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The Space Shuttle Main Engine And Its Maintenance Features

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ABSTRACT

The Space Shuttle Main Engine* (SSME) is a reusable, high-performance rocket engine being developed to satisfy the performance, life, reliability, and operational requirements of the Space Shuttle Orbiter. The design includes simple, low-cost maintenance features resulting from a viable maintainability program dedicated to minimizing engine cost per flight.

DESCRIPTION

The Space Shuttle Orbiter Main Engines provide the primary thrust for the National Aeronautics and Space Administration (NASA) Orbiter vehicles. Three of the engines are clustered in the aft end of the vehicle (Figure 1).

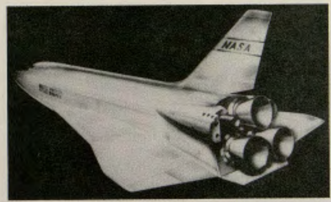

Figure 1. Space Shuttle Orbiter

The engine burn time parallels the solid rocket boosters during the initial ascent phase and continues to burn after solid rocket booster ejection until orbit insertion is attained. Nominal burn time is approximately 10 minutes. Propellants are liquid hydrogen and liquid oxygen supplied to the Orbiter vehicle through an expendable drop tank.

The reusable, high-performance rocket engine (Figure 2) is being developed to satisfy the performance, life, reliability, and operational requirements of the Space Shuttle vehicle. Its design is influenced by the constraints of system safety disciplines, minimum weight, simple low-cost maintenance, and minimum development risk.

The engine is 167 inches long and has a nozzle exit outside diameter of 94 inches. The specification

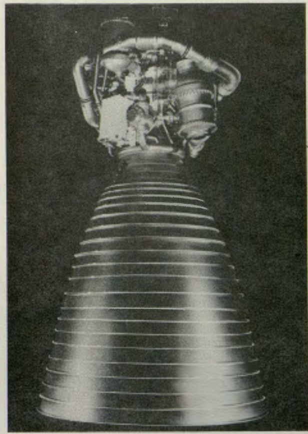

Figure 2. Space Shuttle Main Engine

weight (dry) is 6335 pounds. The engine is slightly shorter than the first-stage Saturn F-1 engine and has a powerhead approximately the same size as the Saturn upper-stage J-2 engines (Figure 3). The thrust is approximately one-fourth that of the F-1 engine and twice that of the J-2 engines.

Engine/Vehicle Interface

The engine/vehicle interface (Figure 4) consists of fluid, mechanical, and electrical connections. The fluid connections are for liquid oxygen, liquid hydrogen, main fuel tank and main oxidizer tank pressurants, nitrogen supply, helium supply, fuel bleed, oxidizer bleed, hydraulic supply and hydraulic return. Mechanical connections are for engine gimbal, thrust vector control actuators, and heat shield.

*Work performed under NASA contract NAS8-27980.

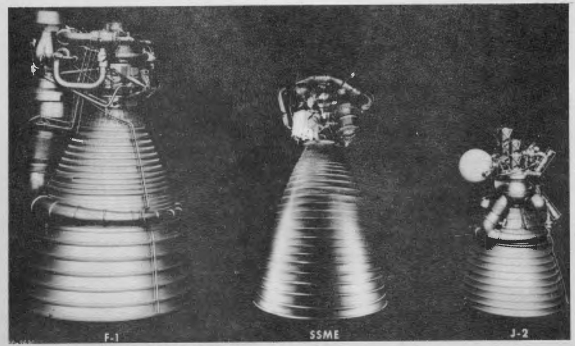

Figure 3. Engine Size Comparison

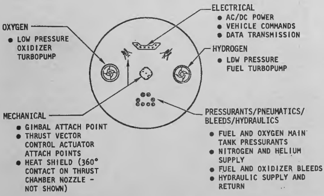

Figure 4. Engine/Vehicle Interface

Electrical connections are for the a-c and d-c power supply, operational and checkout commands to the engine, and data transmission. Two low-pressure turbopumps are fixed to the vehicle propellant ducting. Engine interconnecting ducting to the turbopumps contain internally or externally tied bellows systems to allow flexing. The flexing permits the rest of the engine to gimbal ±11 degrees in pitch and ±9 degrees in yaw for thrust vector control by vehicle-supplied actuators.

