Variable-Mixture-Ratio and Other Rocket Engines for Advanced Shuttles

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Computer models of rocket engines and single-stage-to-orbit vehicles that were developed previously and recently combined have now been extended to include variable-mixture-ratio engines and two-stage vehicles. The variable-mixture-ratio engine is of interest because it offers the opportunity for reduced vehicle dry mass relative to single-mixture-ratio engines without the operational complexity of two fuels or two engine designs. Two-stage vehicles are of interest because the next generation of advanced launch vehicles probably will not use a sufficiently high level of technology to allow a single-stage vehicle to be a reasonable choice from the standpoint of technical risk and economics. Results are presented for vertical-takeoff, horizontal-landing, winged, manned, fully reusable vehicles with a payload of 13.6 Mg (30,000 lb) to low Earth orbit. Both single-stage and two-stage vehicles are included. Hydrogen, methane, and propane engines were studied with a staged-combustion cycle. Optimizations included the nozzle exit pressure, thrust split between the booster and orbiter, chamber pressure, and mixture ratio.

Introduction

OVER the past several years, models have been developed at the DLR Institute of Chemical Propulsion to compare the performance of expendable launch vehicles with various rocket engines. The emphasis of this work was on the calculation of engine performance and mass. During this same time, models were being developed at NASA Langley Research Center to evaluate the effectiveness of various rocket engines on reusable Earth-to-orbit vehicles, with the engine data provided by engine manufacturing companies. From July 1987 through June 1988, the authors worked together at NASA Langley Research Center to combine the capabilities from the two national space organizations.

The initial combined effort provided a capability to optimize the rocket engine and vehicle interaction in a way that was not previously possible, with the capability to evaluate the effects of numerous parameters on the vehicle design. Reference 1 presents a description of the joint effort, the methods and capabilities of the programs developed, and results of the analyses. Figure 1 shows how the analyses were accomplished. Propulsion elements from DLR were combined with NASA vehicle elements. Figure 2 illustrates the kind of analysis that can be performed with the resulting capability. The turbopump efficiencies, which are a propulsion technology parameter, are varied, with the results indicating the effect on the vehicle dry mass. The results of Fig. 2 show that, in order to get the correct effect of the turbopump efficiencies on the vehicle dry mass, the engine chamber pressure must be optimized.

Since the publication of Ref. 1, the combined rocket engine and vehicle work has continued. This paper describes some of the recent results of this cooperative effort. Two of the significant extensions of the capability are the inclusion of variable-mixture-ratio engines and two-stage vehicles. Variable-mixture-ratio engines are of interest because they allow the engine to operate initially at a high mixture ratio, providing a high thrust-to-weight ratio for the engine and a high bulk density, and later (at high altitudes) at a low mixture ratio, providing a high specific impulse. Compared with single-mixture-ratio engines, variable-mixture-ratio engines provide some of the benefits of dual-fuel vehicles without the operational complexities of two fuels or two engine types. Single-stage vehicles are useful for studies because they are less difficult to model and optimize than two-stage vehicles. In the world of harsh realities, however, two-stage vehicles are more likely to be developed in the near future. Single-stage vehicles are too sensitive to design inaccuracies at the technology levels likely to be available for the next generation of Earth-to-orbit vehicles. The extension of the capability to include two-stage vehicles was, therefore, important so that the propulsion assessments would be more useful.

Analysis

The majority of the analysis is described in Ref. 1. Only the variable-mixture-ratio analysis and the two-stage vehicle analysis will be described here.

The variable-mixture-ratio engine analysis was based on the staged-combustion analysis. First, the engine was treated as if it were a single-mixture-ratio engine at the high mixture ratio. Only hydrogen-rich preburners were considered because the results of Ref. 1 indicated that they were best. For the low-mixture-ratio operation, the hydrogen flow rate was held at the value found for the high-mixture-ratio operation. The oxygen flow rate was adjusted to provide the desired mixture ratio. Because the overall flow rate was reduced and the throat area was unchanged, the chamber pressure was reduced. The chamber pressure for the low-mixture-ratio operation was calculated from the new flow rate and the existing throat area. Then the new performance was calculated as if it were a staged-combustion, single-mixture-ratio engine at the new chamber pressure.

No hardware or mass changes were made in the engine design to allow for the variable-mixture-ratio operation. The

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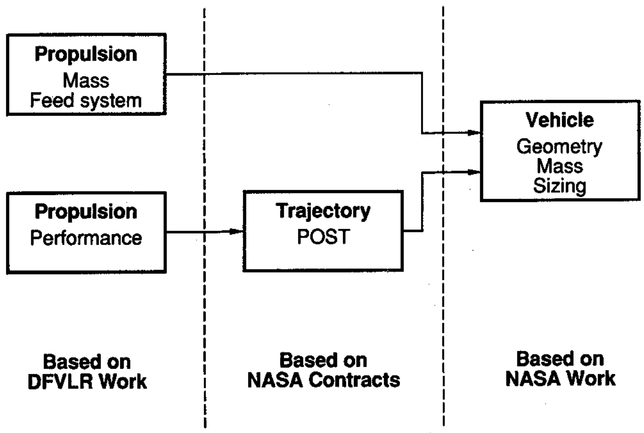

Fig. 1 Analysis flow.[1]

