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Evaluation of Proposed Rocket Engines for Earth-to-Orbit Vehicles

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Abstract

The objective of this paper is to evaluate recently analyzed rocket engines for advanced Earth-to-orbit vehicles. The engines evaluated are full-flow staged combustion engines and split expander engines, both at mixture ratios at 6 and above with oxygen and hydrogen propellants.The vehicles considered are single-stage and two-stage fully reusable vehicles and the Space Shuttle with liquid rocket boosters. The results indicate that the split expander engine at a mixture ratio of about 7 is competitive with the full-flow staged combustion engine for all three vehicle concepts. A key factor in this result is the capability to increase the chamber pressure for the split expander as the mixture ratio is increased from 6 to 7.

Introduction

Development of a new liquid rocket engine for Earth-to-orbit vehicles will be a significant step, in terms of both the cost of the development and the potential impact on the vehicles of the future. Once a new engine is selected and developed, there may be insufficient justification for developing another engine for many years. Candidates may be satisfactory for some vehicles but less satisfactory for others. For these reasons, it is important to consider how potential engines can affect various potential future vehicles before the engine selection is made.

For several years, evaluations of various engine cycles have been conducted and reported (Refs. 1-7). In Refs. 1-4, engines analyzed by major engine manufacturing companies were evaluated. In Refs. 5 and 6, a combined engine and vehicle capability was developed and used. More recently, additional studies of certain cycles that had not been sufficiently analyzed in the previous efforts were initiated. The first results of this effort are reported in Ref. 7.

The vehicles considered in Refs. 1-7 included fully reusable single-stage and two-stage concepts as well as a heavy-lift concept with a reusable flyback booster. The recent effort has been expanded to include liquid-rocket boosters for the Space Shuttle. If the Space Shuttle is to be used into the next century, there may well be reason to develop liquid boosters for safety, environmental, economic, and performance reasons. Any new liquid engine should be considered as a candidate for such boosters.

Two rocket engines cycles were evaluated in the study reported herein, a variation of a staged combustion cycle called full flow (all propellants flow through turbines) and a split expander cycle. Both cycles were considered at fixed

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mixture ratios (ratio of oxidizer to fuel mass flow) from 6 to 9 and with variable mixture ratios Variable mixture ratio is of interest because it can provide a high thrust level and bulk density at liftoff while also providing a high specific impulse later in the flight.

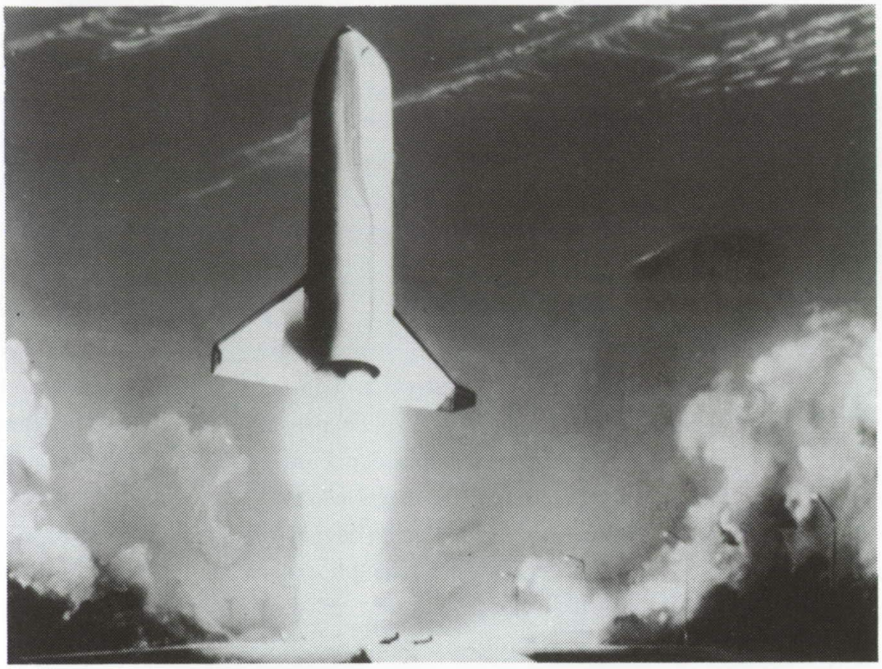

Fig. 1 Illustration of single-stage vehicle.

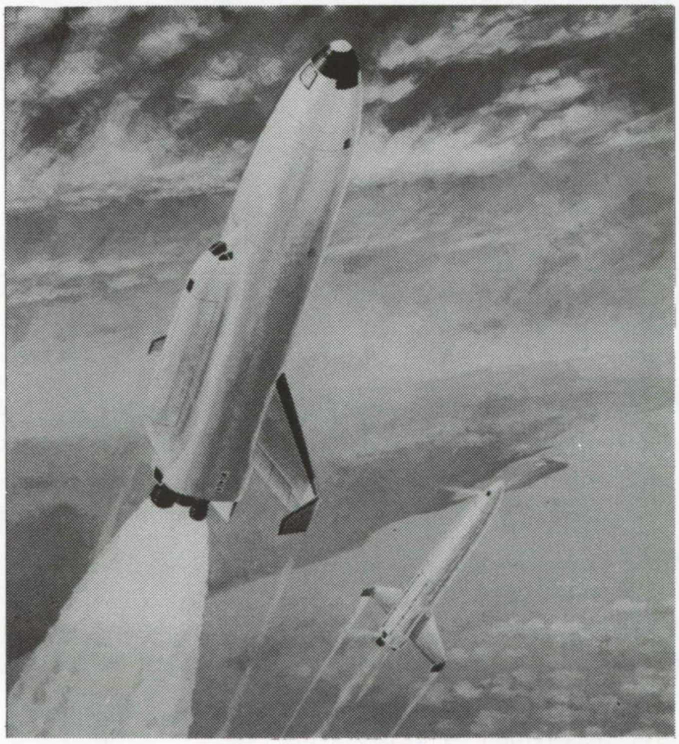

Fig. 2 Illustration of two-stage fully reusable vehicle.

Vehicle Descriptions

The single-stage vehicle, which is illustrated in Fig. 1 and described in Refs. 1-6, is a vertical-takeoff, horizontal-landing concept. The body shape is basically circular to accommodate the propellant tanks. The wings are a modified delta shape with tip-fin controllers. The ascent propulsion is provided by the rocket engines which are varied in this study. There is no air-breathing propulsion for ascent or for landing.

The two-stage fully reusable vehicle system is shown in Fig. 2 just after booster staging. This vehicle also takes off vertically and lands horizontally. The orbiter and booster are mounted parallel with the base of both vehicles in the same plane at liftoff. The shape of each stage is the same as the shape of the single-stage vehicle in the analysis. In this paper, all of the calculations are for parallel burn with crossfeed of propellants from the booster to the orbiter, and the staging Mach number is 3.0 so that the booster can glide back to the launch site.

