SPACE SHUTTLE MAIN ENGINE
THE FIRST TEN YEARS

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Part 3 – Start and Shutdown

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START AND SHUTDOWN

The first hurdle that had to be overcome in the engine test program was to learn how to safely start and shut down the engine. Five years of analysis had produced sophisticated computer models that attempted to predict the transient behavior of the propellants and engine hardware during start and shutdown. With these models, the basic control concepts were defined and initial sequences were developed [19]. The models had shown the engine to be sensitive to small changes in propellant conditions and that timing relative to opening the propellant valves was critical. Expecting difficulties, a cautious step-by-step plan was followed to

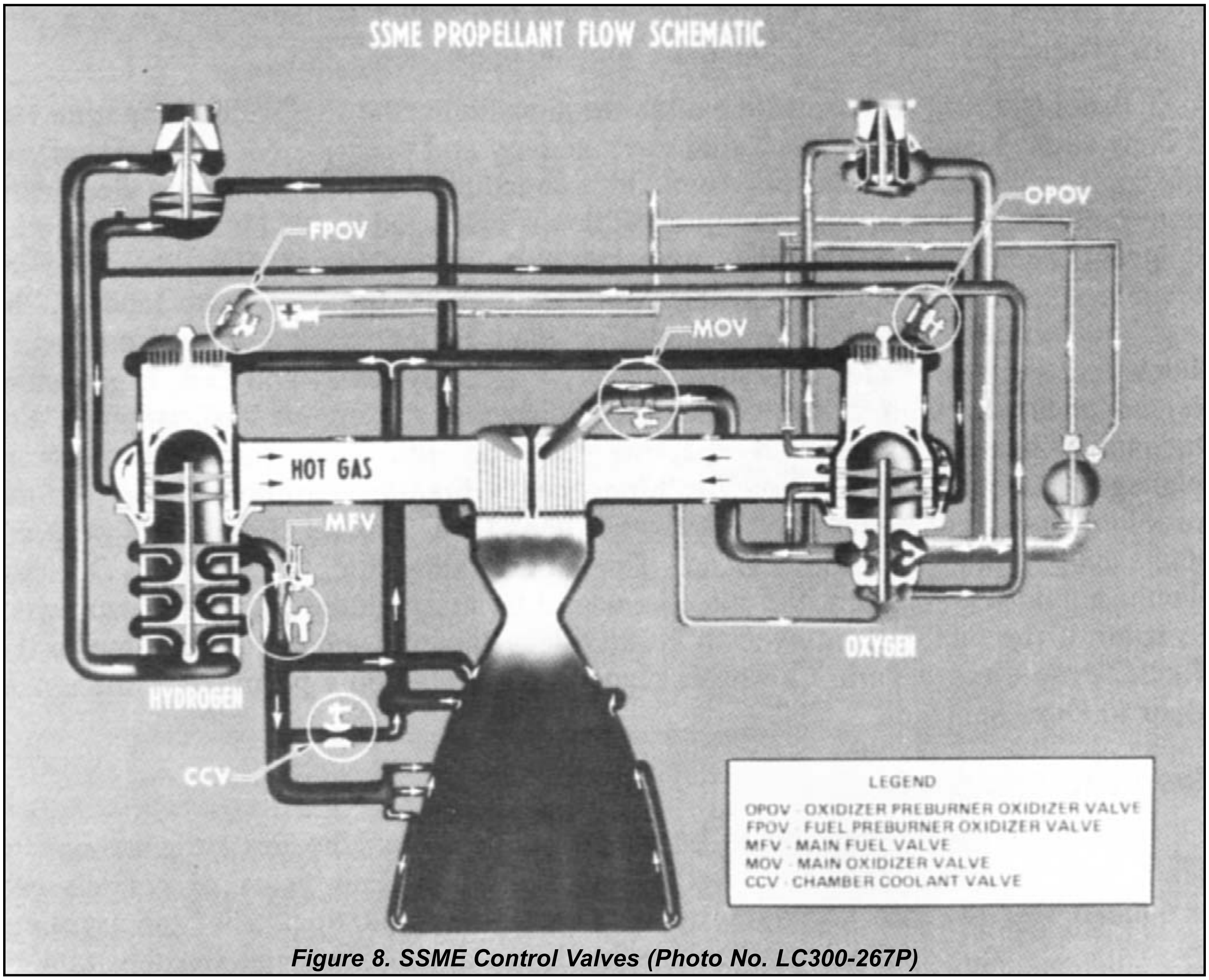

Figure 8. SSME Control Valves (Photo No. LC300-267P)

explore the start sequence in small time increments. Using this approach, it required 19 tests, 23 weeks and 8 turbopump replacements to reach 2 seconds into an eventual 5-second start sequence. It took an additional 18 tests, 12 weeks and 5 turbopump replacements before momentarily touching MPL. A safe and repeatable start sequence was eventually developed by making maximum use of the engine mounted computer (MEC) to control the propellant valve positions. Without the precise timing and positioning allowed by the MEC, it is doubtful that a satisfactory start could have been developed.

