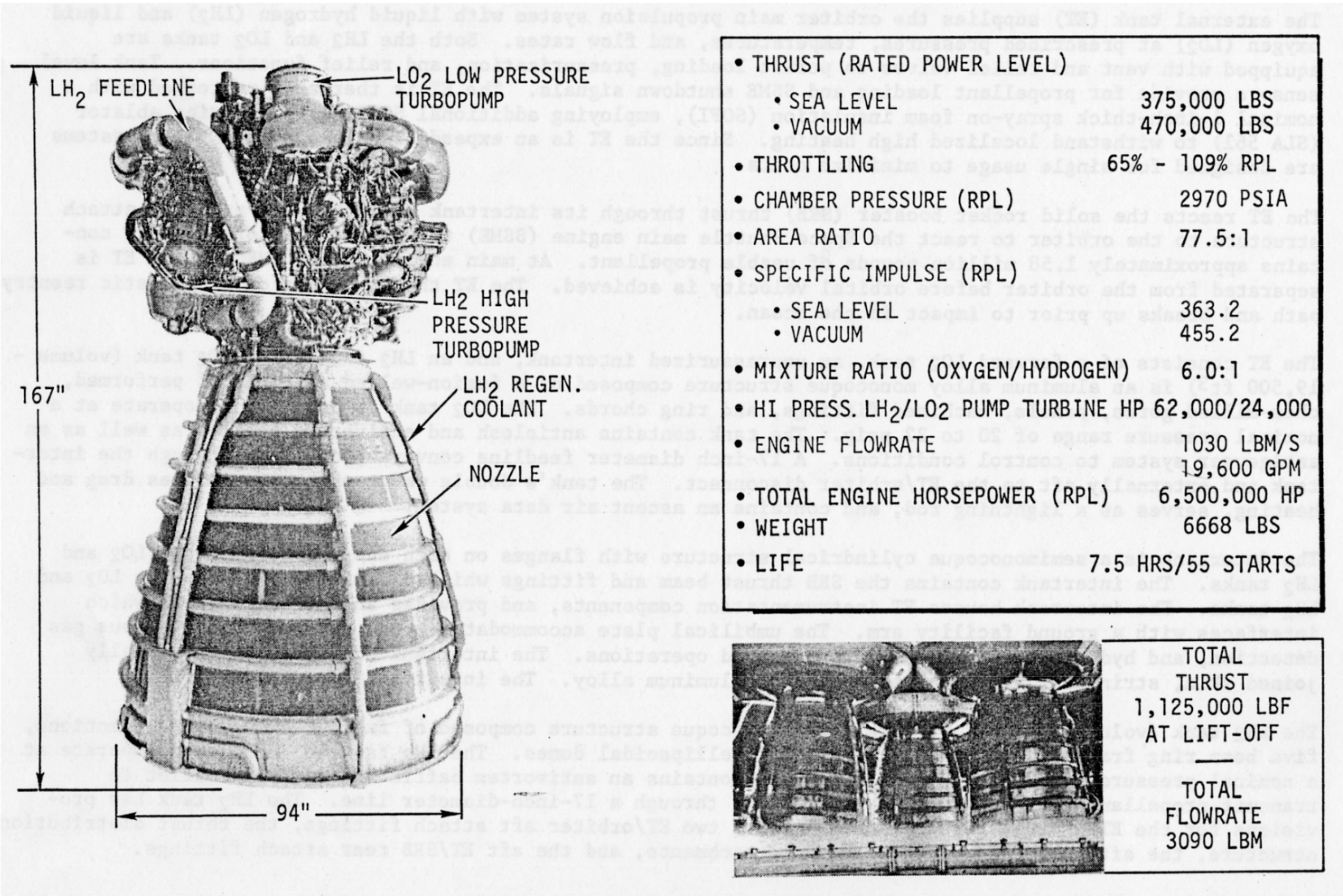
PROPULSION SYSTEM

Space Shuttle Main Engine (SSME)



PROPULSION SYSTEM

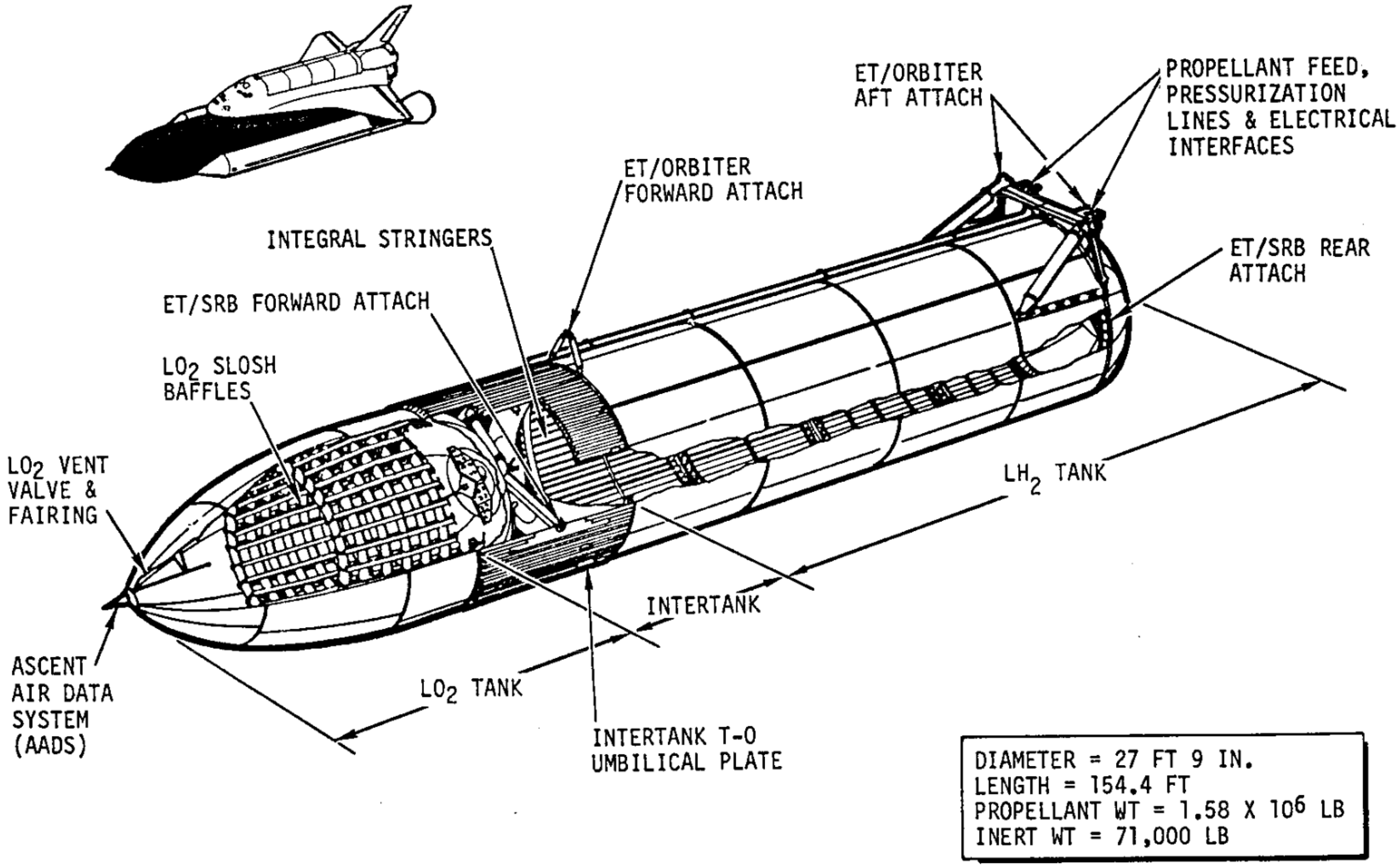
Space Shuttle Main Engine (SSME)

- Mounted in a triangular pattern in the orbiter's aft fuselage, the three Space Shuttle main engines (SSME's) produce a total sea-level thrust of 1.125 million pounds (1.41 million pounds at vacuum). Each engine is capable of producing 6.5 x 10^6 horsepower for a combined total of 19.5 x 10^6 horsepower. Liquid oxygen (L02) and liquid hydrogen (LH2), cryogenic propellants contained in the external tank, are supplied to the three engines at a total flowrate of 3090 LBM per second. Each engine operates with a fixed nozzle area ratio of 77.5:1 at a mixture ratio (L02/LH2) of 6:1 and a chamber pressure of 2970 psia, producing a rated sea-level thrust of 375,000 pounds and a vacuum thrust of 470,000 pounds. The high chamber pressure (significantly higher than previous engines) and flowrate (1030 LBM per second) for each engine is made possible by the use of the efficient staged-combustion engine cycle. This cycle allows high turbopump propellant discharge pressures (7600 psia for L02, and 6200 psia for LH2) which are necessary to overcome pressure losses within the engine and still maintain the 2970 psia chamber pressure.

- The engines can be throttled over a thrust range of 65 to 109 percent of the rated power level, to a maximum thrust of 512,000 pounds per engine. This throttling capability enables the crew to tailor engine thrust to mission needs and limit the orbiter's acceleration to 3 g's. The engines are bearing-mounted and capable of gimbaling +10.5 degrees in pitch and +8.5 degrees in yaw for orbiter steering control. The Shuttle main engine is the first to use a built-in electronic digital controller to accept commands from the orbiter for engine start, shutdown, and change in throttle setting. It will also monitor engine operation and, in case of failure, will automatically correct the problem or shut down the engine safely. Able to operate for 7.5 hours of accumulated firing time, SSME's are reusable for up to 55 missions before requiring major maintenance or overhaul.

PROPULSION SYSTEM

External Tank



PROPULSION SYSTEM

External Tank

- The external tank (ET) supplies the orbiter main propulsion system with liquid hydrogen (LH2) and liquid oxygen (L02) at prescribed pressures, temperatures, and flow rates. Both the LH2 and L02 tanks are equipped with vent and relief valves to permit loading, pressurization, and relief functions. Tank level sensors provide for propellant loading and SSME shutdown signals. The ET is thermally protected with a nominal 1-inch-thick spray-on foam insulation (SOFI), employing additional SOFI and a charring ablator (SLA 561) to withstand localized high heating. Since the ET is an expendable element, the ET subsystems are designed for single usage to minimize costs.

- The ET reacts the solid rocket booster (SRB) thrust through its intertank structure and provides attach structure to the orbiter to react the SSME thrust. At liftoff, the ET contains approximately 1.58 million pounds of usable propellant. At main engine cutoff (MECO), the ET is separated from the orbiter before orbital velocity is achieved. The ET then proceeds on a ballistic reentry path and breaks up prior to impact in the ocean.

- The ET consists of a forward L02 tank, an unpressurized intertank, and an LH2 tank. The L02 tank (volume 19,500 ft^3) is an aluminum alloy monocoque structure composed of a fusion-welded assembly of performed chem-milled gores, panels, machined fittings, and ring chords. The L02 tank is designed to operate at a nominal pressure range of 20 to 22 psig. The tank contains antislosh and antivortex baffles as well as an antigeyser system to control conditions. A 17-inch diameter feedline conveys propellant through through the inter-tank and externally aft to the ET/orbiter disconnect. The tank's double wedge nose cone reduces drag and heating, serves as a lightning rod, and contains an ascent air data system.

- The intertank is a semimonocoque cylindrical structure with flanges on each end for joining the L02 and LH2 tanks. The intertank contains the SRB thrust beam and fittings which distribute SRB loads to LO2 and LH2 tanks. The intertank houses ET instrumentation components, and provides an umbilical plate which interfaces with a ground facility arm. The umbilical plate accommodates purge gas supply, hazardous gas detection, and hydrogen gas boiloff during ground operations. The intertank consists of mechanically joined skin, stringers, and machined panels of aluminum alloy. The intertank is vented in flight.

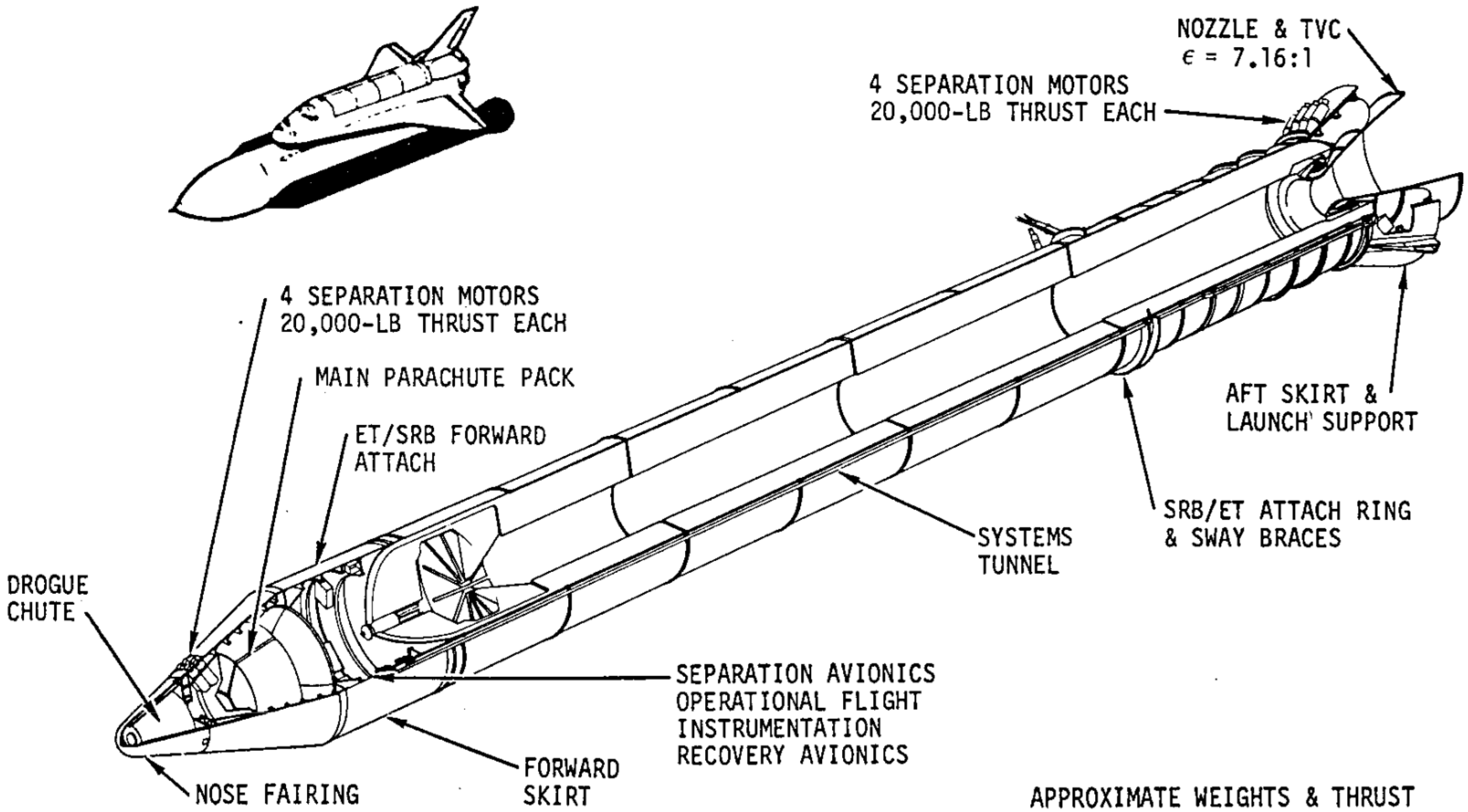
PROPULSION SYSTEM

External Tank

- The LH2 tank (volume - 55,552 ft^3) is a semimonocoque structure composed of fusion-welded barrel sections, five beam ring frames, and forward and aft 0.75 ellipsoidal domes. The LH2 tank is designed to operate at a nominal pressure of 32 to 34 psia. The tank contains an antivortex baffle and a siphon outlet to transmit propellant to the ET/orbiter disconnect through a 17-inch-diameter line. The LH2 tank has provisions for the ET/orbiter forward attach strut, two ET/orbiter aft attach fittings, the thrust distribution structure, the aft SRB/ET stabilizing strut attachments, and the aft ET/SRB rear attach fittings.