Engine Operating Requirements

Engine operating requirements are shown in Table 1. The engine responds to vehicle commands for start and shutdown and variations in thrust and mixture ratio. The operating range of thrust varies from 50 to 109 percent; this includes minimum power level (MPL), normal power level (NPL), and emergency power level (EPL). The maximum level (i.e., EPL) is available for emergencies (e.g., one engine out operations). The engine is started on the launch pad, necessitating a nozzle expansion ratio (ε) that will flow full at sea level and also provide high performance under vacuum conditions. The nominal burn time is 10 minutes (600 seconds) with a total operational service life of 7.5 hours or 100 starts.

Table 1. SSME Operating Requirements

Thrust (NPL), pounds	
• Sea Level	375K
• Vacuum	470K
MPL, percent	50
EPL, percent	109
Chamber Pressure, psia	2970
Area Ratio	77.5
Specific Impulse (nominal), seconds	
• Sea Level	363.2
• Vacuum	455.2
Mixture Ratio	6.0
Length, inches	167
Diameter, inches	
• Powerhead	105 x 95.4
• Nozzle Exit	94
Life	7.5 hours 100 starts: 6 EPL's 94 NPL's
Weight (dry), pounds	6335

Engine System

The engine has a staged combustion power cycle (Figure 5) in which the gases from the individual turbopumps are redirected to the main injector for additional combustion to extract more energy.

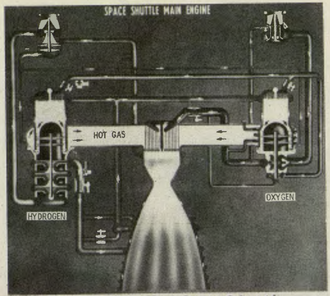

Figure 5. Propellant System Schematic

With this cycle and the highest optimum chamber pressure, the highest performance is obtained, since combustion takes place under ideal mixing conditions followed by expansion through the high expansion ratio nozzle.

Individual preburners are used to provide the power for the high-pressure turbines. This system provides the flexibility to adjust the power split between the two high-pressure turbines by control valves in the oxidizer supply to each preburner.

The propellant system uses four turbopumps. The two low-pressure turbopumps operate at low speed to permit low pressures in the vehicle tanks. The function of these pumps is to provide enough pressure to eliminate cavitation at the inlets of the high-speed, high-pressure pumps. The discharge from the low-pressure pumps is fed to the inlets of the high-pressure turbopumps.

Seventy-five percent of the flow from the high-pressure oxidizer pump goes to the main combustion chamber injector, 10 percent goes to a boost pump that raises the pressure to the preburner operating level, and the remaining 15 percent is used to drive the hydraulic turbine that powers the low-pressure oxidizer pump. This flow is then recirculated to the inlet of the high-pressure pump.

Twenty-one percent of the high-pressure fuel pump discharge flow is used to cool the main combustion chamber, drive the low-pressure fuel-pump turbine, and cool the hot-gas manifold and injector. The remaining fuel is first used to cool the nozzle, then supply the preburners.

The hot-gas from the fuel and oxidizer preburners drives the high-pressure pump turbines, then flows through the main injector, where it burns with oxidizer and additional coolant fuel.

Engine Arrangement

Figure 6 shows a cutaway view of the preburners, high-pressure turbopumps, hot-gas manifold, and main combustion chamber. The preburners are close coupled to their turbines, resulting in minimum-length, hot-gas ducting. The turbopumps are mounted to the hot-gas manifold to provide a compact package and canted outboard from the vertical for ease of removal for maintenance. The hot-gas manifold is the primary structural component for mounting the preburners, high-pressure turbopumps, and the thrust chamber assembly. This manifold also ducts the turbine exhaust gases from both turbines to the main injector, providing uniform flow across the injector face, which is a major factor in achieving high performance.

