Two-Stage Earth-to-Orbit Vehicles with Dual-Fuel Orbiter Propulsion

James A. Martin*
NASA Langley Research Center, Hampton, Virginia

Earth-to-orbit vehicle studies of future replacements for the Space Shuttle are needed to guide technology development. Previous studies that have examined single-stage vehicles have shown advantages for dual-fuel propulsion. Previous two-stage system studies have assumed all-hydrogen fuel for the orbiters. The present study examined dual-fuel orbiters and found that the system dry mass could be reduced with this concept. The possibility of staging the booster at a staging velocity low enough to allow coastback to the launch site is shown to be beneficial, particularly in combination with a dual-fuel orbiter. An engine evaluation indicated the same ranking of engines as a previous single-stage study. Propane and RP-1 fuels result in lower vehicle dry mass than methane, and staged-combustion engines are preferred over gas-generator engines. The sensitivity to the engine selection is less for two-stage systems than for single-stage systems.

Nomenclature

P_B = propellant fraction of the gross mass consumed by the hydrocarbon engines of both vehicles before staging
P_T = propellant fraction of the gross mass consumed by the hydrocarbon engines of both vehicles
T_B = fraction of the total vaccum thrust provided by the booster engines
T_O = fraction of the orbiter vacuum thrust provided by the orbiter hydrocarbon engines

Introduction

IN the early 1970s, when the Space Shuttle concept was being formulated, two-stage, fully-reusable vehicles were seriously considered.[1] Unfortunately, the traffic levels that could be predicted confidently and the available technology could not justify the high development cost of such a system. In order to develop the Space Shuttle at an acceptable level of development cost and still achieve a system with useful capabilities, the concept with expendable tank and solid rocket motors was selected. The penalty for this compromise was higher operating cost.

In the future, when the Space Shuttle is replaced, the economic considerations may be different. The traffic levels may be higher. The capability of the Space Shuttle will lead to increased space flight, and space applications that were just possibilities in the early 1970s will be real elements of future mission models. The technology will be advanced. The Space Shuttle itself has advanced many of the important technologies. The Space Shuttle main engine (SSME) itself may be used on future vehicles. Continued reuse of the thermal protection system of the Space Shuttle will provide increased confidence in thermal protection technology. Other technologies, such as composite materials, will be developed not only for the Space Shuttle but also for terrestrial applications and space payloads, and they can be applied to future vehicles. Finally, some technologies will be developed specifically for advanced vehicles. Crossfeed of propellants from a booster stage to the orbiter is one such technology assumed for the current study.

In order to know what technology should be developed for advanced vehicles, design studies assuming various technology improvements must be conducted. Some technology development, such as that supporting advanced hydrocarbon propulsion, must begin soon in order to be ready for application when needed by new vehicle programs. Several studies have been conducted[2-7] assuming the next new vehicle will be a single-stage-to-orbit (SSTO) concept. Previous comparisons have shown that for small payloads SSTO vehicles have potential advantages over two-stage systems with likely levels of technology advances. On the other hand, two-stage vehicle systems have less risk and can be developed with technology that is more certain at the present time. Therefore, it is useful to consider what technology should be developed for future possible two-stage systems. The present paper proposes a new propulsion concept for two-stage vehicles and compares this concept to other all-rocket concepts.

Propulsion System Selection

One of the important technologies that should be considered for advanced vehicles is hydrocarbon rocket propulsion. One recent engine study[8] provided data on several possible hydrocarbon engines using several fuels and engine cycles. That engine information was used in a study of SSTO vehicles[2] based on the reference vehicle.[7] The results of the engine screening[2] are shown in Fig. 1. These results indicate that in order to minimize vehicle dry mass, which is closely related to costs, propane and RP-1 fuels are preferred over methane fuel, and staged-combustion cycles are preferred over gas-generator cycles. The results of SSTO vehicle optimizations with the selected engine, shown in Fig. 2, indicate that a dual-fuel vehicle has a considerably lower dry mass than either hydrogen or hydrocarbon single-fuel vehicles.