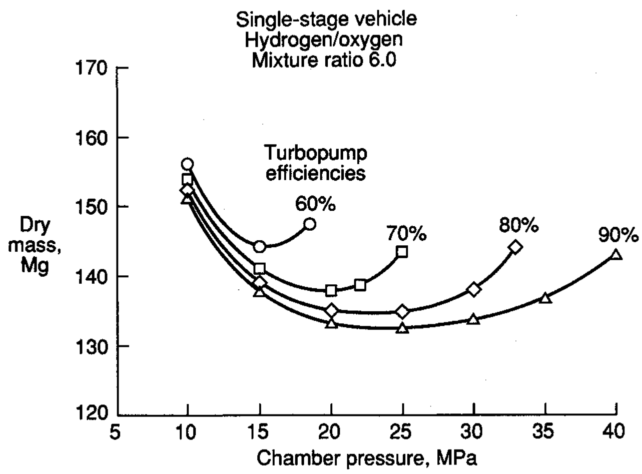

Fig. 2 Effect of turbopump efficiencies on chamber pressure optimization.[1]

chamber pressure reduction should require no changes in the chamber or nozzle. The hydrogen turbopump should need no change because it needs to pump the same flow to a slightly reduced pressure. The preburner may need to operate on a slightly reduced flow, but the difference should not cause a problem for the design. The injector would need to pass a different oxygen flow, but the same hardware should work with reduced velocity in the oxygen posts. Stability problems are unlikely with gaseous hydrogen and liquid oxygen combustion. The most significant change would be in the oxygen turbopump, where the discharge pressure would be reduced as well as the flow rate. For large changes in mixture ratio (ratio of oxidizer mass flow to fuel mass flow), such as from 12 to 6, the oxygen turbopump could be designed as two turbopumps in parallel, with one shut down to provide the reduced flow. This would cause some penalty to the design relative to a single high-mixture-ratio engine because two turbopumps would weigh more than a single large turbopump. The results shown below, however, indicate that large changes in mixture ratio are not useful. A single turbopump should be able to provide sufficient variation in flow rate to change the mixture ratio from 9 to 7, for example. The assumption of no mass changes is, therefore, expected to be correct for optimum designs.

One difficulty has been discovered in the variable-mixture-ratio analysis. Because this engine has two operating modes, the part of the engine analysis code used was that part designed for analysis of dual-expander engines, which has two operating modes. Unfortunately, the mass estimates do not perfectly match those for single-mode engines. Because of this difficulty, the results for the variable-mixture-ratio engines cannot be compared directly with the results for single-mode engines. Nonetheless, a good comparison between single-mixture-ratio and variable-mixture-ratio engines can be made by using the variable-mixture-ratio analysis with only one mode.

The two-stage vehicle analysis actually used the same geometry for both the booster and the orbiter as the single-stage vehicle.[1] The booster and orbiter were mounted in parallel, and all engines were operated in parallel during the boost phase with crossfeed of propellants from the booster to the orbiter such that the orbiter was fully fueled at staging. The booster was staged at a Mach number of 3 so that it could glide to a horizontal landing near the launch site without return propulsion. As with the single-stage vehicle, the engines were sized assuming a total of 12 engines for a gross mass of 1500 Mg. The gross mass of the resulting vehicles was usually under 700 Mg. The engine mass calculations would not be correct if the vehicle were actually built with 12 engines at this gross mass, but the vehicle would probably be designed with a smaller number of engines. The engine mass used in the analysis is believed to be reasonably close to the correct value for likely engine sizes. The thrust-to-weight ratio of the vehicle was assumed to be 1.5 at liftoff, rather than 1.3 for the single-stage vehicle. Because all the engines are not being carried to orbit, a higher thrust-to-weight ratio is reasonable, and previous analyses[2] have shown that 1.5 is nearly optimum for minimum gross mass.

Summary of Single-Stage Results

The single-stage vehicle results are summarized in Fig. 3. Except for the gas generator bar shown in this figure, all of the results in this paper are for the staged-combustion cycle.

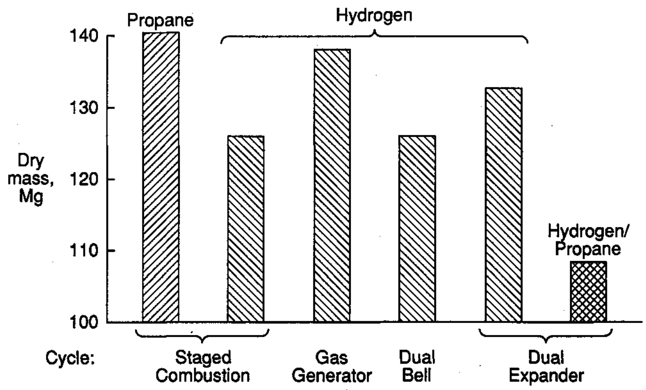

Fig. 3 Summary of engine results for single-stage vehicles.[1]

