolation valve stays open to operate the pneumatic valves during the vacuum inert. The external tank gaseous hydrogen pressurization manifold is manully vacuum inerted by opening the hydrogen pressurization line vent valve by placing the MAIN PROPULSION SYSTEM H2 PRESS LINE VENT switch on panel R4 to OPEN.

After a 1 minute inert period, the switch is taken back to the GND position, which closes the valve. The hydrogen pressurization vent line valve is electrically activated; however, it is normally closed (spring-loaded to the closed position). Removing power from the valve solenoid closes the valve.

NOTE

> After the helium isolation valves are closed, multiple MASTER ALARMS are annunciated as the helium pressure in the regulators bleeds down.

Vacuum Inerting

Fifteen minutes after the MPS dump stops, the GPCs initiate the sequence for vacuum inerting the orbiter's liquid oxygen and liquid hydrogen manifolds. Vacuum inerting allows traces of liquid oxygen and liquid hydrogen trapped in the propellant manifolds to be vented into space.

The LO2 vacuum inerting is accomplished by the GPCs opening the LO2 inboard and outboard fill and drain valves. The LH2 vacuum inerting is accomplished by the GPCs opening the LH2 outboard fill and drain valve and the topping valve (the inboard fill and drain valve was left open at the end of the MPS dump).

The liquid oxygen and hydrogen lines are inerted simultaneously for 1 minute. At the end of the sequence, the GPCs close the LO2 and LH2 outboard fill drain valves. The LO2 and LH2 inboard valves are left open to prevent a pressure buildup between the inboard and outboard valves.

Any GPC or FA MDM failure that will not allow the automatic vacuum inert to function properly will require the crew to perform a manual vacuum inerting procedure.

Following the OMS 2 burn, the LH2 system requires a second vacuum inerting to evacuate all of the residual liquid hydrogen. Residual hydrogen ice sublimates quickly after the OMS 2 burn (and the LH2 manifold pressure rises) due to the vibrations induced by the firing of the OMS engines.

This second vacuum inerting of the LH2 manifold is a crew procedure and is accomplished by opening the LH2 inboard and outboard fill and drain valves for 1 minute. Upon termination of the procedure, the outboard fill and drain valve is closed. The inboard fill and drain valve is left in the open position to prevent a pressure buildup between the inboard and outboard valves.

Post Insertion

In the post insertion portion of the flight, the following switches are powered off since the systems are no longer used: Ascent thrust vector control 1, 2, 3, and 4, EIUs L-C, C-R, R-L, and MECs 1 and 2, all of which are on panel O17. The hardware caution and warning system is reconfigured to inhibit caution and warning on the left, center, and right helium tank pressures and the "A" regulators since the helium system is secured and no longer used. Remember, only the "A" regulators have caution and warning. The LH2 and LO2 manifold pressure caution and warning left enabled to alert the crew to a possible high manifold pressure while on orbit. The engine controller heaters, which are not used, are located on R4 and should remain in the OFF position for the entire mission.

Orbit

All main propulsion systems have been secured by the time post insertion is complete. The MPS orbit procedures deal with off-nominal manifold pressures and are not normally performed. The concern on orbit is possible high manifold pressures due to an incomplete vacuum inert or MPS dump. If high manifold pressures were detected during orbit, the MCC would advise the crew to perform a manual vacuum inert. If the MCC were not available, the manifold pressure caution and warning parameter (left enabled during post insertion) would alert the crew of the high manifold pressure and the malfunction procedure would be performed, relieving the pressure or deducing a manifold pressure transducer failure.

Deorbit Prep

During the deorbit prep timeframe, the MPS hardware caution and warning is reconfigured in preparation for entry. Specifically, the MPS helium "A" regulators are re-enabled since helium will be provided for the entry purge and manifold repressurization. A regulator failed high would alert the crew to the problem and possible over-pressurization of the aft compartment. The manifold pressure caution and warning is inhibited at this time since the manifolds are at a vacuum state and do not need to be monitored during entry. Lastly, the ATVC switches are powered back on to allow the main engine nozzles to return to their entry stow positions, since they typically drift while on orbit.

