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78-976

POTENTIAL SSME MODIFICATIONS TO PROVIDE EXTENDED CAPABILITIES FOR FUTURE APPLICATIONS

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AIAA/SAE 14TH JOINT PROPULSION CONFERENCE

Las Vegas, Nev./July 25-27, 1978

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Abstract

The Space Shuttle Main Engine (SSME) continues to be the baseline oxygen/hydrogen engine in studies of Shuttle growth vehicles, Heavy Lift Launch Vehicles (HLLV) and Single-Stage-to-Orbit (SSTO) vehicles. In these alternate applications, modified SSME engines could provide additional advantages. This paper discusses briefly the alternate vehicle design features as they affect the propulsion system. Further, engine concepts based upon potential modifications to SSME are presented. Advancements in the current technology required by these engine concepts are presented.

Introduction

The Space Shuttle (Fig. 1), scheduled to become operational in 1980, will inaugurate the reusable vehicle phase of space activity. Expendable launch vehicles such as those presented in Fig. 2 will be phased out during the first years of shuttle operation. The payloads currently carried to orbit by these vehicles will be placed in low earth orbit (LEO) by the reusable shuttle. An upper stage carried aboard the shuttle will transfer geosynchronous payloads to the higher altitude. Shuttle can boost heavier payloads than presently placed in orbit by operational expendable vehicles, but its limited payload capability will not be able to support all future activity in space without high intensity launch rates. To alleviate the high traffic rate, Space Shuttle derived vehicles with larger payload capabilities have been studied (Ref. 1 and 2). Single-Stage-to-Orbit (SSTO) vehicles, such as presented in Ref. 3 and 4, offer the same payload capability as the Space Shuttle at a projected lower cost per flight.

Propulsion systems for the Shuttle derived vehicles and the SSTO vehicles can potentially be obtained from modifications of the Space Shuttle Main Engine. Two concepts based on modifications to the basic engine are: an SSME-35 for low altitude operation with liquid rocket boosters (LRB's); and an SSME-150 for operation over the complete altitude range as might be required in an SSTO vehicle application. Another potential modification would provide operation with a hydrocarbon fuel instead of hydrogen. The Space Shuttle Booster Engine (SSBE) concept using oxygen/RP-1 with hydrogen as a coolant is such a concept. The Liquid Rocket

*Work sponsored by the NASA/Marshall Space Flight Center under contracts NAS8-32340 and NAS8-32613.