The various hydrocarbon engines have also been compared in a study of liquid-booster derivatives for the Space Shuttle.[9] The results of that study indicate that propane gas-generator engines provide the lowest life cycle cost.

Studies of two-stage vehicle systems have often assumed the use of hydrocarbon fuel in the booster and hydrogen fuel in the orbiter. Although hydrogen boosters were considered in early Space Shuttle studies, they are no longer believed to be an economical approach.

Submitted June 7, 1982; presented as Paper 82-1150 at the AIAA/SAE/ASME 18th Joint Propulsion Conference, Cleveland, Ohio, June 21-23, 1982; revision received July 18, 1983. This paper is declared a work of the U.S. Government and therefore is in the public domain.

*Aerospace Engineer, Space Systems Division. Senior Member AIAA.

The current paper introduces the concept of using hydrocarbon fuel in both the booster and the orbiter of a two-stage system. Hydrogen fuel also would be used by some of the orbiter engines. Previous studies[7-9] have shown the advantage of hydrocarbon fuel in the booster of two-stage systems. Because dual-fuel vehicles have been shown to be attractive for SSTO vehicles, the use of dual-fuel orbiters in two-stage systems should be considered. The purposes of the current study were to compare dual-fuel orbiters to all-hydrogen orbiters, two-stage and SSTO vehicles, and various hydrocarbon engines for use in two-stage vehicles.

Tripropellant engines, which take advantage of the favorable cooling and power-generating characteristics of hydrogen in an engine which uses hydrocarbon fuel for most of the thrust, are likely to be attractive for future vehicles. One engine of this type which uses a hydrogen-rich gas generator has been shown to be attractive.[6] Except for this engine, the data base for such engines is quite limited at this time, however, so this study was limited to include only the pure hydrocarbon engines from Ref. 8. The engine technologies required would differ with tripropellant engines.

Vehicle Concept

The vehicle concept considered in this study is a two-stage Earth-to-orbit vehicle system with vertical takeoff and horizontal landing of both stages. The two stages are mounted such that the rocket engines of both stages exhaust at the same plane. The booster stage has hydrocarbon liquid rocket engines for ascent and, if needed, air-breathing engines for return to the launch site after staging. The orbiter may have both hydrocarbon and hydrogen rocket engines, as shown in Fig. 3. The hydrogen engines are SSMEs with two-position nozzles. At liftoff the rocket engines on both stages are operated in parallel. During the boost phase all propellants for the orbiter engines are cross fed from the booster. At staging the orbiter still has a complete propellant load.

This concept should result in a two-stage concept with the lowest possible dry mass with vertical takeoff and horizontal landing. A series-burn concept in which the orbiter engines are not used until after staging would have the same orbiter requirements, but the booster would have more engines to provide the same liftoff thrust. A parallel-burn concept without crossfeed would have the same engine requirements, but the orbiter tankage would be larger. The booster tankage would be smaller, but the system is more sensitive to the orbiter tankage, which must be taken to orbit, than to the booster tankage that is staged at a much lower velocity. One possible disadvantage to the parallel-burn concept is the fact that the center of gravity of the mated system moves laterally a significant distance as the propellant is used from the booster. The engines must have a large bimbal capability to compensate for this cener of gravity motion. In this study no penalty has been assumed for this disadvantage. The effects can be minimized by locating the engines close to the dividing line between the orbiter and the booster and by arranging the orbiter tankage locations to achieve a forward ascent center of gravity.

The design payload mass for this study was 13.6 Mg ascent and return; the same as in Refs. 2 and 7. The shape used for both the orbiter and the booster was the shape of the SSTO vehicle of Refs. 2 and 7. All propellants were contained in cylindrical tankage in the fuselage.