Entry

The GPCs reconfigure the MPS helium system in preparation for the entry repressurization and purge at the MM 303 transition.

NOTE

Expect the F7 MPS light to be on until MM 303.

Once MM 303 is entered, the GPCs command the PNEUMATIC ISOLATION A and B, and the L ENG He XOVR to OPEN provided the switch is in the GPC position. At the same time, the MPS He INTERCONNECTS CTR and RIGHT are commanded out/open, while the MPS He INTERCONNECT LEFT is commanded in/open. This feeds all the MPS helium through the left engine, through the PNEUMATICS L ENG He XOVR, and through the pneumatic isolation valves. Also at this time, the LH2 RTLS dump valves go open to insure the LH2 manifold is completely vented prior to entry.

At a ground relative velocity of 5,300 feet-per-second (between 130,000 and 110,000 feet altitude, depending on the entry trajectory), the helium blowdown valves open which allows helium to continuously purge the aft compartment, OMS pods, and the LH2 umbilical cavity area. There is no manual control of the blowdown valves. The blowdown purge continues for 650 seconds and typically ends a few minutes after touchdown. At ground relative velocity of 5,300 fps, the MAIN PROPULSION SYSTEM MANF PRESS LH2 & LO2 valves are commanded OPEN, provided the switches on panel R4 are in the GPC position. This allows the LH2 and LO2 manifolds to be pressurized, preventing contaminates from entering the manifolds during entry. Removing contamination from the manifolds or feedlines can be a long and costly process since it involves disassembly of the affected parts. The manifold repress continues until the ground crews install the throat plugs in the main engine nozzles. The LH2 backup dump valves and the LO2 prevalves go closed at the 5,300 feet-per-second velocity.

RTLS Abort Propellant Dump Sequence

For RTLS abort, immediately post-MECO, the valve sequencing is the same as for a nominal MECO. After ~25 seconds, the vehicle enters MM 602 and the RTLS dump begins. The RTLS entry dump differs only slightly from the nominal entry dump.

During the RTLS dump, liquid oxygen is initially dumped through the LO2 prevalves and through the main oxidizer valves (MOVs) in the SSMEs. When the dynamic pressure is above 20 (plus an I-load) psf, there is a subsequent venting through the liquid oxygen fill and drain valves. This dump is done without helium pressurization and relies on the self-boiling properties of the liquid oxygen. In the RTLS liquid oxygen dump, the GPCs terminate the dump whenever the ground relative velocity drops below 3,800 feet-per-second. The liquid oxygen system is repressurized when the 3,800 feet-per-second velocity is attained, and repressurization continues as in a nominal entry.

LH2 manifold is expelled in the same manner as the nominal post-MECO dump (with one exception) until a ground relative velocity of 3,800 feet per second, at which time the valves are closed. The only exception is that the RTLS LH2 dump is assisted by helium pressurization through the RTLS manifold pressurization valves for 2 minutes, beginning at RTLS dump start.

The entry repressurization and the aft compartment surge also occur during the RTLS.

The helium blowdown valves are opened at Vrel 5,300 feet-per-second, followed by the manifold repress valves opening at 3,800 feet-per-second. As with the nominal entry, the blowdown valves remain open until a few minutes after landing.