Prior to starting the engine, there is a period of time referred to as the start preparation phase. At the beginning of this time period, the oxidizer side of the engine is purged with dry nitrogen to eliminate moisture and the fuel side is purged with dry helium to eliminate air as well as moisture. This is done because the temperature of liquid hydrogen (LH2) is cold enough (less than 40 R) to freeze air into a solid block of ice. After the engine is properly purged, the cryogenic propellants are allowed to flow into the engine to begin thermal conditioning.

Figure 8 is an SSME schematic showing the propellant flow paths and the location of the primary propellant valves relative to the other components. During the propellant conditioning period, LH2 fills the fuel side of the engine down to the main fuel valve (MFV) which is a single shutoff valve for all of the fuel. A small recirculation flow is maintained by flowing through a bleed valve located at the MFV to an overboard dump line or pumped back to the LH2 inlet. Liquid oxygen (LOX) fills the oxidizer side of the engine down to the three oxidizer valves. The main oxidizer valve (MOV), oxidizer preburner oxidizer valve (OPOV) and fuel preburner oxidizer valve (FPOV) act as three parallel shutoff valves for the LOX. Recirculation flow of LOX is maintained by flowing through a bleed valve located at the FPOV to an overboard dump system. The small recirculation flows are maintained for an hour or more to chill the four turbopumps to cryogenic temperatures and to eliminate gas pockets in the propellant feed system.

During the propellant system chill down, the MEC continually monitors the engine to assure that all valves are in the proper position and conducts an automatic checkout of the control system 50 times every second to verify proper operation and retention of full redundancy. About four minutes before the engine start command, the final engine purge is turned on. Dry helium is introduced downstream of the main fuel valve to displace any gas that would freeze at LH2 temperature. The MEC uses engine-mounted sensors to measure propellant temperatures and pressures. When the engine has been purged and all the parameters are in an acceptable range for starting, and if the control system checkout finds no failures, the MEC adopts an "engine ready" status. The status word in the data stream being relayed to the vehicle or test facility is changed to reflect