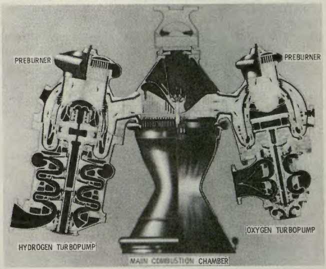

Figure 6. Engine Arrangement

Engine/Vehicle Operation

The engine controller accepts commands from the vehicle to initiate engine prestart, start, mainstage, shutdown, and post-shutdown modes for flight operations.

Prestart operations consist of checkout, purging, and chilldown. On command, the engine performs an automatic self-check, initiates system purging, actuates engine-mounted valves for propellant recirculation, and monitors engine operational readiness to provide a single "engine-ready" signal. The engine is started on receipt of start, thrust, and mixture ratio commands. The commanded level to NPL operation is achieved within 3.5 seconds from the start signal. Mainstage includes all engine operations at power levels above MPL. The same valves used for start and mainstage are used for shutdown. Post-shutdown includes purging and propellant dump operations.

Engine Control

The engine is controlled with an electronic digital control system packaged in a single assembly called the controller. In the control mode, the controller accepts vehicle commands for start, shutdown, mixture ratio, and thrust level. From these commands, the controller provides the appropriate signals to the five hydraulically actuated propellant valves (main fuel, main oxidizer, chamber coolant, and two preburner oxidizer). Primary control is achieved by closed-loop operation of the two preburner oxidizer valves. Thrust is controlled by adjusting the oxidizer preburner valve and mixture ratio is controlled by the fuel preburner oxidizer valve. The controller also monitors engine operation to provide protection in event of malfunction. It receives data from various engine sensors and transmits the data to the vehicle where the information is stored for post-flight analysis. The controller and sensor systems are dual-redundant for a fail-operational, fail-safe capability. The control system data flow is shown in Figure 7. Figure 8 shows the controller mounted to the thrust chamber. The controller is being designed and produced by Honeywell, Inc., under a subcontract from Rocketdyne.

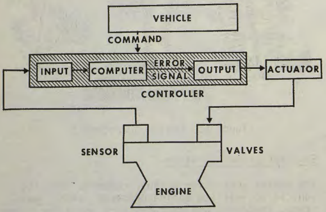

Figure 7. Control System Data Flow

Long-Life Design

The Orbiter main engine is the first large liquid rocket engine designed specifically for a long service life. The engine is capable of completing 100 starts or 7.5 hours of operation between overhauls. Six of the 100 starts are specified for operation at 9-percent overthrust (EPL). Specific changes to earlier engine designs were necessary to fulfill this long service life requirement. However, in each case, the weight of the design change was evaluated for its impact on engine weight-to-orbiter payload capability. Some of the engine systems and components designed for long service life are the hot-gas system, turbomachinery, and valve seats.

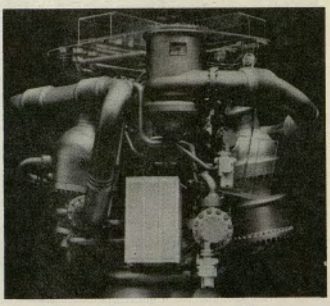

Figure 8. Controller Mounted on Engine

Hot-Gas System - The hot-gas system includes preburners, turbines, hot-gas ducting, and main combustion chamber. Because of the broad range of operating temperatures, differential thermal expansion imposes severe design constraints. If a long service life is to be obtained, stresses resulting from differential thermal expansion and from other loads must be limited to prevent low cycle fatigue of parts. For this reason, the engine design uses a regeneratively cooled hot-gas system. Gaseous hydrogen is circulated through a double-wall system for cooling. The coolant system provides flow around the preburners, turbines, ducts, and other high-temperature areas. Turbine blade roots are cooled directly by a small amount of coolant directed at the blade roots.