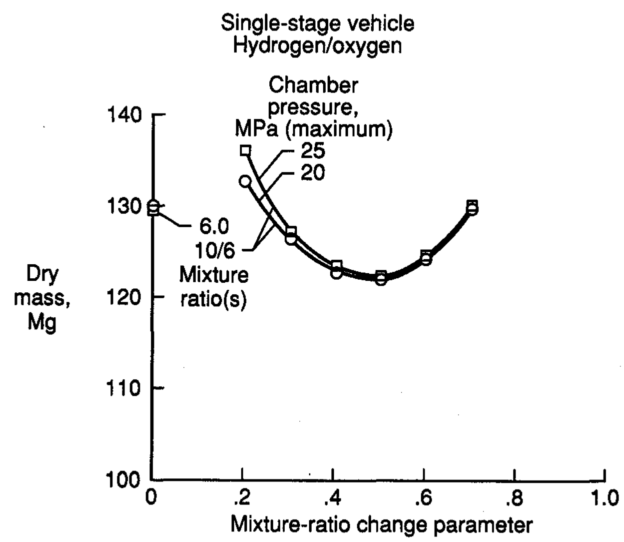

Fig. 4 Effect of chamber pressure on mixture-ratio change parameter optimization.

The advantage shown for the dual-expander engine with hydrogen and propane is significant. Part of this advantage is a result of the altitude compensation inherent in the dual-expander nozzle concept. Only the dual-expander results have any altitude compensation. A two-position nozzle or other form of altitude compensation would probably help the other engines, but the capability to analyze such options has not yet been included.

The disappointing results for the dual-expander engine with only hydrogen fuel compared with the dual-bell engine were unexpected. The dual-expander engine has altitude compensation and operates in two modes, and the switch between the modes was optimized.[1] The difference is the engine mass, which is greater for the dual-expander engine because of the additional complexity to provide the two operating modes.

Variable-Mixture-Ratio Engines on Single-Stage Vehicles

The variable-mixture-ratio engines were first examined on single-stage vehicles. Figure 4 shows how, for a typical case, the mixture-ratio change parameter was optimized. The engine allows a change in the mixture ratio during the trajectory, and the timing of this change must be optimized. The parameter used here is the propellant consumed before the change divided by the gross mass. If this parameter is zero, the low mixture ratio is used for the entire trajectory, and the engine must be sized to provide the required acceleration of 1.3 *g* at liftoff. At any larger value, the engine is sized to provide the liftoff acceleration with the higher mixture ratio, and switching to the lower mixture ratio reduces the thrust. If the switch is made too soon, the resulting low acceleration degrades the performance seriously, leading to large vehicles. If the switch is made too late, the low specific impulse of the high mixture ratio degrades the performance. There is, fortunately, a wide range of mixture-ratio change parameter which provides a benefit compared with the single-mixture-ratio results shown.

The overall effects of the mixture-ratio selection are shown in Fig. 5. Using only a single mixture ratio provides the results shown by the solid curve, with a minimum dry mass of less than 120 Mg in the range of 7.0–8.0. Because the engine may have insufficient cooling in this range, the mixture ratio may be limited to 7.0 or less. With the variable-mixture-ratio engines, 2% lower dry mass can be achieved. The best combination of mixture ratios is 8.0 and 7.0. If this is too difficult to cool, the 9.0 and 7.0 results are almost as good.

The analysis capability does not include a heat transfer model, and so no cooling limits can be established. The importance of the variable-mixture-ratio engine could vary depending on cooling capability. For example, if a single-mixture-ratio engine must be limited to a mixture ratio of 6.0, and a variable-mixture-ratio engine could operate at mixture ratios of 9.0 and 6.0, the benefit for the variable-mixture-ratio engine would be significant.

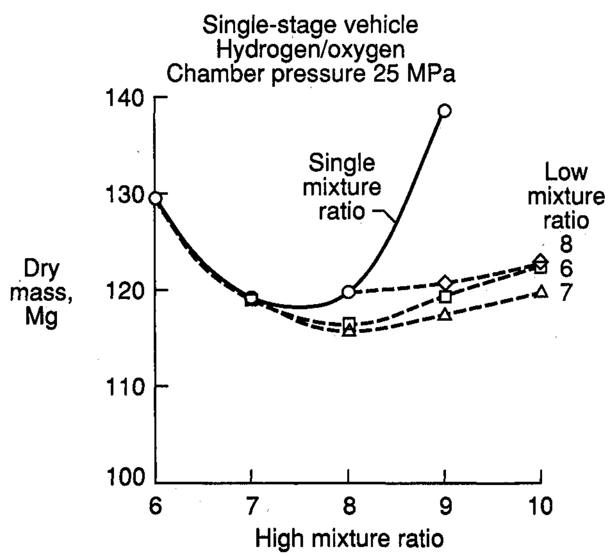

Fig. 5 Effect of low mixture ratio on high-mixture-ratio optimization.

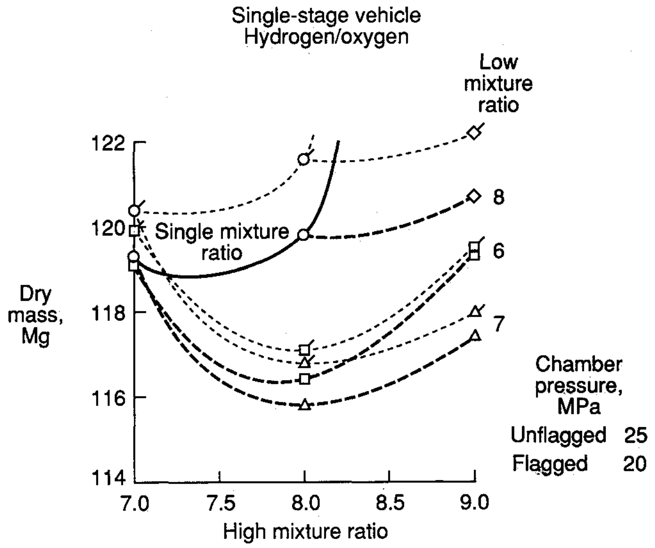

Fig. 6 Effect of chamber pressure on mixture-ratio optimization.