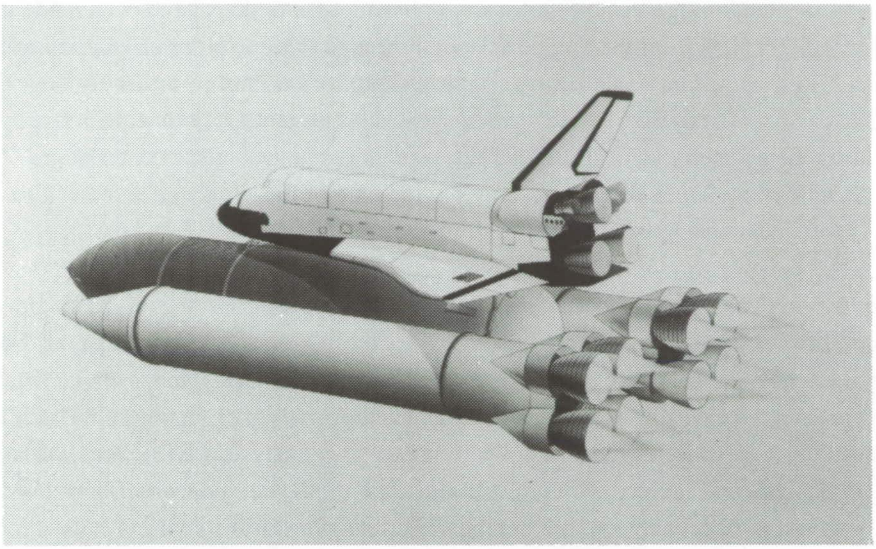

Fig. 3 Illustration of Space Shuttle with liquid rocket boosters.

Booster reference length - 58.58 m

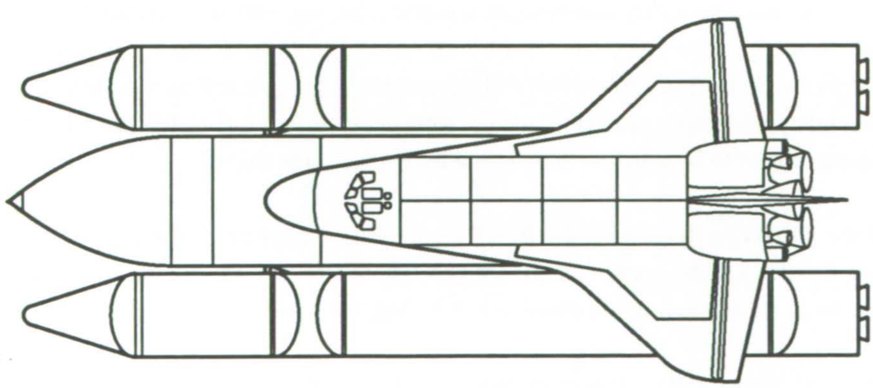

Fig. 4 Schematic of contractor baseline Space Shuttle with liquid rocket boosters.

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The Space Shuttle liquid rocket booster (LRB) concept (Ref. 8) is illustrated in Figs. 3 and 4. The solid rocket boosters are replaced with liquid boosters that provide a payload of 32 Mg. The LRBs are expendable in this analysis and in Ref. 8.

Vehicle Analyses

The single-stage vehicle analysis consists of three sections. The first section is the modelling of the engine thrust, specific impulse, and engine weight data for the trajectory analysis and vehicle sizing. The second section is the trajectory optimization, using the Program to Optimize Simulated Trajectories (POST) described in Ref. 9. The final section is the vehicle sizing in which structure and subsystem masses are calculated; the vehicle size is changed to match the propellant, subsystem, and payload volume requirements; and the propulsion system is scaled to match the liftoff thrust-to-weight ratio. Further discussion of the analysis is presented in Refs. 1-6.

In the analysis of the single-stage vehicle, several simplifying assumptions have been made in order to allow a calculation that proceeds forward from the engine selection through the trajectory calculation to the vehicle sizing without iterating back to the trajectory calculation. These assumptions do not significantly alter the comparison of engines which, is the goal of this analysis. The vehicle shape was held constant. Only changes in size by photographically enlarging or decreasing the geometry were allowed. Thus, no changes in the vehicle center of gravity were calculated to determine aerodynamic trim effects. Also, the changes in the ratio of the wing area to the vehicle mass that change aerodynamic effects were not considered.

The analysis of the orbiter of the two-stage concept is essentially identical to that of the single-stage vehicle. The booster analysis is modified in that the payload mass is the mass of the orbiter, and there is no payload volume. A problem that could lead to a need to iterate the entire analysis is that the booster mass at staging is not known before the vehicle sizing. If the booster mass is incorrect, the thrust-to-weight ratio of the orbiter after staging could be different for the sized vehicle than for the vehicle in the trajectory analysis. When the two-stage analysis was first used, the booster staging mass was changed, and the analysis was iterated. After several calculations, the iteration was dropped because the effect on the vehicle results was insignificant and constant among various engines. If the analysis is used for vehicles that are significantly different from each other, this iteration should be included in the analysis.

The sizing of the LRB uses the same trajectory optimization program, POST (Ref. 9) The vehicle sizing analysis uses WAMI (Ref. 10) to calculate the booster dry mass and volume. The geometry of the booster was changed photographically as in the reusable vehicles. The Space Shuttle orbiter and tank are not changed.

The LRB results, including geometry and subsystem masses (Ref. 8), were used as initial conditions for the present LRB analysis. The ascent aerodynamics were calculated using the same computer program This program uses aerodynamic data from the Space Shuttle program and increments that data based on wind tunnel tests with LRBs. For the calculations presented in this paper, the aerodynamics were not modified as the LRB size varied; thus trajectory drag loss increments were assumed to be small and negligible for engine trade studies.

The results of the present analysis using the Ref. 8 engine data are shown in Table I. Although the input booster propellant mass and booster jettison mass matched the baseline in Ref. 8, a greater mass was injected into orbit The insertion mass must be 161.6 Mg to provide a payload of 32 Mg, but a mass of nearly 165 Mg was inserted.

The difference in the results is in the trajectory analysis. The limits on $q\alpha$, the product of the dynamic pressure and the angle of attack, are shown in Fig. 5. The Ref. 8 limits were input in the Mach number range from 0.5 to 2.0. At a Mach

Table I Comparison of Results with Contractor Baseline Engines.