The engines used in this study, except for the engine screening, are those selected in the previous single-stage study.[2] The SSME with a two-position nozzle is the hydrogen engine, and a subcooled-propane, staged-combustion engine is the hydrocarbon engine.

Method of Analysis

The method of analysis used in this study was very similar to that presented in Ref. 2. For each combiantion of inputs an optimized trajectory was determined and the trajectory mass-ratio results were used as inputs to a sizing analysis. The sizing analysis iteratively varied the vehicle size until the payload requirement and the trajectory mass-ratio requirements were met simultaneously. Mass-estimating relationships based on historical data with projected technology improvements were used to calculate the mass of all vehicle components for each trial size. For the two-stage system the orbiter was sized first. The resulting orbiter gross mass was then used in the booster sizing so that the ratio of the booster propellants to the orbiter gross mass matched the trajectory requirements.

One complicating factor in this method of analysis is that the booster mass is not accurately known until the end of the process, yet a booster mass must be staged during the trajectory calculations. Fortunately, the trajectory results are not very sensitive to the staged booster mass, so most of the trajectory calculations could be made with a fixed booster mass. For some of the cases near the optimum the process was iterated to get a more accurate result by staging a more accurate booster mass.

Four independent variables exist for a two-stage vehicle system with a dual-fuel orbiter. Two of the variables determine the relative thrust of the booster engines to the orbiter engines and the ratio of the hydrocarbon thrust to the hydrogen thrust on the orbiter. The other two determine the relative propellant masses of the booster and orbiter and the ratio of hydrocarbon-engine to hydrogen-engine propellants

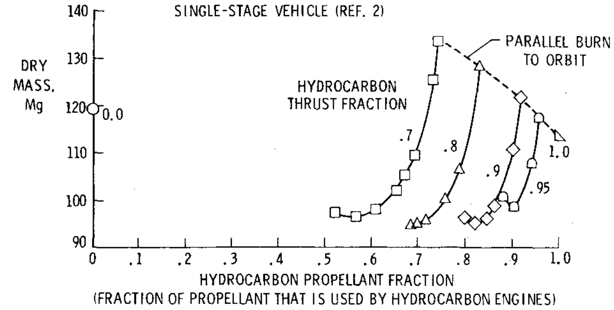

Fig. 2 Single-staged vehicle optimization.

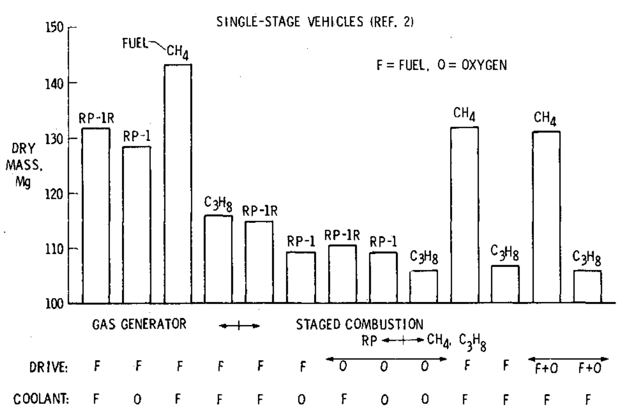

Fig. 1 Engine screening results.

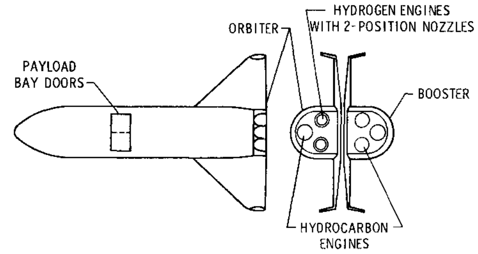

Fig. 3 Two-stage vehicle system schematic.