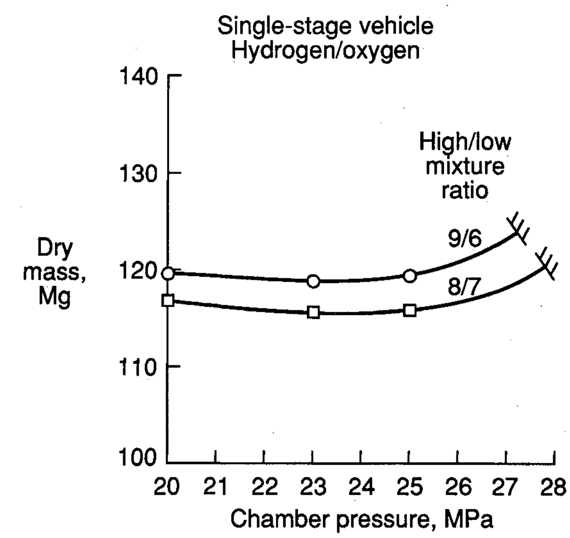

Fig. 7 Effect of mixture ratios on chamber pressure optimization.

One of the interesting results shown in Fig. 5 is that very high mixture ratios are not useful. Some preliminary proposals for variable-mixture-ratio engines have considered mixture ratios of 10.0 or 12.0. The capability to analyze the vehicle and engine together allowed the discoveries that such high values are not useful and that the change in mixture ratio from the high value to the low value does not need to be large to get a variable-mixture-ratio advantage.

Figure 6 shows an expanded view of the optimum region of Fig. 5. On this scale, it can be seen that the difference in vehicle dry mass between a single-mixture-ratio engine with a mixture ratio of 7.0 and a variable-mixture-ratio engine with mixture ratios of 8.0 and 7.0 is less than 3%. This benefit can be provided with little difference in technology or operating complexity, however, and may be worthwhile.

Figure 6 also shows the effect of chamber pressure on the results. The trends are similar at the lower chamber pressure of 20 MPa, but the absolute values are slightly higher. A more complete picture of the effect of chamber pressure is shown in Fig. 7 for two mixture-ratio combinations. The optimum chamber pressure is about 23 MPa.

Two-Stage Vehicles

Results for two-stage vehicles have been generated for several engine combinations. The optimization of the exit pressure is shown in Fig. 8. As with the single-stage vehicles, the optimum exit pressure is between 25 and 35 kPa at any chamber pressure. The optimum is chosen to minimize the total dry mass, which is the sum of the dry masses of the booster and the orbiter. An exit pressure of 30 kPa was used in all of the analyses described later where exit pressure was not varied.

Results for the hydrogen-fueled, two-stage vehicle with staged-combustion engines are shown in Fig. 9. These results are similar to the single-stage vehicle results of Ref. 1 in several ways. The optimum chamber pressure is about 20 MPa. The optimum mixture ratio is between 7.0 and 8.0, and would probably have to be limited to 7.0 to satisfy cooling requirements. There are also some differences from the single-stage vehicle results. The absolute value of the total dry mass is considerably less at 94 Mg, down from 124 Mg, and the dry mass is less sensitive to chamber pressure and mixture ratio, expected effects of staging. Somewhat less obvious is the fact that the dry mass is lower at a mixture ratio of 8.0 than at 7.0. The reverse was found for the single-stage vehicle. This is probably because the two-stage vehicle is less sensitive to specific impulse, and the benefits of higher engine thrust-to-weight ratio and higher propellant density have a direct impact on reducing dry mass. With the single-stage vehicle, the impact through resizing is more important.

Figures 10 and 11 show the basic results for the hydrocarbon fuels, methane and subcooled propane. As with the single-stage vehicle,[1] methane leads to the highest dry mass and propane is between hydrogen and methane. The optimum mixture ratios appear to be slightly higher for the two-stage vehicles. As discussed in Ref. 1 for the single-stage vehicles, the combustion and nozzle efficiencies were set at 0.97 for hydrogen, 0.96 for methane, and 0.95 for propane.

Although most of the work presented was based on identical engines on the booster and orbiter, an investigation was made in which the exit pressure (and, therefore, the nozzle size) was different on the two stages. The nozzles were fixed, single-position nozzles on both stages. The results, shown in Fig. 12, indicate that the dry mass can be reduced about 1.6% if this is done. The optimum exit pressures are 70 on the booster