Both boosters

	Ref. 8 baseline	Current (initial)	Current (sized)
Booster usable propellant mass, Mg	627.5	628	595
Booster jettison mass (input), Mg	116.9	116.9	113
Booster jettison mass (required), Mg	116.9	118.1	113.2
Booster dry mass, Mg	110.6	111.7	107
Booster gross mass, Mg	771	785	746
Orbiter + external tank gross mass, Mg	882	882	882
Orbiter + external tank inert mass, Mg	161.6	164.9	161.6
Payload mass, Mg	32	35.3	32
Gross mass, Mg	1653	1667	1628
Booster reference length, m	53.58	53.90	52.98

number of about 2.2, the $q\alpha$ limit increases to a value of 0. Above that Mach number, no limit was shown. The Ref. 8 trajectory was shown as following the $q\alpha$ limit for the Mach number range from 0.5 to 2.2 and did not have a limit from Mach 2.2 to staging. In the present analysis, a constant $q\alpha$ limit was imposed from Mach 2.2 to staging to avoid large negative $q\alpha$ values in this range. The current trajectory did not have such large negative values of $q\alpha$ as compared to Ref. 8 and continued to have negative values in the Mach number range from 2.2 to 5. These negative values of $q\alpha$ are probably not a problem because the normal force was only about half the normal force near Mach 1, as shown in Fig. 5. Further trajectory and structural analysis would be required to resolve these differences, but the relative impact on the engine comparisons of interest for this investigation are not believed to be significant.

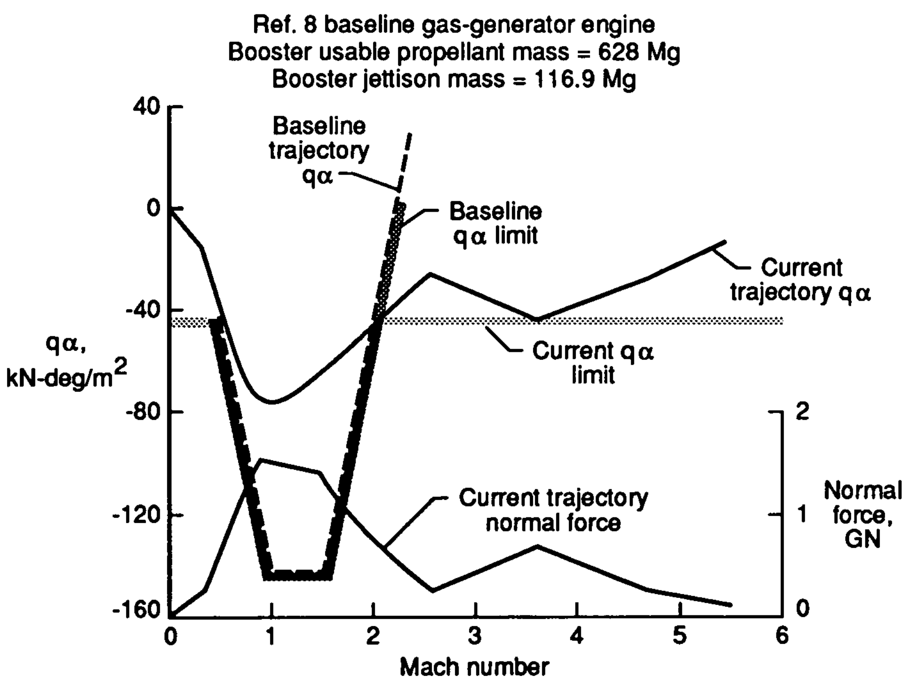

Fig. 5 qα constraint.

In the earlier studies of reusable vehicles (Refs. 1-7), the trajectory and vehicle sizing analysis was not iterated to obtain a matching solution. The analysis could proceed from input forward to the solution because the major sizing parameters of thrust-to-weight ratio and mass ratio were satisfied in the sizing procedure. In the LRB analysis, iterations of the entire analysis must be performed where both the booster propellant mass and the booster jettison mass are varied. One reason is that the orbiter and external tank mass, thrust, and propellant are fixed; and the sizing analysis can not allow resizing of the entire vehicle to meet the required payload. To obtain the correct payload, the booster propellant mass and the booster jettison mass were adjusted to reach an iterated solution. The LRB results presented in this paper have all been iterated to such a matched solution.

A comparison of the baseline LRB in Ref. 8 with the current results is given in Table I. The comparison between the Ref. 8 baseline booster dry mass of 110.6 Mg and the initial current results, 111.7 Mg, shows that the current analysis matched the baseline within 1 percent with the same booster propellant mass The sized results show that the booster dry mass is reduced to 107 Mg in order to meet the required payload. The required booster jettison mass was essentially equal to the input value indicating a converged solution.

Fixed Mixture Ratio

Two engine cycles were examined at fixed mixture ratios from 6 to 9. The full-flow staged combustion engine is similar to the Space Shuttle Main Engine (SSME) except that the oxygen pump is powered by an oxygen-rich preburner. This has the result that all of the propellants can be used for pump power, and the turbine inlet temperatures can be reduced

Table II Split Expander Engine Data (Ref. 7).

Vacuum thrust = 2091 kN

Mixture ratio	6	7	7	8	9
Vacuum specific impulse, sec	436.3	426.7	434.4	422.7	406.5
Chamber pressure, MPa	8.27	8.27	10.34	10.34	10.34
Expansion ratio	33	33	40	40	40
Throat area, cm^2	1348	1330	1048	1039	1042
Mass, kg	2071	2027	1960	1924	1931

Table III Full Flow Staged Combustion Engine Data (Ref. 7).

Vacuum thrust = 2091 kN
Chamber pressure = 20.68 MPa
Expansion ratio = 77.5

Mixture ratio	6	7	9
Vacuum specific impulse, sec	453.0	448.5	421.0
Throat area, cm^2	522.7	511.2	506.1
Mass, kg	2381	2378	2355

significantly. Another use of the cycle is to increase the chamber pressure. In general, the performance is not much different than the SSME at the same chamber pressure, and the mass may also be nearly the same. The difference is a potential increase in reliability as a result of the decreased turbine inlet temperatures. The questions that must be answered are whether or not the oxygen-rich turbine drive gas creates a hazard and how well the injector will work with two warm gas streams.

The split expander cycle is similar to the expander cycle that has been used for several years on the RL-10 engine for the Centaur stage. The expander cycle is believed by many to have an inherent reliability advantage because there are no secondary combustion devices operating at mixture ratios far from stoichiometric. The expander cycle has an inherent limitation to the chamber pressure because the energy that can be absorbed by the coolant is the only energy available for pump power. The split expander is a variation that increases the maximum chamber pressure at thrust levels of 400 kN or greater. In the split expander, all the hydrogen is not pumped to the highest pressure and used for cooling. Some of it is sent directly to the main chamber.

The engine data for the two cycles are presented in Tables II and III from Ref. 7. Increasing the mixture ratio above 6 is quite attractive with the split expander engine. High mixture ratios may lead to problems in cooling the high-pressure staged combustion engine, but with the split expander engine, the chamber pressure is so low that cooling is probably not a problem. The higher combustion temperature increases the energy absorbed, which allows a higher chamber pressure. The increased bulk density not only improves the vehicle results, but it also reduces the pump power required, which allows a higher chamber pressure as well.