TAL Abort Propellant Dump Sequence

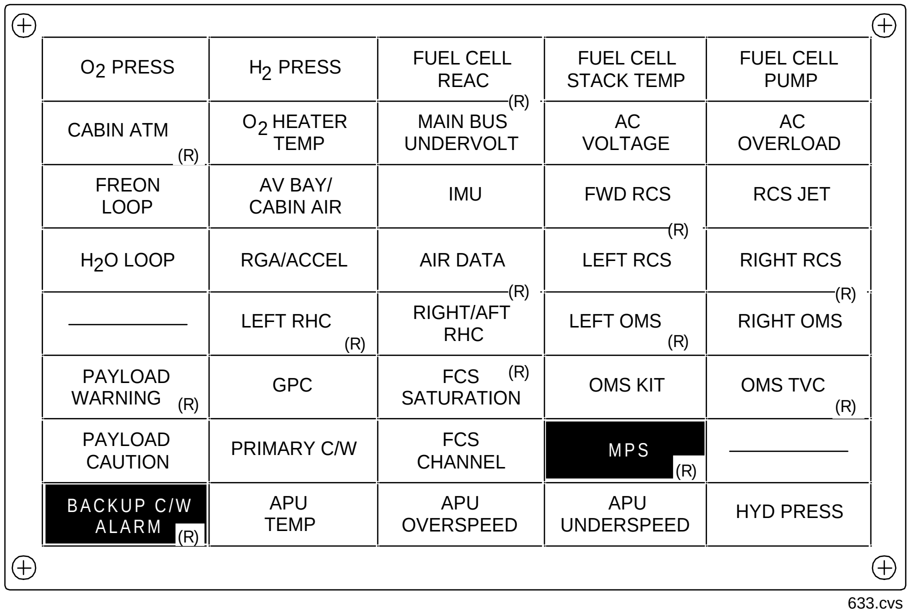
For a TAL abort, the entire dump sequence is the same as that for RTLS. On the TAL, the dump begins at the transition to MM 304.

The LO2 is also dumped at the MM 304 transition through the LO2 prevalves and then out the MOVs, just as in the nominal dump. To assist in removing the LO2 propellants, the LO2 inboard and outboard fill drains are opened at a Vrel of 20,000 feet per second if the LO2 manifold pressure is less than 30 psi.

