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Variable Mixture Ratio Performance Through Nitrogen Augmentation

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ABSTRACT

High/variable mixture ratio O2/H2 candidate engine cycles are examined for earth-to-orbit vehicle application. Engine performance and power balance information are presented for the candidate cycles relative to chamber pressure, bulk density and mixture ratio. Included in the cycle screening are concepts where a third fluid (liquid nitrogen) is used to achieve variable mixture ratio over the trajectory from liftoff to earth orbit. The third fluid cycles offer a very low risk, fully reusable, low operation cost alternative to high/variable mixture ratio bipropellant cycles. Variable mixture ratio engines with extendible nozzle are slightly lower performing than a single mixture ratio engine (MR = 7:1) with extendible nozzle. Dual expander engines (MR = 7:1) are slightly better performing than the single mixture ratio engine. Dual fuel dual expander engines offer a 16 percent improvement over the single mixture ratio engine.

INTRODUCTION

The future progress and possibly even our survivability depends more and more on our accessibility to space. It is imperitive, therefore, that a dependable, low cost propulsion system be developed that will allow future generations to fulfill the demands for the full economical development of space. New propulsion systems wil require the best of the existing technologies and the elimination of marginal technology to bring rocket propulsion to the maturity of jet propulsion.

Our natural approach to technology is to extend and improve the established propulsion system designs at the component level. This is considered a conservative approach, but can be very risky if it results in pushing the current "Model A" technology to its limit. To meet new requirements we must examine the propulsion system as a whole and ask questions like the following. Are there far superior engine cycles that will allow dependable, low cost operation well below

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their technology limit? Are there subsystems of other engine cycles that could be beneficially incorporated into existing propulsion systems?

This paper examines LOX/LH2 engine cycles and concepts that allow a variation in propulsion system mixture ratio. The goals are to achieve a dependable (long life, low cost, zero maintenance) engine concept and to optimize the performance-density of the engine and vehicle systems over the trajectory from earth-to-orbit.

It was known from previous studies that the variable mixture ratio LOX/LH2 engine would not provide the high SSTO vehicle performance of the dual fuel propulsion system. And the initial evaluation of the variable mixture ratio concepts indicated potential materials problems because of alternate operation in an oxidizer-rich and a fuel-rich environment. We, therefore, included liquid nitrogen augmentation, dual chamber configurations, and various engine cycles to achieve the optimum high/variable mixture ratio engine concept (see Fig. 1).

BACKGROUND

The mixed mode principle (Ref. 1) was suggested in 1971 as a means of achieving a practical single-stage-to-orbit (SSTO) vehicle. This principle involves the use of a more dense propellant combination at liftoff followed by a less dense, but higher performing propellant combination at altitude. Mixed mode operation is best for vertical takeoff, horizontal landing (VTOHL) missions with winged vehicles, such as shown in Fig. 2 (Ref. 2). Its benefit is derived from the fact that about 50 percent of the propellant is burned in achieving 15 percent of the velocity to orbit. When a high density propellant combination is burned in the initial phase of flight, the resultant vehicle size and thus dry mass is less for a fixed payload mass. Low dry mass is a design goal for SSTO vehicles because life-cycle cost is directly related to dry mass (Ref. 3).

The mixed mode principle encouraged the preliminary design of unique liquid rocket engines using two fuels and one oxidizer. Typical engines of this type are the dual fuel, dual expander engine (Ref. 4), the dual throat engine (Ref. 5), and a variable mixture ratio LOX/LH2 engine (Ref. 6). This paper is concerned with the evaluation of engine concepts utilizing variable mixture ratio. A comparison is made with both single fuel and dual fuel dual expander engines.

ENGINE CYCLES

A. LOX/LH2

The variable mixture ratio engine cycle shown in the schematic of Fig. 3 is similar to that originally proposed in Reference 6. The designation for the cycle is SOOOF. The engine utilizes the staged combustion (S) cycle, involves oxidizer (O) augmentation, and includes two oxidizer-rich (OO) preburners and one fuel-rich (F) preburner. The engine operates in two modes. At liftoff (Mode 1) all components (turbopump assemblies, preburners, and thrust chamber) are in operation. At altitude (Mode 2) the circuit including oxidizer-rich preburner number 2 is shut down, and the engine operates with one oxidizer-rich preburner and one fuel-rich preburner. As indicated in the engine cycle schematic, the fuel (LH2) is utilized to regeneratively cool the thrust chamber.

The fuel flow rate is constant during both modes of engine operation. The engine is thus throttled by varying the oxidizer flow rate. The resulting engine mixture ratio varies from a typical value of 10:1 to a value of 7:1. There is a considerable drop in engine specific impulse at a mixture ratio of 10:1 (see Fig. 4), but because the density of liquid oxygen (71 pounds/cubic foot) is so large compared with the density of liquid hydrogen (4.4 pounds/cubic foot) there is a significant reduction in vehicle size and mass. The vehicle implications will be referred to later in the paper.

The variation in specific impulse with mixture ratio for LOX/LH2 engines is shown in Fig. 4. It is seen that engine performance varies slightly between mixture ratios of five and seven. Beyond seven the performance drops rapidly with an increase in mixture ratio. Note that the bulk density of the propellants increases with mixture ratio, allowing a trade off between vehicle tank size (dry mass) and overall performance to orbit. Fig. 5 depicts another way of plotting the data in Fig. 4, and also illustrates the change in performance for a typical variable mixture ratio engine during the two modes of operation.

Several other engine cycles were analyzed and compared with cycle SOOOF. Figs. 6 and 7 illustrate typical cycles in schematic form. Cycle SOOFF shown in Fig. 6 is a staged combustion (S) cycle, with oxygen (O) augmentation, with one oxidizer-rich (O) preburner and with two fuel-rich (FF) preburners. The cycle operates in Mode 2 with two fuel-rich preburners, similar to the SSME (space shuttle main engine).

Figure 7 depicts a single fuel (LH2), dual chamber, dual nozzle engine referred to as a single fuel, dual expander engine. The engine is usually designed to generate 70 percent of its sea level thrust by a gas generator cycle and 30 percent by a staged combustion cycle. At altitude, where the highest performance is required, only the staged combustion cycle portion of the engine is in operation. The engine is specifically designed to meet the thrust requirements of the SSTO mission. The two independent chambers exhaust into a single nozzle. The deep throttling requirement of the SSTO mission is easily met with the dual expander engine. Instead of the large performance loss that would occur with the throttling of a single chamber engine, the dual expander performance actually increases. The increase in performance at altitude is due to the effective area ratio change when, in the absence of the inner chamber exhaust, the outer chamber exhaust fills the entire nozzle.

B. LN2/LOX/LH2

The variable mixture ratio LOX/LH2 engine with oxygen augmentation poses a number of technical issues. The life of the thrust chamber is a major issue.

Copper (NASA-Z or ZrCu) was selected for the main chamber material, but there was concern for the cycle life in the combined oxidizer-rich and fuel-rich environment of the oxygen augmented engine cycles. For example, atomic oxygen is present at 1.6 volume percent in chemical equilibrium in a chamber at 3000 psia and a mixture ratio of 10:1. The small diameter of the oxygen atom allows it to enter (diffuse into) the metal lattice. Atomic hydrogen is present at 2.7 volume percent when this same chamber is operated at 3000 psia and at a mixture ratio of 7:1. Atomic hydrogen will enter the metal lattice to combine with the oxygen to form water, which on temperature cycling can cause deep cracks in the copper.