PROPULSION SYSTEM

Solid Rocket Booster



DIMENSIONS	
LENGTH . . .	1790 IN.
DIAMETER . .	146 IN.

APPROXIMATE WEIGHTS & THRUST

GROSS WEIGHT . . .	1,293,500 LB
INERT WT	184,600 LB
THRUST (SL)	2.65M̄ LB

PROPULSION SYSTEM

Solid Rocket Booster

- Two solid rocket boosters (SRB's) burn in parallel with the orbiter main propulsion system (MPS) to provide initial ascent thrust. Primary elements of the booster are the motor, including case, propellant, igniter, and nozzle; structural systems; separation, operational flight instrumentation (OFI), and recovery avionics; separation motors and pyrotechnics; and deceleration system, range safety destruct system, and thrust vector control (TVC) subsystems. Each SRB weighs approximately 1.293 million pounds and produces 2.65 million pounds of thrust at sea level. The propellant grain is shaped to reduce thrust approximately one-third at 55 seconds after liftoff to prevent overstressing the vehicle during the period of maximum dynamic pressure. The grain is of conventional design, employing a star perforation in the forward motor closure and a double truncated cone perforation in each of the segments and aft closure. The contoured nozzle expansion ratio (area of exit to area of throat) is 7.16. The SRB TVC, which is a closed-loop hydraulic system with power provided by redundant APU's and hydraulic pumps, has an omni-axial gimbal capability of 7.1 degrees which, in conjunction with the orbiter main engines, provides the flight control during the Shuttle boost phase.

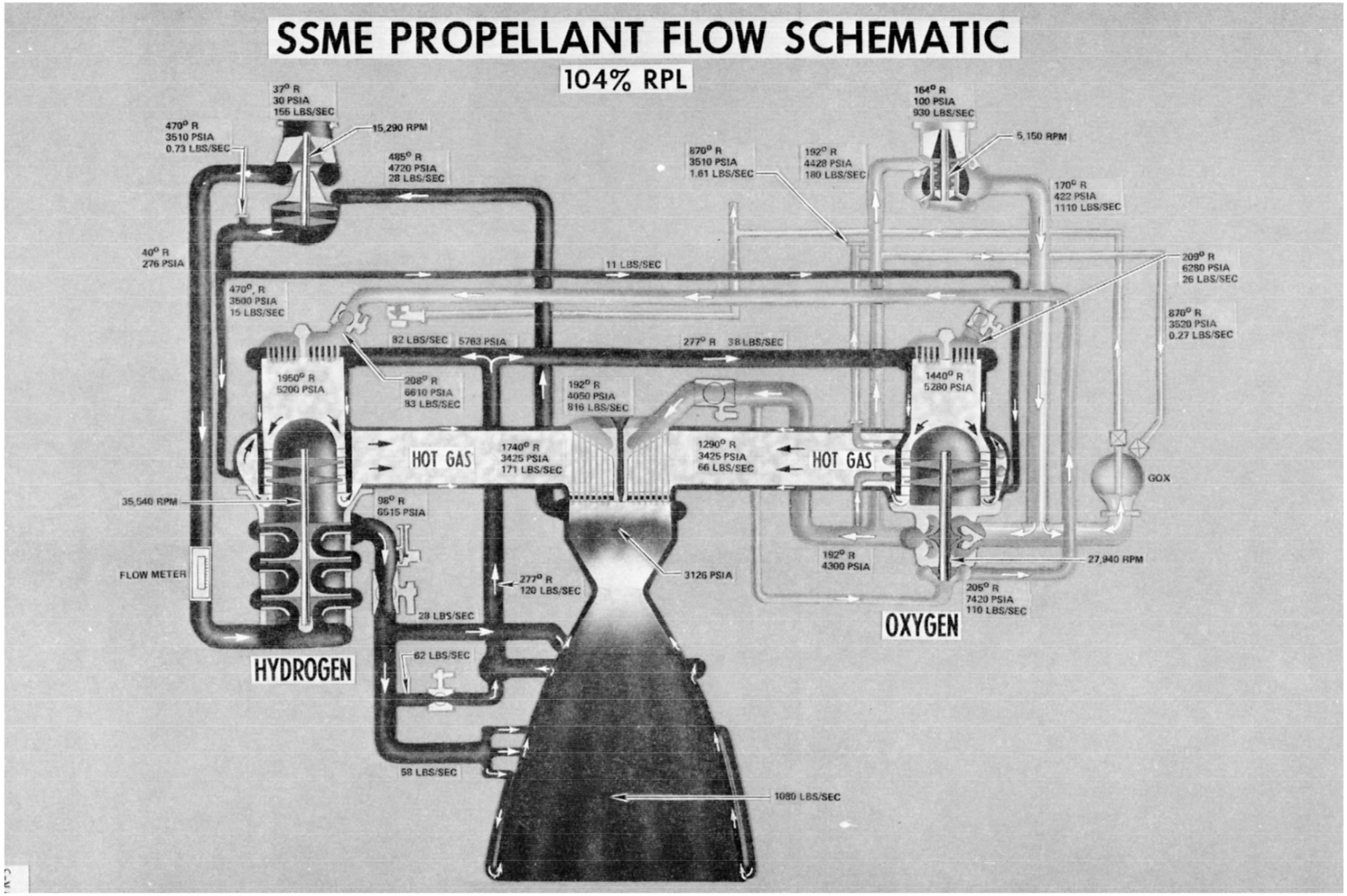
- A segmented case design affords maximum flexibility in fabrication and ease of transportation and handling. A cone-shaped skirt at the aft end of each of the SRB's carries the aft loads between the SRB and the mobile launch pad (MLP). Two lateral sway braces and a diagonal attachment at the aft frame provide the structural attachment between the SRB and external tank. The SRB forward attachment to the external tank is by a single thrust attachment at the forward end of the forward skirt. The same forward skirt is used for attaching the main parachute riser attachments.

- The SRB's are released from the ET by pyrotechnic separation devices at the forward thrust attachment and the aft sway braces. Eight separation motors on each SRB, four aft and four forward, separate the SRB from the orbiter and external tank.

- The SRB forward section provides installation volume for the SRB electronics, recovery gear, range safety destruct system, and forward separation rockets. It also houses the parachute deceleration subsystem which consists of a pilot parachute, a ribbon drogue parachute, and three ribbon main parachutes.

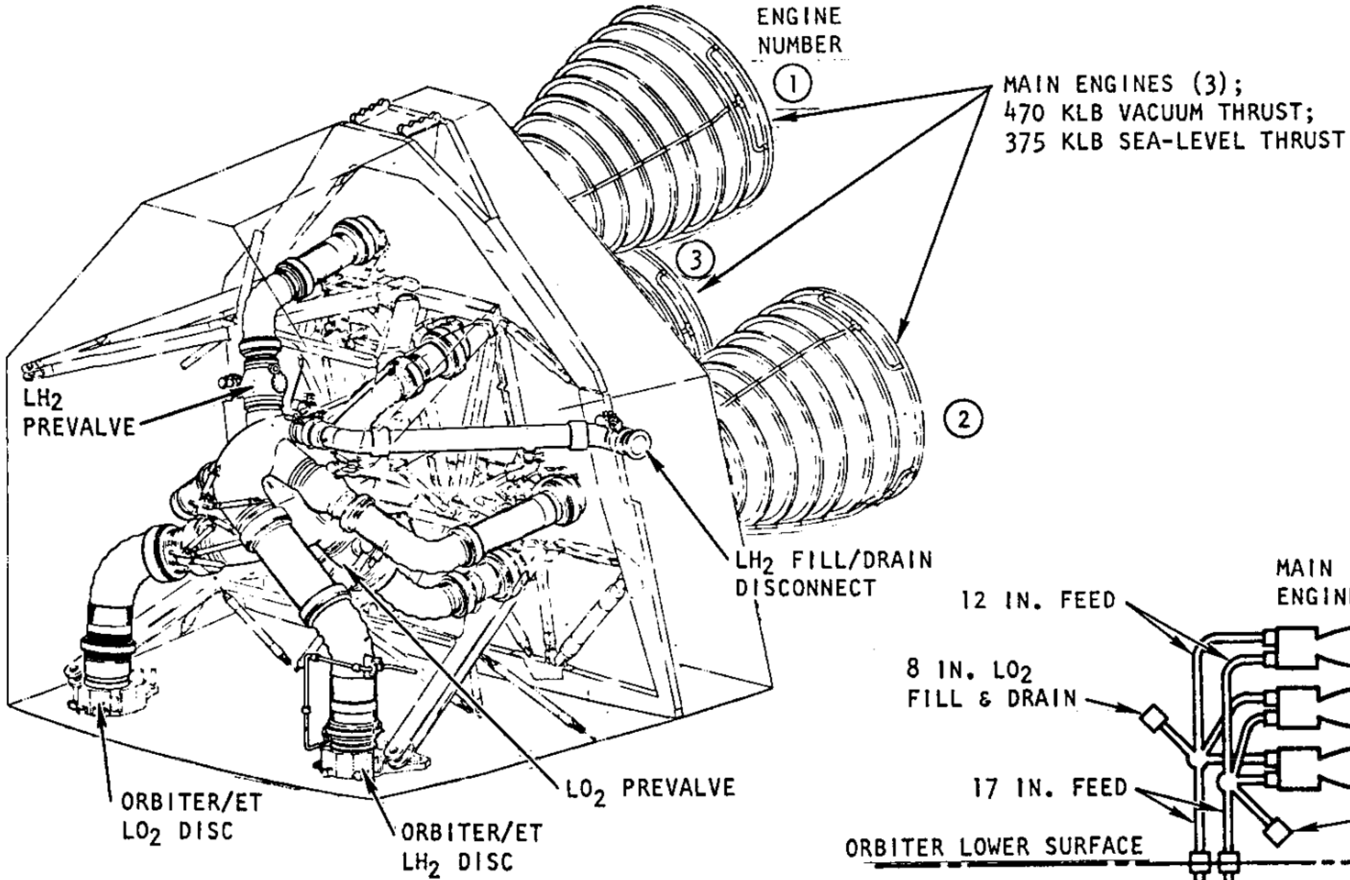
PROPULSION SYSTEM

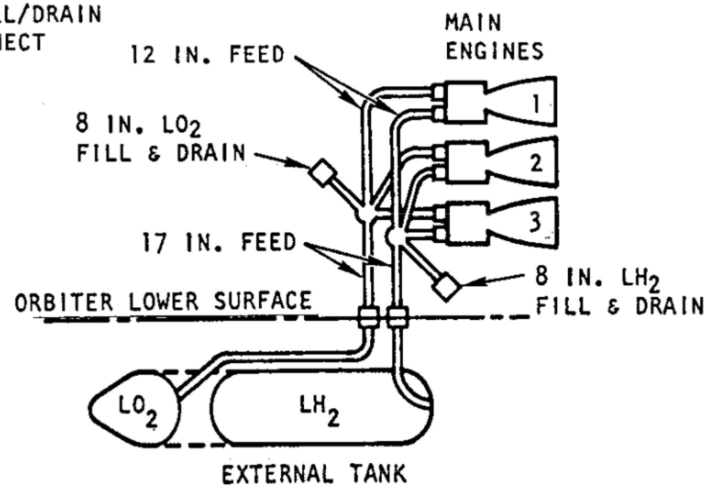
Main Propulsion Subsystem



PROPULSION SYSTEM

Main Propulsion Subsystem





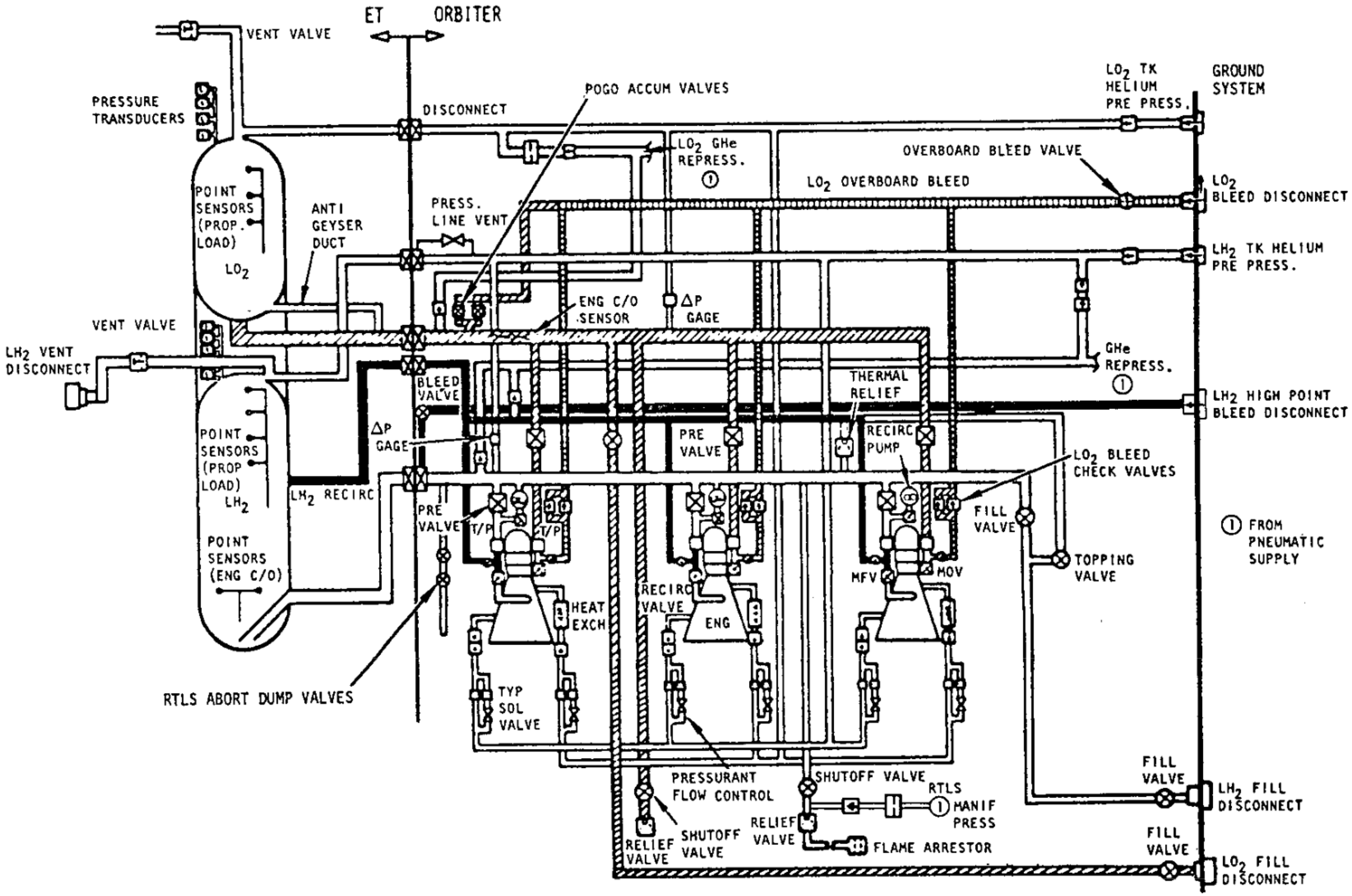
PROPULSION SYSTEM

Main Propulsion Subsystem

- The Space Shuttle main propulsion subsystem (MRS) is shown and consists of the Space Shuttle main engines (SSME's), external tank (ET), propellant feed, management, fill and drain, conditioning, pressurization control, pneumatic supply, and purge. These subsystems are further illustrated in a subsequent schematic diagram of the MPS.
- Each of the three SSME's operates with a fixed nozzle area ratio of 77.5:1 at a mixture ratio (L02/ LH2) of 6:1 by weight and a chamber pressure of 3000 psia to produce a rated sea-level thrust of 375,000 pounds and a vacuum thrust of 470.000 pounds. The engines can be throttled over a thrust range of 65 to 109 percent of the rated thrust level. This allows orbiter acceleration to be limited to 3 g's. The engines are capable of being gimbaled ±10.5 degrees in pitch and ±8.5 degrees in yaw for flight control during the orbiter boost phase.
- The 1,550,000 pounds of usable ascent propellants required for SSME operation are provided from the external tank. The ET is expended after main engine cutoff (MECO) but prior to achieving orbit. The ET impacts in the ocean after separating from the orbiter and is not reusable. Five MPS fluid lines interface with the ET through disconnects located at the bottom of the orbiter aft fuselage. The three hydrogen disconnects are mounted on a carrier plate on the left side of the orbiter (facing forward), and the two oxygen disconnects are mounted on the right side. Ground servicing of the MPS is accomplished through umbilicals on both sides of the aft fuselage (hydrogen is serviced from the left side facing forward, oxygen from the right side).
- The orbiter MPS engines burn for approximately eight minutes, from just prior to liftoff until MECO For the first two minutes, the MPS engines operate in parallel with the solid rocket booster (SRB) motors. The MPS and SKB provide the velocity increment necessary to almost achieve the initial mission orbit. The final small velocity increment to achieve the desired orbit is provided by the orbit maneuvering subsystem.