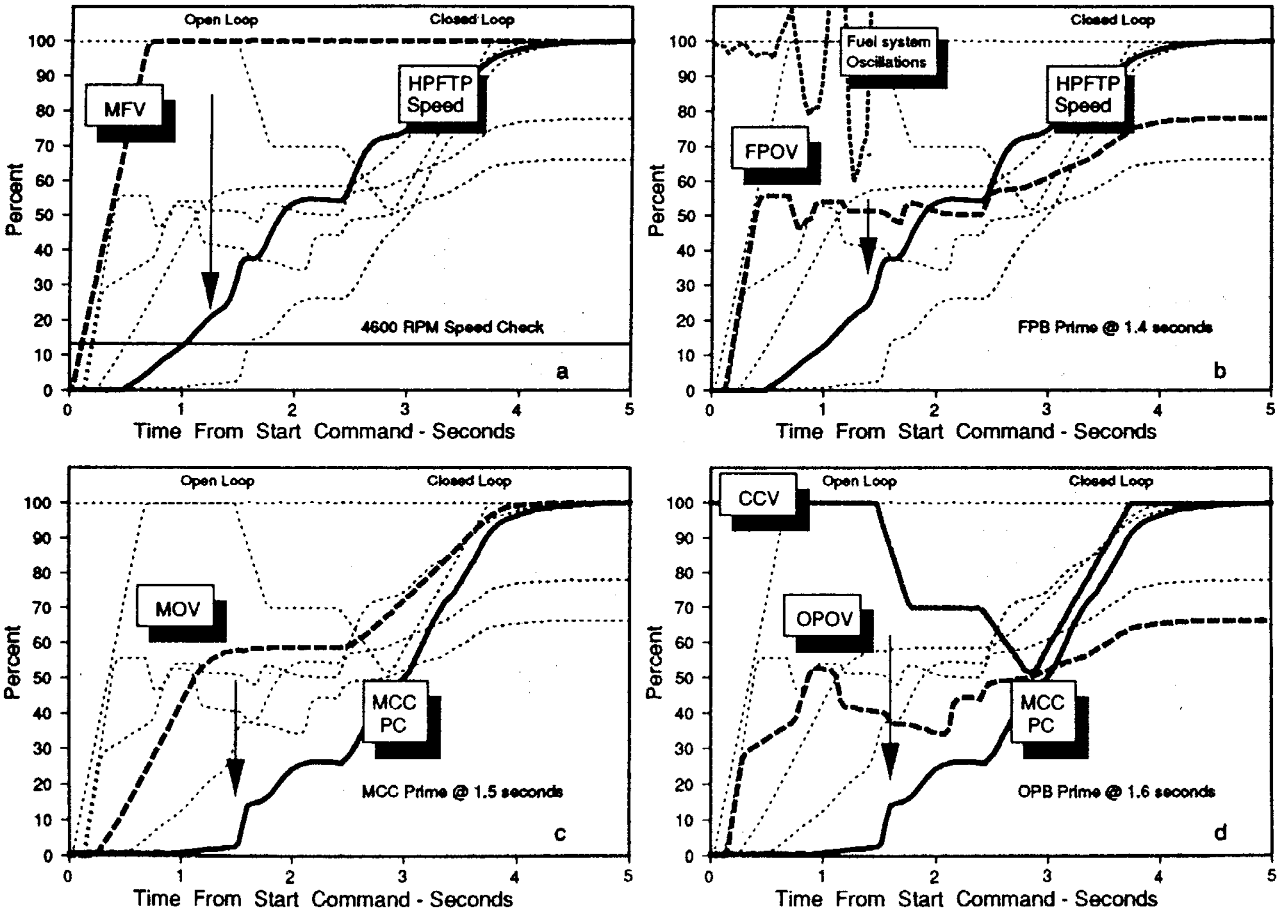

Figure 9. SSME Start Sequence (Photo No. 89c-4-1015)

that all conditions are acceptable for starting the engine. About three seconds before engine start, a "start enable" command is sent to the MEC. The MEC then closes the two bleed valves and waits for a start command.

When a start command is received, the MFV is immediately ramped to its full open position in two-thirds of a second (see Figure 9). This enables the LH2 to fill the downstream system and begin to power the high pressure turbines. The latent heat of the hardware imparts enough energy to the hydrogen to operate as an "expander-cycle" engine for the early part of the start sequence. This eliminates the need for any auxiliary power to initiate the start sequence, however it also creates a thermodynamic instability which is referred to as the fuel system oscillations. When the cold LH2 begins to flow into the thrust chamber nozzle, the hardware latent heat causes the hydrogen to expand rapidly, creating a flow blockage and momentary flow reversal. The result is a pulsating fuel flow rate with an unstable pressure oscillation at a frequency of approximately 2 Hz. The oscillations continue to increase in magnitude with dips (reductions in pressure) occurring at approximately 0.25 0.75 and 1.25 seconds, until the establishment of MCC chamber pressure causes it to stabilize after 1.5 seconds. Events prior to stabilization had to be made to conform to the idiosyncrasies of the fuel system oscillations. Simultaneously with the opening of the MFV, electrical power is provided to the spark plugs in the augmented spark igniters (ASI) included in each of the three combustors. The ASI will then ignite the combustors when both fuel and oxidizer are present in the proper mixture ratio. The fuel is provided first by the MFV being opened and then the oxidizer is provided later for each combustor separately through the three oxidizer valves. Each valve has an ASI LOX supply line that allows LOX to flow to the ASI upon initial valve motion (about 5 percent). The proper mixture ratio for ignition is achieved by the second dip in pressure caused by the fuel system oscillations.