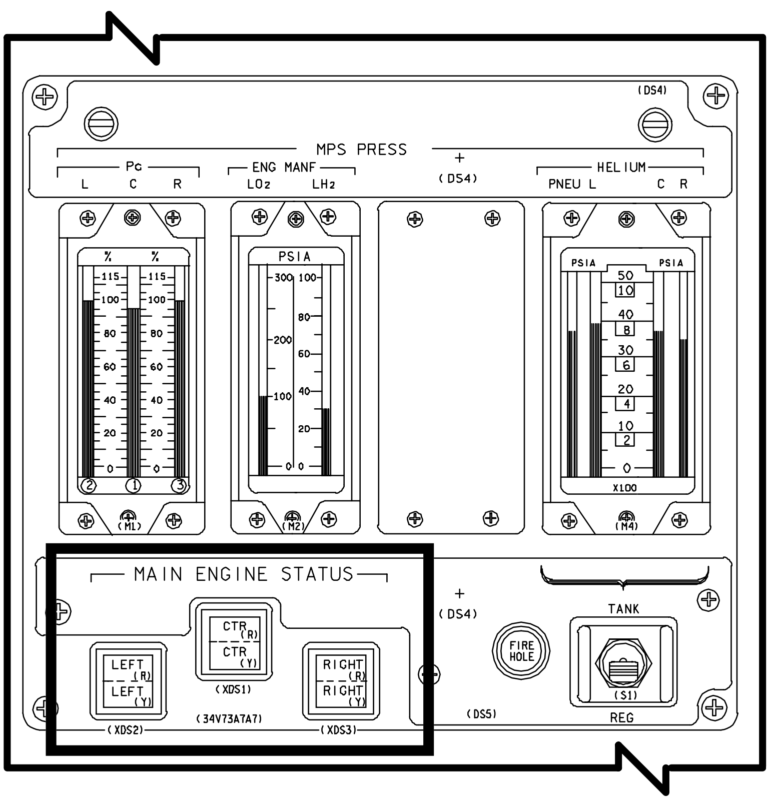
MPS Caution and Warning Summary

- **Data path failure** is the loss of both the primary and secondary data paths from an engine. Data path failure indications include an *SM ALERT* light and audio tone, a yellow *MAIN ENGINE STATUS* light on panel F7, the engine Pc meter on panel F7 driven to zero, and an MPS DATA L (C, R) message.
- **Command path failure** is the loss or rejection of GPC commands to the main engine controller. The engine will no longer throttle or accept commands. Indications include an *SM ALERT* light on panel F7 and audio tone, yellow *MAIN ENGINE STATUS* light on panel F7, no change in the Pc meter during throttling, and an MPS CMD L (C, R) message. This message will only annunciate on the PASS pre-BFS engage.
- **Hydraulic lockup** occurs when any of the five hydraulically actuated engine valves fails to achieve its commanded position; the engine does not throttle. Indications are an *SM ALERT* light and audio tone, a yellow *MAIN ENGINE STATUS* light on panel F7, no change in Pc meter during throttling, and an MPS HYD L (C, R) message.
- **Electrical lockup** occurs when the controller loses all Pc or all fuel flow rate data from the engine. Indications are *SM ALERT* light and audio tone, a yellow *MAIN ENGINE STATUS* light on panel F7, no change in Pc meter during throttling, and MPS ELEC L (C, R) message .
- **Engine failure** indications are a visual and audible *MASTER ALARM*, a red *MAIN ENGINE STATUS* light, engine Pc meter reading of zero, a Backup C&W Alarm light on the F7 C/W matrix and an SSME FAIL L (C, R) message on the CRT. A drop in acceleration will also occur, but may not be detectable in MM 102.
- **ET SEP** switch failures are indicated by an SM alert light and an ET SEP MAN or ET EP AUTO message. EP SEP MAN is the default software position for OPS 1 and ET SEP AUTO for OPS 6. This is annunciated by the PASS only since BFS has no switch RM.
- Main engine shutdown pushbutton failures may result in an ME SHDN SW C(L,R) message and an SM alert light and tone. This is annunciated by the PASS only since BFS has no switch RM.
- **Liquid hydrogen ullage pressure below 31.6** psia is indicated by an *SM ALERT* light and audio tone, one or more down arrows by the LH2 pressure readings on the BFS GNC SYS SUMM 1 display, and an MPS LH2/O2 ULL message on the BFS CRT.
- **High liquid hydrogen or liquid oxygen manifold pressure** indications are: a visual and audible *MASTER ALARM*, an up arrow by the applicable MANF P reading on the BFS GNC SYS SUMM 1 display, and an MPS LH2/LO2 MANF message on the CRT. The limits are 249 psia for liquid oxygen, and 65 psia for liquid hydrogen.
- **Helium tank leaks** or regulator failure are indicated by an *SM ALERT* light and audio tone, an up arrow by the applicable dP/dT or regulator on the BFS GNC SYS SUMM 1 display, and an MPS He P C (L, R) message .
- **ET separation inhibit** is indicated by an *SM ALERT* light and audio tone and an ET SEP INH message.
- **The MPS** light on panel F7 will illuminate (red) if liquid hydrogen manifold pressure exceeds 65 psia on orbit or liquid oxygen manifold pressure exceeds 249 psia on orbit. *A MASTER ALARM* also illuminates, an audio alarm sounds, and the red *BACKUP C/W ALARM* on panel F7 illuminates as well. The light will also illuminate for helium pressure below 1,150 psia or regulated helium pressure below 680 or above 810 psia on the "A" regulators only.
- **The red upper half of the MAIN ENGINE STATUS** lights on panel F7 will be illuminated for an engine in shutdown or post-shutdown phase or exceeding redline limits with limits inhibited.
- **MPS** pneumaitc system anomalies are annunciated by an SM alert light and audio tone, and an applicable message on the BFS CRT. The following pneumatic system messages will be annunicated along with an SM alert light and audio tone for the given condition. MPS PNEU TK, pneumatic tank pressure drops below 3800 psi. MPS PNEU ACUM, pneumatic accumulator pressure drops below 700 psi. MPS PNEU REG, pneumatic regulator pressure drops below 700 psi or goes above 810 psi.

MPS Caution and Warning Summary (continued)



MPS Caution and Warning Lights on Panel F7



MAIN ENGINE STATUS Lights on Panel F7

MPS Summary Data

- The main engines, assisted by two solid rocket motors during the initial phases of the ascent trajectory, provide the vehicle acceleration from lift-off to MECO at a predetermined velocity.