PROPULSION SYSTEM

Main Propulsion Subsystem Schematic



PROPULSION SYSTEM

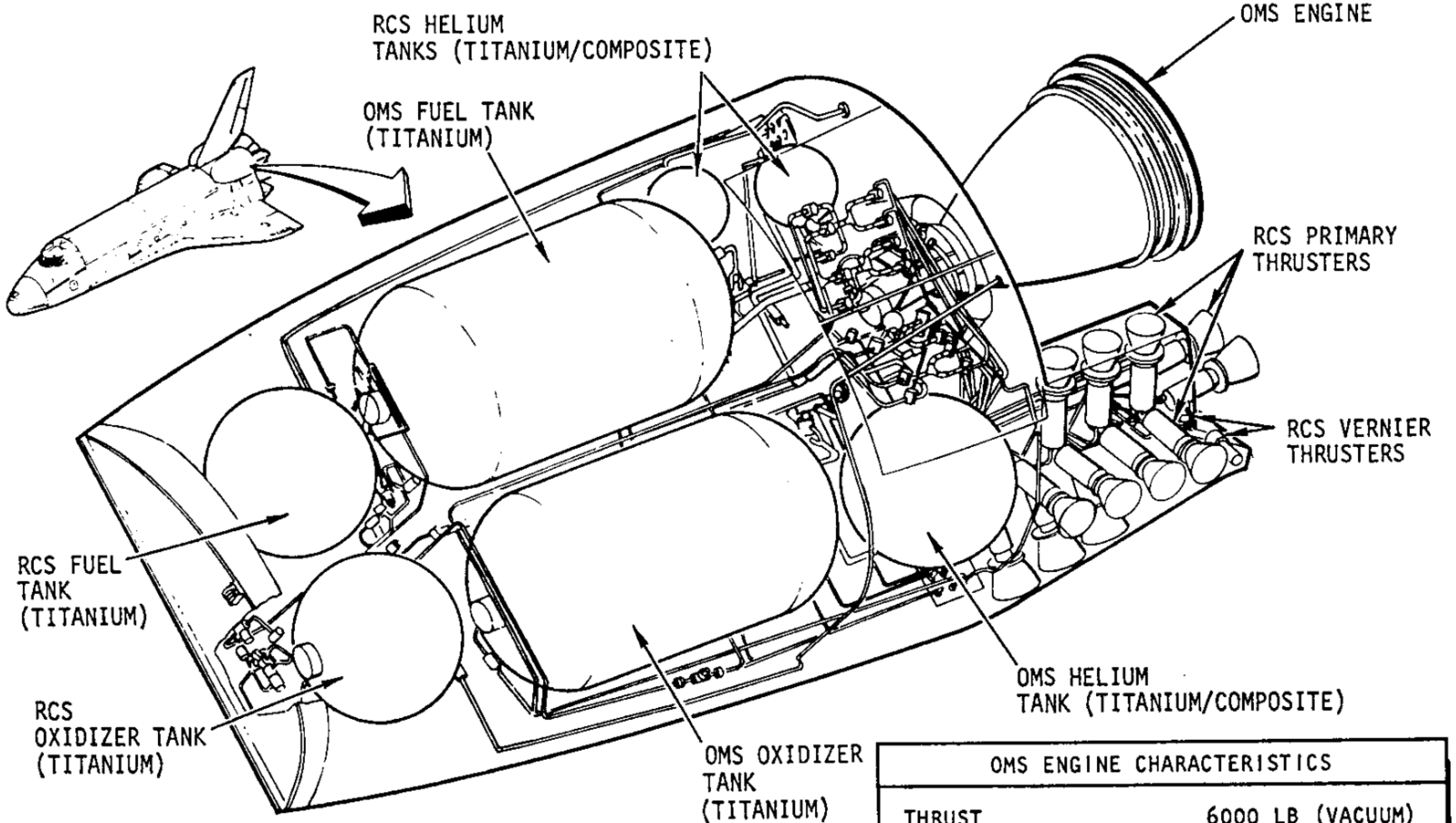
Main Propulsion Subsystem Schematic

- The MPS consists of the following subsystems: propellant feed, propellant fill and drain, propellant conditioning, pressurization control, gaseous helium (GHe) pneumatic supply, gaseous nitrogen(GN2) purge, propellant management, main engines, and external tank. The schematic does not show the pneumatic supply or GN2 purge.

- The propellant feed supplies propellants (LH2 and L02) to the main engines from the ET The propellant fill and drain provide propellants to the ET during loading and propellant drain capability on the ground. The propellant conditioning system provides conditioned propellants to the SSME's for engine start. The pressurization control maintains the proper pressures in the ET. Tank prepressurization with ground-supplied GHe plus hydrostatic head provides the required pressure to the engine pump inlets for the starting transient. Following engine thrust build up, tank pressure is maintained with vaporized propellants extracted from the engines. The ET ullage pressures during boost operation will be maintained at 20 to 22 psig in the L02 tank and 32 to 34 psia in the LH2 tank. Pneumatics are supplied by a 4000-psi helium storage system with 750-psi regulation for valve actuation, SSME purge and backup SSME shutdown. Expulsion of residual propellants after main engine cutoff (MECO) and repressurization of MPS lines for reentry are provided by a 20-psi helium regulated supply. The GN2 purge provides an inerting purge to the SSME's prior to start. The propellant management controls propellant loading and a low-level cutoff which is a backup to the normal velocity cutoff. The three SSME's ignite, burn, and expend the propellants at a mixture ratio of 6:1 (oxidizer/fuel) to provide a vacuum thrust of 470,000 pounds each at normal power level. The ET provides the 1,550,000 pounds of usable ascent propellants required to provide the velocity increment which must be supplied by the MPS.

PROPULSION SYSTEM

Orbital Maneuver Subsystem



OMS ENGINE CHARACTERISTICS	
THRUST	6000 LB (VACUUM)
SPECIFIC IMPULSE	313.2 SEC
CHAMBER PRESSURE	125 PSIA
MIXTURE RATIO	1.65
GIMBAL CAPABILITY	±6° PITCH ±7° YAW

OMS ΔV CAPABILITY	1000 FT/SEC (65,000 LB PAYLOAD)
USEABLE OMS PROPELLANT:	23,876 LB TOTAL: 14,866 LB N_2O_4 9010 LB MMH

PROPULSION SYSTEM

Orbital Maneuver Subsystem

- The orbital maneuver subsystem (OMS) provides the thrust to perform orbit insertion, orbit circularization, orbit transfer, rendezvous, and deorbit. The integral OMS tankage is sized to provide propellant capacity for a delta-V of 1000 feet per second when the vehicle carries a payload of 65,000 pounds. A portion of this delta-V is used during ascent. This propellant quantity (23,876 pounds of usable propellant, plus 1280 pounds of residuals and other allowances) is provided in two pods, one located on each side of the aft fuselage. Each pod contains a high-pressure helium storage bottle, tank pressurization regulators and controls, a fuel tank, oxidizer tanks, and a pressure-fed, regeneratively cooled rocket engine. Each engine produces a vacuum thrust of 6000 pounds, at a chamber pressure of 125 psia, and specific impulse of 313.2 seconds, utilizing nitrogen tetroxide (N204) as the oxidizer and monomethylhydrazine (MMH) as fuel, at an oxidizer/fuel mixture ratio of 1.65:1. Nozzle expansion area ratio is 55:1.
- The OMS and RCS propellant lines are interconnected (1) to supply propellant from the OMS tanks to the RCS thrusters on orbit and (2) to provide crossfeed between the left and right OMS and RCS systems. In addition, propellant lines from optional auxiliary OMS tanks located in the orbiter cargo bay interconnect with the OMS propellant lines in each pod. Propellant and pressure tank features are presented in the table below:

OMS TANK FEATURES

Item	Dia (in.)	Length (in.)	Vol (ft^3)	Pressure (PSI)
OMS Fuel & Oxidizer Tank	49.1	94.3	90.0	313
OMS Helium Tank	40.2	–	17.4	4875

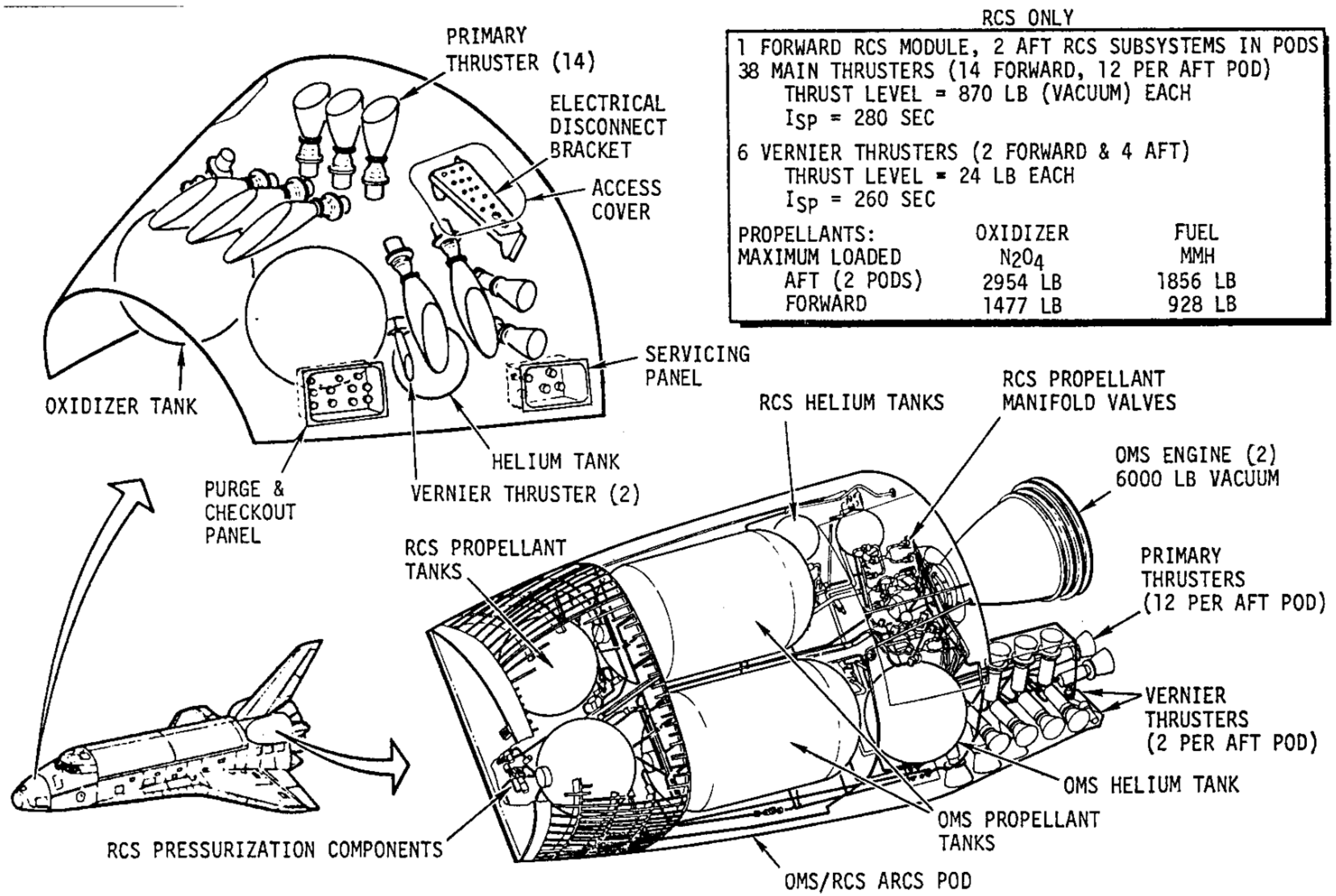
PROPULSION SYSTEM

Orbital Maneuver Subsystem Schematics

- The orbital maneuver subsystem (OMS) is housed in two independent pods located one on each side of the aft fuselage. The pods, which also house the aft reaction control subsystem, are referred to as the OMS/RCS pods. The propellant quantity required for the OMS design mission is contained in these pods; the propellants are nitrogen tetroxide (N204) as the oxidizer and monomethylhydrazine (MMH) as the fuel.
- The OMS system in each pod consists of a high-pressure (4800 psia at 100 degrees F) helium storage bottle, tank pressurization regulators and controls, a fuel tank, an oxidizer tank, a propellant distribution system, and a pressure-fed, gimbaled rocket engine. Both pods of this system and the payload bay kit (PBK) are shown schematically on the facing page.
- The 6000-pound-thrust rocket engines can be utilized singly (by directing the thrust vector through the vehicle c.g.) or together (by directing the thrust vector of each engine parallel to the other). A pod crossfeed line provides the capability of utilizing the propellant in both pods for operation of either engine. An interconnect between the OMS crossfeed line and the aft RCS manifolds also provides RCS crossfeed capability. In addition, the interconnect allows 1000 pounds per pod of OMS propellant to be used by the RCS thrusters for on-orbit maneuvers.
- The pods are removable and can be transported to a facility separated from the launch site for repair. Overall, the OMS is a flexible subsystem with each (port and starboard) system designed to be fail safe.

PROPULSION SYSTEM

Reaction Control Subsystem (RCS)



RCS ONLY

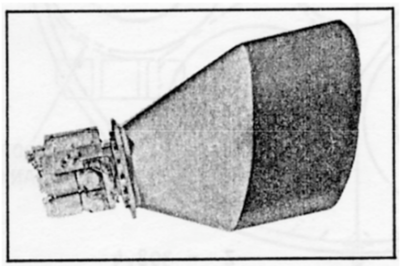
1 FORWARD RCS MODULE, 2 AFT RCS SUBSYSTEMS IN PODS
38 MAIN THRUSTERS (14 FORWARD, 12 PER AFT POD)
THRUST LEVEL = 870 LB (VACUUM) EACH
I_{SP} = 280 SEC
6 VERNIER THRUSTERS (2 FORWARD & 4 AFT)
THRUST LEVEL = 24 LB EACH
I_{SP} = 260 SEC

PROPELLANTS:	OXIDIZER	FUEL
MAXIMUM LOADED	N_2O_4	MMH
AFT (2 PODS)	2954 LB	1856 LB
FORWARD	1477 LB	928 LB

PROPULSION SYSTEM

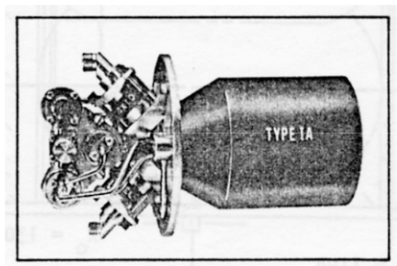
Reaction Control Subsystem (RCS)

- The reaction control subsystem (RCS) employs 38 bipropellant primary thrusters and 6 vernier thrusters to provide attitude control and three-axis translation during the orbit insertion, on-orbit, and entry phases of flight.
- The RCS consists of three propulsion units, one in the forward module and one in each of the aft propulsion pods. All modules are used for external tank separation, orbit insertion, and orbital maneuvers. Only the aft RCS modules are used for entry attitude control.
- The RCS propellants are nitrogen tetroxide (N204) and monomethylhydrazine (MMH). The design mixture ratio of 1:6 (oxidizer weight to fuel weight) was set to permit the use of identical propellant tanks for both fuel and oxidizer. The propellant tank internal configuration varies from forward module to aft pod due to the variation of operational requirements; i.e., aft RCS must operate during entry while the forward RCS is inactive during this period. The propellant capacity of the tanks in each module is 928 pounds of MMH and 1477 pounds of N204. An interconnect between the OMS and the RCS in the aft pods permits the use of OMS propellant by the RCS for on-orbit maneuvers. In addition, the interconnect can be used for cross feeding propellants between the right- and left-hand RCS pods.