The word metal customarily conveys the idea of a hard, dense solid. So it is difficult to imagine metals swelling like balloons or developing surface blisters. Yet this is precisely what can happen because of entrained gases. Much of the understanding of the mechanism of bubble formation and growth has come from work conducted in the 1950s and 1960s to determine the nature of the failure of materials exposed to nuclear radiation (Ref 13). Controlled experiments were conducted where metals were bombarded with helium and hydrogen ions. Because the ions were smaller than the gap between the atoms comprising the metal structure they were able to penetrate deep into the lattice. Once within the metal lattice the ions picked up electrons and became neutral atoms and molecules too large to have much mobility within the lattice. Temperature cycling of the metals, with and without stress loads, showed how the entrapped gas coalesced and diffused to form visible bubbles with internal pressures of 200,000 psia that eventually led to enlargement of the grain boundaries and to blisters and cracks in the surface of the metal.

References 14 to 16 show that the same phenomena occur when gases interact with metals within the metal lattice (as opposed to surface reactions). Gases can enter metals in atomic form because of their small size compared to the interatomic distance of the metal lattice. Hydrogen and oxygen, in many cases, diffuse (channel) through the metal at rates comparable to vacancies. When a hydrogen atom meets an oxygen atom within the lattice it can react chemically and eventually form a water (H2O) molecule. Fig. 8 shows a specimen of 99.999 percent pure silver annealed two and three times, respectively, at 1470 deg F (800 deg C) for 2 hours in air followed by 2 hours in pure hydrogen. Note the increase in impingement and grain boundary cracking with the additional cycle. The magnification is 115 times (Ref. 15).

It is expected that a copper chamber will behave in a similar manner to the silver specimens studied in Ref. 15. Potential solutions to this problem are coatings of nickel or gold, utilization of dual chambers, utilization of a transpiration cooled chamber, or use of inert fluid augmentation.

Inert fluid, liquid nitrogen augmentation resolves the life issue and provides several unique benefits to the engine and vehicle systems. Fig. 9 shows a typical engine schematic for the nitrogen augmented cycle SNNFF.

Engine cycle SNNFF (Fig. 9) operates in two modes as described for cycle SOOOF. At launch all components are in operation. The nitrogen-rich preburner is a stoichiometric preburner (see Ref. 4) burning LOX and LH2 at a mixture ratio of 7.94:1. Nitrogen is introduced to the preburner through a control valve. The nitrogen dilutes and cools the hot combustion gas to the proper temperature for turbine drive. The resulting preburner gas temperature is best maintained at or below 1600 deg R to allow use of conventional turbine blade materials and for long operational life. Higher gas temperatures can be used if higher risk systems are allowed.

The nitrogen-rich turbine exhaust gas is introduced into the main injector which is specially designed to accomodate two modes of operation. At altitude the nitrogen circuit is shut down, and the engine utilizes two fuel-rich preburners, similar to the SSME. A significant departure from the SSME is allowed with the use of nitrogen. An auxiliary nitrogen pump can be installed to replace the interpropellant seal (1700 pound weight penalty for the Space Shuttle vehicle). This auxiliary pump would operate in both modes to supply tank pressurization gas to a nitrogen heat exchanger (replace the category 1 failure mode oxygen heat exchanger), bearing coolant, etc. (see Fig. 10).

Nitrogen in the engine cycle provides additional benefits to the engine/vehicle system besides giving equivalent performance to that which is achieved with a conventional LOX/LH2 variable mixture ratio engine. During Mode I operation the high pressure nitrogen turbopump (HPNTP) delivers the diluent flow to the main combustion chamber (MCC) for thrust augmentation. In Mode II the HPNTP is shutdown, terminating LN2 flow to the MCC. However, if a small auxiliary nitrogen pump (ANP) stage is installed on the high pressure oxygen turbopump (HPOTP) shaft in place of the interpropellant seal (IPS) a supply of LN2 could be made available during Mode II operation. The implications of this possibility are as follows (see Fig. 10).

<u>IPS Elimination</u>: The ANP can replace the IPS and act as a high pressure buffer between the LOX pump and the fuel-rich turbine. The need for high pressure helium buffer gas is thus eliminated.

<u>LOX Tank Pressurization</u>: A portion of the LN2 source available in Mode II may be converted to a gas for LOX tank pressurization. A nitrogen heat exchanger (HEX) would then replace the LOX HEX, eliminating the safety hazard associated with a fuel-rich gas/LOX HEX.

<u>Pneumatic Gas Supply</u>: The pressurized nitrogen gas can also be used in place of helium as the presurant for the pneumatic actuation system.

<u>Helium System Elimination</u>: The use of nitrogen for buffering, tank pressurization and pneumatic supply allows the elimination of a high pressure helium supply system for the engine. A reduction in system weight, complexity and cost appears possible with this approach.

<u>Bearing Coolant and Thrust Balancer Supply</u>: The ANP can provide LN2 to cool the turbine bearing on the HPOTP and thereby eliminate the need to transfer LH2 from the HPFTP discharge line for this purpose. Additionally, the nitrogen can be used as the pressurant for the HPOTP thrust balancer.

LOX Rub Suppression: The supply of LN2 can also be considered for use as a buffer in LOX areas that might be susceptible to rubbing. Pump labyrinth seals are a typical application area.

The theoretical performance for the nitrogen augmented LOX/LH2 engine is slightly higher than the performance of an oxygen augmented engine as shown in Fig. 11. The lower molecular weight of nitrogen compared to oxygen probably accounts for the increased performance. The lower density of liquid nitrogen (50.4 lb/ft3) compared to liquid oxygen (71 lb/ft3) trades off the gain in perforamnce for a reduction in propellant bulk density, as indicated in Fig. 12.

CYCLE PARAMETRICS

A. PERFORMANCE

Typical engine performance data are given in Tables I and II for cycles SOOFF and SNNFF. These data were generated utilizing the Aerojet Preliminary Engine Design (APED) computer program. The program allows computation of engine performance, flow rate and, power balance data, and sizes components for the determination of engine envelope and component weights.

Parametric power balance data were generated for selected cycles using the APED program. Chamber pressure limits were determined as a function of turbine inlet temperature and pump discharge pressure. Guidelines (see Fig. 13) for propellant circuit pressure drops were kept consistent with previous work on LOX/hydrocarbon engines (Ref. 7). Engine weights are calculated using 1970 technology so that a direct comparison of engine cycles can be made. It should be noted, however, that previous studies have indicated a weight reduction of 26 percent as being feasible when reinforced plastic composites are applied to a liquid rocket engine (Ref. 8).

Plots of LH2 pump discharge pressure versus chamber pressure are given in Fig. 14 for cycle SOOFF. The fuel-rich turbine temperature was maintained constant and the oxidizer-rich turbine temperature was varied. Similar plots were prepared with the oxidizer pump discharge pressure, but in most cases the fuel pump discharge pressure is the limiting parameter. Fig. 15 depicts the variation in LH2 pump discharge pressure with chamber pressure for cycle SOOFF when the fuel-rich turbine temperature is varied and the oxidizer-rich turbine temperature is maintained constant. The curve at a fuel-rich temperature of 1980 deg R is essentially the same for an oxidizer-rich temperature of 1503 deg R.