After the MFV starts to open, the three oxidizer valves are separately subjected to a series of position commands intended to precisely control the oxidizer system priming times for the three combustors. Priming is the process of filling the system with liquid, as with an old hand-cranked water pump. An oxidizer system is said to be "primed" when it is filled with liquid down to the combustor such that the flow rate entering the injector is equal to the flow rate leaving the injector to be burned in the combustor. This event generally results in a rapid rise in combustion chamber pressure. The target priming times for the three combustors are a tenth of a second apart; FPB prime at 1.4 seconds, MCC prime at 1.5 seconds and OPB prime at 1.6 seconds. Although part of the valve positioning is accomplished under a limited form of closed loop control, it is merely a convenient method of commanding the valves to a predetermined position and therefore will be treated as if it were all done as open loop commanded positions as a function of time. The first oxidizer valve to be commanded is the FPOV. After a delay of 0.100 seconds, the FPOV is ramped to 56 percent open at its maximum slew rate. At 0.72 seconds, the FPOV is given a "notch" command to close about 10 percent and then reopen. This is done to compensate for the second pressure dip caused by the fuel system oscillations and avoid damaging temperature spikes in the HPFTP turbine. During this dip, the FPB is ignited and the additional power causes a slight acceleration in the HPFTP speed. Just prior to the third fuel system oscillation pressure dip, the FPOV is given another notch command, which is maintained throughout the priming sequence.

A safety check is made at 1.25 seconds to assure that the HPFTP speed is high enough to safely proceed through the priming sequence. The speed must be high enough at MCC prime to be able to pump hydrogen through the downstream system against the back pressure rise created by the MCC prime, or an engine burnout will occur due to the resulting oxygen-rich combustion. It was determined from test experience that if the speed were to be less than 4,600 RPM at 1.25 seconds (Figure 9a), then it would likely be too low at MCC prime to maintain pumping capability. The engine must be shut down at 1.25 seconds because if the speed is discovered to be too low later in the start sequence, there is insufficient time to react and shut down safely.

When the FPB prime occurs at 1.4 seconds, there is a rapid rise of pressure at the inlet to the HPFTP turbine. Since the turbine back pressure is not provided until MCC prime, this pressure rise causes a high turbine pressure ratio and a significant acceleration in the HPFTP speed (Figure 9b). The higher HPFTP speed is desirable for a cool fuel-rich start, however, the turbine back pressure must be applied (MCC prime) soon to prevent a runaway condition.

MCC prime is primarily controlled by positioning of the MOV. After an initial delay of 0.200 seconds, the MOV is slowly ramped to just under 60 percent open. This combination of time delay, ramp rate and position provides a LOX flow rate that causes MCC prime to occur at 1.5 seconds and creates an engine system balance that will produce a safe low mixture ratio (between 3 and 4) for the stabilized operation just prior to activating the closed loop thrust control system at 2.4 seconds. When MCC prime occurs at 1.5 seconds, it causes a rapid rise in MCC chamber pressure (Figure 9c) which, because it increases the turbine back pressure, acts as a break to decelerate the HPFTP (Figure 9b).

The OPOV is used to control OPB prime. Its initial opening is after a delay of 0.120 seconds; however, the opening only retracts the valve inlet seal, which is designed to provide sufficient oxygen to ignite the ASI and to have a small leakage flow into the OPB injector. The valve is designed so that the major flow path does not start to open until an indicated position of 46 percent. The slow ramp shown in Figure 9d has no effect on the OPB LOX flow rate except to delay until 0.84 seconds when the main flow path through the valve starts to open. This flow path is partially open for about a third of a second before it recloses and the OPB is again run on valve leakage flow. The timing for this opening is scheduled to provide sufficient oxygen to allow the ASI to ignite the OPB before the second fuel oscillation pressure dip recovers and causes a significant decrease in mixture ratio. The next opportunity for ignition would be about a half a second later. With valve leakage flow, OPB prime occurs at 1.6 seconds and causes an increase in drive power to both high pressure turbines. The power increase stabilizes at about 2 seconds with the MCC chamber pressure at approximately 25 percent of RPL. During this time the chamber coolant valve (CCV), which was full open at start, is throttled down to 70 percent in order to force additional coolant flow through the MCC. The Engine is allowed to run at this condition until 2.4 seconds to assure stable operation. The additional time period of 0.4 seconds is to allow for and absorb normal variations in propellant pressures and temperatures.

By using the engine-mounted sensors, the MEC verifies proper ignition and operation of the three combustors at 1.7 seconds and again at 2.3 seconds. If no malfunctions are discovered, the closed loop thrust control system is activated at 2.4 seconds. The MEC compares the measured MCC chamber pressure to a preprogramed chamber pressure ramp to RPL and modulates the OPOV in an attempt to zero out any differences. During this time, the FPOV is simply moved by the MEC with position changes that are proportional to the amount of OPOV movement, and the CCV is commanded open at a rate commensurate with the commanded chamber pressure ramp rate. Because of the engine dynamic response characteristics, the resulting chamber pressure lags behind the command by about 0.200 seconds. At 3.8 seconds, the closed loop mixture ratio control system is activated using the FPOV to adjust fuel flow rate until the commanded mixture ratio is achieved. At 5 seconds, the engine has achieved stabilized operation at RPL with a mixture ratio of 6.