The vehicle dry mass is shown in Figs. 6, 7, and 8 for the single-stage vehicle, the two-stage vehicle, and the LRB,

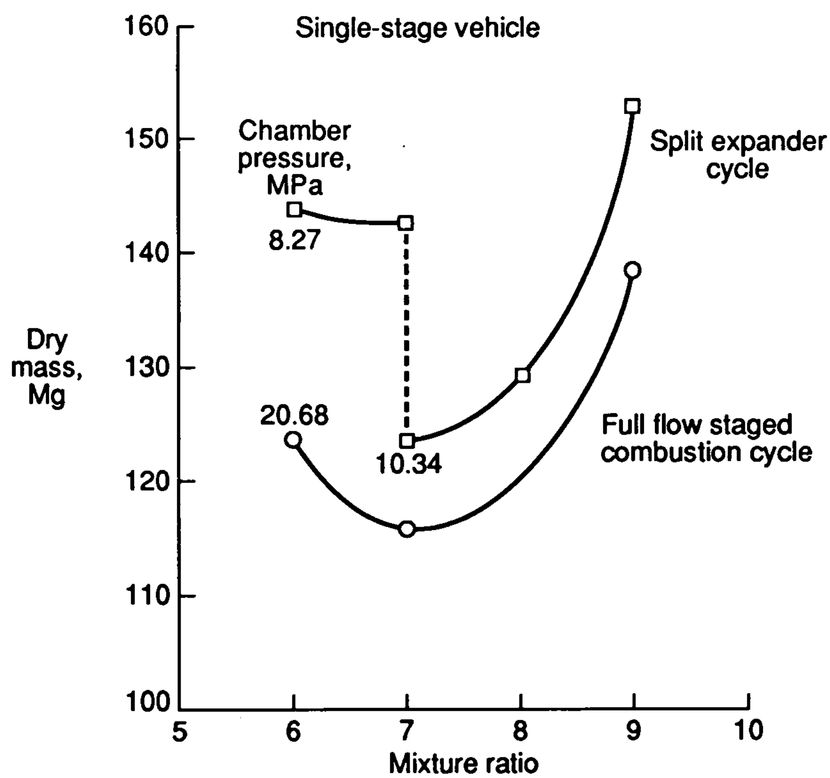

Fig. 6 Effect of cycle on mixture Ratio trends for Single-stage vehicle.

respectively. In general, the split expander at a chamber pressure of 8.27 MPa is less attractive, but the increase in chamber pressure to 10.34 MPa at a mixture ratio of 7 improves the results considerably. The staged combustion engine results in the lower dry mass for the single-stage vehicle at any single mixture ratio (Fig. 6). However, if the engine cooling requirements limit the mixture ratio of the staged combustion engine to about 6, the split expander could provide the same dry mass. For the two-stage concept, the dry mass is approximately the same for both the split expander and the staged combustion systems at a mixture ratio of 7. For the LRB, the dry mass is less with the split expander engine than with

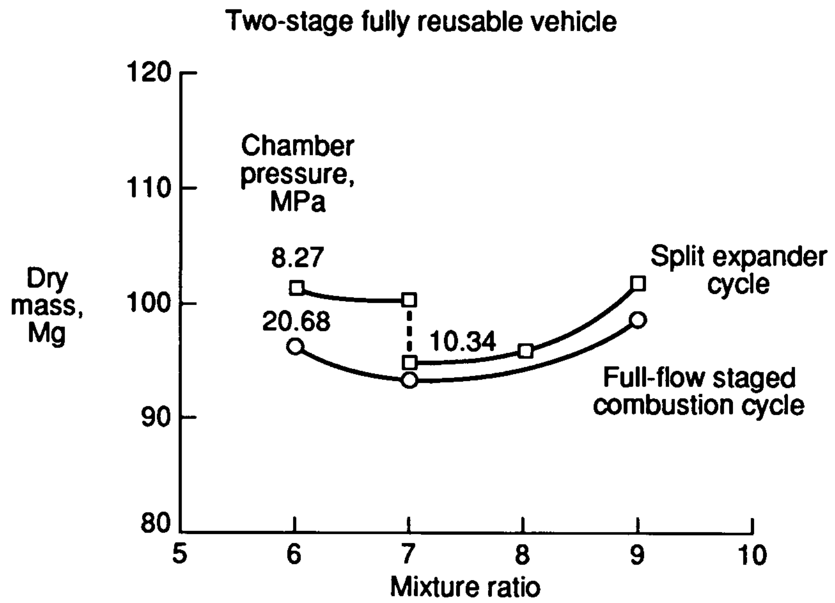

Fig. 7 Effect of cycle on mixture ratio trends for two-stage fully reusable vehicle.

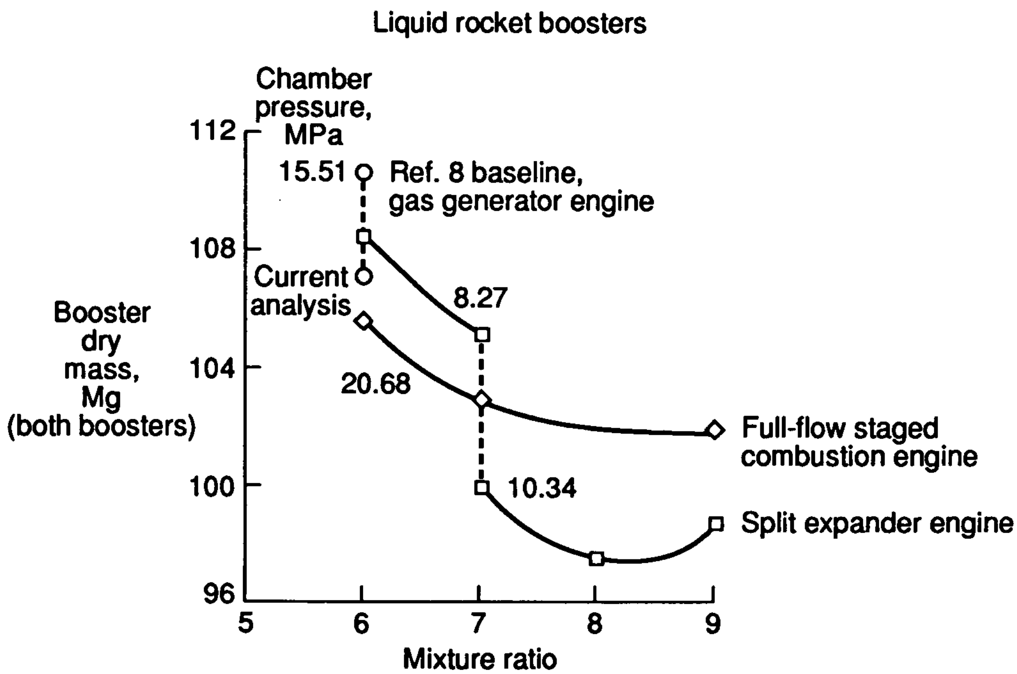

Fig. 8 Effect of engine on dry mass trends for liquid rocket boosters.

the staged combustion engine. The expansion ratio has not been optimized for either engine, which could change these results somewhat.The designs have comparable exit pressures and are both overexpanded for the LRB. As shown in Fig. 9, the gross mass favors the staged combustion engine because it has the highest specific impulse. The booster length trends (Fig. 10) show that the split expander at higher mixture ratios can be competitive with the staged combustion engine if cooling constrains the latter to a mixture ratio of 6.