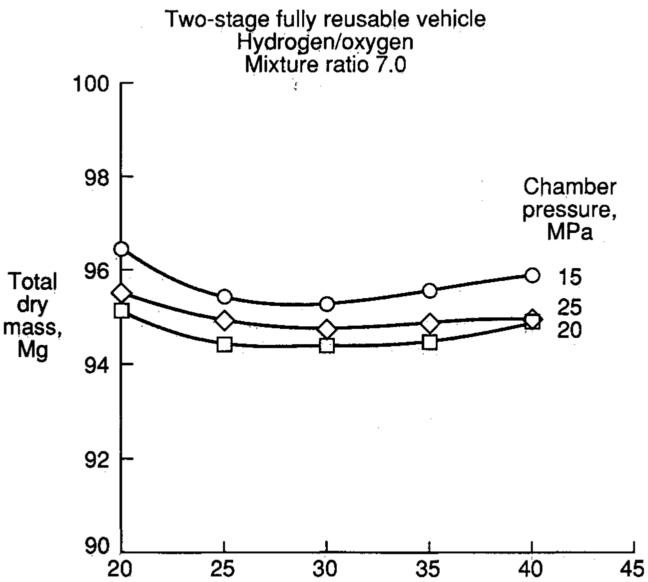

Fig. 8 Effect of chamber pressure on nozzle optimization.

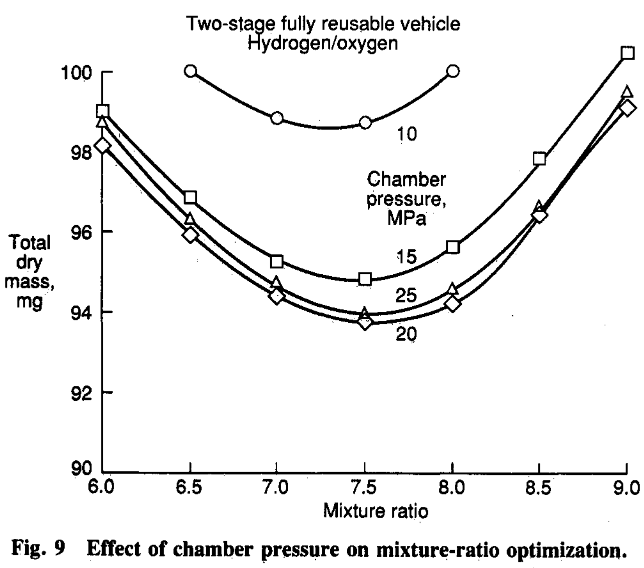

Fig. 9 Effect of chamber pressure on mixture-ratio optimization.

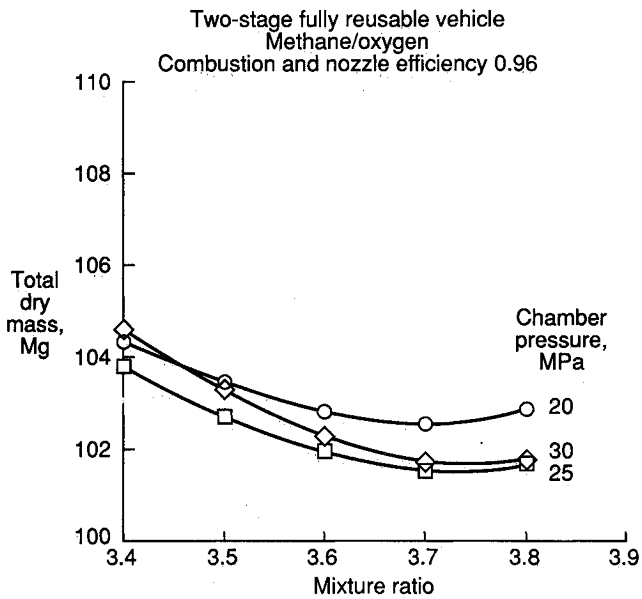

Fig. 10 Effect of chamber pressure on mixture-ratio optimization for methane fuel.

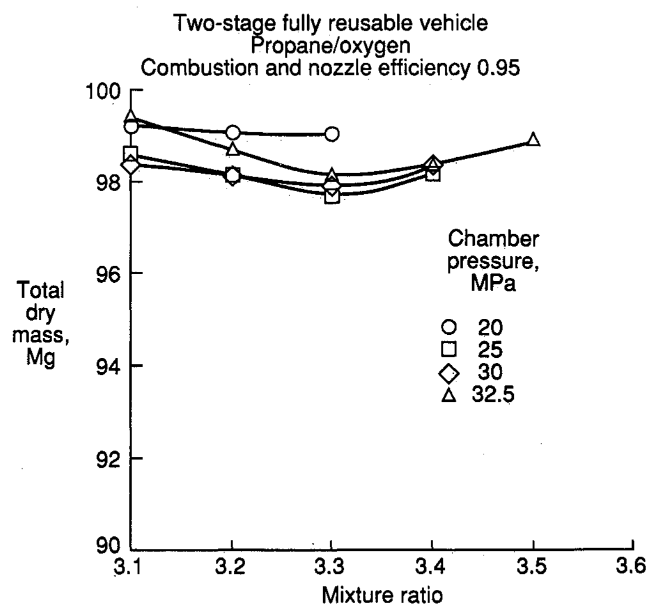

Fig. 11 Effect of chamber pressure on mixture-ratio optimization for propane fuel.