on the orbiter. Many sets of independent variables could be used, including such variables as staging velocity and orbiter thrust-to-weight ratio, but the solution process for most sets would require an iteration between the trajectory analysis and the sizing analysis. One unique set of variables was found which essentially eliminated this iteration. This set consists of P_B, P_T, T_B, and T_O as defined in the nomenclature list. Note that these parameters are not equal to the hydrocarbon thrust fraction and hydrocarbon propellant fraction used in the single-stage studies.[2] The values of T_B and T_O determine the split of propellant flow between hydrocarbon and hydrogen engines initially. When the integrated hydrocarbon-engine propellant flow reaches the fraction of the gross mass given by P_B, the boosters are staged. Similarly, T_O determines the propellant flow after staging, and P_T provides the signal for switching to only hydrogen engines. The nozzle extensions of the hydrogen engines are extended at this switch point.

The mass estimating relationships for the booster were the same as those for the orbiter except for a few items. The payload volume of the orbiter was not included in the booster. The mass of the thermal protection system of the booster and the mass of the air-breathing engines and cruise fuel were assumed to be zero for staging velocities of 1 km/s or less and, for higher staging velocities, to be a constant plus a small increase with staging velocity. The mass estimates for these items were based on early Space Shuttle designs with fly-back boosters.[10] The thermal protection system mass becomes zero at low staging velocities because the heating decreases to values that unprotected titanium or possibly even aluminum can absorb. The air-breathing engine mass and fuel are not needed at low staging velocities because the booster can turn aerodynamically and glide back to the launch site. The exact staging velocity at which coastback becomes possible would need to be the subject of a more detailed trajectory analysis and booster design study, but the value chosen is a reasonable estimate based on previous preliminary analyses.

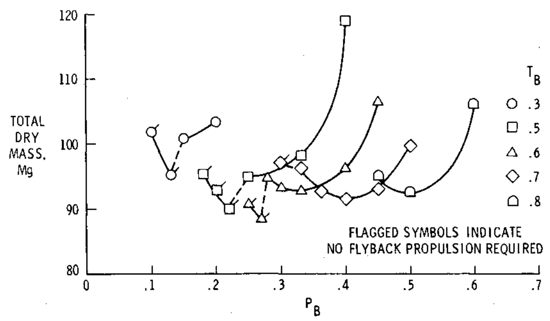

Fig. 4 Optimization of two-stage vehicle for propane-fueled booster.

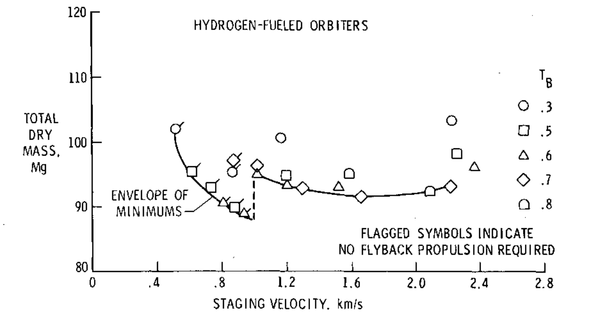

Fig. 5 Effect of staging velocity of two-stage vehicle.

All-Hydrogen Orbiters

The simple case of all-hydrogen orbiters will be considered first. No orbiter hydrocarbon thrust or propellant exists for this case. The vehicle variables which are free to be optimized are the fraction of the vacuum thrust provided by the booster engines, T_B, and the staging condition. In order to allow the analysis to proceed in a straightforward manner without iteration, the staging condition was determined by the parameter P_B rather than staging velocity.

Results are shown in Fig. 4 for various combinations of these parameters. The total dry mass of the two stages is shown, which is a good indication of system costs. The combinations which result in the lowest total dry mass are all flagged symbols, which represent staging velocities lower than 1 km/s. As discussed previously, boosters for these cases can coast back to the launch site without air-breathing engines.

The results are shown in Fig. 5 as a function of staging velocity. The optimum staging condition would be considerably higher than 1 km/s except for the break in the trends when the air-breathing engines are eliminated. The envelope curve shown in Fig. 5 will be used later for comparison.