The chamber pressure limits for cycle SOOFF are 3800 and 3550 psia for pump discharge pressures of 9000 and 8000 psia, respectively. These values correspond to fuel-rich turbine temperatures of 1600 degrees R and oxidizer-rich turbine temperatures of from 1260 to 1785 degrees R. Cycle SOOOF is capable of achieving higher chamber pressures at a pump discharge pressure limit of 8000 psia, but essentially the same chamber pressure at a pump discharge pressure limit of 9000 psia. As shown in Fig. 16 the chamber pressure capability of cycle SOOFF is above 4000 psia if the fuel-rich turbine temperature is increased to 1980 and the oxidizer-rich turbine temperature is 1503 degrees R.

The corresponding chamber pressure limits for cycle SNNFF are 3750 to 3500 psia over a similar turbine temperature range (see Fig. 16). The fuel-rich turbine temperature is controlling the chamber pressure capability. The nitrogen-rich gas temperature from 1438 to 2543 degrees R does not change the pump discharge pressure

Fig. 16 includes the pump discharge pressure for the LOX/LH2 dual expander engine cycle (Fig. 7). The significantly lower pump discharge pressure for a 4000 psia chamber pressure is because of the combination gas generator/staged combustion cycle used for this engine.

B. HEAT TRANSFER LIMIT

The propellant mixture ratio and/or the type of propellants burned in the thrust chamber establishes the combustion gas chemistry. And the gas chemistry in turn can have a profound effect on the maximum heat flux and the chamber pressure structural limit achievable with any given engine cycle. Fig. 17 illustrates how the LOX/LH2 chamber cooling requirements vary with chamber pressure at mixture ratios between 6:1 and 12:1. The SSME operating at a mixture ratio of 6:1 and at a chamber pressure of 3200 psia is indicated for reference. A chamber operating at a mixture ratio of 7:1 is seen to have a slightly higher chamber pressure capability based on the throat heat flux. A chamber operating at a 10:1 mixture ratio (LOX/LH2 or LOX+LN2/LH2) can achieve a chamber pressure of about 3900 psia at this same heat flux. A mixture ratio of 12:1 allows a chamber pressure of about 4300 psia.

Fig. 17 also gives the chamber pressure capability for a LOX/propane/LH2 and an N2O4/MMH propellant combination based on the SSME throat heat flux. The tripropellant engine is able to achieve a chamber pressure of about 4200 psia and the storable propellant engine a chamber pressure of about 5000 psia.

The message given in Fig. 17 is that chamber pressure structural limits should be established based on the cooling requirement of a given propellant combination or mixture ratio and not on an absolute value.

C. MISSION APPLICATION

The previous SSTO vehicle studies (Refs. 1 - 3) have shown a benefit in vehicle dry mass through optimization of the performance-density of the engine and vehicle systems. An indication of this effect might be gained by examining the data plotted in Fig. 18. The figure gives the delivered vacuum specific impulse and bulk density values for several engines operating in two modes. The data for Mode II are essentially equivalent as each engine is burning LOX/LH2 propellants at a mixture ratio of 7.0. The difference in the Mode II values is because of a difference in expansion area ratio.

The engines with the highest bulk density in Fig. 18 are the dual fuel dual expander engines burning LOX/LH2 and subcooled propane. Engines operating at three chamber pressure combinations are shown in the figure. Because of the unique design of this engine, it can operate with two different nozzle expansion area ratios without variable geometry. The higher the chamber pressure capability, the larger the area ratio and the higher the performance in Mode II. A recently completed study (Ref. 9) has confirmed the performance and thermal design of this dual chamber, single nozzle engine.

The engine with the lowest performance in Fig. 18 burns LOX/LH2 at a mixture ratio of 12:1 at a chamber pressure of 4000 psia. The data point is representative of a staged combustion engine cycle such as SOOFF or SOOOF. Its low performance and low density rule out an engine operating at this mixture ratio as being competitive. An engine operating at a mixture ratio of 10:1 and a chamber pressure of 4000 psia, however, delivers higher performance than a dual fuel engine, but at a significantly lower bulk density.

The nitrogen augmented engine SNNFF operating at a mixture ratio of 10:1 and at a chamber pressure of 4000 psia delivers slightly higher performance than its LOX/LH2 clone. There is a small density penalty for the nitrogen augmented engine as seen in the figure.

Fig. 19 illustrates the single-stage-to-orbit (SSTO) mission performance of LOX/LH2 engines operating at different mixture ratios. The vehicle dry mass data are consistent with those reported in Ref. 3, but have been generated using the engine data from Ref. 10 to verify the Aerojet SSTO computer model. As reported in Ref. 3, the minimum in dry mass occurs at an engine mixture ratio between 7:1 and 8:1 for staged combustion engines with an extendible nozzle. The engine area ratio in Mode I is consistent with a one dimensional equilibrium (ODE) nozzle exit pressure of 6.0 psia. In Mode II an extendible nozzle is deployed to provide an area ratio of 150:1.

Mission performance data for variable mixture ratio engines are compared in Fig. 20 with engines at mixture ratios of 7:1, 10:1 and 12:1 from Fig. 19. Also included for comparison are data for parallel burn separate engines and dual expander engines, consistent to data found in Ref. 3. All of the engines, except the dual expander engines, utilize an extendible nozzle in Mode II. The vehicle with dual expander LOX/LH2 engines operating at a mixture ratio of 7:1 has the lowest dry mass (243,000 pounds). The reference single chamber LOX/LH2 engine at a mixture ratio of 7:1 (with extendible nozzle) gives a vehicle dry mass of 250,000 pounds (3 percent increase). The vehicle with variable mixture ratio engines at mixture ratios of 10:1 and 7:1 (series burn) has a larger dry mass (13 percent) than the reference vehicle. The corresponding variable mixture ratio engine at mixture ratios of 12:1 and 7:1 requires a vehicle dry mass increase of 35 percent. The reasons for the lower performance of the variable mixture ratio engines are: (1) the drop in Mode II performance, which results fron the lower (throttled) chamber pressure, and (2) the density increase is not sufficient enough to balance the loss in performance that occurs at mixture ratios greater than 7:1 (see Fig. 18).

The nitrogen augmented engines operate at a LOX/LH2 mixture ratio of 7.94:1 with nitrogen addition to bring the mixture ratio to 10:1 or 12:1. Vehicles utilizing these engines have a dry mass increase of 21 and 40 percent, respectively, as shown in Fig. 20. Although the nitrogen augmented engines are not as high performing as the oxygen augmented engines, they compare favorably when engine system factors are considered.

The application of two separate engines in an SSTO vehicle where one engine operates at a high mixture ratio (10:1 or 12:1) and the other engine operates at a mixture ratio of 7:1 in a sustainer or parallel burn mode is nearly competitive with the single mixture ratio engine at 7:1. The increase in dry mass is 4 and 10 percent, respectively. In this case it is primarily the loss in performance (specific impulse) with only a slight gain in density that penalizes these systems.

The variable mixture ratio dual expander engine at 10:1 and 7:1 and at a chamber pressure of 3500/2500 psia results in a vehicle dry mass increase of 8 percent.