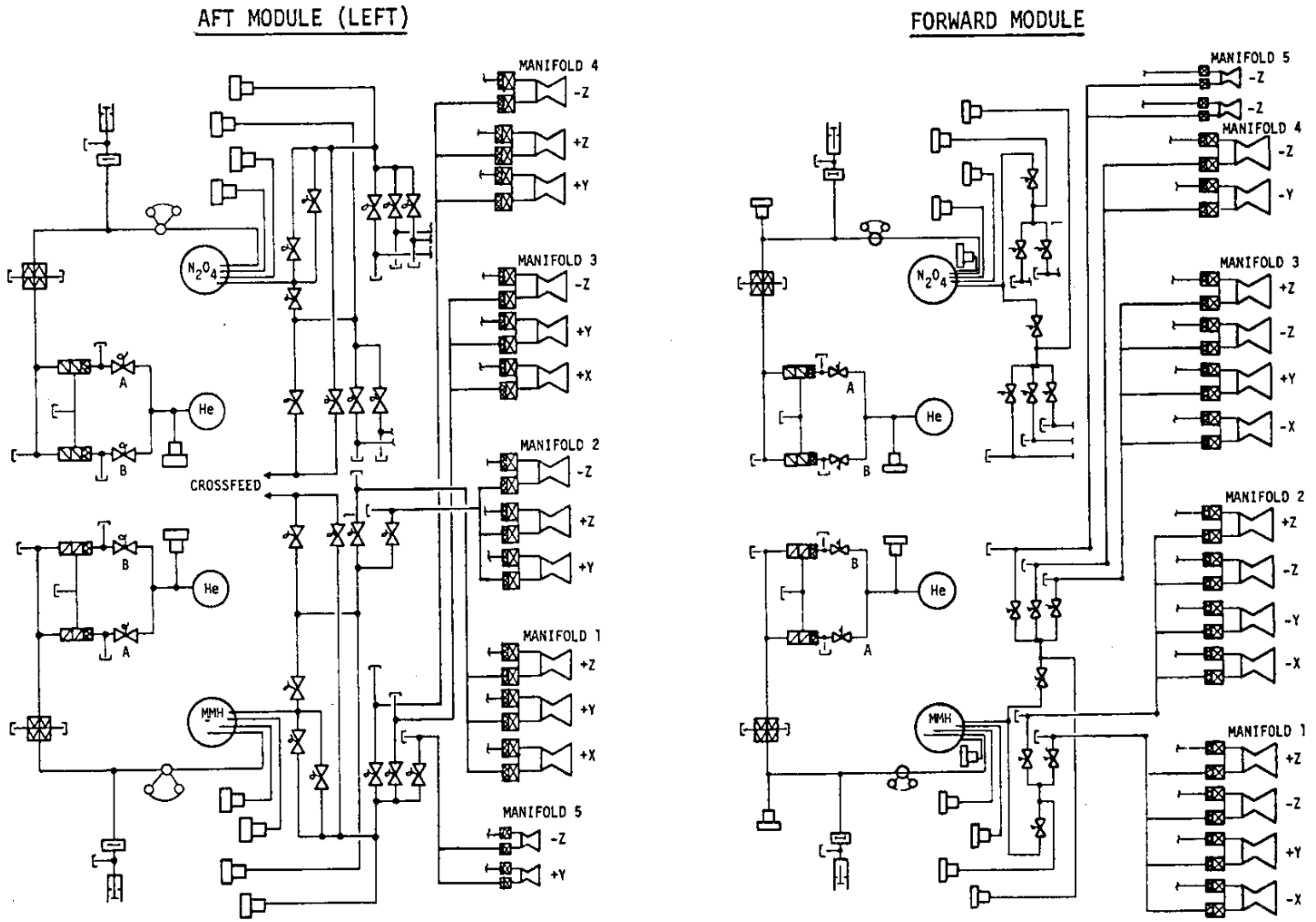
Performance

	Primary	Vernier
Thrust	870 lb	24 lb
MR	116	116
Life	50,000 starts	500,000 starts
	20,000 sec	125,000 sec



PROPULSION SYSTEM

RCS Schematics



PROPULSION SYSTEM

RCS Schematics

- *RCS - Aft Module*

  Each aft RCS module contains 12 primary thrusters and two vernier thrusters. Propulsive thrust is generated by pressure-fed, hypergolic fueled rocket engines. The aft right and left hand RCS propellant systems are interconnected to the orbiter maneuvering systems (OMS) propellant systems, in each pod, thus allowing the RCS thrusters to operate from the OMS propellant tanks or opposite RCS tanks. Each RCS unit contains a propellant storage and distribution system; a helium pressurant gas storage, regulation, and distribution system to pressurize the propellant tanks; multiple thrusters; a thermal control system; and electrical and flight instrumentation systems. Sensing devices are used throughout the RCS modules to provide subsystem operating performance inputs to controls and displays monitored by the crew.

- *RCS - Forward Module*

  The forward RCS module is a removable unit containing 14 primary and two vernier thrusters. High-pressure helium is used to pressurize propellants and tanks through redundant dual pressure regulators and check valves.

  A pressure relief system is provided to accommodate a dual regulator failure or pressure rise due to unforeseen thermal excursions.

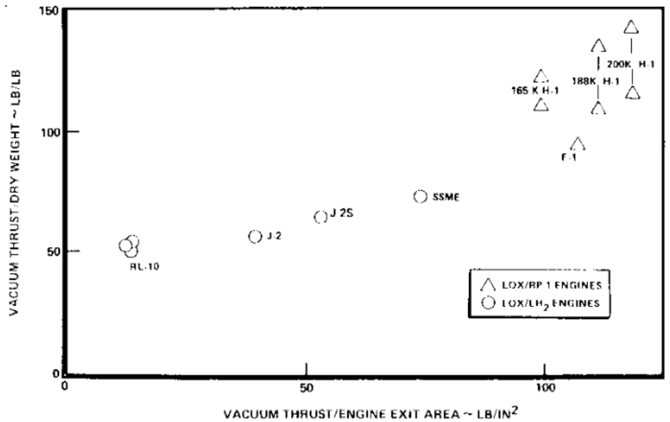
  Propellant storage tanks containing a zero-g propellant acquisition system and an entry sump provide propellant feed-out capability over the orbiter operational g levels and attitudes. Propellant distribution manifolds are independently controlled by tank and manifold isolation valves, providing propellant management capability and system redundancy.

  Common components are used, wherever possible, throughout the forward and aft RCS.

SPACE SHUTTLE MAIN ENGINE

Technology Evolution

ENGINE SYSTEM WEIGHT



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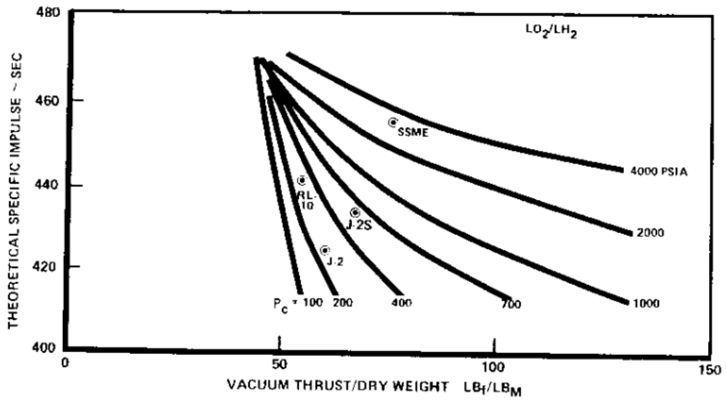
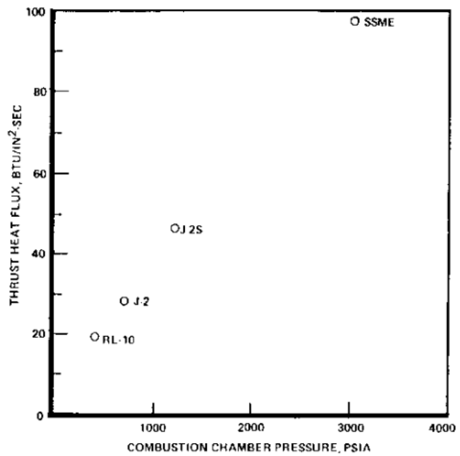
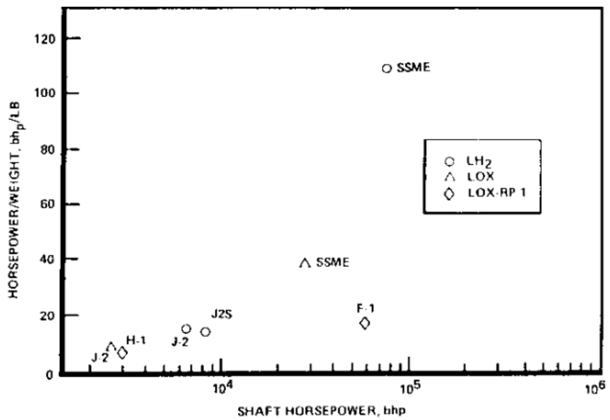
LH2/LO2 ROCKET ENGINE PERFORMANCE CHARACTERISTICS



COMBUSTION CHAMBER HEAT FLUX



TURBOPUMP POWER/WEIGHT EXPERIENCE



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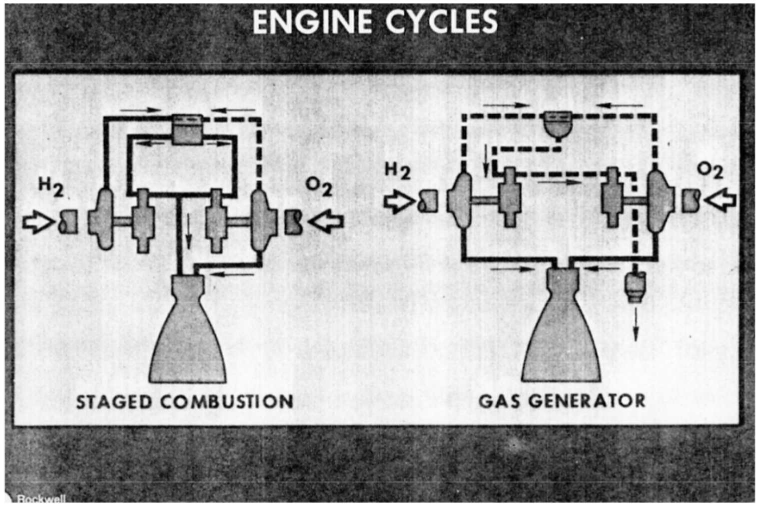
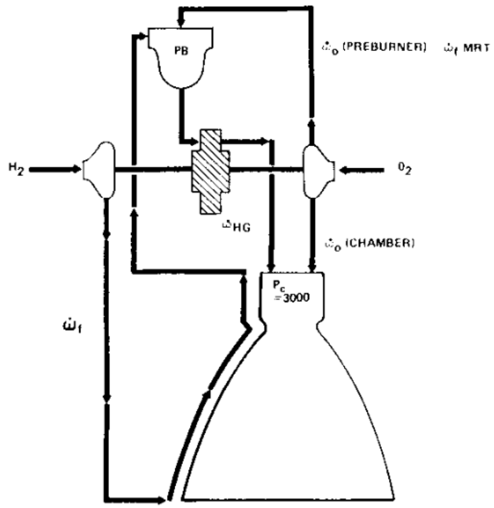
SPACE SHUTTLE MAIN ENGINE

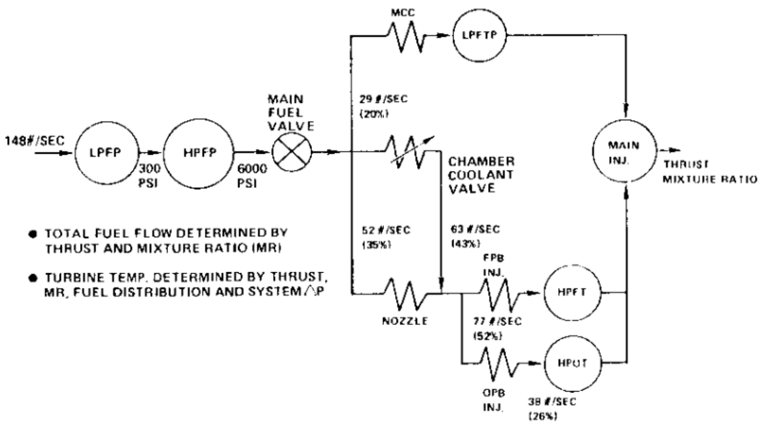
SSME Propellant Cycle

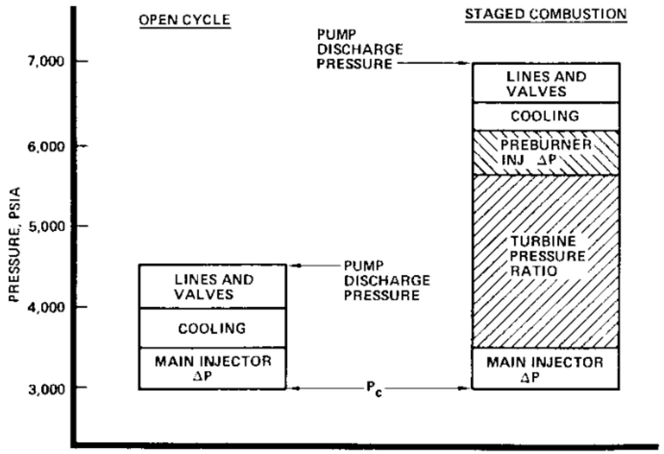




$$\eta_t \dot{m}_t c_{pt} T_{t1} \left[1 - \left(\frac{p_{t2}}{p_{t1}} \right)^{(\gamma-1)/\gamma} \right] = \frac{\dot{V}_F p_{F2}}{\eta_{pF}} + \frac{\dot{V}_O p_{O2}}{\eta_{pO}}$$