Dual-Fuel Orbiters

When hydrocarbon engines and propellant are included in the orbiter, there are four parameters to be optimized, instead of just the two in the all-hydrogen case. In addition to the T_B value, the value of T_O, the fraction of the orbiter thrust that comes from the hydrocarbon engines, also must be optimized. Likewise, in addition to the staging condition determined by P_B, the condition for shutting down the orbiter hydrocarbon engines and using only hydrogen fuel must be optimized. As in the case of the staging condition, it is convenient to determine this switching point by P_T, the fraction of the gross mass that is burned by all of the hydrocarbon engines. For an all-hydrogen orbiter, P_T is equal to P_B, and, for dual-fuel orbiters, P_T is greater than P_B by an amount that determines the hydrocarbon propellant fraction of the orbiter.

Optimizations were performed by parametrically varying P_T for fixed values of T_O, T_B, and P_B, and the optimum P_T was selected. The resulting designs are shown on Figs. 6-8. Some of the curves in these figures show a break because of the possibility of coastback boosters. These breaks in the curves are indicated by a dashed line.

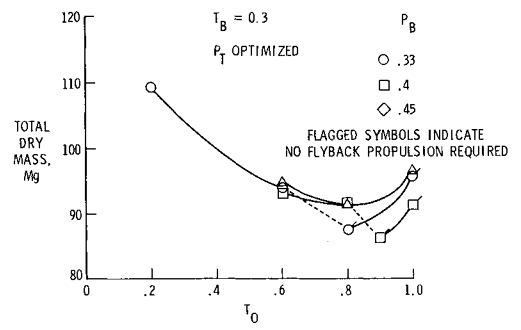

Fig. 6 Summary of optimization of two-stage vehicle systems with dual-fuel orbiters with P_T optimized for T_B of 0.3.

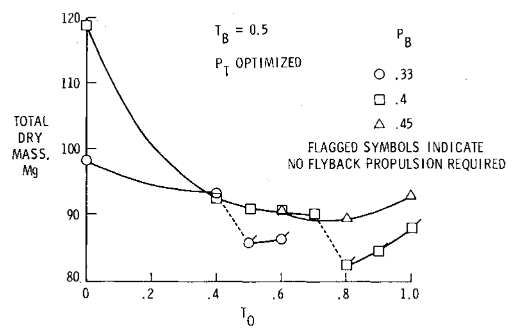

Fig. 7 Summary of optimization of two-stage vehicle systems with dual-fuel orbiters with P_T optimized for T_B of 0.5.

If only the minimum dry-mass values of the orbiter parameters P_T and T_O are plotted, the results for the dual-fuel orbiter concept can be plotted in the same form as the results for the all-hydrogen orbiters. This has been done; Fig. 9 corresponds to Fig. 4 and shows the total dry mass as a function of P_B for parametric values of T_B. Coastback booster combinations have minimum dry mass for each T_B.

Comparisons

The total dry mass is shown as a function of staging velocity in Fig. 10. Even without the possibility of a coastback booster, it is obvious that the optimum staging velocity is near 1 km/s for the dual-fuel orbiter. The envelope curve for the all-hydrogen orbiters from Fig. 5 is also shown in Fig. 10. Comparing the two envelope curves shows that the dual-fuel orbiter has a lower minimum total dry mass by over 6%. At high staging velocities the difference is not large. The results for the dual-fuel orbiter can be no worse than the all-hydrogen orbiter results. This occurs because the all-hydrogen option is part of the range of optimization. As the staging velocity decreases the advantage of the dual-fuel orbiter increases. Because the optima of both concepts are with coastback boosters, the advantage of the dual-fuel orbiter is enhanced. If only flyback boosters are considered, the total dry mass is reduced about 3% by the dual-fuel orbiter concept.