The best LOX/LH2 SSTO engine cycles are compared with dual fuel dual expander engines in Fig. 21. The dual fuel engines shown operate at chamber pressures of 6000/3000, 5000/2500 and 4000/2000 psia. Because the dual expander engines use a combination gas generator and staged combustion cycle they are able to operate at a higher chamber pressure and still require only a pump discharge pressure of less than 7700, 6000 and 4800 psia, respectively. The single chamber engines at a chamber pressure of 4000 psia require a pump discharge pressure of about 10000 psia, beyond the present state-of-the-art of flight weight rocket turbomachinery.

It is seen in Fig. 21 that the dual fuel dual expander engine vehicle dry mass is 16 percent less than the single chamber engine at a mixture ratio of 7:1. The vehicle dry mass for a mixture ratio 7:1 single fuel dual expander engine is 3 percent less than the single chamber engine at a mixture ratio of 7:1.

CONCLUSIONS

The conclusions from this study are that the variable mixture ratio LOX/LH2 engine is feasible. The dual chamber (dual expander) engine at a mixture ratio of 7:1 is the optimum performer providing 3 percent less dry mass than the reference engine. The single chamber variable mixture ratio (MR = 10/7:1) engine requires an extendible nozzle and is a higher risk approach. The vehicle dry mass for the single chamber engine is 13 percent greater than the reference engine. The liquid nitrogen augmented engine offers a significant number of engine and vehicle system advantages.

The fixed mixture ratio (MR = 7:1) reference engine with extendible nozzle is a good performer with a vehicle dry mass of 250,000 pounds. The optimum mixture ratio for SSTO missions appears to be 7:1 based on the results of the study.

The dual fuel dual expander engine burning LH2 and propane with LOX is superior to the LOX/LH2 engines giving a vehicle dry mass 16 percent less than the reference engine. Propellant density and the delivered thrust-over-trajectory are the major factors in the performance of this engine.

Third fluid engines offer reliability advantages. They provide high margin cycle options with inert drive and coolant fluids. Their significant system advantages indicate a need for further study of these types of engine cycles.

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Figure 1. SSTO Mission Engine Options (VTOHL)

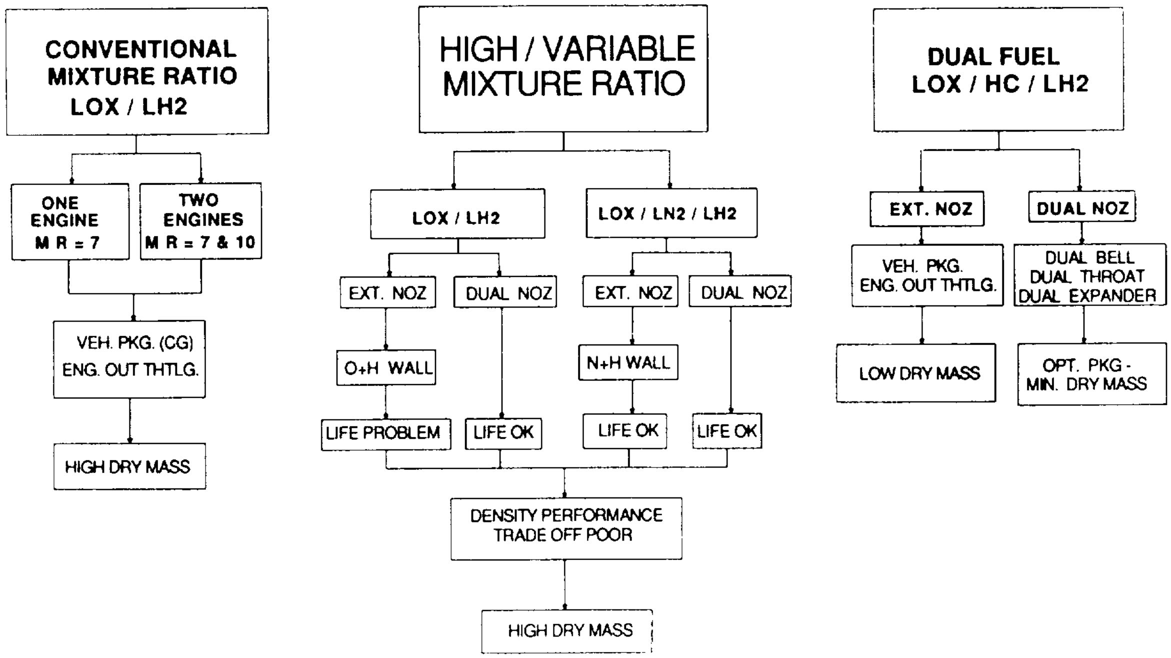


Figure 2. Reuseable Airplane To Space

Figure 3. STME Staged Combustion Cycle Engine System Schematic

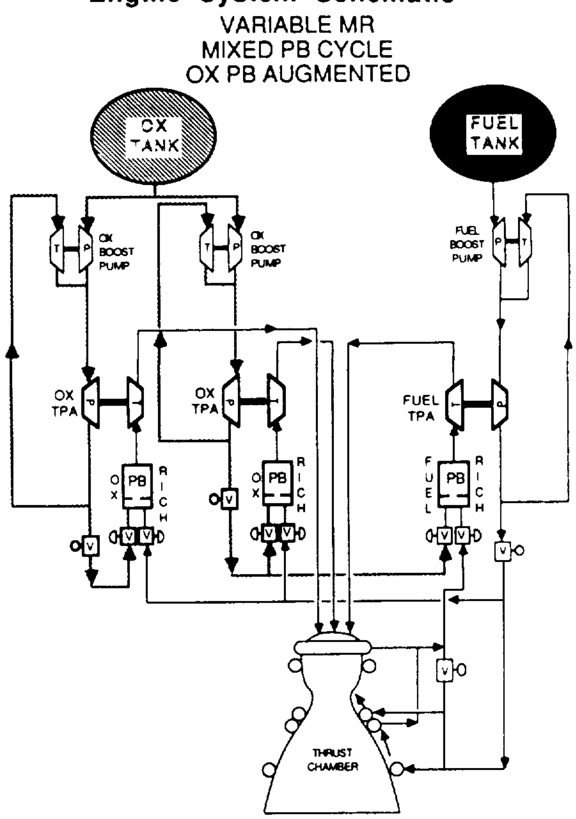


Figure 4. LOX/LH$_2$ Engine Performance Decreases Rapidly After Mixture Ratio of 7 ODE Pe=6.0