Turbomachinery - Cumulative damage from both fatigue and creep rupture has been considered in the turbine designs (Figure 9) to ensure durability. All turbopump seals operate with a positive clearance to prevent wear and ensure long life. Low bearing loads are ensured by a balance piston system within the turbopump that reduces axial shaft loads. Turbopump bearing life is determined by rolling-contact fatigue, which is a function of speed and load. Bearing fatigue data are treated statistically, so the recommended design approach is to maximize the probability of survival within the desired duty period. The standard criterion of bearing fatigue life is B_{10} or 90-percent survival probability. The fatigue life criterion used for the Orbiter main engine turbopump bearings is B_1 or 99-percent survival probability. This is based on the most severe load, speed, and life requirements. The use of vacuum melted materials further increases life so the average predicted bearing life is approximately 65 times the B_1 life value.

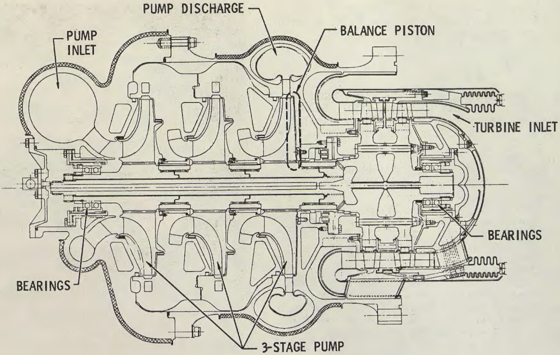

Figure 9. High-Pressure Fuel Turbopump

Propellant Valves - A retractable seal for the propellant ball valves (Figure 10) is a feature unique to the engine, added specifically to provide long life and reusability. The valves are required to modulate during operation (to provide performance control) and to provide positive shutoff during start and stop operations. They must function with high reliability in the severe operating environment of cryogenic temperature, high vibration, and high stress. The long service life of the valve is ensured by eliminating rubbing between the ball and ball seal by lifting the ball seal before the ball moves. This feature allows the ball seal to be made from a plastic material having sealing properties required for zero liquid leakage.

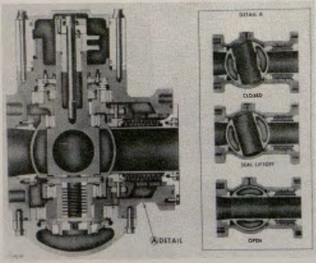

Figure 10. Main Oxidizer Valve (Typical Ball Valve)

Check and Antiflood Valves - Check valve seat life has been a concern on previous engines because of poppet chatter. As poppet opening or seating occurs, small pressure variances occur because of changes in flow. These conditions set up alternating controlling forces on the closing spring or the pressure/area force. SSME check valves and the antiflood valve (Figure 11) have an augmented seat area feature to open or seat the poppet positively without oscillation. In the antiflood valve, as the pressure buildup acts on the opening area, spring forces are overcome and the poppet retainer retracts. However, the poppet remains seated through a smaller compressed spring acting between the poppet and poppet retainer. As

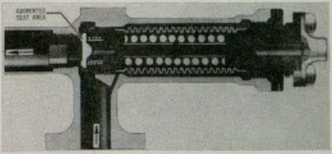

Figure 11. Antiflood Valve

poppet retainer travel takes place, mechanical restraining contact is made with the poppet and it is unseated. As the poppet opens, the poppet seat area is exposed to downstream pressure and the poppet unseating force increases. The reverse action takes place on closing. In the purge check valves, after the poppet initially opens, pressure downstream of the poppet seat acts on a larger area to increase the unseating force.

MAINTENANCE FEATURES

An engine maintenance concept that was automated and simple, yet provided confidence that the engine was ready to fire again, was developed to meet the turnaround time constraints of the Orbiter vehicle.