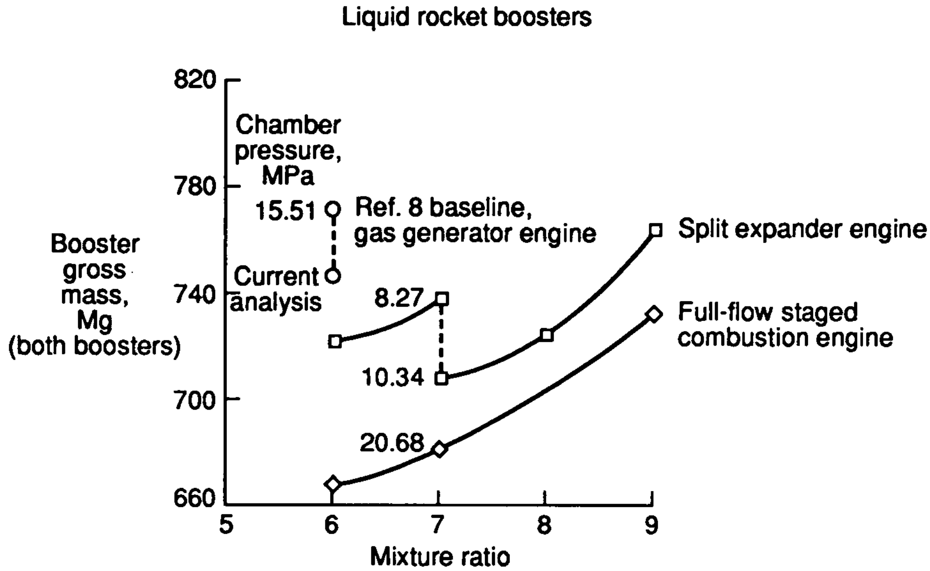

Fig. 9 Effect of engine on gross Mmass trends.

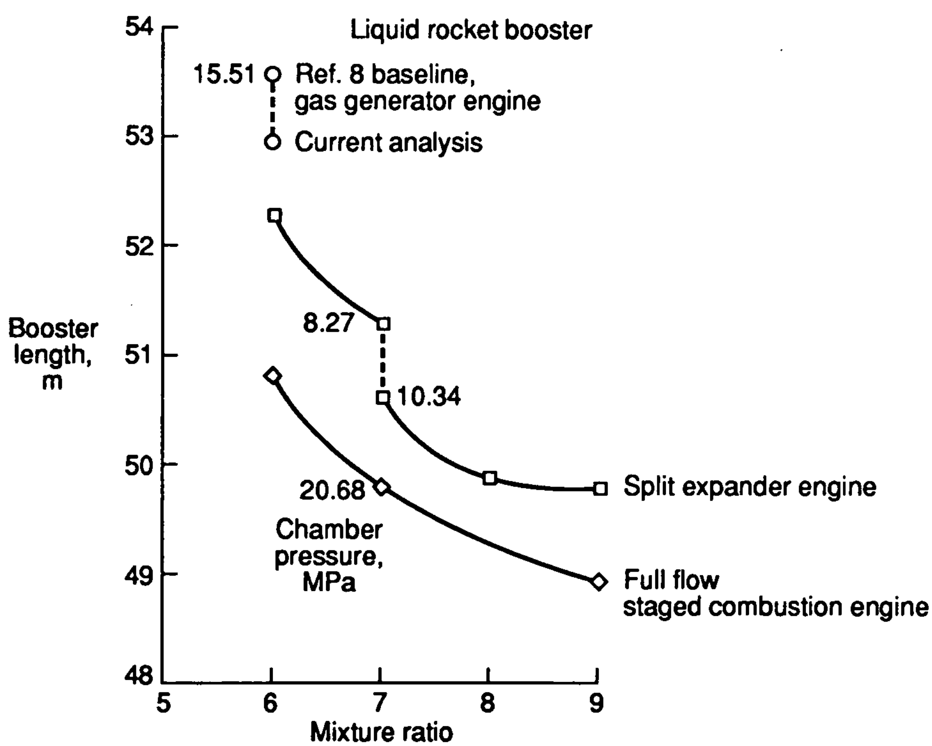

Fig. 10 Effect of engine on booster length trends.

The LRB results include the gas generator engine used in Ref. 8. Because the engine data come from different sources, there may be aspects that are not directly comparable. In general, the gas generator results are less attractive than the other engines. Note that a mixture ratio of 6 for the gas generator engine represents a mixture ratio in the main chamber of about 6.7. Increasing the mixture ratio would probably lead to cooling problems.

Based on the results shown, the split expander engine at a mixture ratio of 7 and a chamber pressure of 10.34 MPa appears quite attractive for all three vehicle concepts. Further verification of the engine data appears worthwhile.

Variable Mixture Ratio

Both the full-flow staged combustion engine and the split expander engine were examined as variable mixture ratio engines as well as fixed mixture ratio engines. The engine data are presented in Table IV. The only change in the engine data from the data for a fixed mixture ratio of 9 was a small increase of about 2 kg in the engine mass to allow for the additional control. In both cases, the engines were designed for the high mixture ratio in essentially the same way a fixed mixture ratio engine at the same mixture ratio was designed. To achieve the mixture ratio variation, the oxygen flow rate was reduced while keeping the hydrogen flow rate constant. Because the throat area was fixed, the chamber pressure and thrust fell. The same approach was taken in Ref. 6. In Refs. 3 and 4, a variable mixture ratio engine (Ref. 11) was designed with some advanced technologies that led to greater engine enhancements, larger mixture ratio shifts , and a somewhat different philosophy for achieving the mixture ratio change. These technologies were not included in the evaluation.

With a variable mixture ratio engine, the point in the trajectory at which the mixture ratio is reduced must be optimized. This point is represented by the ratio of the extra oxygen used during the first phase to the total propellant, called the high-density-propellant fraction The optimization of this parameter is shown in Fig. 11 for the staged combustion engine on the single-stage vehicle with several vehicle lift-off thrust-to-weight ratios (T/W). Normally, the T/W for the single-stage vehicle is 1.3, which nearly minimizes dry mass and allows some lift-off thrust margin. The increased T/W values were considered to compare fixed and variable mixture ratio engines. Figure 12 shows the points with the optimum high-density-propellant fraction and indicates that the fixed mixture ratio is preferred at all T/W values considered. Similar results are shown for the split expander engine in Figs. 13 and 14. In all cases, the dry mass resulting from variable mixture ratio engine application is greater than that with a fixed mixture ratio of 7.