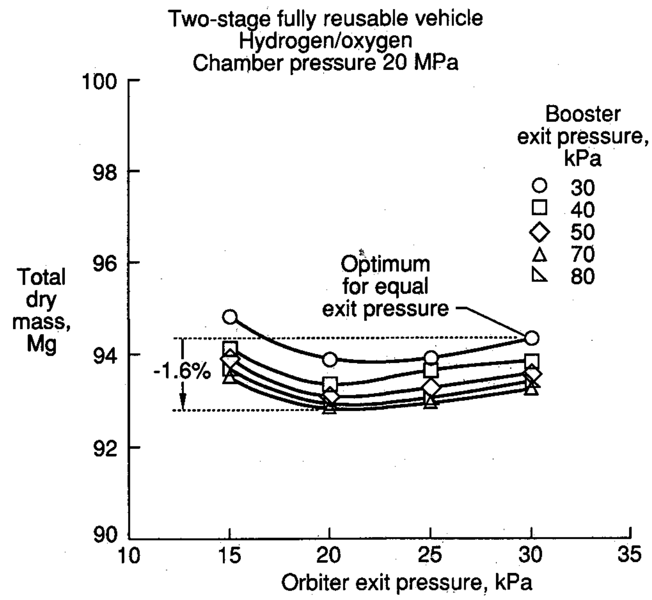

Fig. 12 Effect of different exit pressure on booster and orbiter engines.

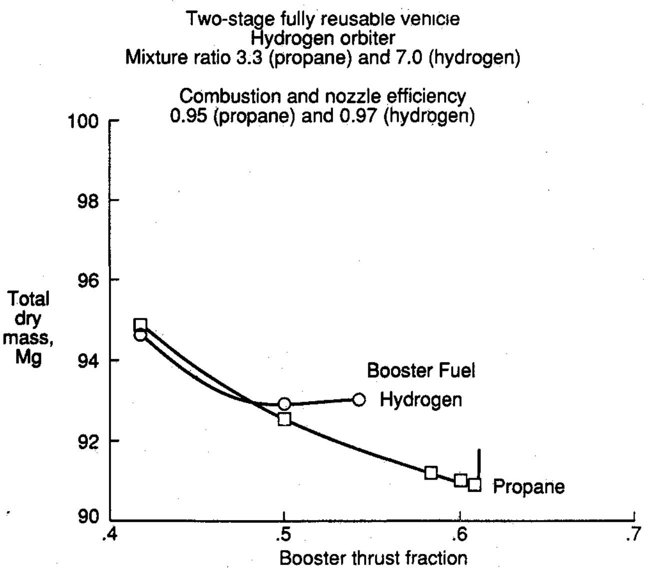

Fig. 13 Effect of booster thrust fraction for propane-fueled booster and hydrogen-fueled orbiter.

and 20 on the orbiter. On some proposed vehicle concepts, engines are moved from a reusable booster to an expendable orbiter after a few flights, but on concepts such as the two-stage, fully reusable vehicle analyzed here, there is little reason to move the engines. Having two different nozzle designs might therefore be worthwhile.

Another case in which two different engines were considered is shown in Fig. 13. Propane engines were used on the booster, and hydrogen engines were used on the orbiter. The optimum exit pressures for separate booster and orbiter engines were used. The fraction of the liftoff thrust provided by each stage was also varied. The curve for the hydrogen booster and orbiter shown in Fig. 13 indicates that the optimum thrust fraction is 0.5, which was used for most of the analyses presented. When two different engines are used, the optimum shifts. Because the propane engines have bulk density and thrust-to-weight advantages over the hydrogen engines for the early part of the flight, the vehicle benefits from increasing the fraction of the thrust provided by the booster from 0.5 to 0.6. Just a little above 0.6, however, the orbiter thrust after staging is so low that a suitable trajectory becomes difficult to find, and the gravity losses increase rapidly. The difference between the best hydrogen vehicle and the best dual-fuel vehicle is about 2%, which probably is not sufficient to justify the extra costs involved in building and maintaining two different engines and two fuel systems.

Variable-Mixture-Ratio Engines for Two-Stage Vehicles

Variable-mixture-ratio engines were also considered for two-stage vehicles. The same engine was used on both stages. All of the engines were used at the high mixture ratio at liftoff and for the entire boost portion of the flight. The engines on the orbiter were used at the high mixture ratio during the first part of the trajectory after staging, and they were changed to the low mixture ratio at some point determined by the mixture-ratio change parameter. This parameter is the fraction of the gross mass that is burned by the orbiter engines before the mixture ratio is changed, including the propellant burned by the orbiter engines during the boost phase. This is a parameter that can be conveniently specified before the trajectory is optimized and before the vehicle is sized. It has little physical significance, but increasing this parameter increases the burn time and velocity before the mixture-ratio change.

The basic results are shown in Figs. 14–18, in which the total dry mass is shown as a function of chamber pressure and mixture-ratio change parameter for several mixture-ratio

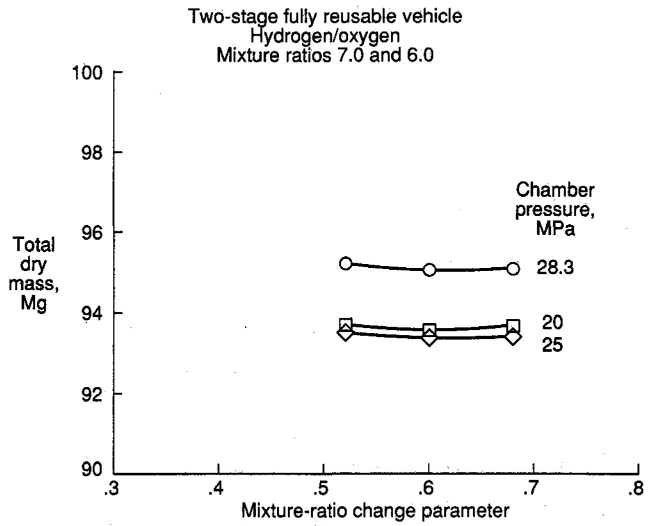

Fig. 14 Effect of chamber pressure on mixture-ratio change optimization for mixture ratios of 7.0 and 6.0.