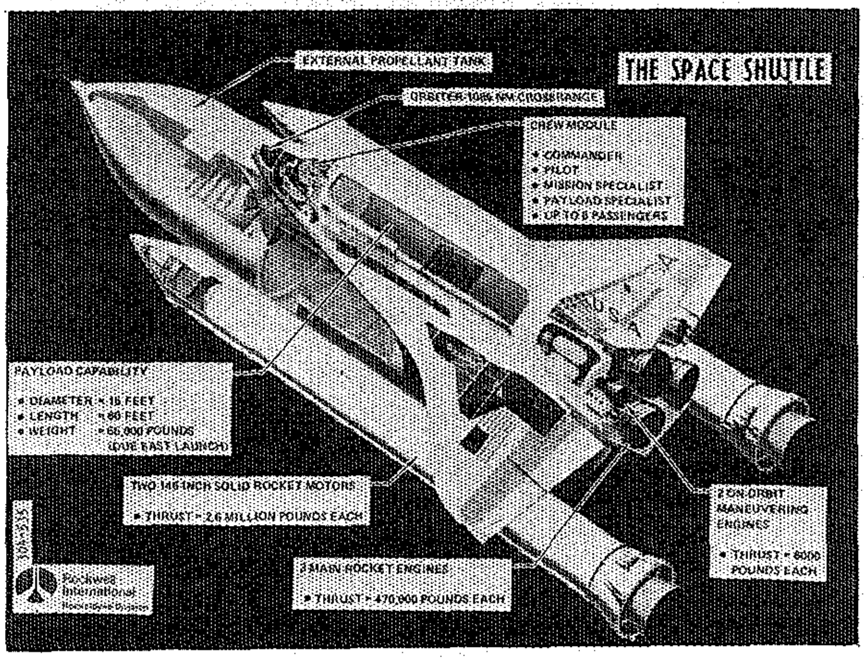


Figure 1. Space Shuttle

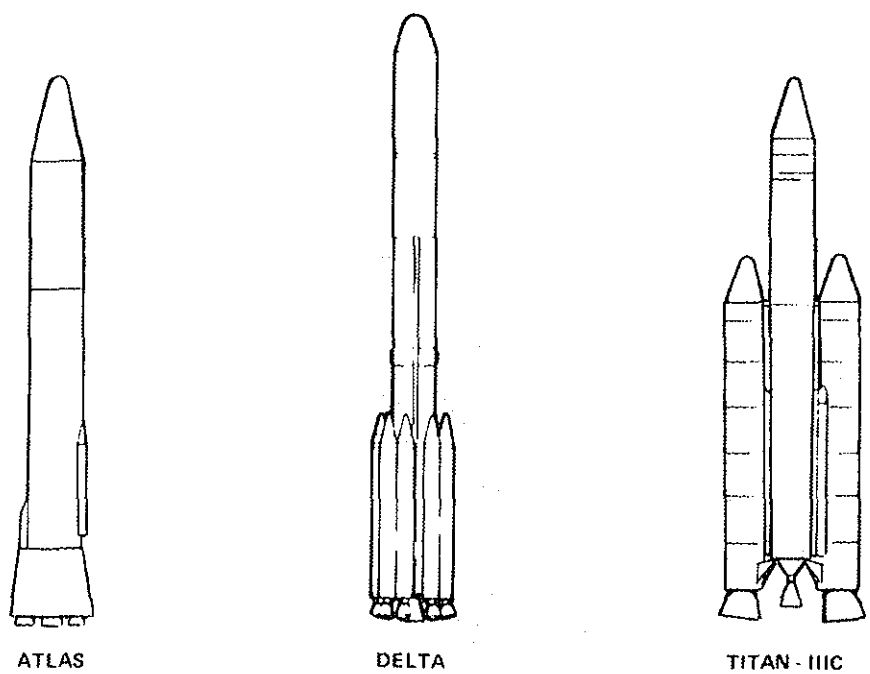


Figure 2. Expendable Launch Vehicles

Booster Engine (LRBE) based on oxygen/methane propellants is an alternate hydrocarbon fueled engine concept that could be very attractive. Each potential SSME modification must be evaluated in vehicle applications to determine the tradeoffs between options and other engine concepts such as those presented in Ref. 5 and 6.

Shuttle Derived HLLV

The Space Shuttle has been examined in several studies to define derivatives that may launch heavier payloads to LEO than the nominal 65,000 pounds for due East launches out of Kennedy Space Center. One concept would replace the orbiter with a cylindrical unmanned payload module (Fig. 3). The orbiter main propulsion subsection with its cluster of three SSME's is retained in this design. It provides propulsion during operation of and after separation of the Solid Rocket Motors (SRM's). This vehicle configuration is capable of placing 150,000 pounds payload in a 50 x 100 nautical mile orbit. A potentially important modification to the vehicle would be replacement of the SRM's with reusable LRB's to increase the payload capability to 180,000 pounds. The LRB's could be designed for one of three engine concepts: The SSME-35 with oxygen/hydrogen propellants; the LRBE with oxygen/methane; or the SSBE with oxygen/RP-1/hydrogen. For each of these three engine options and an equal payload capability, different size LRB's (Fig. 4) are required.

SSTO

The single-stage-to-orbit vehicle concept has several different design approaches. One has been selected to show the application of potential SSME modifications. This one is an all oxygen/hydrogen propellant vehicle with a cluster of 10 engines that require a two-positon nozzle to achieve near optimum performance in low- and high-altitude regions of operation. The SSME-150 concept provides this capability of operating at a low-expansion-area ratio initially, followed by operation with a high-area-ratio nozzle. In this vehicle concept, the SSME-150 also incorporates advanced low-pressure turbopump designs to minimize tank pressure and propellant residuals.

The dual-mode SSTO (Ref. 4) shown in Fig. 5 has a combination of SSME-150's and oxygen/hydrocarbon engines. Parallel burn of the eight engines provides the power for liftoff and travel through the lower altitudes. The SSME-150's operate initially with the nozzle retracted to produce higher thrust and specific impulse. The combination of fuels is a vehicle/mission compromise between the high density fuel engines with lower specific impulse and the hydrogen fuel engines with higher performance. At a designated altitude, the hydrocarbon engines are cut off, and the SSME-150 high-area-ratio nozzle is extended. This mode of operation gives high performance from the SSME-150 during the high altitude portion of the flight.