- Most of the MPS is located at the aft end of the orbiter beneath the vertical stabilizer.

- The MPS consists of three SSMEs and controllers, the external tank, propellant management and helium systems, four ascent thrust vector control units, and six hydraulic servoactuators.

- The SSMEs are reusable, high-performance engines that use liquid hydrogen for fuel and cooling and liquid oxygen as an oxidizer.

- The SSMEs can be throttled 67 to 109 percent in 1 percent increments. Thrust level values are: 100 percent = 375,000 pounds at sea level, 470,000 pounds in a vacuum; 104 percent = 393,800 pounds at sea level, 488,000 pounds in a vacuum; 109 percent = 417,300 pounds at sea level, 513,250 pounds in a vacuum.

- Major SSME components are fuel and oxidizer turbopumps, preburners, a hot gas manifold, main combustion chamber, nozzle, oxidizer heat exchanger, and propellant valves.

- Each SSME has a controller with two redundant digital computer units. Operating in conjunction with engine sensors, valves, actuators, and spark igniters, the controllers form a self-contained system for engine control, checkout, and monitoring.

- The propellant management system consists of manifolds, distribution lines, and valves that transport propellant from the external tank to the three main engines for combustion, and gases from the engines to the external tank for pressurization.

- The helium system consists of 10 supply tanks and associated regulators, check valves, distribution lines, and control valves.

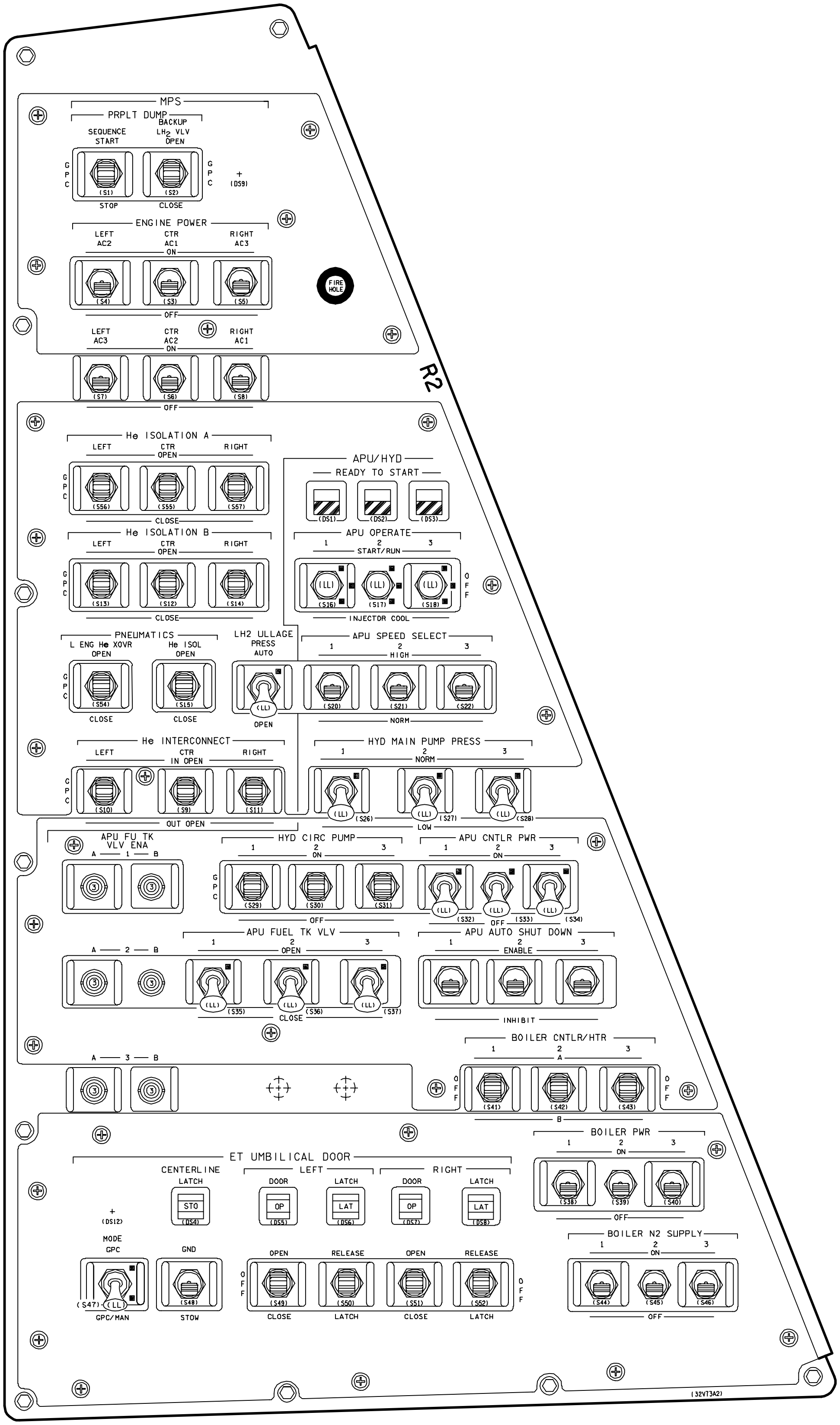
- The helium system is used for: (1) in-flight engine purges, (2) pressure for emergency closing of engine valves, (3) pressure to actuate pneumatically operated propellant valves, (4) expelling the propellants during the MPS dump and (5) entry purge and repressurization.