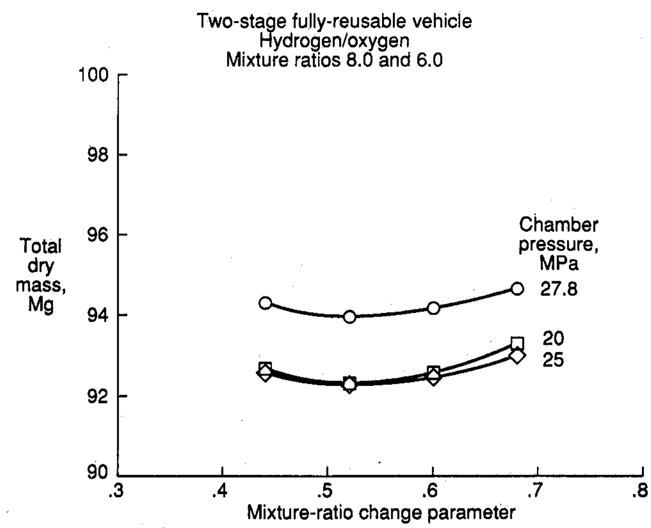

Fig. 15 Effect of chamber pressure on mixture-ratio change optimization for mixture ratios of 8.0 and 6.0.

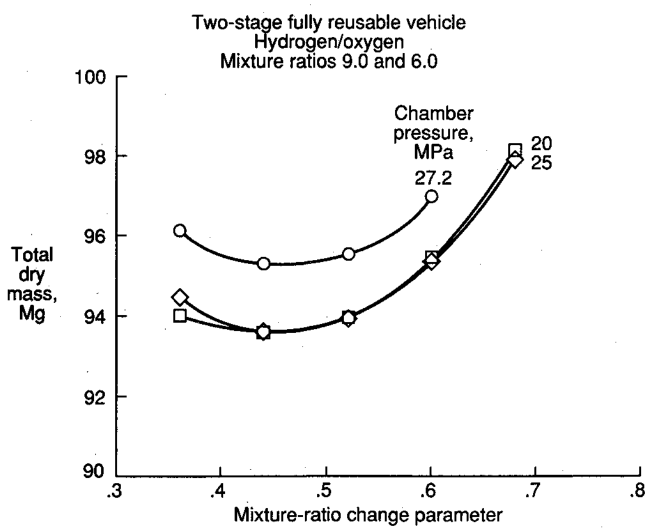

Fig. 16 Effect of chamber pressure on mixture-ratio change optimization for mixture ratios of 9.0 and 6.0.

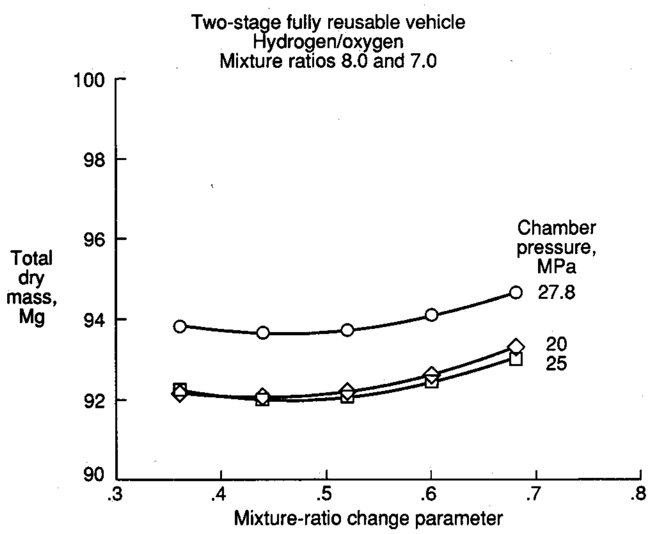

Fig. 17 Effect of chamber pressure on mixture-ratio change optimization for mixture ratios of 8.0 and 7.0.

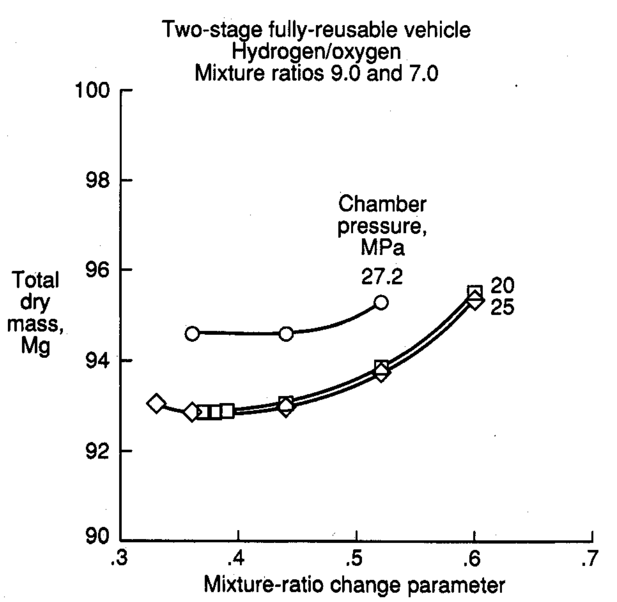

Fig. 18 Effect of chamber pressure on mixture-ratio change optimization for mixture ratios of 9.0 and 7.0.