Figure 10 also shows the minimum-dry-mass SSTO vehicle result from Ref. 2. Comparing the SSTO with the all-hydrogen orbiter with a coastback booster, the two-stage may not reduce the dry mass enough to justify using two stages. With the dual-fuel orbiter and the coastback booster, however, the reduction in dry mass is approximately twice as great and favors the two-stage vehicle system.

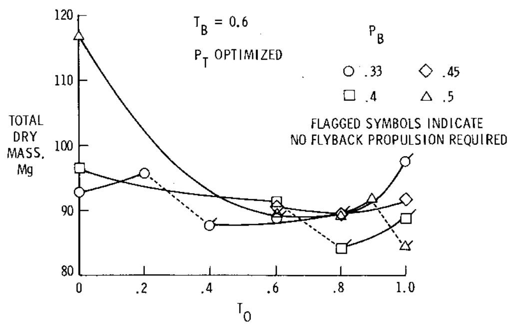

Fig. 8 Summary of optimization of two-stage vehicle systems with dual-fuel orbiters with P_T optimized for T_B of 0.6.

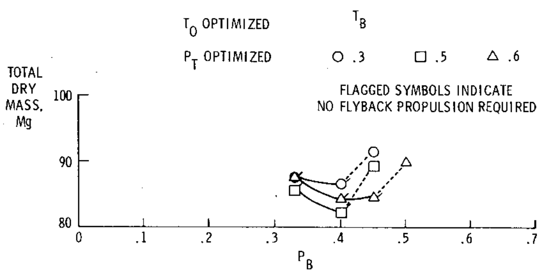

Fig. 9 Summary of optimization of two-stage vehicle systems with dual-fuel orbiters with T_O and P_T optimized.

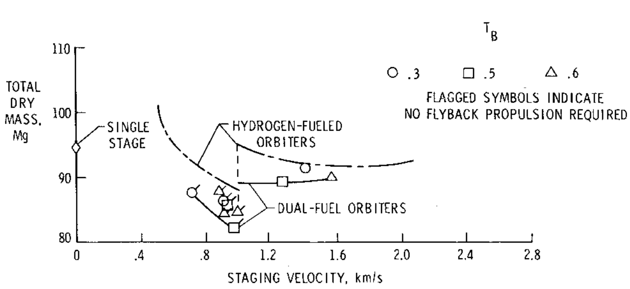

Fig. 10 Two-stage concept comparisons.

Engine Screening

An important question for technology development is whether or not the two-stage system and the SSTO vehicle should have different engines. If the number of engine concepts can be reduced, the technology development resources can be focused on the remaining engines. In order to evaluate the hydrocarbon engine options for two-stage systems, vehicles were analyzed using six engines. In Ref. 2 more engines were analyzed, but the relative merits of several of these engines would not change, so only the best engines of each type were considered in this study. The optimum vehicle from Fig. 9 was used for these comparisons. The results shown in Fig. 11 indicate that the two-stage system is not very sensitive to the hydrocarbon engine selection. For minimum dry mass, propane and RP-1 are the preferred fuels, and staged combustion is the preferred cycle. These results are qualitatively the same as the SSTO vehicle results (Fig. 1).

Selected Vehicle

Based on the results presented above, the vehicle which has the lowest total dry mass was selected as the most attractive for further study. The characteristics of the selected vehicle are presented in Table 1. The gross mass shown includes items not listed separately. The hydrocarbon engine is a subcooled-propane, staged-combustion engine. A cycle with both fuel-rich and oxygen-rich preburners was selected because this cycle was selected in Ref. 2. The difference between cycles within the staged-combustion class of cycles should be similar to the difference found for single-stage vehicles and was not examined. The expansion ratio should also follow the trend found in Ref. 2 and was not optimized for two-stage vehicles.

The engine size was assumed to be variable in this study. In reality, a thrust split would be chosen based on keeping the proper number of engines on each stage and keeping the same hydrocarbon engine on the booster and orbiter. These considerations are not important at this time.