Table IV Variable Mixture Ratio Engine Data (Ref. 7).

	Full-Flow Staged Combustion Engine	Split Expander Engine
Mixture ratio	9/7	9/7
Vacuum thrust, kN	2091/1780	2091/1780
Specific impulse, sec	421.0/448.0	406.5/423.5
Expansion ratio	77.5	40
Maximum chamber pressure, MPa	20.68	10.34
Throat area, cm^2	906.1	1042
Mass, kg	2357	1933

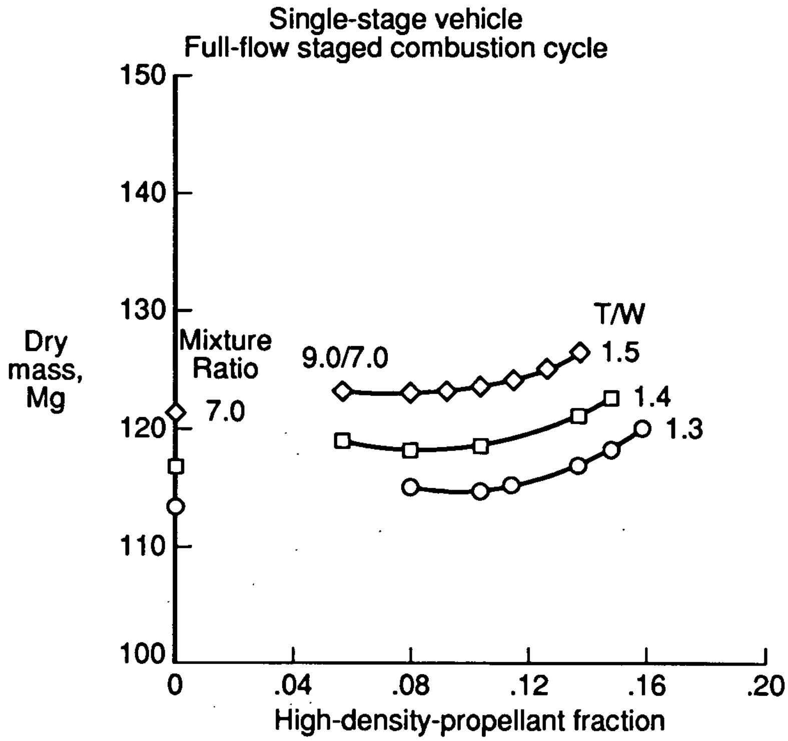

Fig. 11 Effect of thrust-to-weight ratio on variable-mixture-ratio optimization for full-flow staged combustion engine.

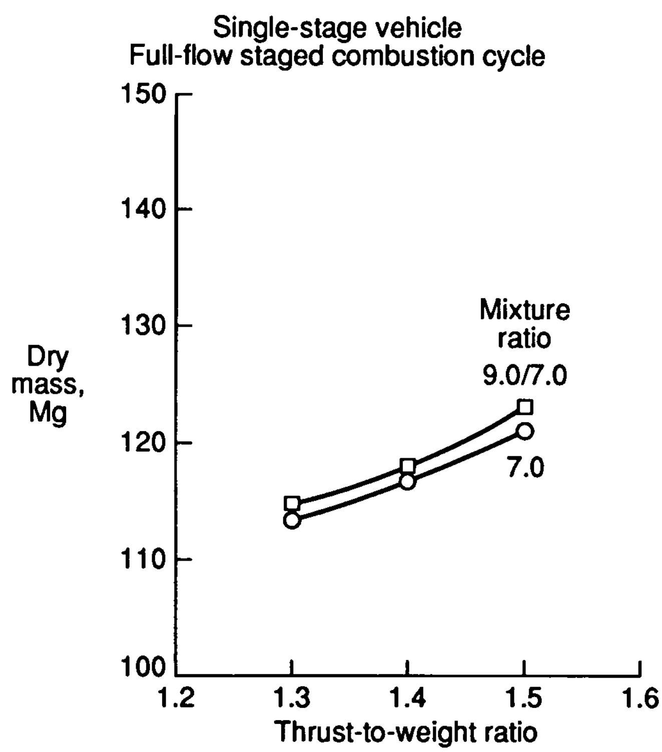

Fig. 12 Effect of variable mixture ratio on thrust-to-weight ratio trends.

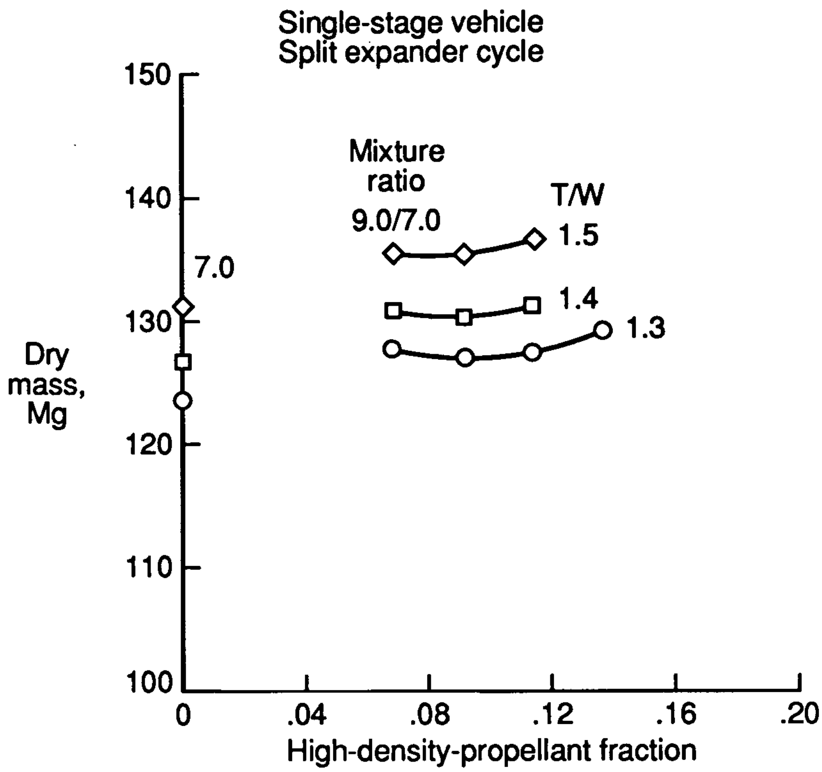

Fig. 13 Effect of thrust-to-weight ratio on variable-mixture-ratio optimization for split expander cycle.