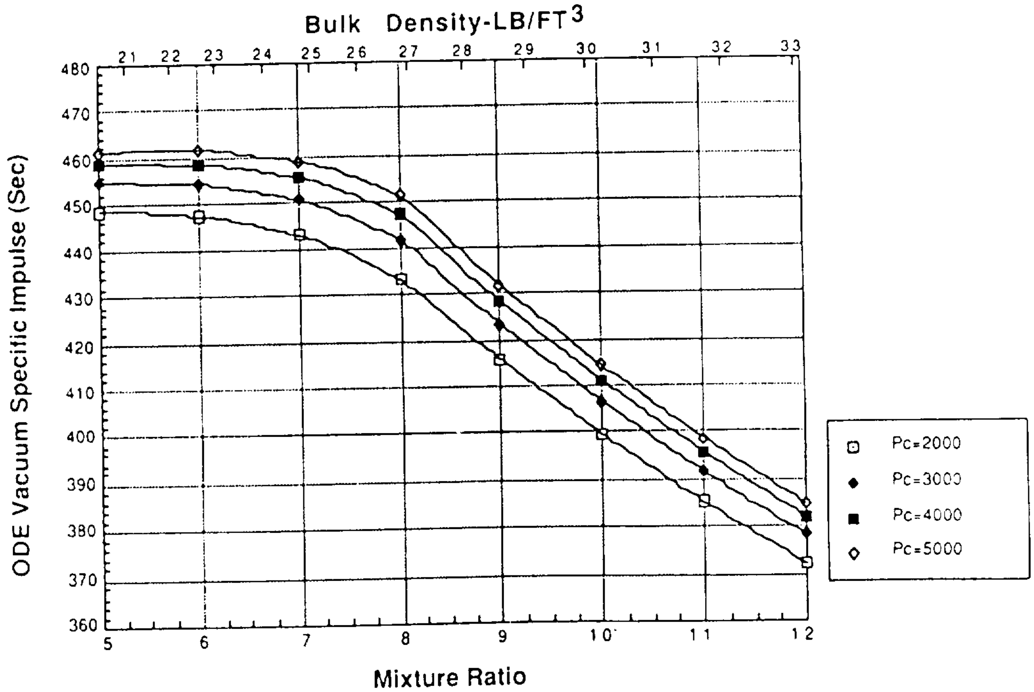


Figure 5. Typical Point Design Engine Performances is Shown as a Function of Mixture Ratio ODE Pe=6.0