Space Shuttle Main Engine

The SSME has been discussed in many papers (e.g., Ref. 7 and 8), but it is important to review the basic design since it is the baseline for the modifications associated with the propulsion systems for advanced vehicles. The engine rated power level of 470,000 pounds thrust (Fig. 6) is produced by operating at a chamber

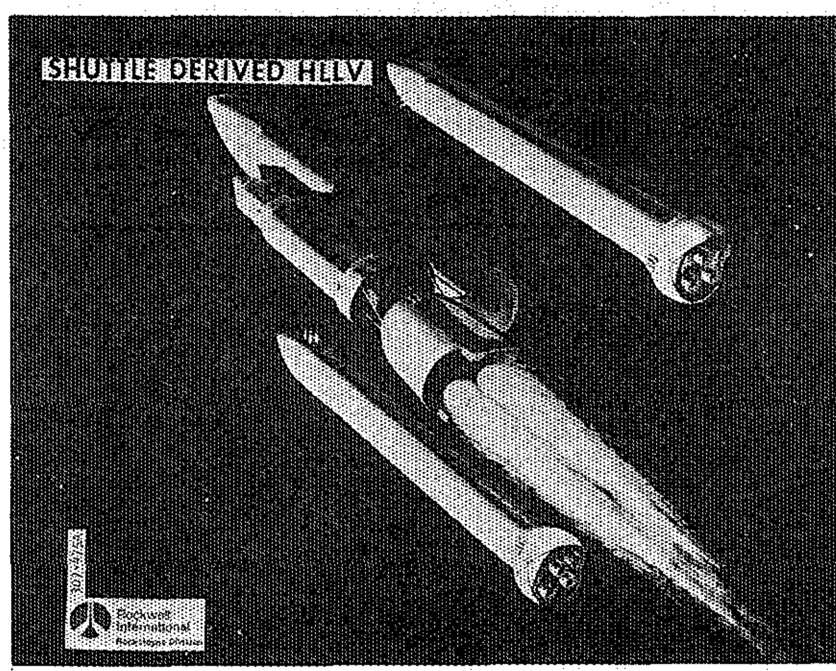


Figure 3. Shuttle Derived HLLV

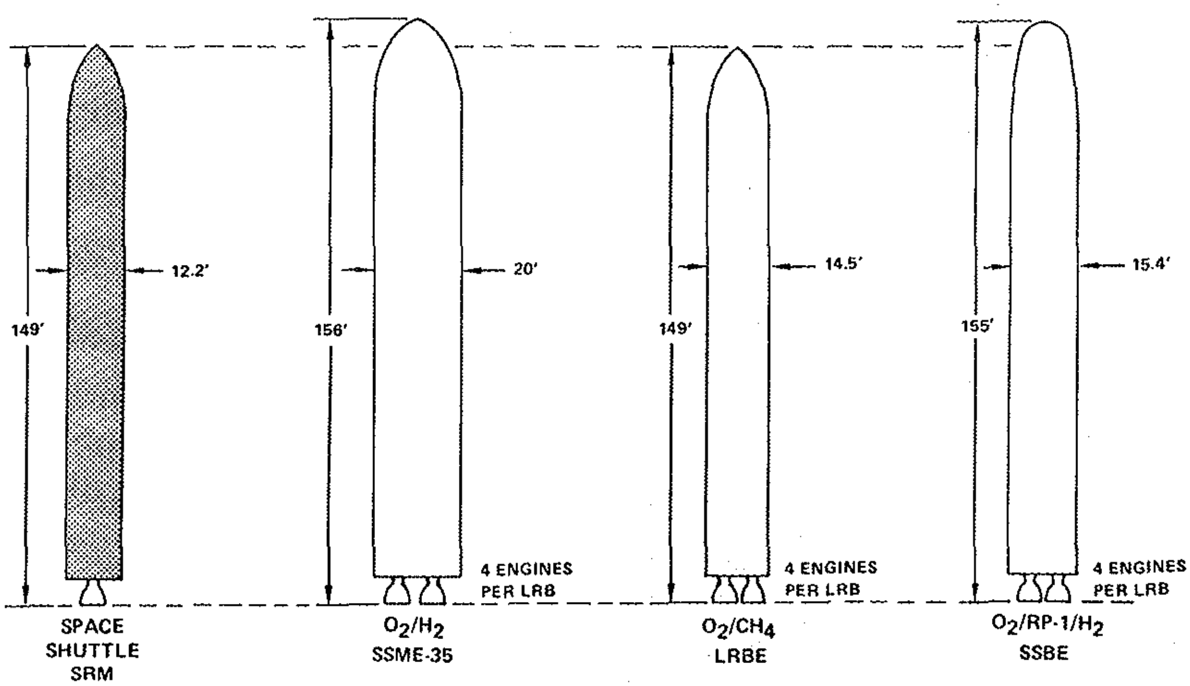


Figure 4. Candidate LRB's for Shuttle Derived HLLV

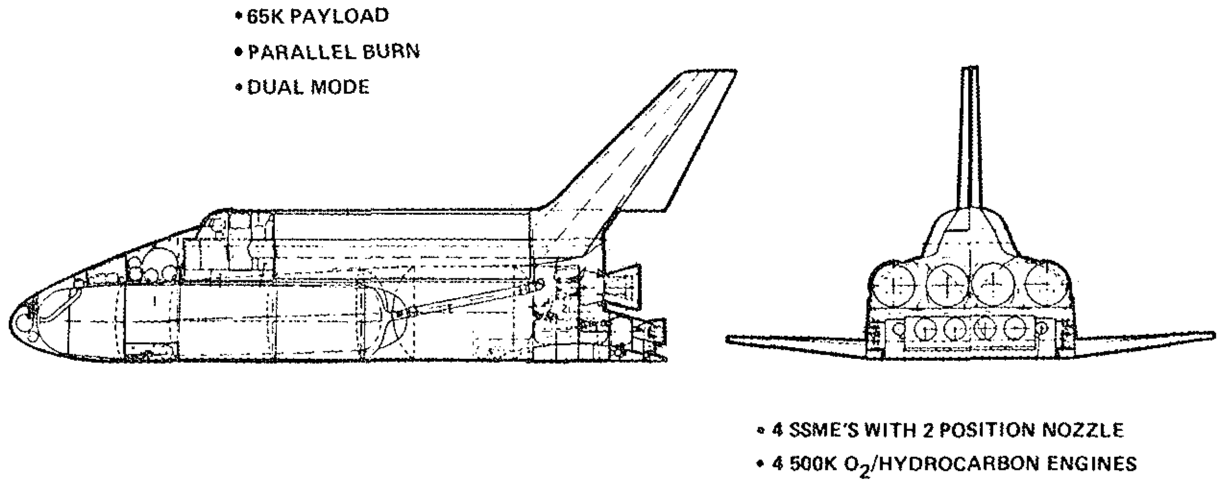
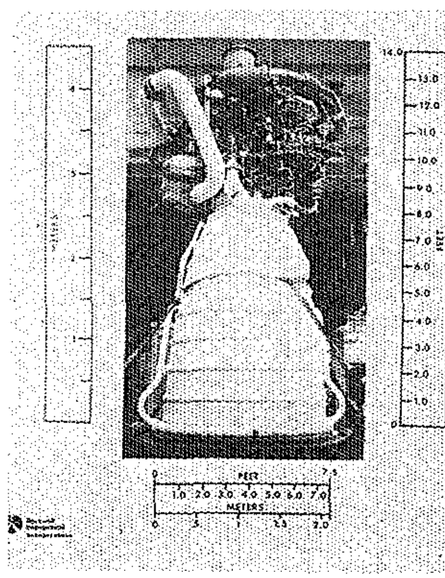


Figure 5. Dual-Mode Single Stage to Orbit (SSTO) Martin Marietta/NASA-Langley Research Center Design



THRUST		
SEA LEVEL	375K	(1,668,080 N)
VACUUM	470K	(2,090,660 N)
FPL	109%	109%
CHAMBER PRESSURE	2970 PSIA	2048 N/cm^2
AREA RATIO	77.5	77.5
SPECIFIC IMPULSE (NOM)		
SEA LEVEL	363.2	3562 $\frac{N\ sec}{kg}$
VACUUM	455.2	4464 $\frac{N\ sec}{kg}$
MIXTURE RATIO	6.0	6.0
LENGTH	167"	424 cm
DIAMETER		
POWERHEAD	105" x 95"	267 x 240 cm
NOZZLE EXIT	94"	239 cm
LIFE	7.5 HRS	7.5 HRS
	55 STARTS	55 STARTS
LEVEL II CONTROL WEIGHT	6632 LBS	3014 kgms

Figure 6. Space Shuttle Main Engine Characteristics

pressure of approximately 3000 psia. The current engine weight specification is 6632 pounds. Specific impulse at vacuum conditions is 455.2 seconds. The high performance is due to the staged-combustion cycle and an expansion-area ratio of 77.5:1. Engine envelope is an important factor in vehicles that must package a large number of engines in a minimum cross-sectional base area. SSME dimensions, length and exit diameter are shown in the figure. These dimensions will change with the potential modifications to be discussed, but the powerhead dimensions will remain essentially the same.