SSME FUEL SYSTEM FLOW SCHEMATIC





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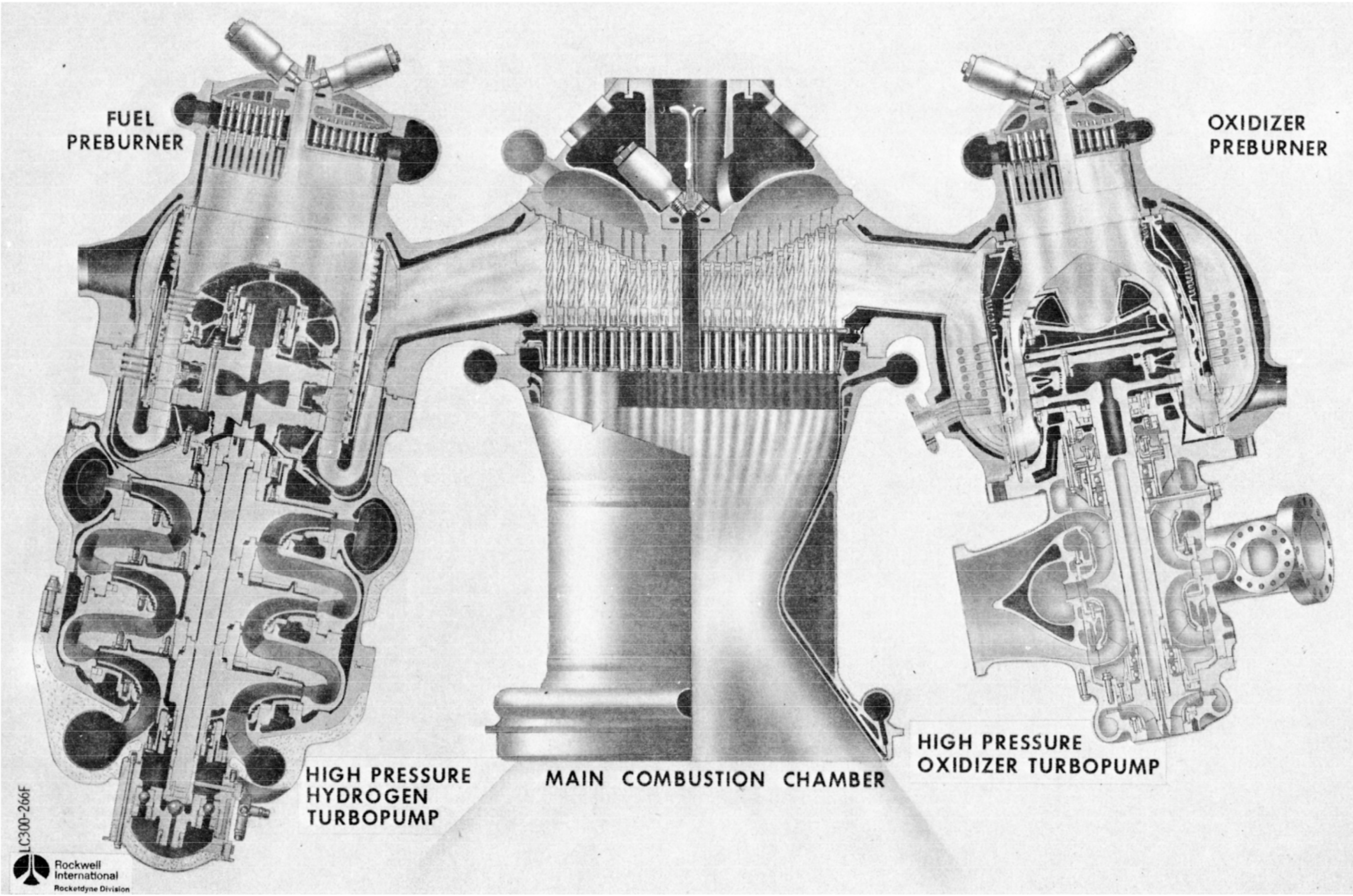
SSME COMBUSTION DEVICES

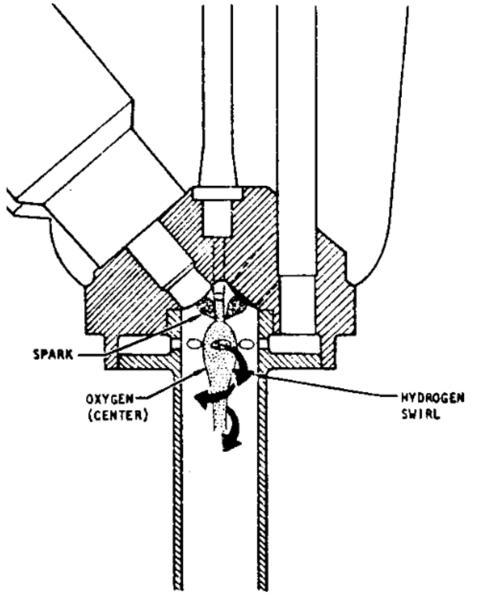
Powerhead Component Arrangement

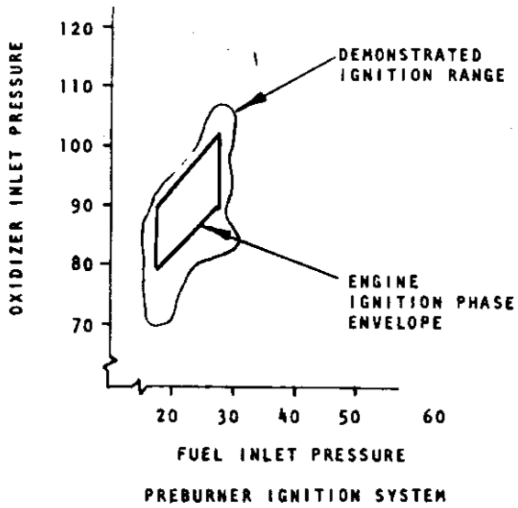


SSME AUGMENTED SPARK IGNITERS

Design Requirements and Solutions

- Reliable ignition over engine start box:
  - adaptation of proven Saturn igniter concept
- Compatibility with other system components:
  - use of LOX/H2 with a non-residue ignition source
- Adequate ignition energy for preburners and main combustion chamber:
  - flow rate/mixture ratio control
- Service life: 60 starts / 7.5 hours:
  - high thermal conductivity injector body
  - film cooled combustor wall





Development Problems and Solutions

- Ignition delay caused by warm oxygen:
  - addition of by-pass system to increase effective oxygen flow
- Hot core plume impingement on turbine dome:
  - addition of secondary hydrogen diluent downstream of ignition zone

SSME PREBURNERS

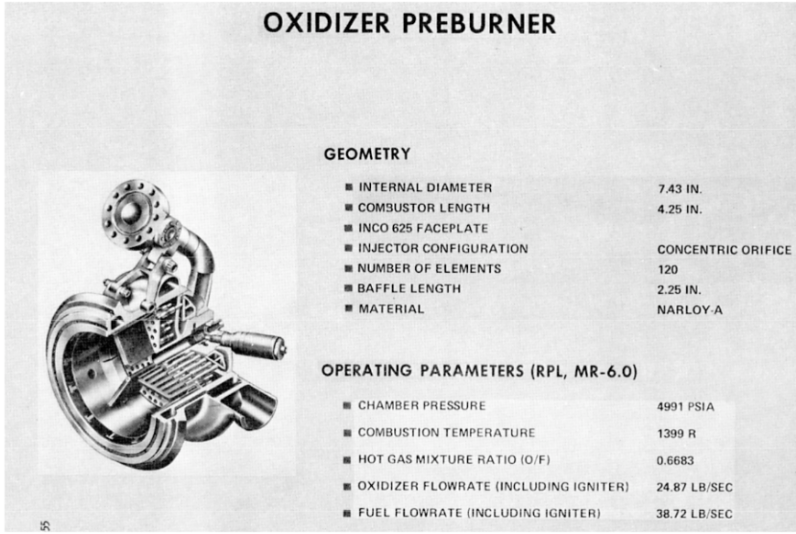
Design Requirements and Solutions

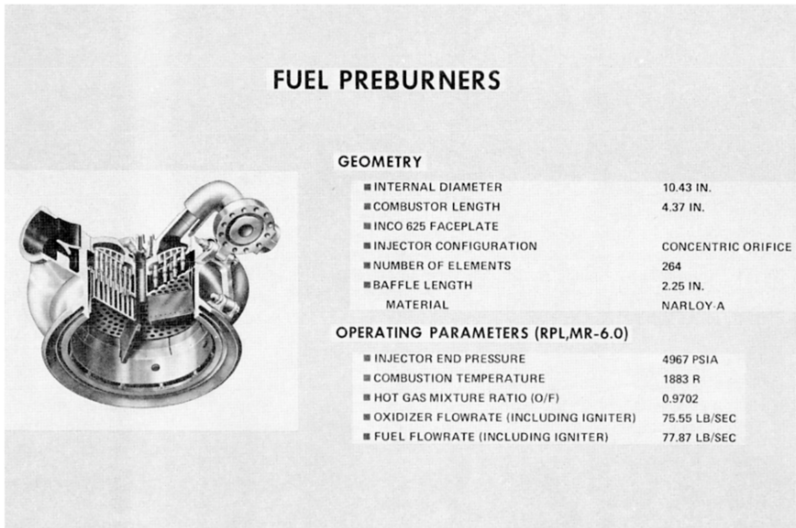
- Uniform hot gas temperature distribution:
  - uniformly spaced co-axial injectors
  - tapered manifold
- Continuously throttleable operation (3:1):
  - manifold volume control
  - co-axial injectors
- Stable combustion:
  - trivane baffles
  - co-axial injectors
- Service life: 60 starts/7.5 hours:
  - control of thermal strains:

    Narloy baffles

    combustion wall coolant liners

    free expansion faceplate

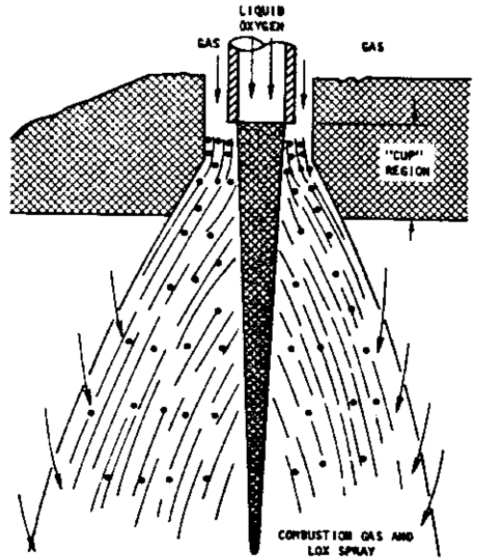


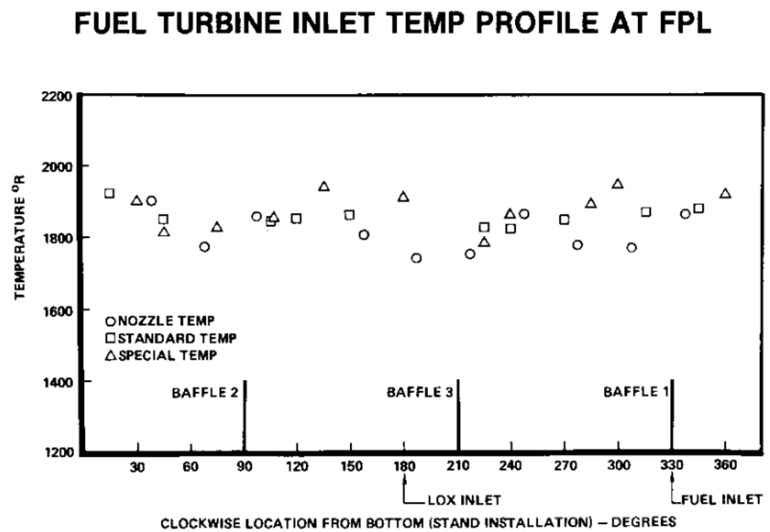


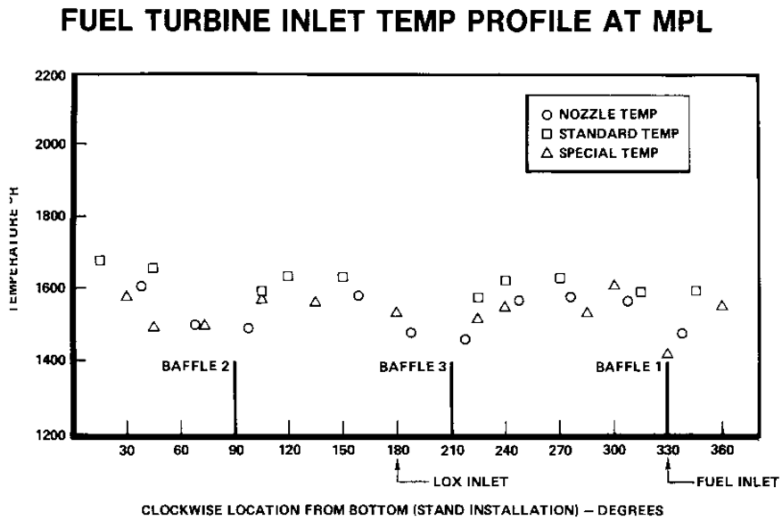
SSME PREBURNERS

Co-axial Injector Configuration

- Favorable design features:
  - high differential gas-liquid velocities
  - recess cups
  - thin LOX post trailing edge
  - uniform element spacing







98-922

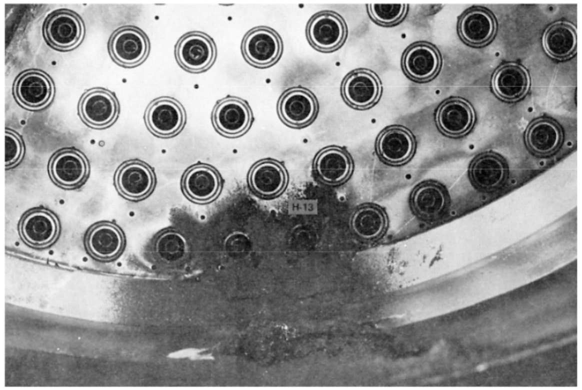
SSME PREBURNERS

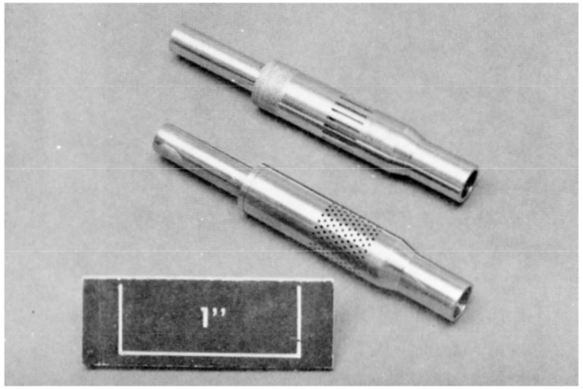
Development Problems

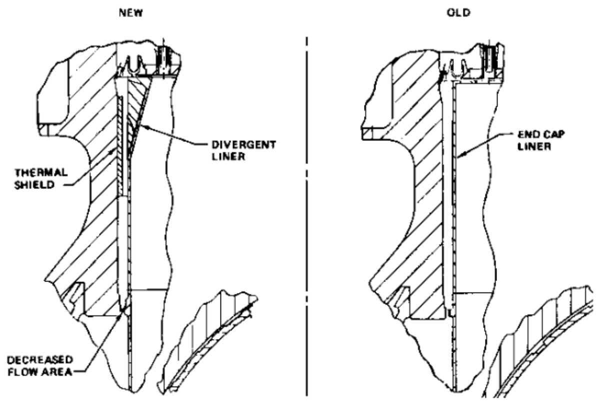
- Fuel preburner combustor wall burnout:
  - element fuel annulus blockage:
    - tip nibbling during start/shutdown transients
    - contamination
  - liner and body burn-through during main stage
    - local high mixture ratio
    - hot gas flow into coolant passage behind liner

Solution:

- multi-holed fuel sleeve filter
  - precludes contamination from fuel system
- divergent ring liner
  - reduced recirculation potential
  - increased thermal capacity
- increased liner coolant Δp:
  - reduces potential of hot gas flow behind liner
- thermal shield (Moly with disilicide coating)
  - increased thermal capacity







SSME PREBURNERS

Development Problems

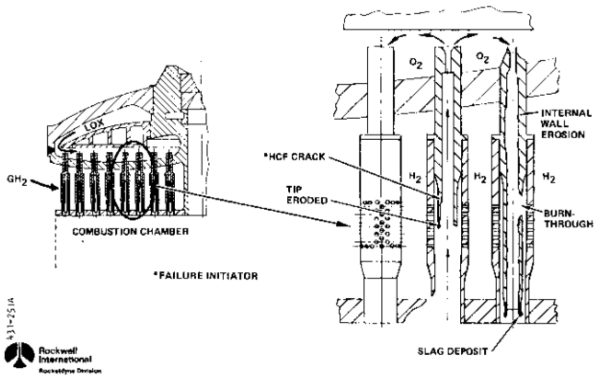
- Injection element tip fatigue:
  - mechanical vibration load source:
    - below endurance limit
    - only one element tip of 260 cracked
    - fatigue required additional load source
  - flow excitation:
    - low response with radial feed holes
    - excitation increased with offset feed holes
  - combined loads exceed material endurance limit