- There is one helium system per engine, plus a fourth pneumatic system to operate the propellant valves.

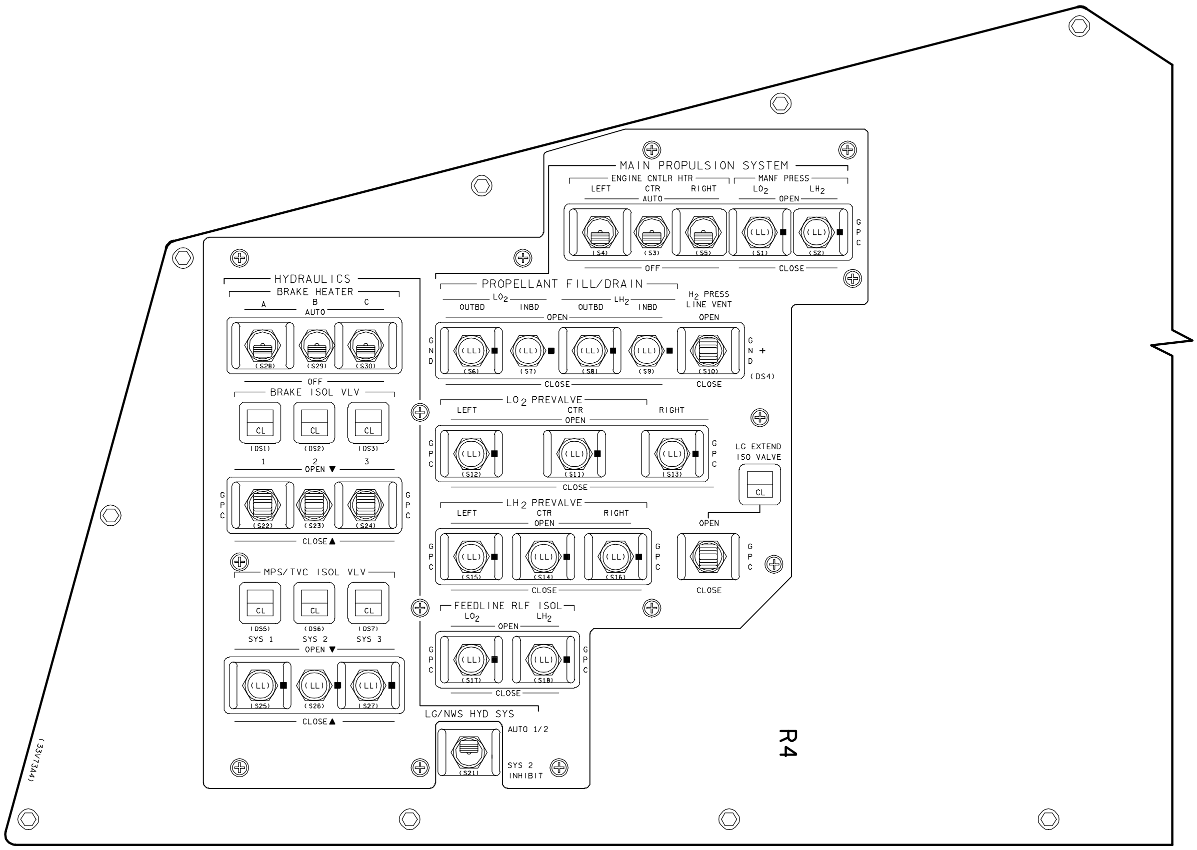
- The three orbiter hydraulic systems supply hydraulic pressure to the MPS to actuate engine valves and provide engine gimballing for thrust vector control.