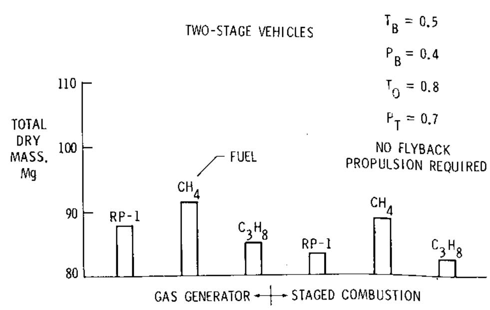

Fig. 11 Two-stage engine screening.

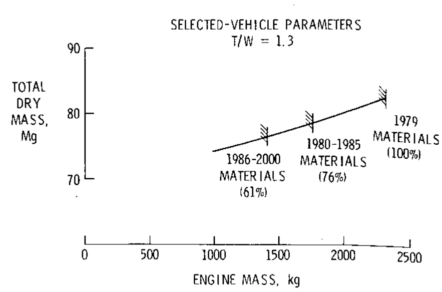

Fig. 12 Effect of engine mass on two-stage vehicle mass.

Table 1 Selected two-stage Vehicle Characteristics

	Booster	Orbiter	Total
Dry mass, Mg	33.5	48.8	82.3
Gross mass, Mg	395.6	423.3	818.9
Payload mass,Mg	---	13.6	13.6
Oxygen mass, Mg	272.9	275.5	548.4
Propane mass, Mg	79.9	59.7	139.6
Hydrogen mass, Mg	4.2	15.0	19.2
Hydrocarbon vacuum thrust fraction	1.0/0.5 (Vehicle/System)	0.8/0.4	0.9

Hydrocarbon engine
Subcooled propane staged combustion
Fuel cooled
Fuel-rich and oxygen-rich preburners
Chamber pressure = 24.1 MPa
Expansion ratio = 60

Hydrogen engine
Space Shuttle main engine
Full power level
Expansion ratio = 40 and 150

$P_B = 0.4$, $P_T = 0.7$, $T_B = 0.5$, $T_O = 0.8$

No Hydrogen Cross Feed

The booster for the selected vehicle system has only 4.2 Mg of hydrogen. This is a small amount because of the low staging velocity and high hydrocarbon thrust fraction. Since this amount was so small the characteristics of a vehicle without hydrogen crossfeed were calculated. All of the input parameters were the same as for the selected vehicle. The total dry mass increased from 82.3 Mg for the selected vehicle to 84.0 Mg for the vehicle with no hydrogen crossfeed. This 2% increase in dry mass probably represents a small price to pay for the reduction in complexity. The crossfeed is limited to two propellants and the booster would not need a hydrogen tank.

Technology Assessments

The most important technologies for the main propulsion of advanced Earth-to-orbit vehicles are those needed to allow the development of advanced hydrocarbon engines. These include hydrocarbon and oxygen cooling; hydrocarbon-rich and oxygen-rich preburners or gas generators; and, in the case of engines with both fuel-rich and oxygen-rich preburners, main injectors for two hot gas streams. In the case of engines with only one type of preburner or gas generator the interpropellant seal problem must be solved. Solving this seal problem with a helium purge, as in the early SSMEs, can result in a significant vehicle penalty.

Beyond the technologies required to allow the development of a particular type of engine, the most significant technology may be engine mass reduction through materials substitution. The potential of advanced composite materials is shown in Fig. 12. Engine mass estimates are shown based on recent experience (labeled 1979 materials) and on projected materials for the near future and for the more distant future. The engine mass estimates are described in detail in Ref. 8. The results indicate vehicle dry-mass reductions of 5% with near-future materials and 7% with more advanced materials. Although these results are less dramatic than the results for single-stage vehicles,[2] the engine mass reductions are certainly worth pursuing.