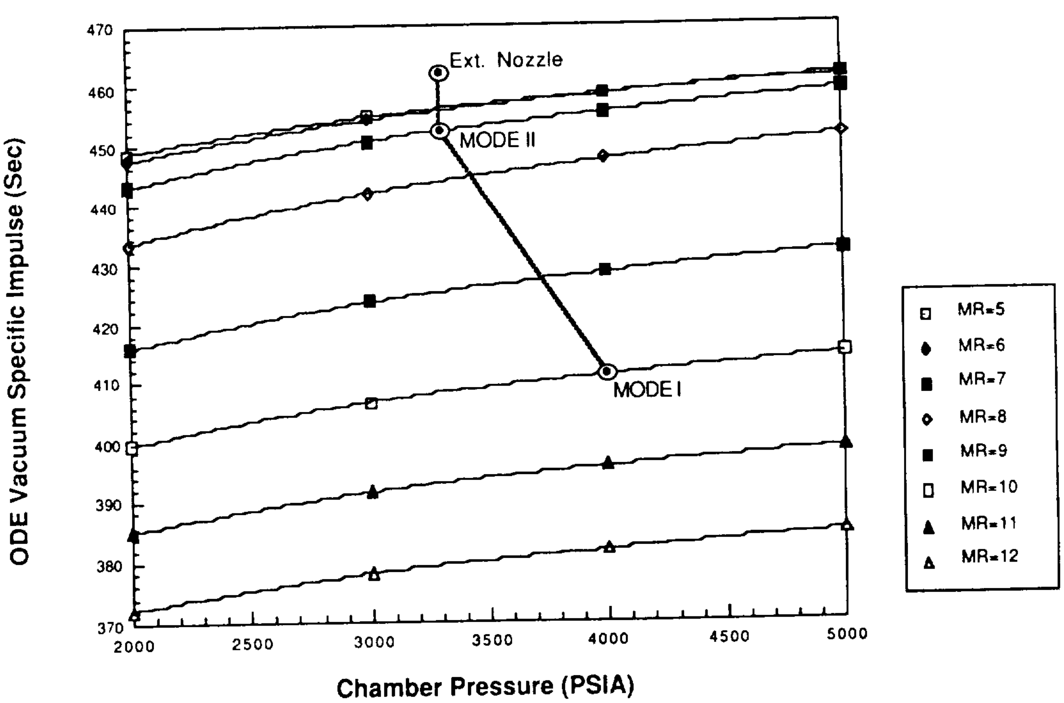


Figure 6. STME Staged Combustion Cycle Engine System Schematic

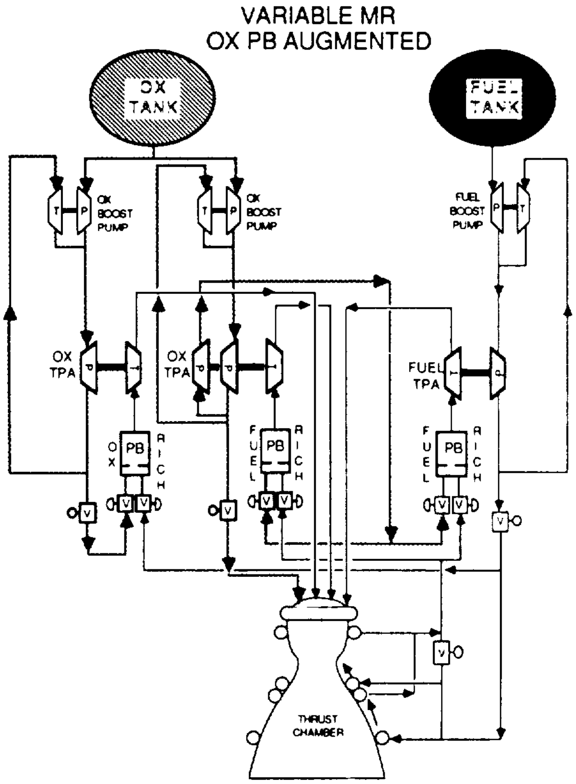


Figure 7. STME LO_2 /LH_2 Dual Expander Cycle Engine, SC/GG System Schematic

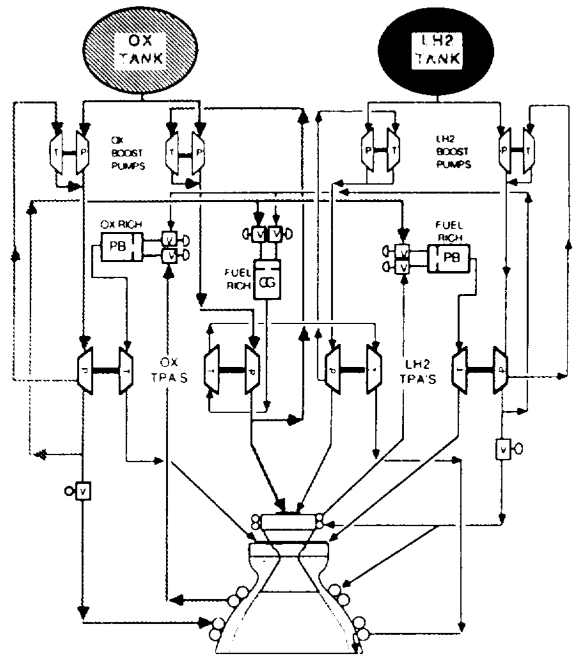


Figure 8. Gas Bubble Grain Boundary Cracks in Silver

TWO CYCLES AIR + H_2 **THREE CYCLES AIR + H_2**

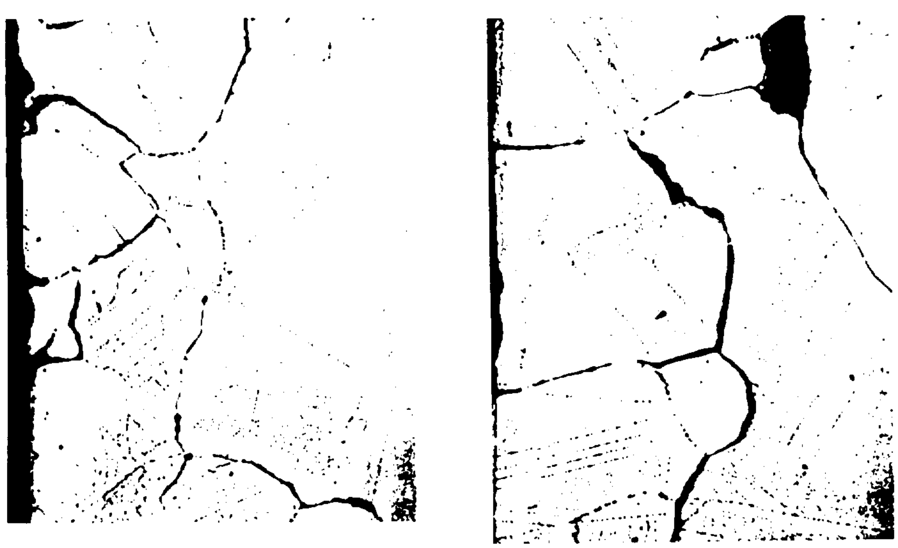
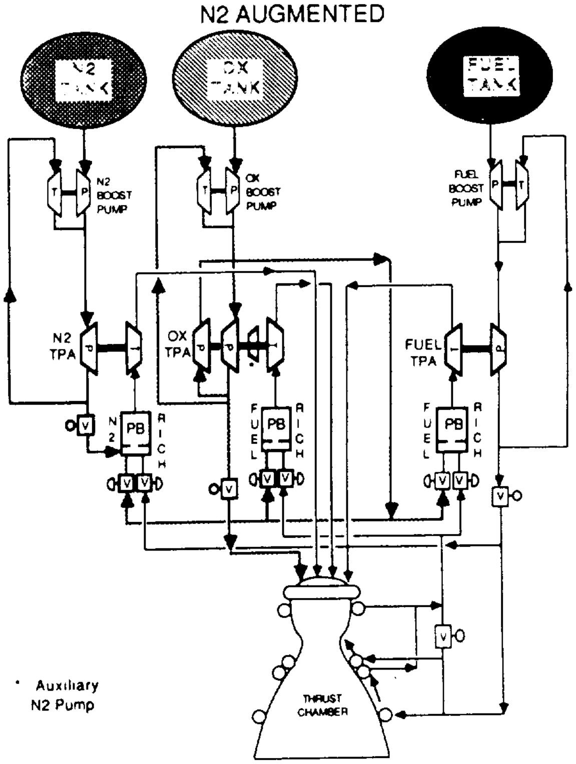


Figure 9. STME Staged Combustion Cycle Engine System Schematic

N2 AUGMENTED



* Auxiliary N2 Pump

Figure 10. N_2 Augmentation Benefits

- SAFE, RELIABLE ENGINE SYSTEM
  - NO OX-RICH ENVIRONMENT
  - NO LOX TPA INTERPROPELLANT SEAL
  - NO LOX/FUEL-RICH HEX FOR TANK PRESSURIZATION
  - LOX TPA RUB SUPPRESSION FLUID
  - INERT BEARING COOLANT
- ENGINE/VEHICLE SYSTEM
  - PNEUMATIC GAS SUPPLY (REPLACE HELIUM)
  - THERMAL MANAGEMENT OF VEHICLE SURFACES
  - RADOME COOLING

Figure 11. Comparison of Effect of Excess Nitrogen and Excess Oxygen on Vacuum ODE Performance

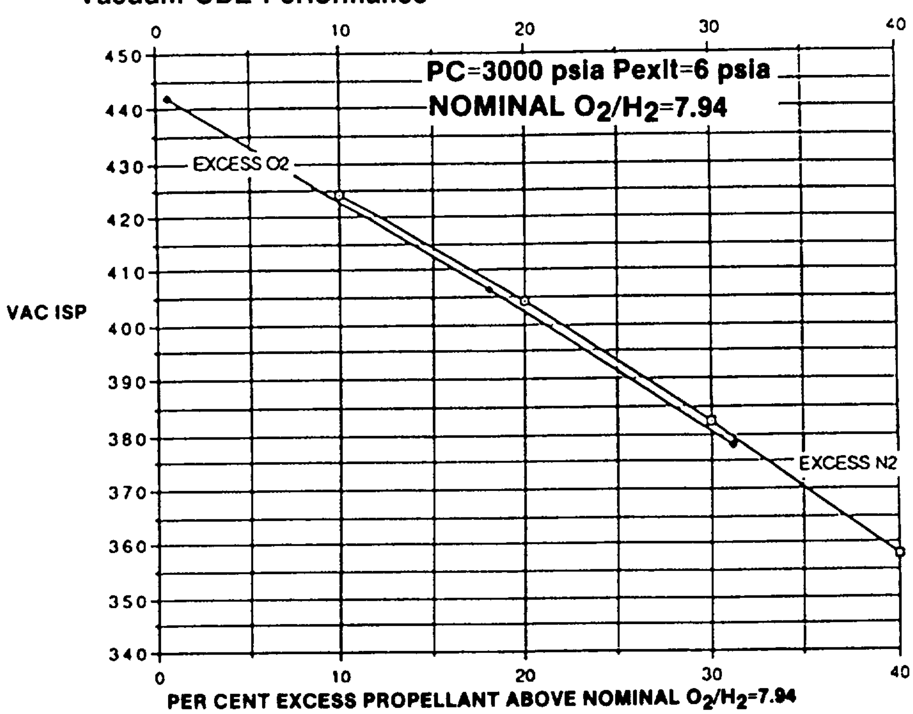


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Figure 12. Nitrogen Addition Cycles Trade Off Bulk Density for System Operational Benefits