- MPS controls are located primarily on panels R2 and R4, and C3 with a few on panels F7, O17, and R1.

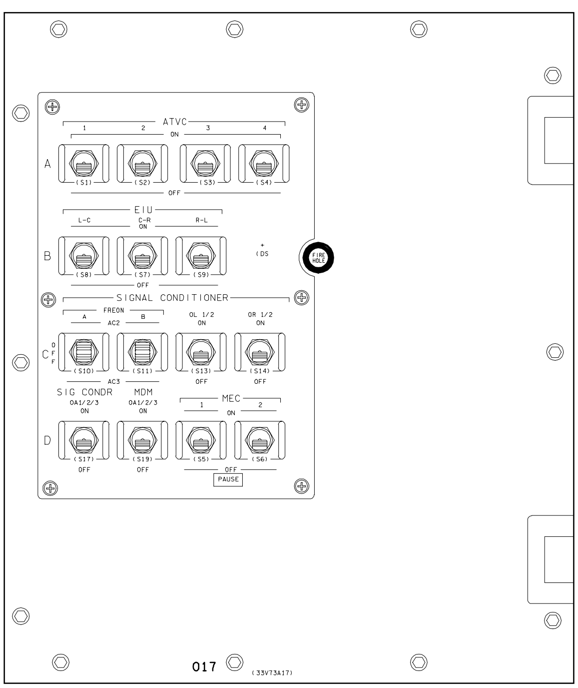
- MPS system status indicators appear on panel F7. The BFS GNC SYS SUMM 1 CRT displays several MPS system parameters. The BFS ASCENT TRAJ 1 and 2 CRT displays engine throttling level (commanded by BFS, if engaged).


MPS
PRPLT DUMP
SEQUENCE START
BACKUP LH2 VLV OPEN
GPC
STOP
CLOSE
(DS9)
ENGINE POWER
LEFT AC2
CTR AC1
RIGHT AC3
ON
OFF
FIRE HOLE
LEFT AC3
CTR AC2
RIGHT AC1
R2
He ISOLATION A
LEFT
CTR
RIGHT
OPEN
CLOSE
He ISOLATION B
APU/HYD
READY TO START
APU OPERATE
START/RUN
INJECTOR COOL
OFF
PNEUMATICS
L ENG He XOVR OPEN
He ISOL OPEN
LH2 ULLAGE PRESS AUTO
APU SPEED SELECT
HIGH
NORM
He INTERCONNECT
IN OPEN
OUT OPEN
HYD MAIN PUMP PRESS
NORM
LOW
APU FU TK VLV ENA
HYD CIRC PUMP
APU CNTLR PWR
APU FUEL TK VLV
APU AUTO SHUT DOWN
ENABLE
INHIBIT
BOILER CNTLR/HTR
ET UMBILICAL DOOR
CENTERLINE
LATCH
DOOR
STO
OP
LAT
MODE
GPC
GPC/MAN
GND
STOW
OPEN
RELEASE
LATCH
BOILER PWR
BOILER N2 SUPPLY
(32VT3A2)