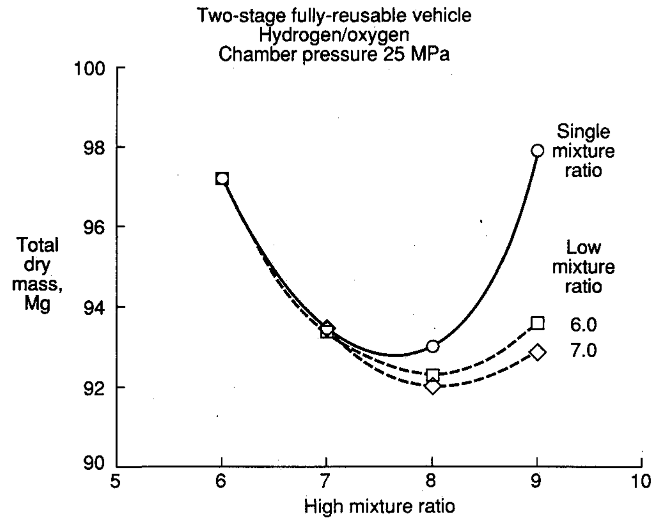

Fig. 19 Effect of low mixture ratio on high-mixture-ratio optimization for two-stage, fully reusable vehicle.

combinations. The chamber pressure that yields the lowest total dry mass is 25 MPa in all cases. The results for the optimum mixture-ratio change parameter values are summarized in Fig. 19, which also includes data for single-mixture-ratio engines. As with the single-stage vehicles, the best combination of mixture ratios is 8.0 and 7.0. The total dry mass is about 1% less than for the best single mixture ratio. This difference could be greater if cooling limits force the single-mixture-ratio engine to mixture ratios significantly below 7.0. The variable-mixture-ratio engine could operate at a mixture ratio that is relatively high and, therefore, cool, initially. After the reduction in mixture ratio, the chamber pressure is reduced and cooling would not be as difficult. The true benefit of the variable-mixture-ratio engine will not be known until a more complete analysis with cooling limits can be conducted.

Comparisons to Previous Results

Other variable-mixture-ratio results have been published in Refs. 3–5. The results in those studies were based on engine data provided by engine companies. In Refs. 3 and 4, the same vehicle analysis was used as in the current study, but differences in the propulsion system calculations make direct comparisons of results difficult. Proprietary and limited-distribution engine characteristics preclude direct engine comparisons.

One of the variable-mixture-ratio engines proposed by an engine company appears to provide significant benefits to several vehicles in Refs. 3 and 4. This engine design uses several techniques discussed in Ref. 5 to allow a higher turbine inlet temperature than current engines. These techniques include cooled, vaneless, counter-rotating turbines. The increased turbine inlet temperature results in a higher chamber pressure in the high-mixture-ratio mode and higher performance without a corresponding increase in the mass of the engine. The current study did not use these techniques, and the results are more comparable to the Space Shuttle main engine. The capability of the analysis used in this study does not include some aspects that would be needed to evaluate those techniques. A more complete study that would show the vehicle results with a more complete set of parametric variations of the variable-mixture-ratio engine, including with and without the improved techniques, would be useful. There seems to be little question that the increased turbine inlet temperature could improve the engine performance. The degree of improvement and the difficulty of developing the improved techniques needs further analysis. Some of the engine characteristics from the current study are given in Table 1 to allow future comparisons.

Table 1 Selected variable-mixture-ratio engine characteristics

Mixture ratio	Vacuum thrust, kN[b]	Specific impulse, s	Chamber pressure, MPa	Engine mass, kg[c]
9; 6[a]	2168; 1637	419.2; 452.1	250; 195	2363
9; 7	2168; 1850	419.2; 447.0	250; 215	2363
9; 7	2183; 1985	437.8; 447.9	250; 231	2427
9; 7	2192; 1871	415.9; 443.9	200; 172	2238
8	2183	445.5	250	2427
7	2148	437.8	250	2432
6	2120	448.9	250	2483

[a]High-mixture-ratio mode value; low-mixture-ratio mode value.
[b]Sea level thrust is 1838.5 kN for all engines in the high-mixture-ratio mode.
[c]Does not include pressurization and feed subsystems.

Concluding Remarks

A unique capability to analyze the effects of rocket engines on reusable launch vehicles has been expanded to include two-stage vehicles and variable-mixture-ratio engines. Results have been generated showing the relative merits of several engines.

Results with the variable-mixture-ratio engines have shown that there is an advantage for the variable-mixture-ratio engine for both single-stage and two-stage vehicles. This advantage could be significant, depending on cooling limits, which have not been included in the analyses. The results indicate that the high mixture ratio should not be very high and that the mixture-ratio change should not be large. The optimum mixture-ratio combination is 8.0 and 7.0 if cooling can be accomplished.

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