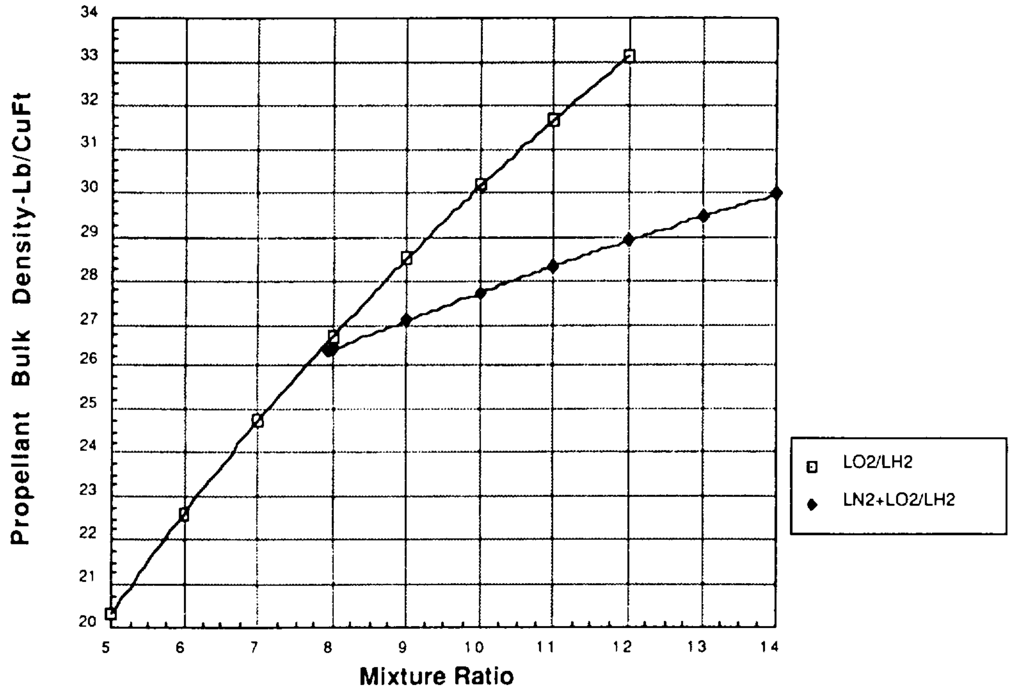

Table I. Staged Combustion Cycle SOOFF.4.10.7 Propellants LOX/LH_2

STAGED COMBUSTION CYCLE SOOFF.4.10.7

PROPELLANTS LOX/LH2

	MODE I	MODE II	MODE II EXT NOZ
THRUST (SL)	667371.00	521202.	415020.
THRUST (VAC)	750112.19	603366.	625085.
MIXTURE RATIO	10.00	7.00	7.00
AREA RATIO	58.67	58.67	150.0
CHAMBER PRESSURE	4000.00	3229.	3229.
ODE ISP (SL)	366.50	--	--
ODE ISP (VAC)	411.10	455.6	472.0
DEL ISP (SL)	359.17	385.7	307.1
DEL ISP (VAC)	403.70	446.5	462.6
ISP EFFICIENCY (SL)	0.980	--	--
ISP EFFICIENCY (VAC)	0.982	0.980	0.980
TOTAL FLOW RATE	1858.09	1351.36	1351.36
LOX FLOW RATE	1689.17	1182.44	1182.44
FUEL FLOW RATE	168.92	168.92	168.92
ODE CSTAR	6667.00	7404.	
DEL CSTAR	6600.33	7330.	
CSTAR EFFICIENCY	0.990	0.990	
THROAT AREA	95.29	95.29	95.29
EXIT AREA	5590.93	5590.93	14294.
ODE EXIT PRESSURE	6.00	4.70	--
THROAT DIAMETER	11.02		--
EXIT DIAMETER	84.37		--
ENGINE WEIGHT (1970 TECHNOLOGY)	9767.		

Table II. Staged Combustion Cycle SNNFF.4.10.7 Propellants LOX/LN_2/LH_2 Chamber Pressure=4000

STAGED COMBUSTION CYCLE SNNFF.4.10.7

PROPELLANTS LOX/LN2/LH2 COOLED
CHAMBER PRESSURE = 4000.

	MODE I	MODE II	MODE II EXT NOZ
THRUST (SL)	665529.0	518775.	414078.
THRUST (VAC)	750111.5	602714.	623915.
MIXTURE RATIO	10.00	7.0	7.0
AREA RATIO	60.00	60.0	150.
CHAMBER PRESSURE	4000.00	3227.	3227.
ODE ISP (SL)	366.20	--	--
ODE ISP (VAC)	411.90	456.0	472.0
DEL ISP (SL)	358.88	384.6	307.0
DEL ISP (VAC)	404.49	446.9	462.6
ISP EFFICIENCY (SL)	0.980	--	--
ISP EFFICIENCY (VAC)	0.982	0.980	0.980
TOTAL FLOW RATE	1854.48	1348.71	1348.71
LOX FLOW RATE	1338.01	1180.13	1180.13
FUEL FLOW RATE	168.59	168.59	168.59
LN2 FLOW RATE	347.88	0.0	0.0
ODE CSTAR	6673.00	7404.	
DEL CSTAR	6606.27	7330.	
CSTAR EFFICIENCY	0.990	0.990	
THROAT AREA	95.19	95.19	95.19
EXIT AREA	5711.70	5711.70	14278.5
ODE EXIT PRESSURE	5.85	4.72	
THROAT DIAMETER	11.01		
EXIT DIAMETER	85.28		
ENGINE WEIGHT (1970 TECHNOLOGY)	10154.		

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Figure 13. Power Balance/Engine Weight Guidelines

INJECTOR ΔP	LIQUID	15%
	GAS	8%
VALVE ΔP	SHUTOFF	1%
	LIQ. CONTROL	5%
	GAS CONTROL	10%
LINE LOSS		0.5%
MAIN PUMP SUCT. SPEC. SPEED		20,000
COMP. WEIGHT TECHNOLOGY		1970

Figure 14. Cycle SOOFF Power Balance

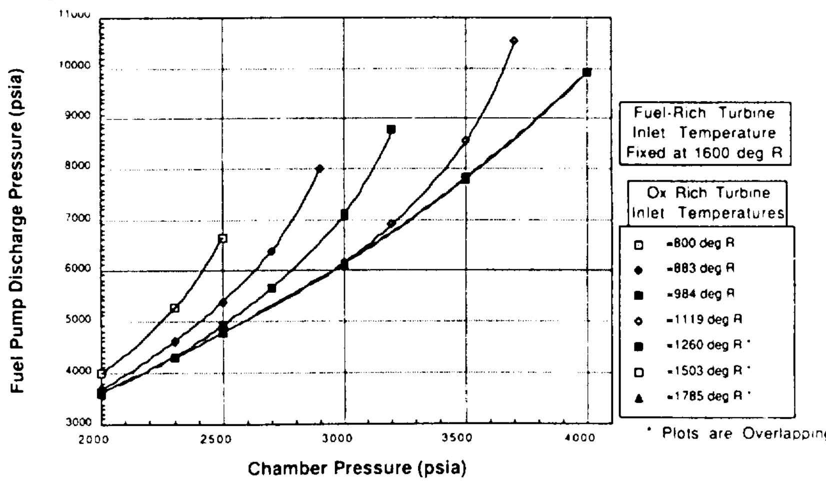

Figure 15. Cycle SOOFF Power Balance

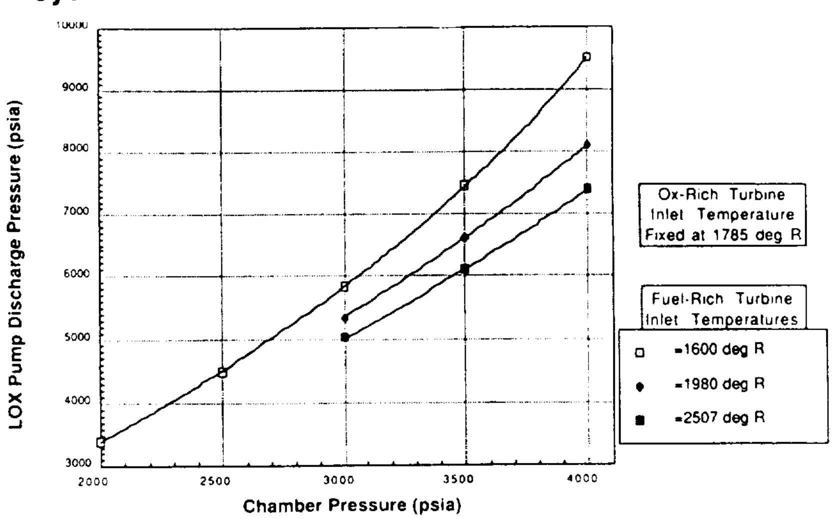

Figure 16. Chamber Pressure Limits

CYCLE	P_D LIMIT (PSIA)	Pc LIMIT (PSIA)	TTFR (DEG R)	TTOR (DEG R)
SOOFF	10000	4000	1600	1260
	9000	3800		
	8000	3550		
	9000	4100	1980	1503
	8000	3800		
SNNFF	10000	3950	1600	1438
	9000	3750		
	8000	3500		
DE43H	7400	3000	1600	1260
		4000		