Panel R2



Panel R4



Panel O17

```
1011/   /018    GNC SYS SUMM 1       5 000/02:46:03
                                     BFS 000/00:00:00

     SURF       POS   MDM         DPS    1 2 3 4
      L OB                        MDM FF
        IB                            FA
      R IB                            PL
        OB
       AIL
       RUD                        FCS CH 1 2 3 4
       SPD BRK
       BDY FLP

MPS               L      C      R     NAV  1 2 3 4
 HE TK P        4280   4230   4240   IMU
   REG P A       784    768    768   TAC
         B       776    766    770   ADTA
   dP/dT
                                      MPS PNEU HE P
ULL P LH2       42.5   42.7   42.9         TK   4350
      LO2       21.1   21.0   20.8         REG   798
                                           ACUM  760
GH2 OUT P         70↓    50↓    40↓ MANF P LH2  46
GO2 OUT T         79↓    97↓    70↓        LO2 110
```

BFS GNC SYS SSUMM 1

MPS Rules of Thumb

- Direct insertion MECO is usually close to 8 minutes 30 seconds.

- An SSME will consume approximately 4 percent propellant per engine per minute at 104 percent. Propellant remaining is displayed on the ASCENT TRAJ display and is a guidance-calculated number.

- When an engine fails, the helium dP/dT is greater than 40 for several seconds, due to engine shutdown purges, and then it goes to zero. This is a good crosscheck to confirm engine shutdown.

- Two automatic ways to set MECO confirm are: three Pc's < 30% or two Pc's <30% and a data path failure on the other SSME. Three manual ways to set MECO confirm are: push the three SSME PB's OPS 104 PRO, or FAST SEP.

- BFS, like the PASS, does not require all three MAIN ENGINE SHUT DOWN pushbuttons simultaneously to set MECO confirmed.

- To shut an engine down, both contacts on the MAIN ENGINE SHUT DOWN pushbutton must be good. If one contact is commfaulted, the button can be used to set the safing flag on an engine that failed under a data path failure. If a contact is power-failed, the button is inoperative to shutdown an engine but can be used to safe an engine that shuts down behind a data path if the corresponding FF is commfaulted.

- If a MAIN ENGINE SHUT DOWN pushbutton is commfaulted in BFS, or failed otherwise, it is inoperative.

- An SSME command path failure must always be shut down manually with the A/C switches and PBs.

- An SSME FAIL C (L, R) message indicates that the GNC software has recognized an engine shut down. Two of these messages will enable single engine roll control mode.

- An engine in data path failure will never display a red MAIN ENGINE STATUS light.

- There are no direct indications to the crew of limit shutdown enable/inhibit status. The status is available to the MCC, or it can be deduced by the crew.

- Limits <u>must</u> be enabled on an engine when the helium regulator pressure begins to decay due to a helium leak. An SSME will fail catastrophically if there is insufficient helium, and limit shutdown is inhibited.

- Manual shutdown of hydraulically or electrically locked SSME is dependent on the performance call, due to NPSP requirements.

- Actual throttle levels on the first stage throttle bucket can vary due to SRB thrust level dispersions. This is an artifact of "first stage adaptive guidance."

- Loss of an APU in powered flight will result in a hydraulic lockup.

- 23 k, 22.5 k, and 24.5 k V_I are about 30 seconds before MECO on the three-engine uphill, TAL, and two-engine uphill cases, respectively, so these numbers can be used for engine shutdown cues.

- MPS ENGINE POWER switches look very similar to He ISOLATION switches and are located close together on panel R2. **Use caution.**

- Shutdown with A/C switches will always cause a data path failure.

- Loss of ALC 1, 2, 3 (APC 4, 5, 6) will cause SSME helium isolation A to close on the C, L, R SSME with no direct indication to the pilot. Do not attempt subsequent helium leak isolations.