The SSME staged combustion power cycle (Fig. 7) has two preburners, both operating fuel-rich, providing power to the two high pressure pumps. Like turbine fluids simplify the routing, manifolding, and injecting the hot gases into the main chamber. A drawback is that turbine power is limited to a level that can be achieved by available fuel flow and turbine inlet temperature limit since turbine pressure ratio must be kept as low as possible in the staged-combustion cycle to avoid increasing the turbopump discharge pressure. For SSME, all hydrogen except the portion used to drive the low-pressure hydrogen pump, is burned in the two preburners. Turbine fluid temperature at full power is approximately 1960 R. The staged-combustion cycle is complex, but the performance advantage it provides makes it very important in evaluating future rocket engine candidates.

SSME-35

The easiest of all potential modifications that may be considered for the SSME is a change in the nozzle from the current 77.5:1 area ratio to a 35:1 area ratio. This modification produces an engine concept (Fig. 8) with approximately 50,000 pounds higher thrust than SSME at sea level. In addition, the specific impulse at sea level is over 40 seconds higher. The engine performance is near maximum performance for an oxygen/hydrogen booster (or first stage) application. The engine operation would be essentially identical to the SSME since the 35:1 area ratio nozzle produces basically the same heat input to the hydrogen coolant. The engine is nearly 2 feet shorter and the nozzle exit is 2-1/2 feet smaller in diameter. Engine design life would be unchanged. The nozzle would be a flight-weight version of the engine development nozzle used in the SSME program for testing the engine at low power levels without using a diffuser.

SSME-150

This concept is based upon a potential modification that replaces the current SSME nozzle with a two-position retractable nozzle (Fig. 9). The nozzle separates at a 50:1 expansion area ratio (ε) and the portion from ε = 150:1 is retractable during low altitude operation. On the SSME-150, the jack screws are located for noninterference with the powerhead components. Figure 10 shows a candidate arrangement using the hot gas manifold as the structural support for the upper end of the jack screws. As shown in Fig. 9, the lower ends are supported by the fixed nozzle. Engine performance, envelope and weight projections are also given. A two-position nozzle concept has been tested by Pratt & Whitney (Ref. 9), but it has not been developed for a flight engine.