Significant constraints were placed on the start sequence by the engine design characteristics. The priming sequence is the most critical. Very high (damaging) temperature spikes occur if any combustor prime coincides with the pressure dips caused by the fuel system oscillations. The timing of the sequence relative to each other is also critical. If the FPB prime were late or the MCC prime early, the insufficient fuel pump speed would cause very LOX-rich operation with major burning of the engine hardware. If the OPB prime were early or the MCC prime late, a rapid acceleration of the HPOTP could lead to its destruction. Because of the very compact design of the high pressure pumps (highest horsepower to weight ratio ever achieved) the very low inertia causes them to accelerate and decelerate extremely quickly under abnormal conditions. If only the normal operating torque were applied to the HPOTP without the fluid load applied (gas in the pump or in cavitation) it could accelerate from a dead stop to a destructive overspeed condition in less than a tenth of a second. The acceleration rate under this condition is almost 400,000 rpm per second [20].

The initial start sequence development tests on the ISTB were limited to starting to MPL (then 50 percent of RPL). The first test to achieve MPL was Test 901-037, a 3.36-second start transient test, at the end of January 1976. The first test to achieve stabilized operation with the closed loop mixture ratio control system activated was Test 901-042 on March 8, 1976. Operation at RPL was not achieved until January 1977 (Test 901-095). Although the ISTB start development tests resulted in a start sequence that would allow the continuation of the ground test program, the final start sequence was not arrived at until the end of 1978. The current operation of the preburner valves evolved over that time period to better compensate for variations in external conditions and in response to specific problems as they occurred.

The last significant start problem occurred on October 3, 1978. Test 902-132 on Engine 0006 began with a HPFTP breakaway torque that was slightly higher than normal. At the same time, the MOV actuator was misaligned such that the valve was 2 percent further open than indicated by the valve position measurement. The combination of these two unrelated events led to a slight reduction in HPFTP speed and an early MCC prime. The HPFTP was unable to pump against the downstream pressure, so the turbine horsepower was dissipated by heating up the LH2 and causing it to vaporize. This resulted in a major burnout of the turbines and hot gas system [21].

The evolution o f the SSME start sequence has resulted in a repeatable and reliable start; however, it must be remembered that the SSME is a very high-powered, low inertia system that is susceptible to extreme energy releases if subjected to abnormal conditions. An error in valve position of 2 percent (1 percent for the OPOV) or a timing error of a tenth of a second can lead to significant damage to the engine. Because of the inability to automatically compensate for unexpected variations in external conditions (such as the Engine 0006 incident) it is required that all new engines undergo a 1.5 second priming sequence verification test before a start is attempted.

As with the start, the SSME shutdown must contend with high power and low inertia; however, it does not have the further complications of fuel system oscillations and critical priming sequences. Although some problems were encountered during the evolution of the shutdown sequence, they were not as significant as the start problems. This discussion will be limited to a brief summary of the reasons for the various features of the final shutdown sequence. The shutdown sequence, which is totally open loop, is shown graphically in Figure 10.

The goal of the shutdown sequence is to shut the engine down as quickly and as safely as possible. The initial step is to remove power from the HPOTP turbine to reduce the LOX flow faster than the fuel flow reduction. This reduces the engine mixture ratio and, thereby, the combustion temperatures. The initial OPOV closing rate is limited to 45 percent per second because a faster rate would violate the ICD requirement for a maximum thrust decay rate of 700,000 pounds per second, the orbiter structural limit. The FPOV initial closing rate was chosen to assure that the oxidizer side will power down first. The OPOV and FPOV positioning for the rest of the shutdown maintains a balance with low mixture ratio and maximum oxidizer pressure decay short of allowing hot gas back flow into the oxidizer.

The MOV is scheduled to close as quickly as possible to terminate all LOX flow. The closing rate, however, is limited to 40 percent per second because the MOV must allow enough LOX flow to keep the MCC chamber pressure high enough relative to the turbine inlet pressures. Any further reduction in turbine back pressure would cause a turbine pressure ratio increase and a potential overspeed condition.