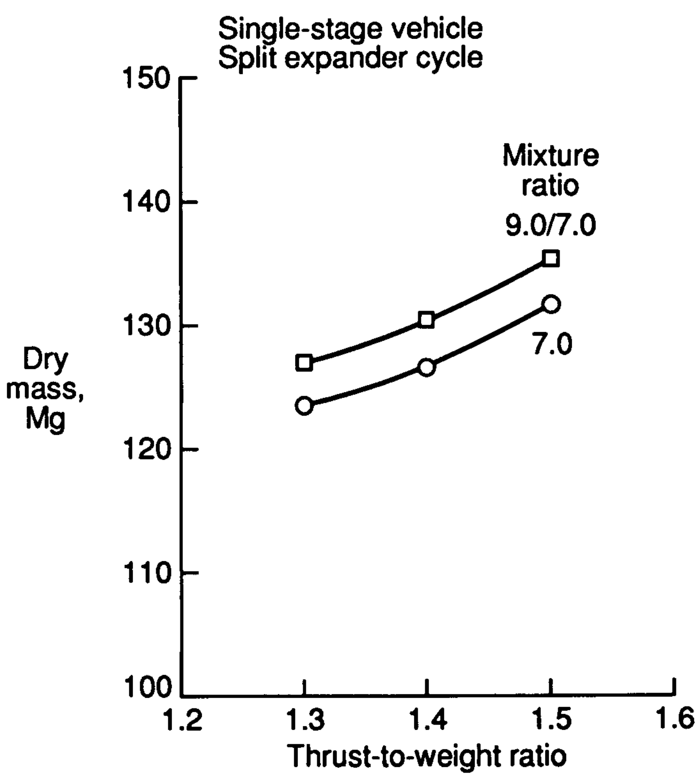

Fig. 14 Effect of variable mixture ratio on thrust-to-weight ratio trends.

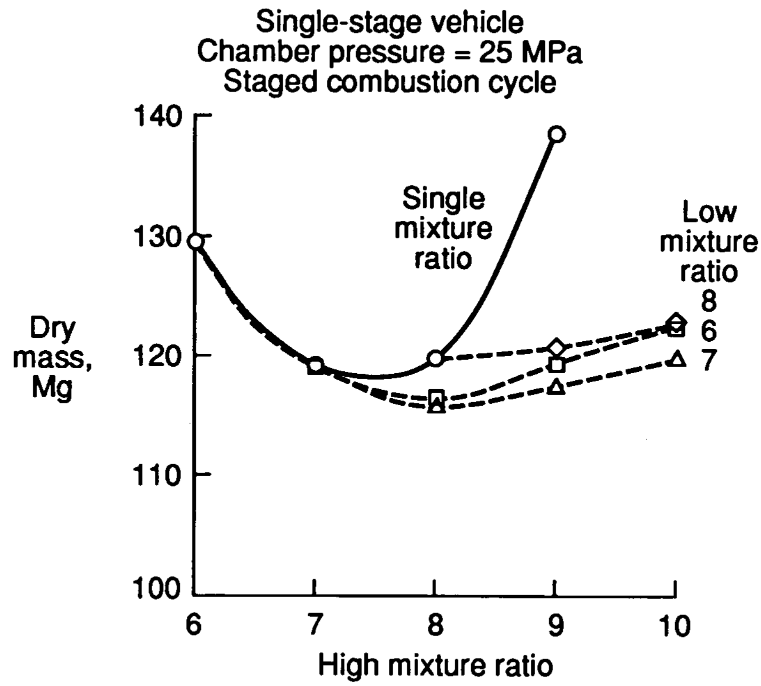

Fig. 15 Effect of low mixture ratio on high-mixture-ratio optimization for a variable-mixture-ratio engine (Ref. 6).

The results shown in Figs. 11-14 do not agree with results of Ref. 6 shown in Fig. 15, where variable mixture ratio engines reduced vehicle dry mass below that of the best fixed mixture ratio. The difference can be partly understood by considering the engine data shown in Figs. 16 and 17. The vacuum specific impulse data from the two sources are quite similar, as shown in Fig. 16. The engine thrust-to-weight ratios are also in the same range, as shown in Fig. 17, but the slope of the curves is different. As the mixture ratio increases, the engine thrust-to-weight ratio increases significantly for the Ref. 6 data but stays fairly constant for the current data. Because the Ref. 6 results were for an engine that does not have a full flow cycle, the engine calculations were repeated for a full flow cycle resulting in essentially no change in engine mass. Additional engine analysis will be required to resolve the differences in engine characteristics between Refs. 6 and 7.

The engine thrust-to-weight data for the split expander engine are also shown in Fig. 17. The improvement over the staged combustion engines is evident, and the benefit of increasing the mixture ratio above 6 is also shown. There are two reasons for the increases in the engine thrust-to-weight ratio with mixture ratio: the direct effect of mixture ratio from 6 to 8 shown as the positive slope and the increase in chamber pressure shown as the discontinuity at mixture ratio 7.

The effect of chamber pressure on the vehicle dry mass was examined for the full-flow engine with variable mixture ratio on a single-stage vehicle. The results shown in Fig. 18 indicate that there is a benefit to increasing the chamber pressure. One of the advantages of the full-flow engine is that it is not as limited by pump power availability as is the staged combustion engine with only fuel-rich preburners. The improved vehicle results must be weighed against increased turbine inlet temperature in the oxygen-rich turbine, which is an unproven technology.

The variable mixture ratio calculations were not repeated for the two-stage vehicle. Reference 6 shows the difference between the single-stage and two-stage vehicles with variable mixture ratio, and the engines examined in this paper would not show a different effect. The calculations for the LRB shown for a fixed high mixture ratio engine are also applicable to the variable mixture ratio engine because there is essentially no difference in the engine when used at the high mixture

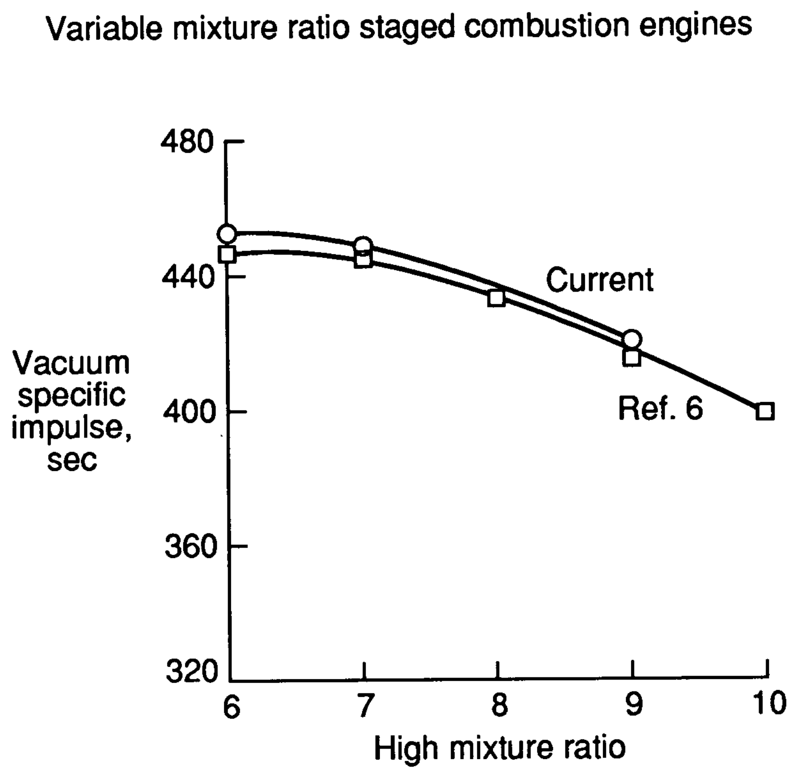

Fig. 16 Variation of engine performance models.