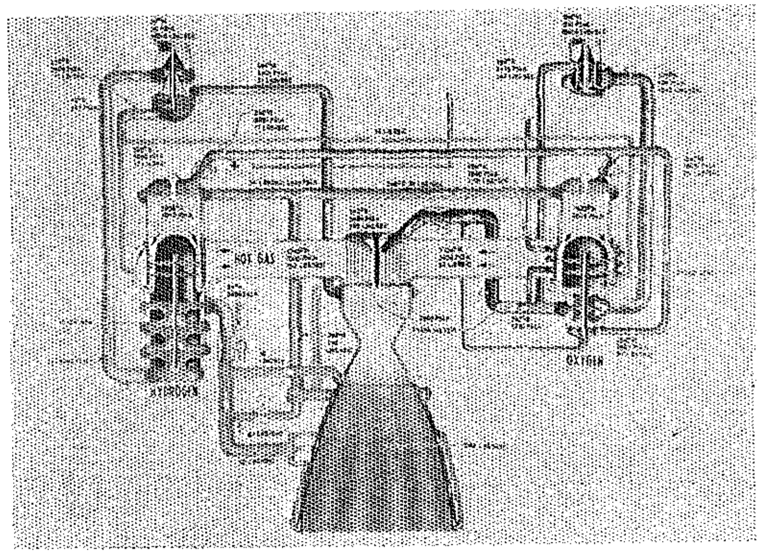


Figure 7. SSME Staged-Combustion Power Cycle

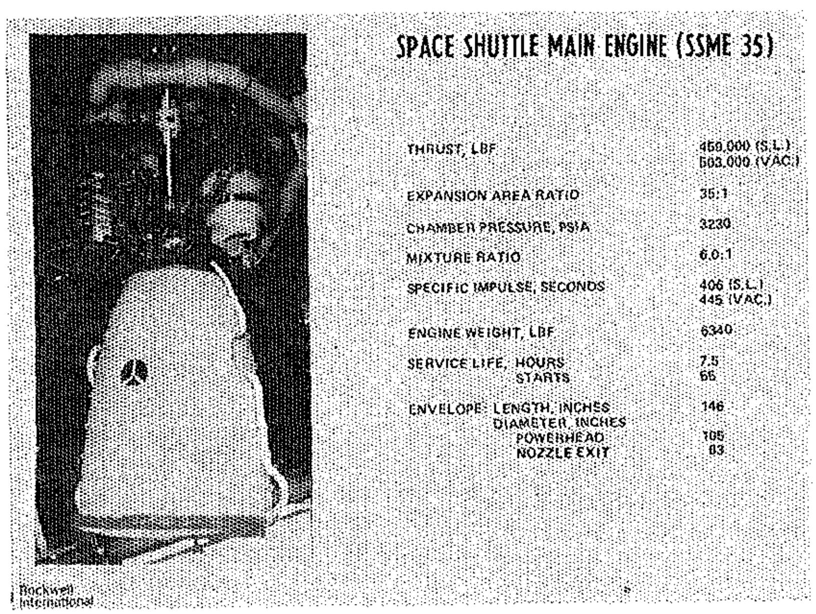
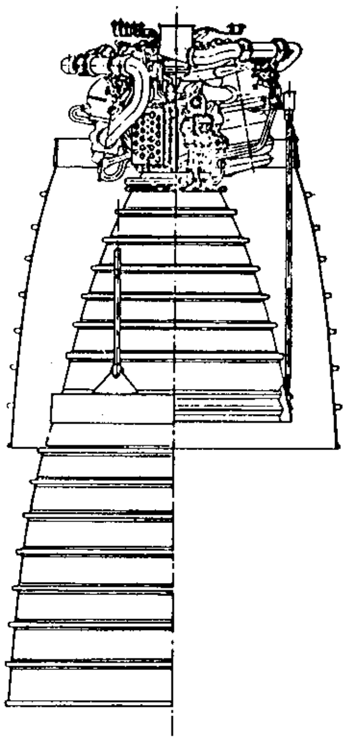


Figure 8. Space Shuttle Main Engine (SSME-35)



• PROPELLANTS	O_2/H_2
• THRUST, LBF (S.L.)	405,000
(VAC.)	465,000/480,000
• EXPANSION AREA RATIO	50/150
• CHAMBER PRESSURE, PSIA	3000
• MIXTURE RATIO	6.0:1
• COOLANT MEDIA	H_2
• SPECIFIC IMPULSE, SECONDS	
SEA LEVEL	391
VACUUM	450/464
• ENGINE WEIGHT, POUNDS	7900
• ENGINE LENGTH, INCHES	176/219
• ENGINE DIAMETER, INCHES	
POWERHEAD	105 X 95
NOZZLE EXIT	126