Other technologies which have been identified are those related to increasing the chamber pressure, including increased turbine inlet temperature, increased pump discharge pressure, and determination of the existence of a carbon deposit which might reduce cooling requirements. Although increasing the chamber pressure is worthwhile, the benefits in terms of vehicle dry-mass reduction would be small. In the single-stage vehicle analysis,[2] the effects were on the order of 1%, and the effects would be less for staged vehicles.

Other technologies that are related to propulsion are handling subcooled propane and propellant crossfeed. One potential method for maintaining propane at the subcooled temperature is to add a small amount of a liquid that has a boiling point near the desired temperature, such as methane, nitrogen, or argon. Crossfeed requires development of the technology for switching propellant sources without changing the flow rate and pressure to the engines.

Conclusions

This study included two-stage Earth-to-orbit vehicles with paralled burn, crossfeed, dual-fuel orbiters, no tripropellant engines, and a payload of 13.6 Mg. The results indicate the following conclusions:

1) Dual-fuel orbiters reduce total dry mass compared to equivalent all-hydrogen orbiters.

2) If the booster is staged at a low enough staging velocity such that it can coast back to the launch site without air-breathing engines, the dry mass may be lower than the dry mass of systems staged at higher velocities requiring air-breathing flyback engines if that low staging velocity is approximately 1 km/s.

3) The dual-fuel orbiter concept minimizes dry mass more at the low staging velocities required for coastback boosters than at higher staging velocities.

4) Two-stage systems have lower dry mass than comparable single-stage systems, and the difference is greater with dual-fuel orbiters.

5) The sensitivity of the dry mass to engine selection is less with two-stage systems than with single-stage systems, but the trends are the same for both systems: Subcooled propane and RP-1 fuels result in lower total dry mass than methane fuel and staged-combustion engines result in lower dry mass than gas-generator engines.

References

[1] Malkin, M. S., "Space Shuttle/The New Baseline," *Astronautics & Aeronautics*, Vol. 12, No. 1, Jan. 1974, pp. 62-78.

[2] Martin, J. A., "Hydrocarbon Rocket Engines for Earth-to-Orbit Vehicles," *Journal of Spacecraft and Rockets*, Vol. 20, May-June 1983, pp. 249-256.

[3] Eldred, C. H., "Looking Toward Single-Stage Launch Systems," IAF Paper 80 F 242, Sept. 1980.

[4] Freeman, D. G. Jr. and Powell, R. W., "Impact of Far-Aft Center of Gravity for a Single-Stage-to-Orbit Vehicle," *Journal of Spacecraft and Rockets*, Vol. 17, July-Aug. 1980, pp. 311-315.

[5] Wilhite, A. W., "Optimization of Rocket Propulsion Systems for Advanced Earth-to-Orbit Shuttles," *Journal of Spacecraft and Rockets*, Vol. 17, March-April 1980, pp. 99-104.

[6] Martin, J. A., "Cost Comparisons of Dual-Fuel Propulsion in Advanced Shuttles," *Journal of Spacecraft and Rockets*, Vol. 16, July-Aug. 1979, pp. 232-237.

[7] Caluori, V. A., Conrad, R. T., and Jenkins, J. C., "Technology Requirements for Future Earth-to-Geosynchronous Orbit Transportation Systems," NASA CR 3265, April 1980.

[8] O'Brien, C. J. and Ewen, R. L., "Advanced Oxygen-Hydrocarbon Rocket Engine Study," Aerojet Liquid Rocket Co., Sacramento, Calif., Rept. 33452F, April 1981.

[9] Williams, F. L., "Shuttle Derived Vehicles Technology Requirements Study, Phase I Final Report," Martin Marietta Corp., New Orleans, La., Rept. MMC-5DV-DR-61, July 1981.

[10] Raynes, T., "Alternate Space Shuttle Concepts Study," Grumman Aerospace Corp., Bethpage, N.Y., Rept. MSC-03810, July 1971.