Figure 17. Throat Heat Flux Indicates Chamber Cooling Requirements

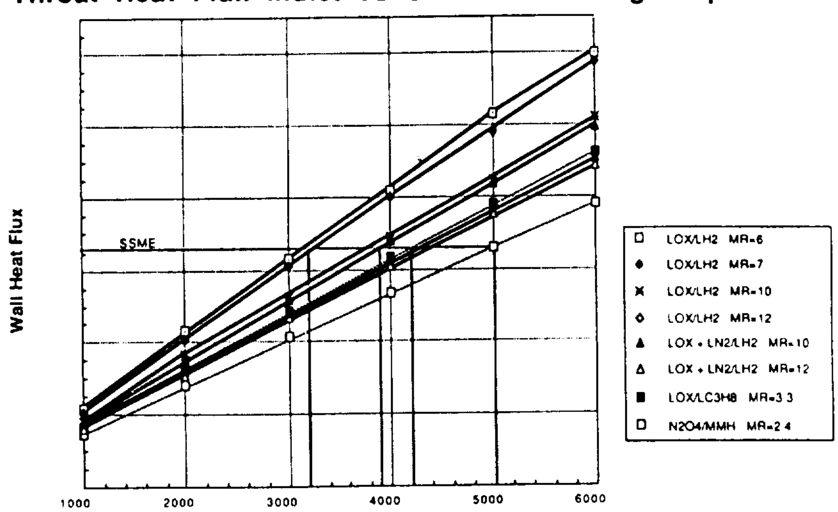

Figure 18. Comparison of Engine Types Illustrate Trade Off of Performance with Propellant Bulk Density

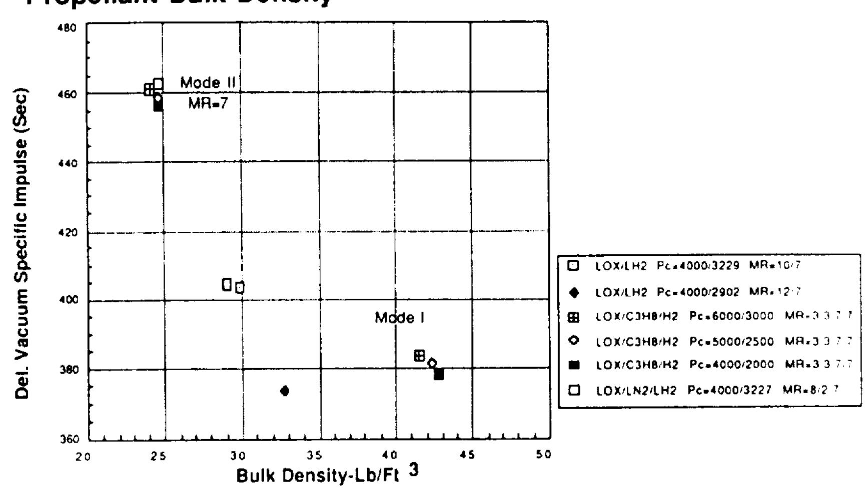

Figure 19. Single Stage to Orbit LOX/LH_2 Engine Optimum Mixture Ratio (ref.3)

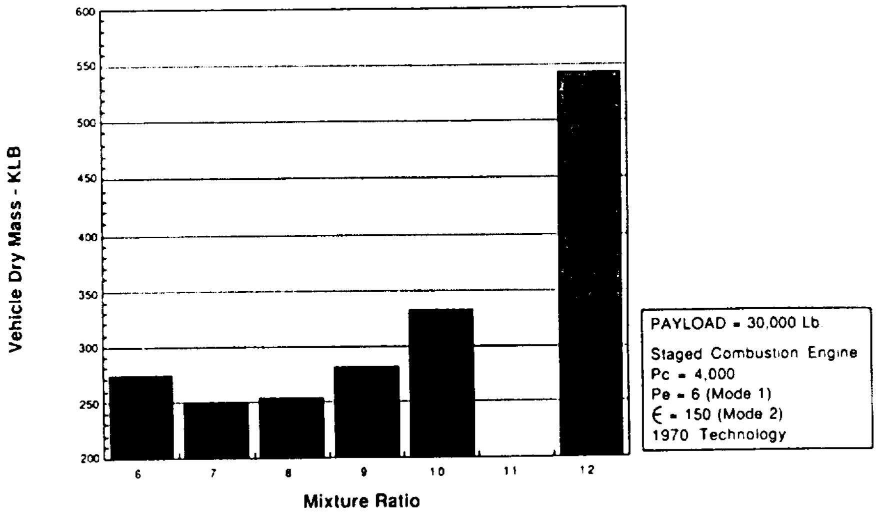

Figure 20. SSTO High/ Variable Mixture Ratio LOX/LH_2 Engines

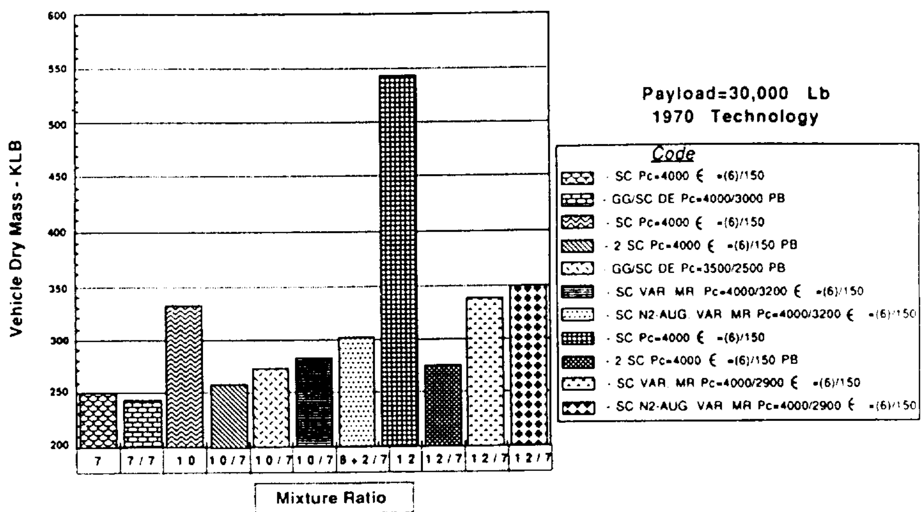

Figure 21. SSTO Engine Comparison