Figure 9. SSME-150 Engine Concept

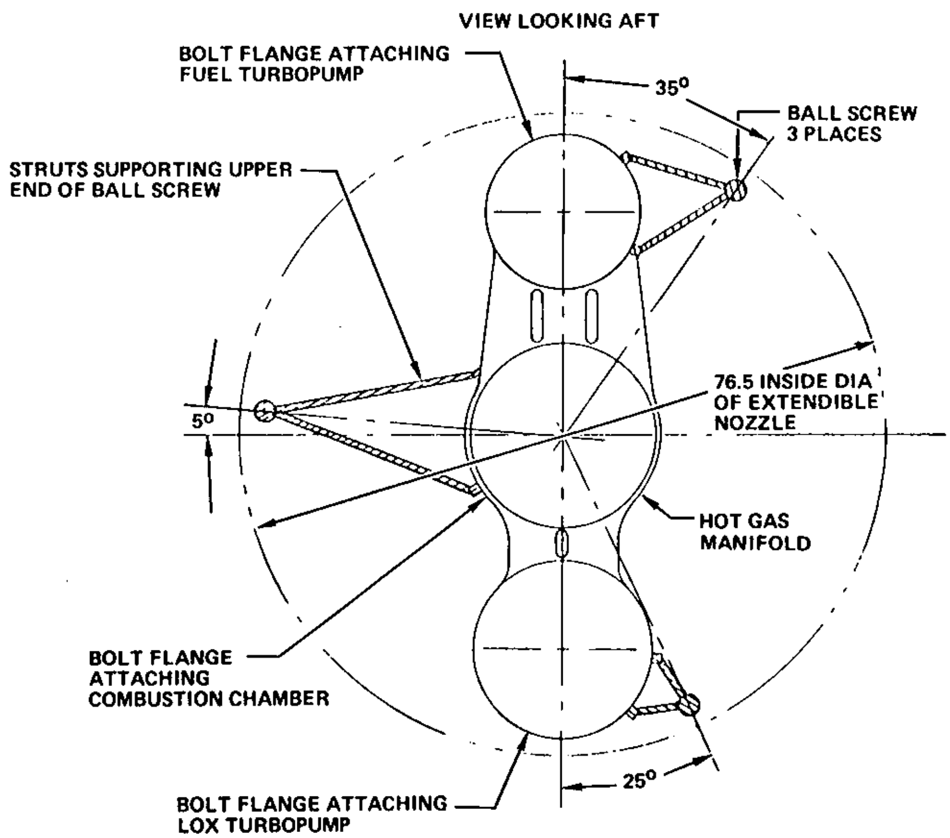


Figure 10. Extendible Nozzle Ball Screw Locations for Booster Nozzle (ϵ = 55)

SSBE

The Space Shuttle Booster Engine concept, discussed extensively in Ref. 10, is a potential derivative of SSME that could be used in vehicles needing a high density fuel engine such as a dual mode SSTO. The engine (Fig. 11) operates with hydrogen cooling just as in the basic SSME. Since the maximum gas side heat transfer coefficient with oxygen/RP-1 at 3230 psia chamber pressure is only 0.012 Btu/in.^{2}-sec-F compared to the oxygen/hydrogen value of 0.020 Btu/in.^{2}-sec-F, the hydrogen coolant flowrate for the entire engine is only 34 lb/sec. Three fuel-rich (RP-1) preburners provide power to the high pressure turbopump turbines. To derive sufficient power using all fuel in the preburners, the turbine hot gas temperature must be increased approximately 200 degrees. The effect of the higher temperature upon turbine materials must be evaluated in technology programs. Some coking may form on the wetted turbine surfaces and act as a barrier protecting the parts from the higher temperatures.

Operational and physical characteristics of this tripropellant engine are also presented in Fig. 11. The nozzle expansion area ratio of 35:1 provides near optimum expansion for maximum sea level thrust. The 467,000-pound thrust at lift-off with the nominal combustion chamber throat area could be increased to 537,000 pounds thrust by a 15-percent enlargement of the throat area.

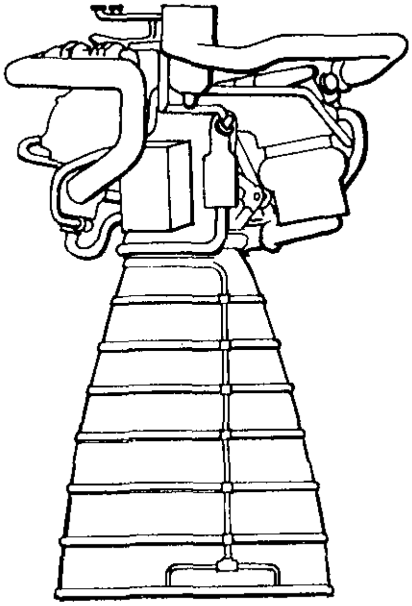
LRBE

The Liquid Rocket Booster Engine concept (Fig. 12) is based on modifying the SSME to operate with methane as the fuel and the coolant. The staged combustion power cycle operates with two fuel-rich preburners producing turbine drive hot gases at approximately 250 degrees higher temperature than the basic SSME. This approach preserves the SSME hot gas manifold and main injection design concepts. Materials compatible with hydrocarbon rich hot gases will be required in the hot gas flow circuit. Thrust chamber cooling with methane will be possible in this concept since the coking temperature of methane is higher than the allowable hot gas wall temperature.

Since this engine concept is for a booster application, the 35:1 expansion area ratio nozzle is incorporated into the design. Sea level thrust and performance of 500,000 pounds and 325 seconds are obtained when operating at the SSME chamber pressure level of 3230 psia. The combustion chamber throat area could be increased if a small thrust increase is desired. Engine envelope and weight estimates are also presented in Fig. 12. Engine service life is projected to be equal to SSME.

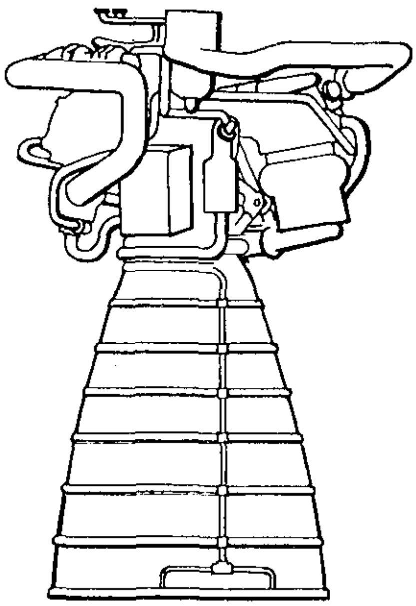
Technology Requirements

Modifications to the SSME to provide candidate propulsion systems for future vehicles should be preceded by technology programs designed to demonstrate feasibility of the concept. Several key areas of technology that are identifiable from the preliminary analyses of these engine concepts are presented in Fig. 13.