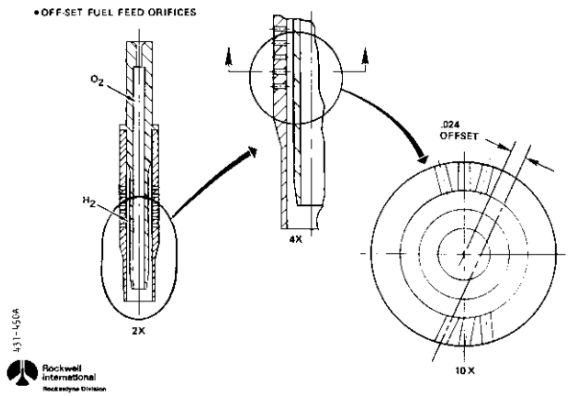
Constraints:

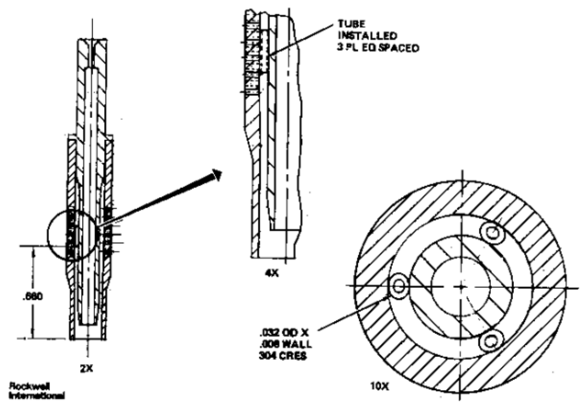
- reworkable solution (elements not replaceable)
- small dimensions
- compatible with injector operation

Solution:

- support the cantilever tip as far downstream as possible



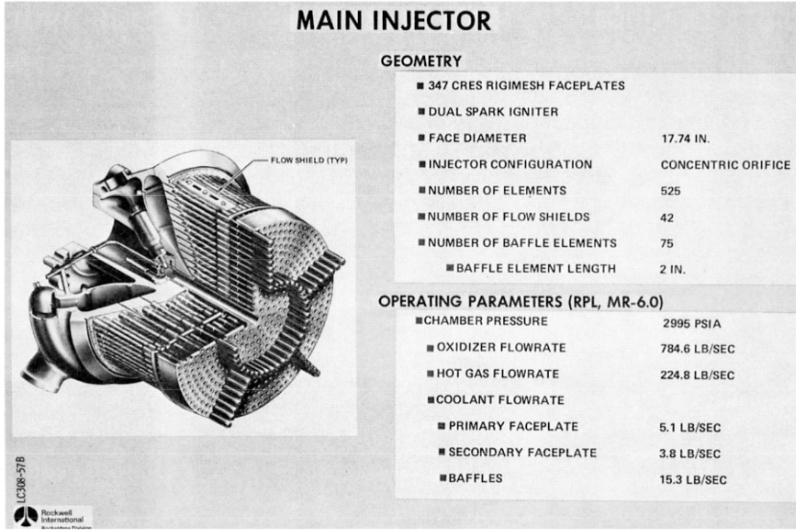


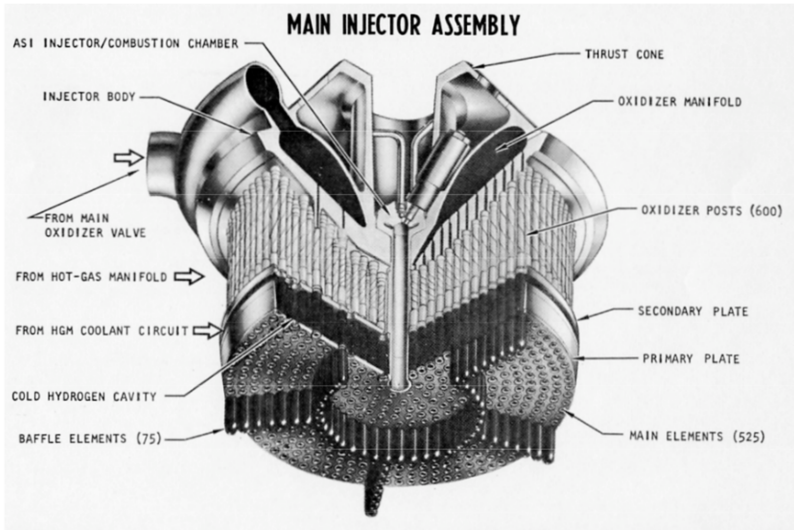


SSME MAIN INJECTORS

Design Requirements and Solutions

- High combustion performance:
  - uniformly spaced co-axial injectors
  - active baffle elements
- Stable combustion:
  - five vane/hub baffles
  - acoustic absorbers
- Face cooling:
  - transpiration cooling
- Thrust chamber compatibility:
  - boundary layer cooling
- Service life:
  - Haynes 188 LOX posts
  - LOX post flow shields
  - transpiration cooled faceplate





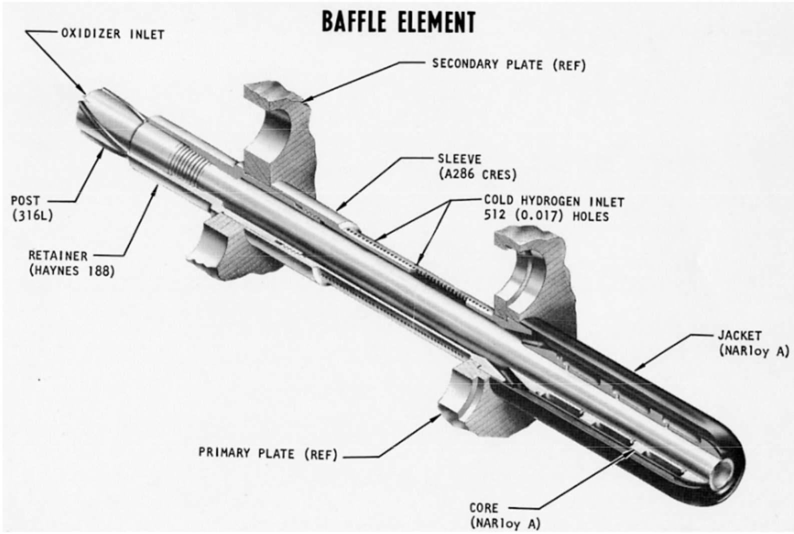
SSME MAIN INJECTORS

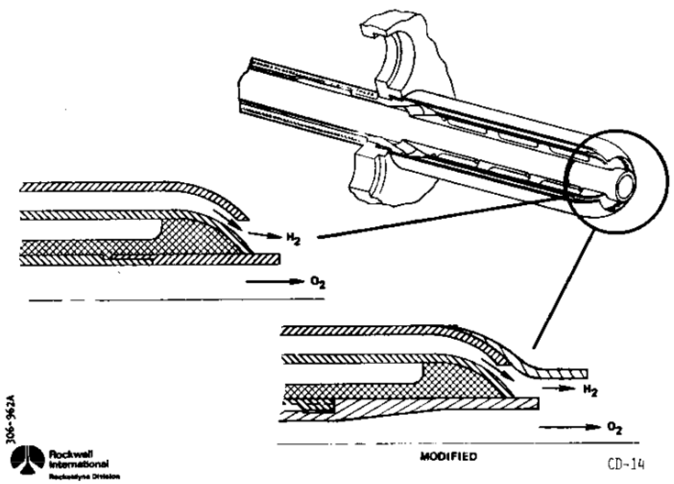
Development Problems

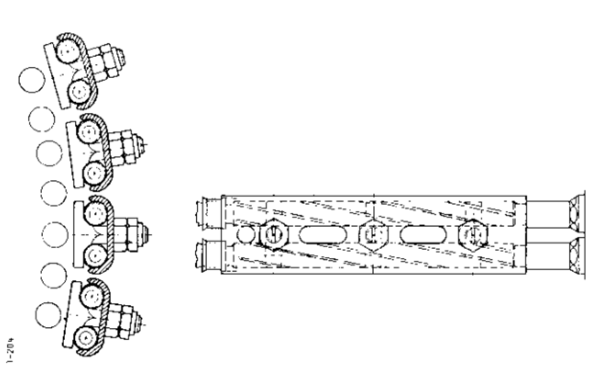
- Baffle element tip erosion
- Baffle element reverse flow during transients
- LOX post high cycle fatigue

Solution:

- modification of baffle tip material
- modification of baffle injection geometry
- addition of outer row flow shields (20,000 seconds RPL life limit)
- material changed to Haynes 188 to provide more than 7.5 hours at FPL







SSME MAIN INJECTORS

LOX Post Development Problems

- Initial design:
  - material: Haynes 188
  - dynamic environment:

    high external flow temperature
    mechanical vibrations
    vortex shedding - swirler incorporated
    design validation by analysis and tests
  - aerodynamic drag load: 60 lb/post

Solution:

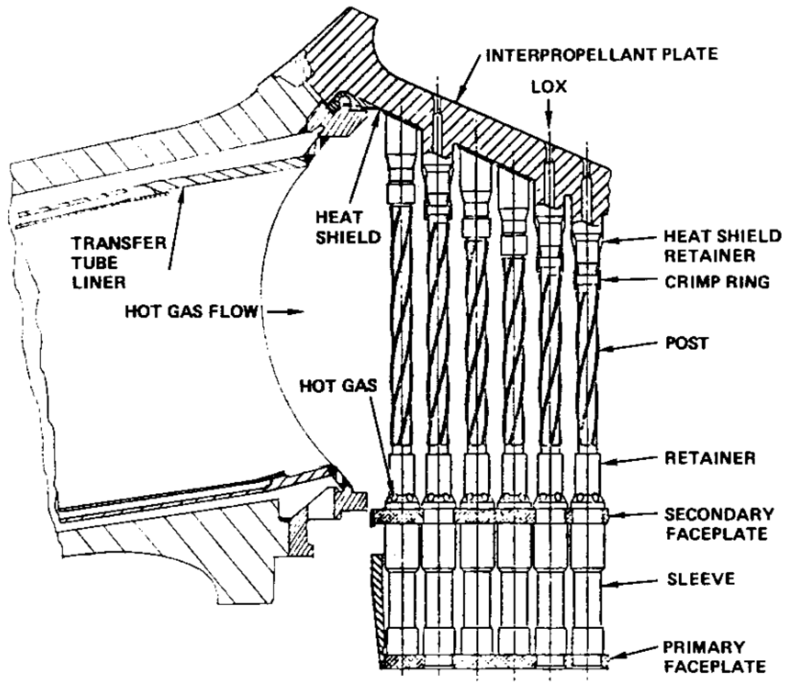
- modified design to incorporate 316L CRES:
- mixture ratio required excursion deleted:

  lowered LOX post temperature
- producibility of Haynes 188 tubing:

  design validation by analysis
- aerodynamic spoilers added in order to:

  breakup shedding
  reduce aerodynamic drag

HARDWARE DESCRIPTION

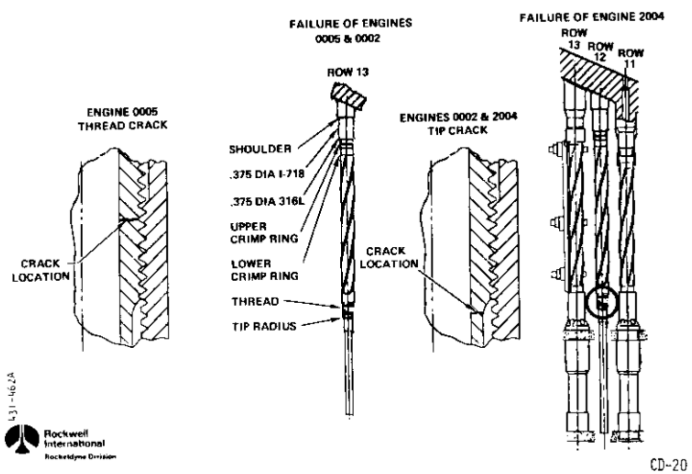


SSME MAIN INJECTORS

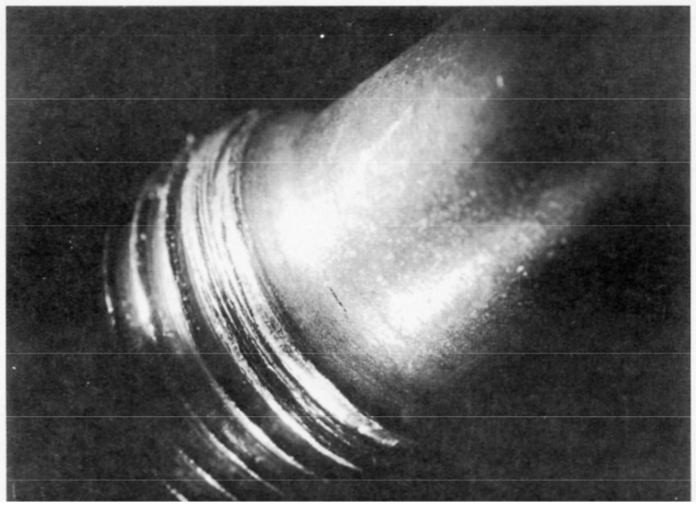
LOX Post Development Problems

- Tip fillet failure at 770 equivalent RPL sec.
- Thread failure at 780 equivalent RPL sec.
  Solution:
  - analyses indicated that:
    loose threads => max stress at fillet
    tight threads => max stress at threads
  - life extension to 16,000 equivalent RPL sec. by:
    flow shields at outer row 13
    plugging of two critical posts in row 12

ENGINE FAILURES IN THE THREAD AREA



FATIGUE CRACK IN FILLET



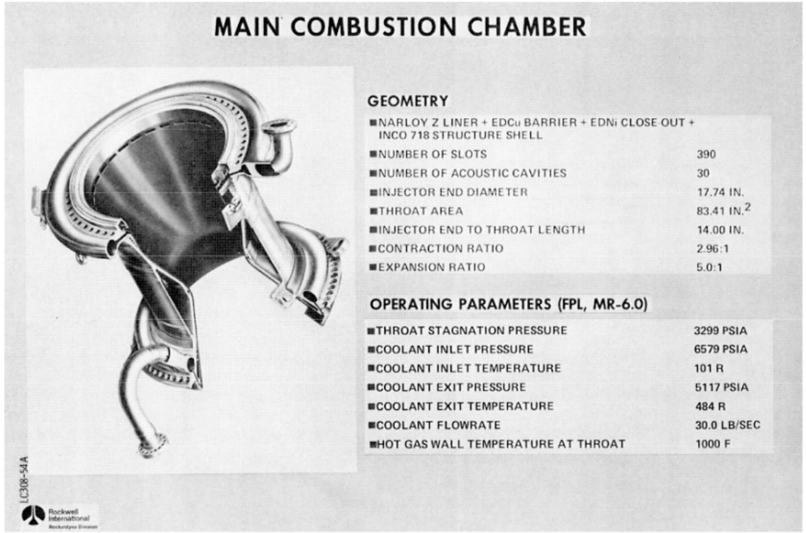
Design Achievement Summary

- 99.0% combustion efficiency:
  - 0.7% degradation by baffle tip and BL cooling
- Combustion stability, face cooling validated by tests
- Service life required addition of flow shields
- Local thrust chamber wall distress still encountered

SSME MAIN COMBUSTION CHAMBER

Design Requirements and Solutions

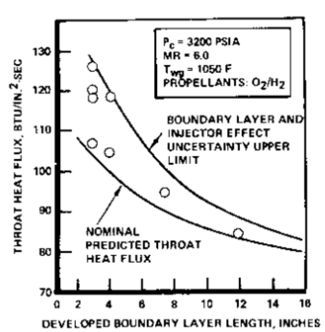
- Minimum engine weight:
  - high strength-high ductile material
- 240 cycle life capability:
  - channel configured coolant passages
  - combustor contoured for minimum gas wall temperature
  - high thermal conductivity - highly ductile material
- Maximum performance:
  - regeneratively H2 cooled combustor
- Dynamically stable combustion system:
  - acoustic absorbers