Automatic checkout, operational monitoring of flange leakages, and automatic propellant valve seat leakage detection have replaced the manual leak and functional techniques used on previous engine systems. Life monitoring techniques of internal inspection, maintenance instrumentation, and drain system leak checks resulted from a maintainability analysis conducted early in the design phase. Since corrective maintenance represents the largest single expenditure of resources during the SSME turnaround cycle, hardware accessibility and handling were emphasized early in the design phase. This maintenance concept results in a maintenance cycle for the three Orbiter main engines requiring an average of 25 hours of the 160-hour Orbiter turnaround.

Automatic Checkout

Programs for hardware checkout are loaded into the engine controller from the launch processing system (LPS). The engine controller programs the checkout, analyzes the data, and reports to the LPS via the vehicle engine electrical interface (VEEI) and the vehicle. Redundant components are checked individually.

Components checked automatically include the controller, all sensors, propellant valve actuators, bleed valves, solenoids, pressure-actuated valves, spark igniters, burst diaphragms, and check valves.

Flange Leakage Monitoring

It is important that the leak detection and isolation system function during hot-fire operation (flight) and retain the data for ground use. Flight environment leaks may not be reproduced when leak checking under the less-severe ground checkout conditions, since the operating environment of cryogenic temperature, high-pressure and stress levels, and vibration cannot be adequately simulated during turnaround ground checkout. Chemically treated color-change tape (Figure 12) or a leak-indicating coating (Figure 13) is applied to each separable connection and external leak point. The external leak detectors are inspected during the 100-percent external visual inspection of each engine between flights. Comparison standards developed in the engine test program are used during the inspection.

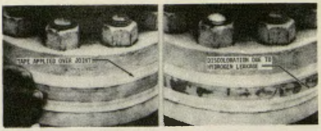

Figure 12. Hydrogen Leak-Detecting Tape

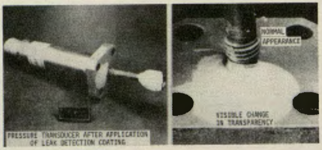

Figure 13. Leak-Indicating Coating

Propellant Valve Seat Leak Detection

Automatic downstream seat leakage detection replaces manual leak checks used on earlier rocket engines. This checkout uses ultrasonic sensors located (Figure 14) in four of the valves (main fuel, main oxidizer, and fuel and oxidizer preburner oxidizer). The characteristic sound of leakage at each valve will be established during development testing. During checkouts, vehicle systems will be pressurized and the sensor signals measured and compared with acceptable levels stored in the controller memory.

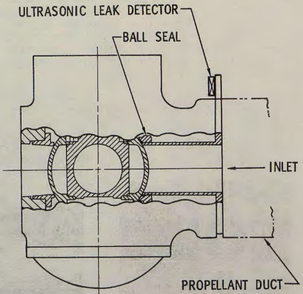

Figure 14. Ultrasonic Leak Detector Location

Life Monitoring

Engine life is monitored by internal inspection, maintenance instrumentation, and drain system leak checks.

Internal Inspection - Commercial airlines agree that internal inspection of propulsion systems is cost effective. Studies with TWA show the airlines and the Space Shuttle Program have similar requirements. For this reason, a major effort was expended to provide full internal inspection capability. This effort defined requirements, selected equipment, scheduled usage, and designed access ports.

Figure 15 shows locations that have been designated as internal inspection points in the low-pressure and high-pressure turbopumps, oxidizer dome, flowmeters, thrust chamber injector, and preburners.

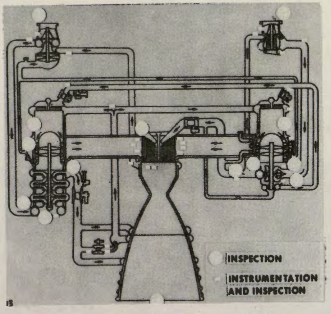

Figure 15. Internal Inspection Locations

Scheduled inspection requirements were studied and each normal engine access point and instrumentation port has been located to facilitate these inspections. In addition, all other engine access points and instrumentation ports were studied during the preliminary design period and located to provide access to potential inspection points.