• PROPELLANTS	$O_2/RP\text{-}1/H_2$
• THRUST, LBF (S.L.)	467,000
• EXPANSION AREA RATIO	35:1
• MIXTURE RATIO	2.8:1
• COOLANT MEDIA	H_2
• SPECIFIC IMPULSE, SEC.	361 (VAC) 331 (S.L.)
• ENGINE WEIGHT, LBM	6870
• CHAMBER PRESSURE, PSIA	3230
• TURBINE TEMPERATURE, °R	2200
• ENGINE LENGTH, INCHES	146
• ENGINE DIAMETER, INCHES	
• POWERHEAD	105 X 95
• NOZZLE EXIT	63

Figure 11. Space Shuttle Booster Engine (SSBE) Concept



• PROPELLANTS	O_2/CH_4
• THRUST, LBF (S.L.)	500,000
• EXPANSION AREA RATIO	35:1
• CHAMBER PRESSURE, PSIA	3230
• TURBINE TEMPERATURE, °R	2250
• MIXTURE RATIO, O/F	3.5:1
• COOLANT MEDIA	CH_4
• SPECIFIC IMPULSE, SEC	325 (S.L.) 355 (VAC.)
• ENGINE WEIGHT, LBM	6340
• ENGINE LENGTH, INCHES	146
• ENGINE DIAMETER, INCHES	
• POWERHEAD	105 X 95
• NOZZLE EXIT	63

Figure 12. Liquid Rocket Booster Engine Concept

TECHNOLOGY PROGRAMS	SHUTTLE DERIVED HLLV	SSTO
HIGH PRESSURE LOX/HYDROCARBON COMBUSTION	X	X
HIGH PRESSURE HYDROCARBON COOLING	X	X
HIGHER TEMPERATURE TURBINES	X	X
COMPOSITE MATERIAL COMPONENTS	X	X
ADVANCED FABRICATION TECHNIQUES	X	X
VARIABLE EXPANSION RATIO NOZZLE		X
LOW NPSH OPERATION		X
ENGINE DIAGNOSTIC SYSTEMS	X	X

Figure 13. Technology Programs to Support Advanced Liquid Boosters

The high pressure combustion of oxygen/hydrogen propellants in preburners and the main combustion chamber should be investigated. Cooling with hydrocarbon at high pressures is another important factor to be addressed analytically and experimentally. High temperature turbine operation is a third area for technology development in support of staged-combustion cycle engine concepts.

Conclusions

The engine concepts discussed provided high performance with operating pressure levels that exist in the SSME. Modifications to the SSME appear practical based on the projected technology level that could be available at the time an engine development program would begin.

References

1. Systems Concepts for STS Derived Heavy Lift Launch Vehicles Study, Boeing Aerospace Company, NAS9-14710.
2. Bell, M. W. Jack, "Advanced Launch Vehicle System and Technology," Spacecraft, April 1978.
3. Technology Requirements for Advanced Earth-Orbit Transportation Systems, The Boeing Aerospace Company, NAS1-13944.
4. Technology Requirements for Advanced Earth-Orbit Transportation Systems, Dual-Mode Propulsion, Martin-Marietta Corporation, NAS1-13916 (NAS CR-2868).
5. Beichel, R. and C. J. O'Brien, "Dual Fuel Engine for Single-Stage Shuttles," AIAA Paper #75-1249, October 1975.
6. Beichel, R., "The Dual-Expander Rocket Engine - Key to Economical Space Transportation," Astronautics and Aeronautics, November 1977.
7. Wilhelm, W. F., "Space Shuttle Orbiter Main Engine Design," SAE Paper 78-807, October 1972.
8. Castenholz, P. D., "The Space Shuttle Main Engine," presented at XXIV Congress International Astronautical Federation; Baku, USSR, October 1973.
9. Advanced Cryogenic Rocket Engine Program Staged-Combustion Concept, Pratt & Whitney Aircraft, AFRPL-TR-67-298, Vol. 2, December 1967.
10. Sobin, A. J., S. P. Poynor, and E. Cross, "Booster Engines Derived From the Space Shuttle Main Engine," AIAA Paper 77-891, July 1977.