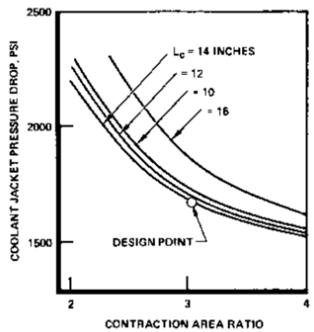
SSME MAIN COMBUSTION CHAMBER

Design Parameters and Considerations

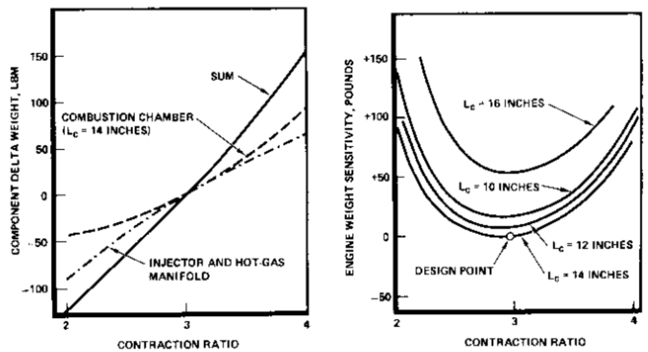
- Coolant channel wall thickness:
  - – channel material coining
- Coolant channel width:
  - – structurally compatible with wall thickness
- Coolant channel land width:
  - – channel plating capability
- Coolant channel height:
  - – heat transfer & coolant pressure drop
- Chamber length:
  - – performance
- Contraction ratio:
  - – engine weight & coolant pressure drop
- Throat radius of curvature:
  - – discharge loss & throat heat flux



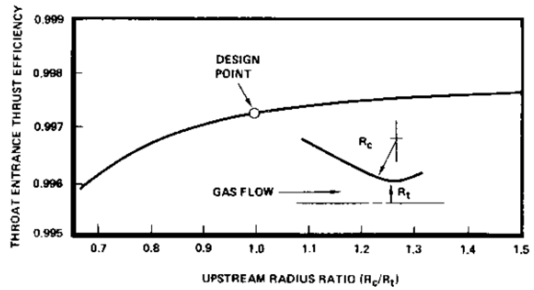
• INFLUENCE OF COMBUSTION CHAMBER LENGTH ON THROAT HEAT FLUX



• INFLUENCE OF COMBUSTION CHAMBER CONTRACTION AREA RATIO AND LENGTH ON COOLANT LINER PRESSURE DROP



MAIN THRUST CHAMBER ASSEMBLY WEIGHT SENSITIVITY



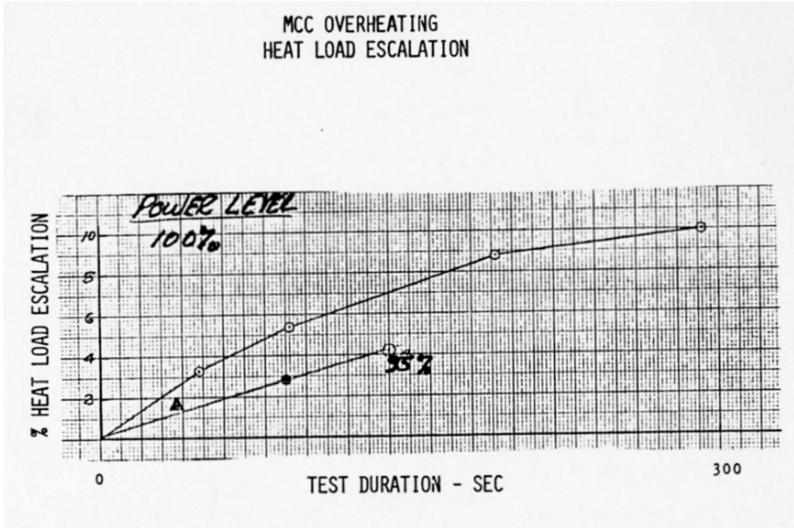
SSME MAIN COMBUSTION CHAMBER

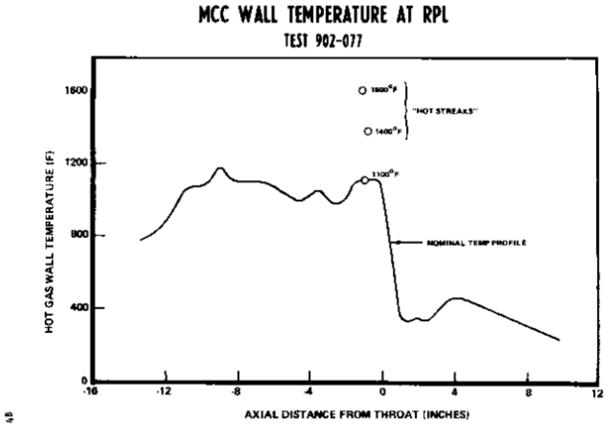
Development Problems

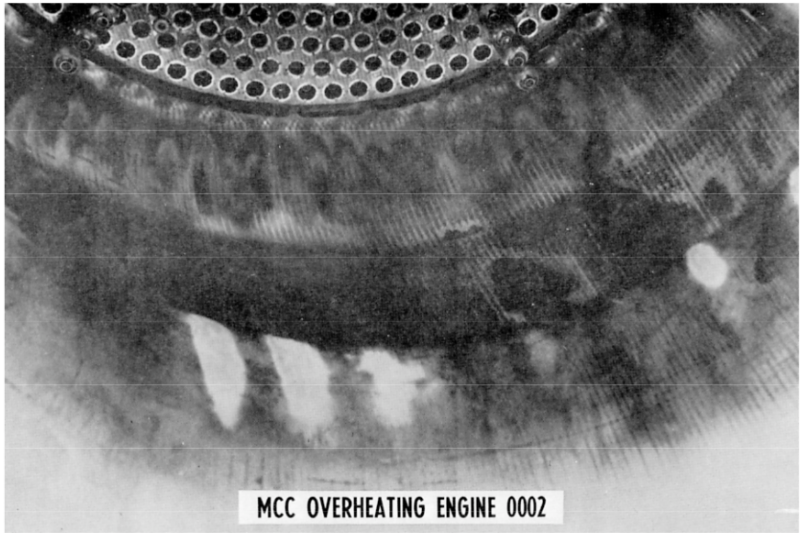
- Hot gas wall surface roughening
- Heat load escalation
- Localized hot spots

Solution:

- polish hot gas wall surface
- add film coolant adjacent to wall
- increase outer zone mass flux
- decrease outer zone mixture ratio
- locally enlarge film coolant holes



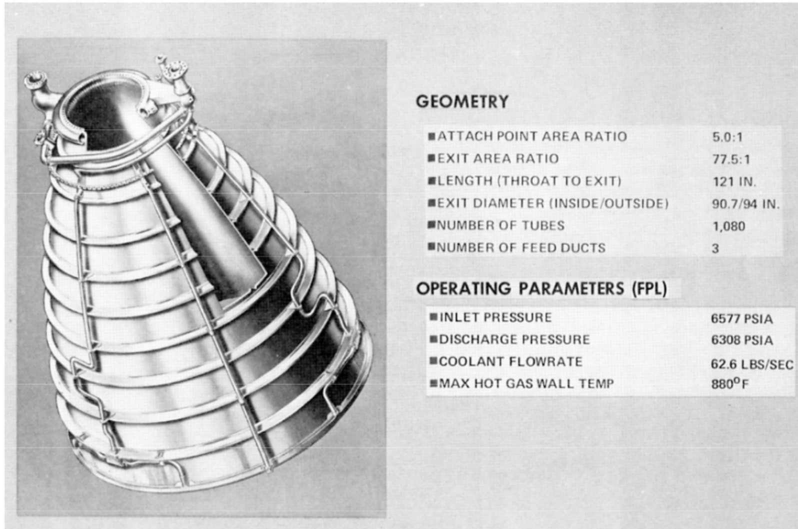


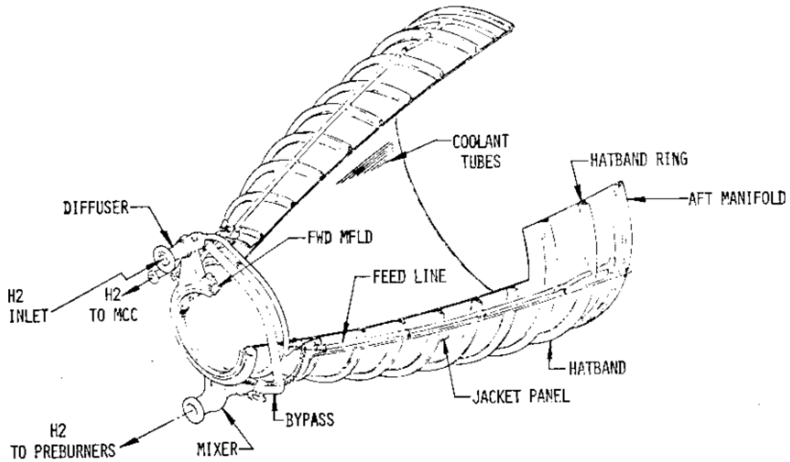


SSME NOZZLE

Design Requirements and Solutions

- Max performance contour within envelope:
  - 80.6% bell chamber
- Min transient loads:
  - continue decreasing pressure contour
- Sea level throttle capability to 90 power level:
  - contour control of nozzle exit wall pressure
- Minimum weight:
  - high strength materials
  - furnace brazed thin wall
  - tubular assembly
  - up-pass coolant circuit design
- 250 cycle life capability:
  - small diameter, high strength coolant tubes

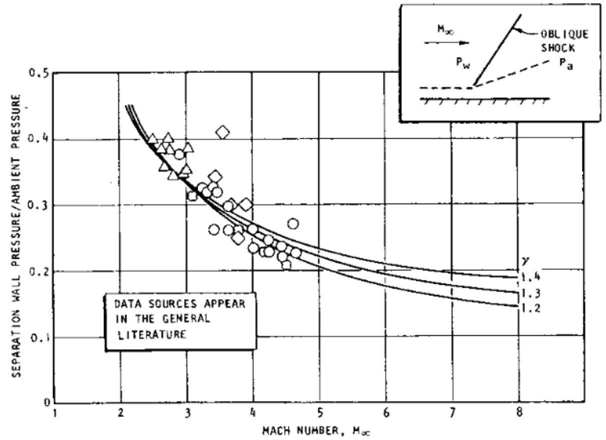




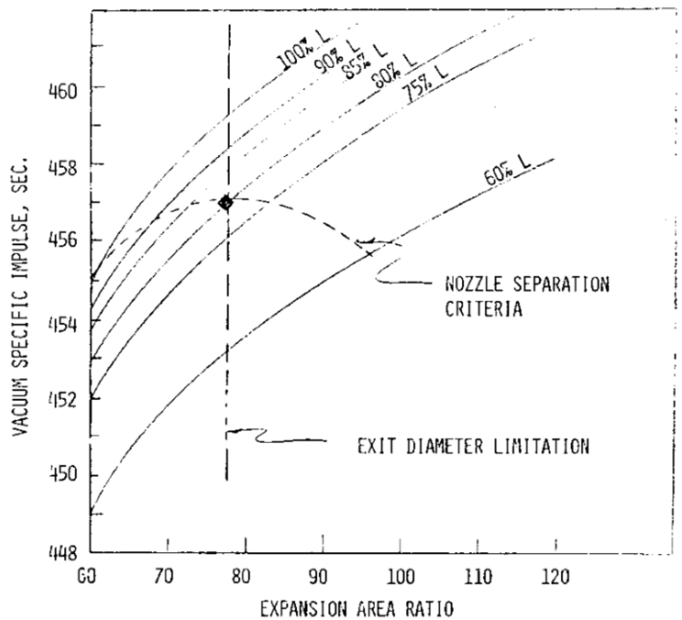
SSME NOZZLE

Design Parameters and Considerations

- Nozzle expansion ratio:
  - steady flow separation in atmospheric operation (overexpanded nozzles)
  - thrust performance
  - lateral envelope
- Nozzle length (% of conical nozzle length of equal expansion ratio):
  - weight
  - thrust performance
  - longitudinal envelope
- Nozzle shape:
  - thrust performance
  - flow separation during start-up transients
  - wall heat transfer rates



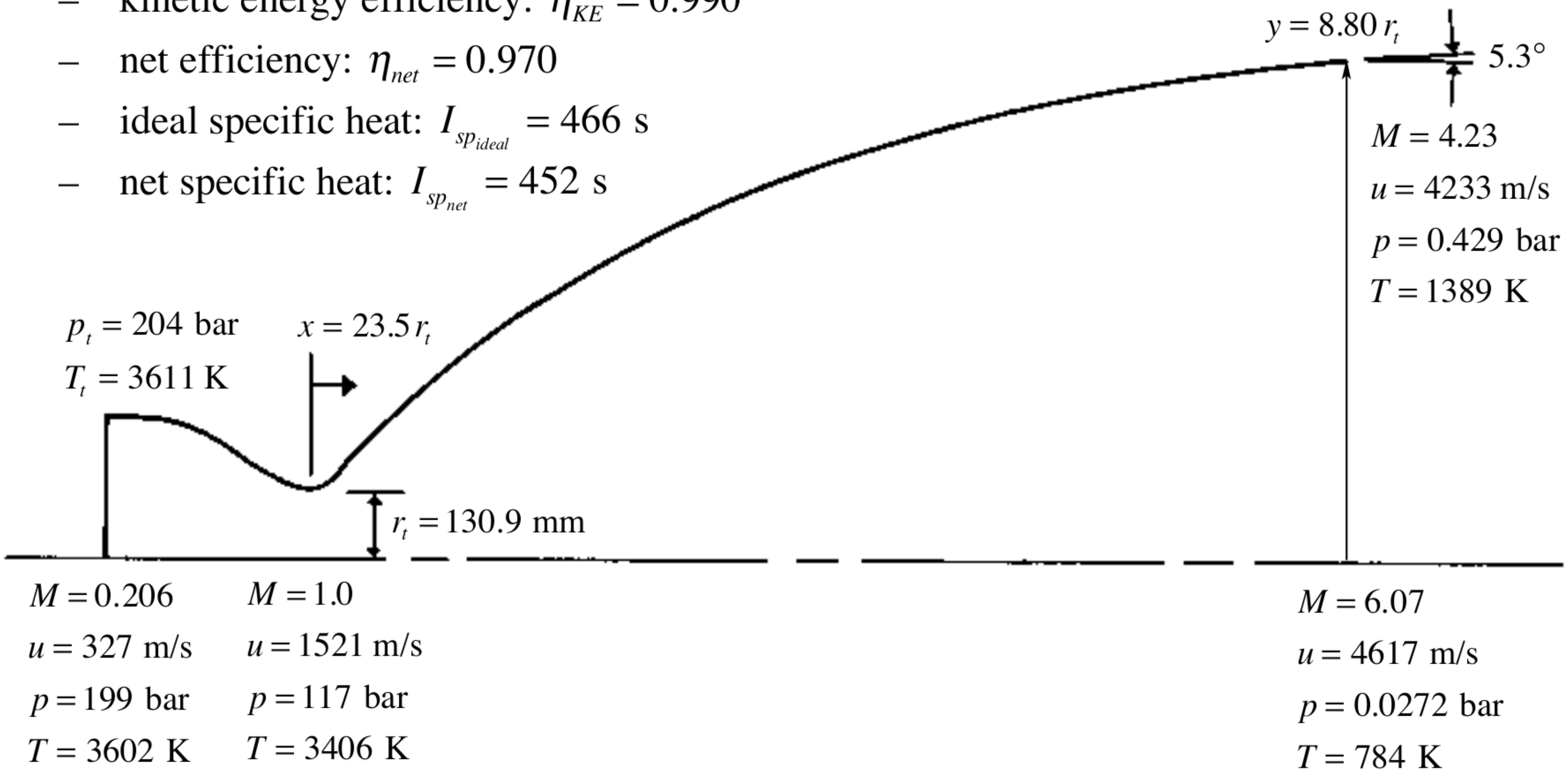
SSME NOZZLE SELECTION
SPECIFIC IMPULSE VS. EXPANSION AREA RATIO
PARAMETERS WITH PERCENT LENGTH (L)