The internal inspection equipment (Figure 16) consists of flexible and rigid optic borescope devices, photographic attachments (color and black and white), and closed-circuit television with videotape recording capability.

A special guide tube (Figure 17) has been devised to reduce the time required to orient and hold inspection devices once they have been inserted. These guide tubes are supplied as GSE with the engine.

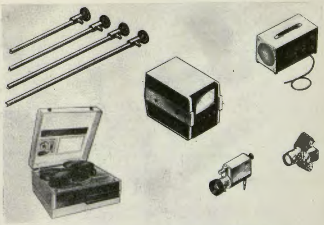

Figure 16. Internal Inspection Equipment

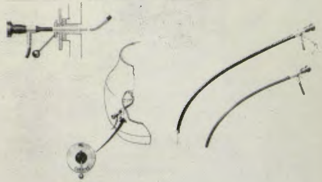

Figure 17. Borescope Guides

Figure 18 shows a typical internal inspection with the inspection equipment inserted in the preburners.

Special Data Analysis - Trend analyses of maintenance data are conducted periodically with the data obtained from internal inspection. Figure 19 shows the maintenance data recording sensors (used also for turnaround corrective maintenance determinations) that provide the data for the trend analysis.

Drain Systems Leak Checks - An analysis of internal drain systems resulted in noncritical systems drains to be ducted overboard. These systems are periodically leak checked to determine trends and assist in establishing overhaul tasks.

Fastener Load Verification - In the event loss of fastener load is suspected during engine maintenance, it can be verified by the ultrasonic extensometer (Figure 20) without backing off and retorquing the fastener. On this engine, designers will specify axial preload in lieu of torque values for critical fasteners. These preloads will be measured by an extensometer that measures bolt length change (bolt load) by ultrasonic wave travel time. It is easy to use by attaching a small sensor to the bolt head. Readout is visual.

INSPECTION

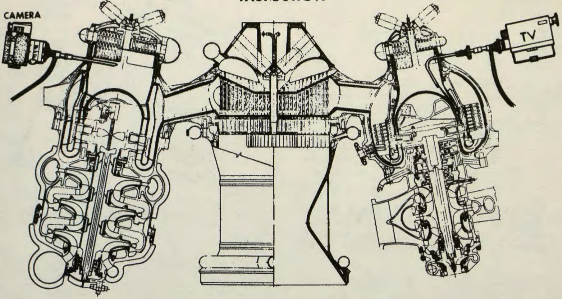

Figure 18. Preburner Internal Inspection

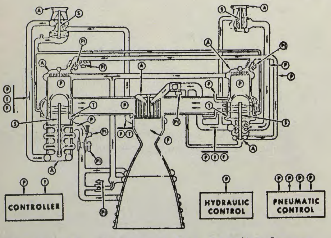

Figure 19. Maintenance Data Recording Sensors

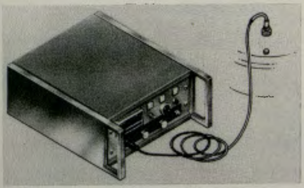

Figure 20. Fastener Load Verification Equipment

Fastener unloaded length information will be permanently retained and the information will allow load verification in the installed condition by setting the unloaded reference data for the fastener into the reader.

LRU Accessibility

Corrective maintenance represents the largest single expenditure of time and resources during the SSME turnaround cycle. It consists of on-the-vehicle repair of engines, and in a limited number of cases, engine removal. On-the-vehicle maintenance of the SSME gives lowest maintenance cost and highest reliability. Although an engine can be changed faster than some of the larger components, the engine change usually involves violating many more systems to make the repair and removes a complete system that has been functioning satisfactorily. This increases cost. To reduce cost and retain integrity, line replaceable unit (LRU) replacement is preferable and LRU's of the SSME were selected on this basis.

LRU's have GSE attach lugs and handling adapters, when required by their weight or size, and when required for easy maneuvering. Figure 21 shows a typical engine component being removed with an overhead hoist. (A component manipulator is used if engine clocking causes hardware interference.)