The CCV is partially closed to force more coolant flow into the MCC and nozzle to accommodate the increased heat load due to throttling. The MFV is held open for more than a second to assure a very fuel-rich shutdown, and then the MFV and CCV closing schedules are the fastest possible without causing damage to the HPFTP While the HPFTP is coasting to a halt, it is necessary for the pump to continue pumping. If the flow rate through the pump were to be reduced to below the critical value, the excess power would be dissipated by vaporizing the LH2. The conversion from a liquid to a gas would cause the loss of axial thrust control and significant internal rubbing. After five seconds, the HPFTP speed is low enough (below 7,000 rpm) that the “boilout” effect is no longer damaging.

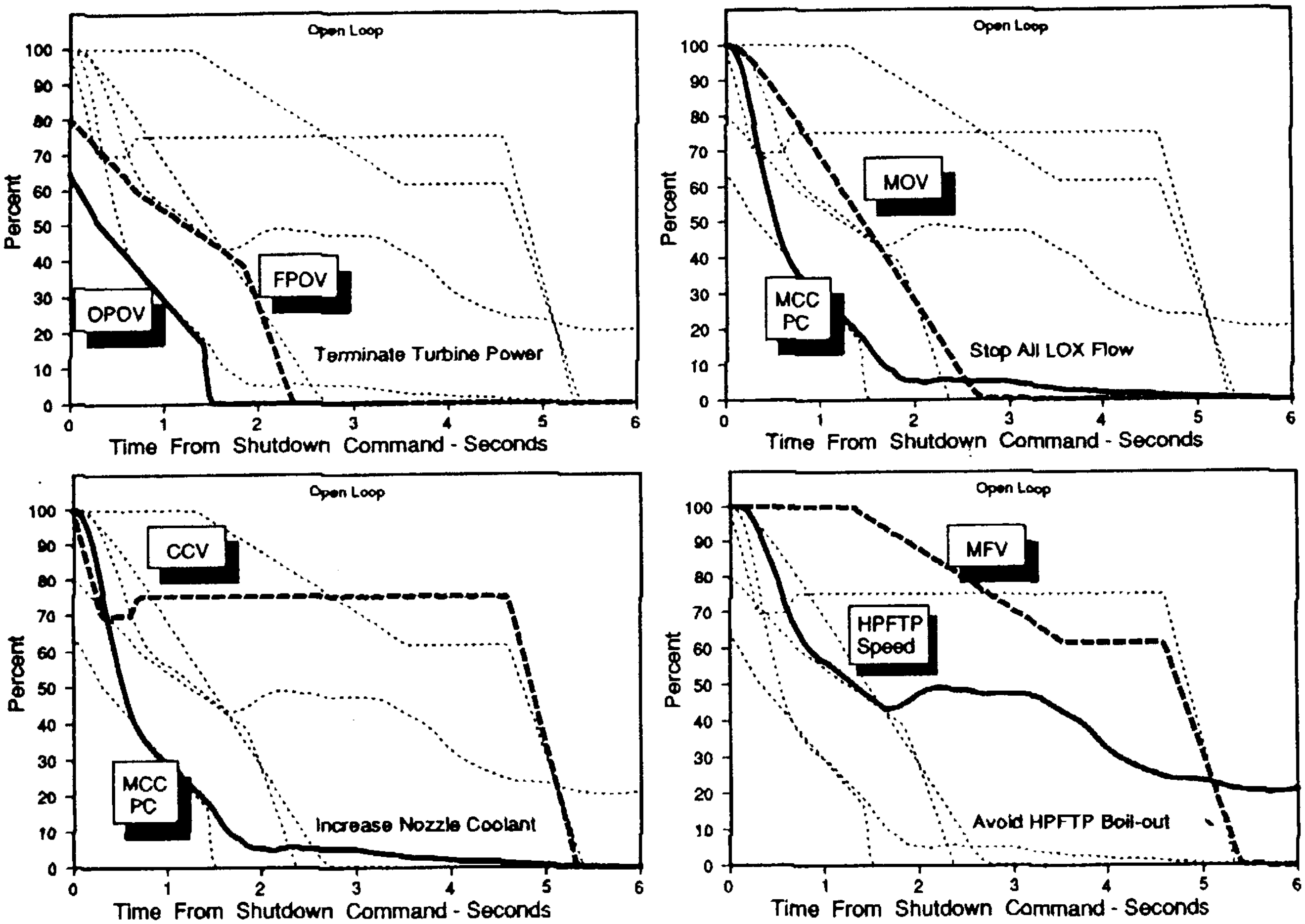

Figure 10. SSME Shutdown Sequence (Photo No. 89c-4-1016)