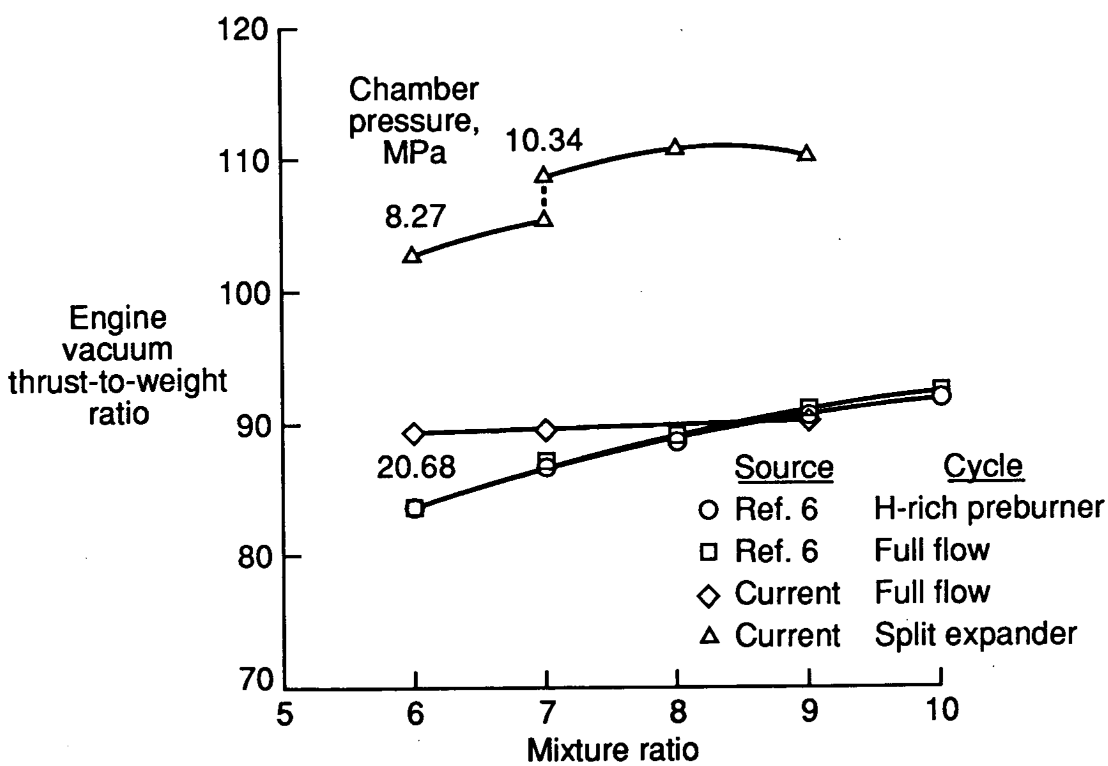

Fig. 17 Variation of engine mass models.

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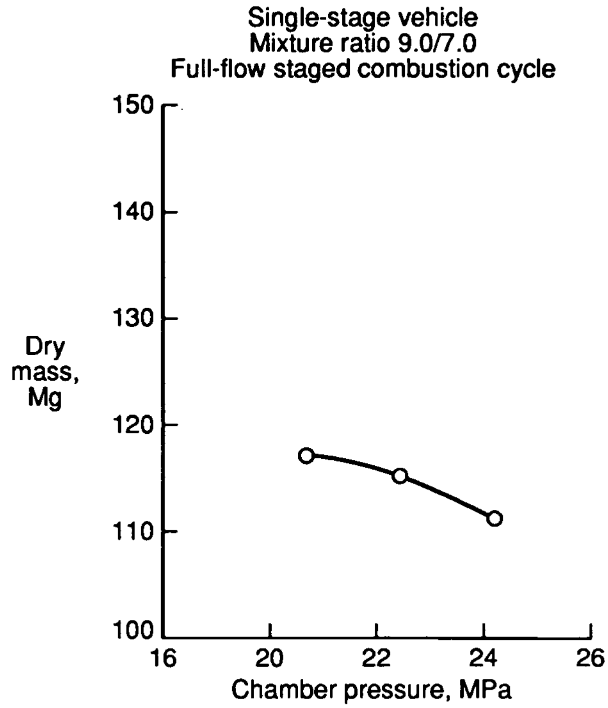

Fig. 18 Effect of chamber pressure on dry mass.

ratio. There is a possibility that a variable mixture ratio engine used on a LRB should be transitioned from the high mixture ratio to the low mixture ratio before staging. The present analysis does not include the capability to examine this option, but the effects would probably be minimal. A more important option that should be considered in the future is replacing the Space Shuttle Main Engine on the orbiter with the same variable mixture ratio engine used on the LRB.

Concluding Remarks

This paper evaluates full-flow staged combustion engines and split expander engines at mixture ratios of 6 and greater with oxygen and hydrogen propellants. The vehicles considered are single- and two-staged fully reusable vehicles and the Space Shuttle with liquid rocket boosters.

The most significant result of this study is that the split expander engine becomes very attractive when the mixture ratio is increased above 6. With a higher mixture ratio, the combustion temperature increases and the pump work decreases; this allows a higher chamber pressure and thus increases engine thrust-to-weight ratio. The increased capability at higher mixture ratios reduces vehicle dry mass for the single stage and two-stage fully reusable vehicles and for the liquid rocket booster for the Space Shuttle.

The results of this study could be the incentive for additional efforts. The results should be verified by other engine and vehicle analyses. Additional cycles related to the expander should be considered. One possibility is an expander cycle with both hydrogen and hydrocarbon fuels. The hydrogen would provide the cooling and power while the hydrocarbon would be pumped directly into the main combustion chamber. A dual-mode engine could result if the hydrocarbon flow could be shut off during flight. Another possiblility is a hybrid expander bleed cycle in which the fuel side is a normal closed expander cycle but the oxygen side uses warmed oxygen to pump the oxygen and dumps the turbine exhaust as in the expander bleed cycle.

Acknowledgment

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