Figure 22 shows a propellant duct being removed with bellows support (strong back). Compared to earlier rocket engines, SSME propellant ducts carry very high pressure. Although designed for minimum weight, the ducts are rugged and therefore difficult to separate from mating hardware. To help separate the mating surfaces for corrective maintenance, duct flange spreaders (Figure 23) will be developed and attach points included in the engine design.

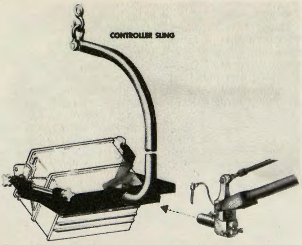

Figure 21. Component Handling Equipment

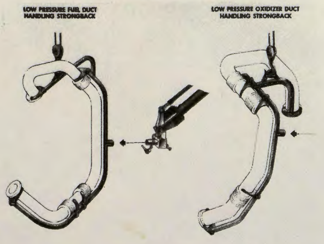

Figure 22. Propellant Duct Handling Equipment

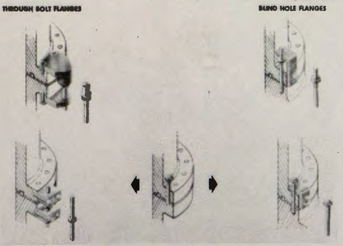

Figure 23. Duct Flange Spreaders

Maintenance Cycle

Production engines are acceptance tested at NASA's Mississippi Test Facility and delivered to Kennedy Space Center for installation in the vehicles. Following a program of integrated system tests, flight readiness tests, and verifical flight tests, the vehicles become operational. A typical operational maintenance cycle is shown in Figure 24 and described below.

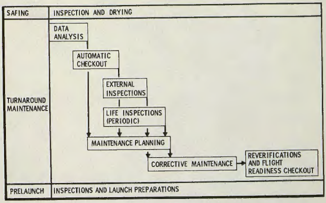

Figure 24. Maintenance Cycle

Safing Inspection - After the vehicle has cooled down from re-entry, the engine is dried and an external visual inspection conducted. The visual inspection ensures there are no gross leakages or damage that would endanger personnel in the turnaround maintenance area. Flight data plus the results of the safing inspection are sent to the vehicle Maintenance Planning function and corrective maintenance planning is initiated.

Turnaround Maintenance - During the routine maintenance period, an automatic checkout and a 100-percent external visual inspection are conducted. In addition, each engine periodically receives a life inspection. These inspections are alternately scheduled for optimum man loading. The results of routine maintenance are sent to the Maintenance Planning function where it is combined with the results of the safing inspection and flight data analysis to determine the corrective maintenance actions. Corrective maintenance is conducted on the vehicle or, in a limited number of cases, the engine is removed for maintenance or replacement.

Checkouts and leak checks are performed at the conclusion of turnaround maintenance to verify the corrective maintenance actions. A flight readiness test, performed before mating the Orbiter with the solid rocket motors and external tank, confirms all maintenance actions taken during turnaround and certifies the engines ready for the next flight.

Prelaunch Inspection and Preparations - Protective covers and closures are removed at the launch pad and the engines are visually inspected to ensure the engines are ready for launch. Controller memory verifications are conducted and the engines are ready for the launch activities.

SUMMARY-

The advent of the Space Shuttle introduced many new challenges to the rocket engine designer. A high-performance, lightweight, long-life propulsion system was needed. Moreover, a propulsion system was needed that could be maintained in an airline-type maintenance environment (i.e., low cost, fast turnaround). The SSME has successfully answered these challenges. Tried and proved technologies were used to ensure that performance, weight, and life requirements are satisfied. However, innovations in turnaround maintenance, heretofore unnecessary to space engine maintenance programs, will be used to ensure fast, reliable turnaround maintenance. Designs for automatic checkout, leak detection, and hardware accessibility will be verified during a Maintainability Demonstration Program.