SSME NOZZLE

SSME Nozzle Geometry and Performance at Rated Power Level

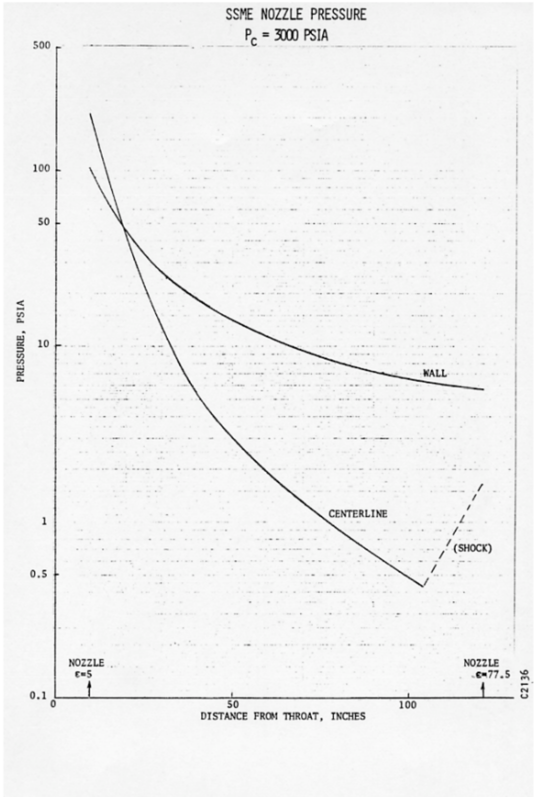
- Main performance parameters:
  - expansion ratio: $A_e / A_t = 77.5$
  - flow divergence efficiency: $\eta_{div} = 0.992$
  - drag efficiency: $\eta_{drag} = 0.987$
  - kinetic energy efficiency: $\eta_{KE} = 0.990$
  - net efficiency: $\eta_{net} = 0.970$
  - ideal specific heat: $I_{sp_{ideal}} = 466$ s
  - net specific heat: $I_{sp_{net}} = 452$ s



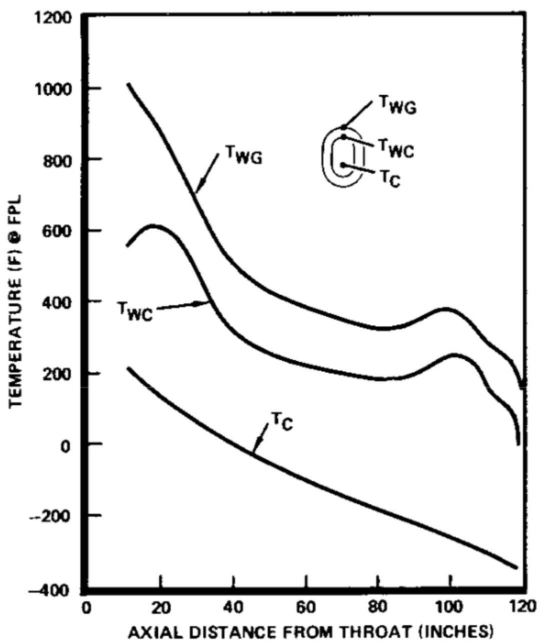
SSME NOZZLE

Nozzle Exit Plane Conditions

- Wall angle: 5° 32’
- Gas velocity, core: 14,550 ft/s (4413 m/s)
- Gas pressure, wall: 5.64 psia (0.384 atm.)
  core: 2.62 psia (0.178 atm)



FLIGHT NOZZLE TUBE WALL/COOLANT TEMPS



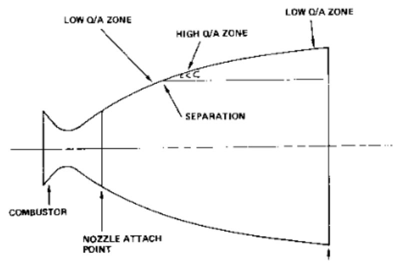
- Gas temperature, total: 6560 °R (3644 K)
  static: 2190 °R (1216 K)
- Gas specific heat ratio: 1.256 (shifting)
- Gas molecular weight: 13.30 gr/mole

SSME NOZZLE

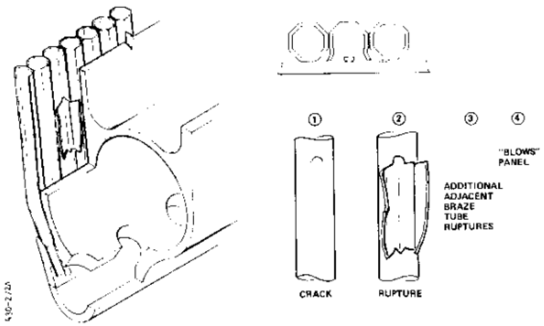
Development Problems

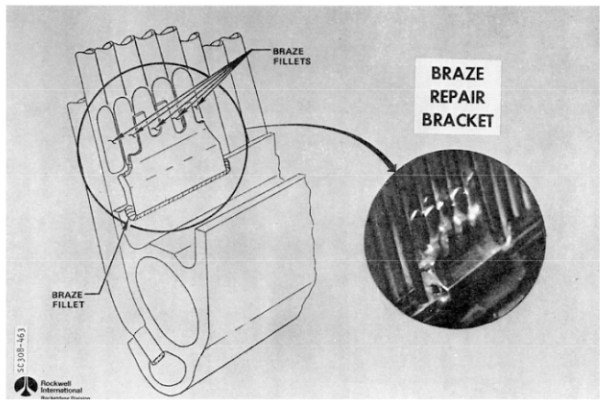
- Splits in nozzle forward section (10” dia.):
  - contaminant restrict coolant flow
    - fabrication and tube repairs
- Hot gas wall tube splits in nozzle aft section (60–110” dia.):
  - local high stresses & forming defects of tubes:
    - increased wall thickness
    - fabrication defect control
- Multiple hot side tube splits:
  - high heat flux at separation shock during shutdown
    - reduced shutdown mixture ratio
    - increased coolant flow
- Cold wall tube cracks at aft manifold braze joint:
  - poor braze joint & high stress during transients:
    - retrofitted with “fingers” & heavier tubes
    - improved braze joint

BEHAVIOR OF NOZZLE WALL HEAT TRANSFER UNDER SHUTDOWN CONDITION



AFT MANIFOLD TUBE RUPTURE - FAILURE MECHANISM
AFT MANIFOLD BRAZE JOINT AREA





SSME NOZZLE

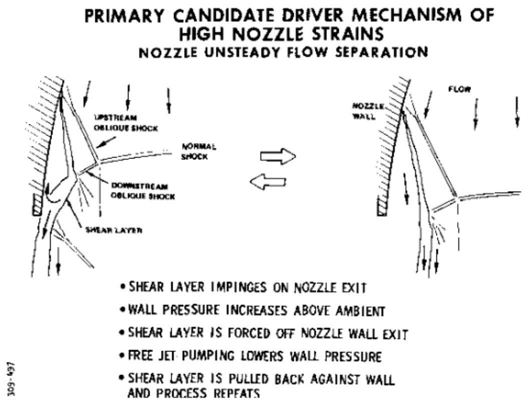
Development Problems (continued)

- Cold wall tube cracks at No. 9 hatband:
  - braze joint separation during steerhorn mode
  - oscillating flow separation stresses during transients:

    max. pressure oscillation: 2.59 bar
    max. oscillation frequency: 120 Hz
    number of oscillations: 10 ca. per test cycle
    pressure loading region: last 90 cm of nozzle
  - life improvement not realized with heavier wall tubes

Life highly dependent on:
- braze joint
- transient loads

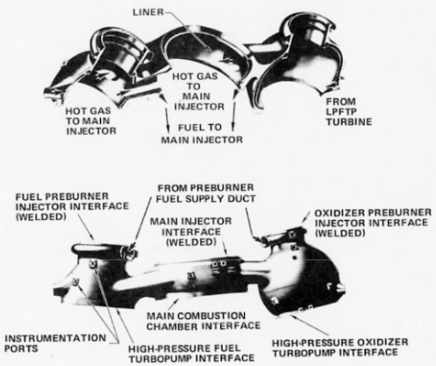
Expected minimum life:
- with minor maintenance: 20-25 starts/shutdowns
- overall life: 34-44 flights



SSME HEAT TRANSFER

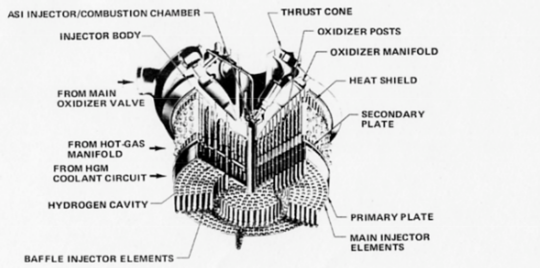
Critical Components and Areas

SSME HEAT TRANSFER HOT GAS MANIFOLD



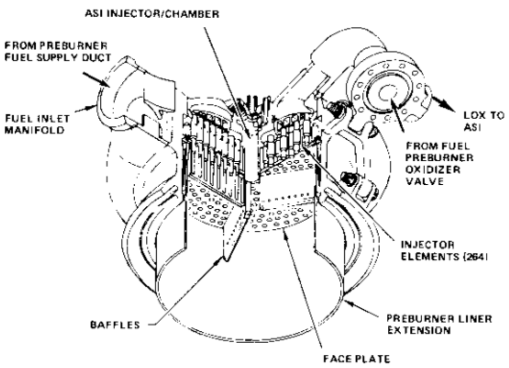
- HAS 3 WALLS
  - OUTER STRUCTURAL
  - COOLANT LINER
  - SCRUB LINER
- HEAT TRANSFER OF OUTER WALL TO DETERMINE STRENGTH

SSME HEAT TRANSFER MAIN INJECTOR



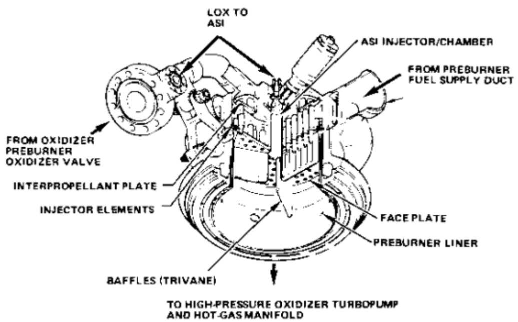
- AUGMENTED SPARK IGNITOR HAD TIP EROSION
- INTERPROPELLANT PLATE
  - CRACK ANALYSIS
- FACE PLATE TEMP
- LOX POST ANALYSIS
- ASI INLET LINE LEAKAGE

FUEL PREBURNER THERMAL ANALYSIS



- LIMITED FATIGUE POST ANALYSIS
- NIBBLING PROBLEM ON TIPS
- BAFFLE PLATE EROSION
- WALL BURNTHROUGH
- REVISED BAFFLE PLATE TO LOWER ASI PLUME TEMPERATURES

OXIDIZER PREBURNER



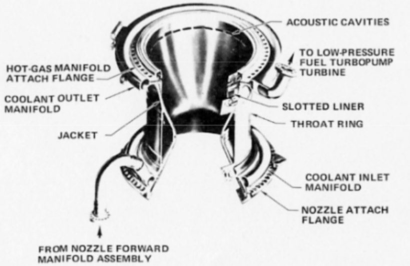
- LOX POSTS AND TIPS
- BAFFLE FLOW ISSUES
- FACEPLATES
- ASI LINES
  - STEADY STATE TEMPS IN RESPONSE TO FLIGHT CUTOFF DETONATION

298-940

SSME HEAT TRANSFER

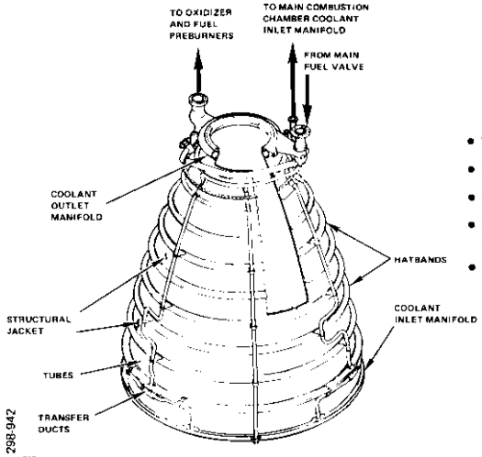
Critical Components and Areas

SSME HEAT TRANSFER MAIN COMBUSTION CHAMBER



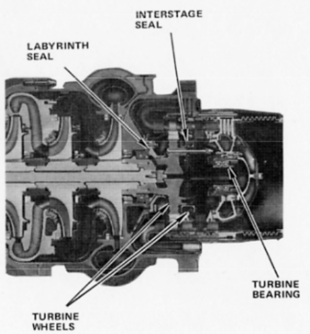
- PRIME TASK IS COOLING SURFACE OF COMBUSTION CHAMBER BY CONVECTION
- CALCULATE RELATIVE EXPANSION OF JACKETS AND CHAMBER WALLS
- DETERMINE HEAT LOAD
- DETERMINE PRESSURE DROPS

ENGINE NOZZLE



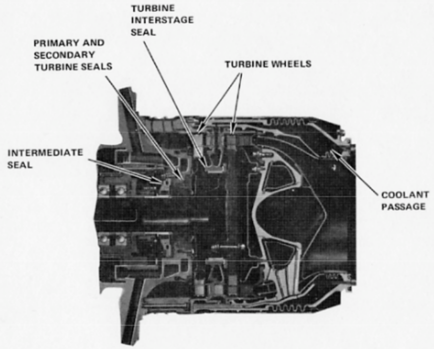
- VERIFY COOLING CIRCUIT ADEQUACY
- DETERMINE HEAT PICKUP OF COOLANT
- KEEP HATBANDS COOL
- RE-ENTRY ANALYSIS. ARE HATBANDS AND AFT MANIFOLD PROTECTED?
- ASCENT HEATING

HIGH PRESSURE FUEL TURBOPUMP



- VIRTUALLY EVERY PORTION OF THE TURBINES REQUIRED EXTENSIVE ANALYSIS OR HAD PROBLEMS
- LOCKING NUT STACKUP AND EROSION
- BEARING COOLANT PROBLEM
- DISK TEMPERATURES
  - CLEARANCES
  - GRADIENTS
  - STRENGTH
- HOUSING TEMPERATURES
  - GRADIENTS
  - STRENGTH
- NOZZLES AND BLADES
  - LOW CYCLE FATIGUE
  - HIGH CYCLE FATIGUE
- SEAL TEMPERATURES
- SHEET METAL TEMPS FOR BUCKLING
- BELLOWS FOR STRENGTH

HIGH PRESSURE OXIDIZER TURBOPUMP



- STRUCTURAL STRENGTH AND LOW CYCLE FATIGUE
- THERMAL ANALYSIS SHOWED NEED FOR MIXED COOLANT HOLLOW VANES, ETC.
- JET COOLANT TO SHANKS
- SEAL PACKAGE OF PARTICULAR SIGNIFICANCE
  - SEAL CLEARANCES
  - INTERMEDIATE SEAL
  - FACE SEAL REPLACED
- PUMP FLANGE IS UNIQUE

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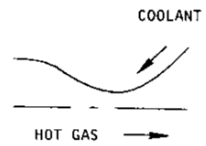
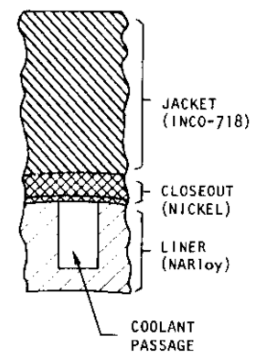
SSME HEAT TRANSFER

Main Combustion Chamber Liner

- 14 inch injector-to-throat length to minimize injector effects in throat heating rating rates and allow sufficient boundary layer development



- Up-pass cooling circuit (single-pass) for coolant coefficient curvature enhancement benefit
- %:1 expansion ratio for optimum coolant bulk temperature in high heat flux region
- Baffles and acoustic cavities to dampen combustion instabilities which could increase heating rates



- Minimum coolant channel geometry (within manufacturing controllable limits) for maximum cooling capability
- 3:1 contraction ratio for stable boundary layer development
- Throat entrance radius ratio of 1.0 to minimize the surface area in the high heat flux transonic flow region