Effects of Tripropellant Engines on Earth-to-Orbit Vehicles

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Vehicle studies are needed to guide development of technology for future Earth-to-orbit vehicles. Recent studies have examined single- and two-stage systems with bipropellant hydrocarbon-fueled rocket engines used with separate hydrogen-fueled engines. Earlier studies indicated the potential of tripropellant engines which use the unique capabilities of hydrogen in cooling and power generation. This paper provides a comparison of bipropellant and tripropellant engines. Engines which are essentially hydrocarbon engines with hydrogen for cooling and power generation are considered as well as dual-mode engines with separate hydrogen operating modes. The results indicate that tripropellant engines can reduce vehicle dry mass below that of bipropellant engines. The dual-expander engine yields the lowest vehicle dry mass. However, the dual-bell engine yields a vehicle dry mass that is almost as low, and its design would be easier to cool.

Introduction

THE Space Shuttle has successfully completed the test-flight phase and is now considered operational. Columbia has been joined by Challenger, and the fleet will soon be expanded to at least four orbiters. The capabilities of the Shuttle can be fully utilized and can provide excellent Earth-to-orbit transportation for many years.[1] Improvements and derivatives that can enhance the Shuttle capabilities are being considered.[2,3]

Although Shuttle operations are just beginning, technology developments must proceed now if future Earth-to-orbit vehicles are to be a viable option when they are needed. The growth in the communications satellite market, coupled with increased military needs for space transportation, could lead to a justification for advanced vehicles near the turn of the century.[4] Significant advances in such areas as manufacturing in orbit could further increase the need for future vehicles.

Studies of future vehicles have been conducted for several years in order to indicate which vehicle concepts might be preferred for future vehicles and to show which technologies should be pursued with the limited funding available to enhance these preferred vehicle concepts. One conclusion that has been shown repeatedly is that dual-fuel propulsion, combining a high-density hydrocarbon fuel with high-specific-impulse hydrogen, enhances vertical-takeoff rocket vehicles.[5] Dual-fuel propulsion reduces vehicle dry mass and size compared to vehicles with either fuel alone. For single-stage vehicles, such as the concept developed in Ref. 6, dual-fuel propulsion can reduce dry mass over 15%, as shown in Fig. 1.[5,10,11] For two-stage vehicles shown in Fig. 2,[7] using hydrocarbon fuel in just the booster reduces the dry mass 4% compared to an all-hydrogen system, as shown in Fig. 3. Using some hydrocarbon fuel in the orbiter can reduce the dry mass an additional 7%, or a total of 11%.[7]

The dry-mass reductions just discussed are significant, and the results indicate that hydrocarbon propulsion is a technology that should be pursued. Even these reductions, however, may not represent the best use of dual-fuel propulsion. These previous results were based on separate hydrocarbon engines[8] used in parallel with modified Space Shuttle Main Engines (SSMEs), which use hydrogen fuel. Such hydrocarbon engines may be the proper selection for some vehicle designs, such as a liquid-booster Space Shuttle derivative; but, because the advanced vehicles (single- or two-stage vehicles) will have some hydrogen fuel on board, a tripropellant engine which takes advantage of the unique capabilities of hydrogen may be a more appropriate selection. The purpose of this paper is to show the effects of tripropellant engines on Earth-to-orbit vehicles. Engines which are essentially hydrocarbon engines with hydrocarbon for cooling and power generation are considered as well as dual-mode engines with separate hydrogen operating modes. Previous vehicle studies examining effects of tripropellant engines include Refs. 6, 10, and 11.

Tripropellant Engines

Tripropellant engines use hydrocarbon fuel with oxygen for most of the thrust produced. Hydrogen is used as an auxiliary

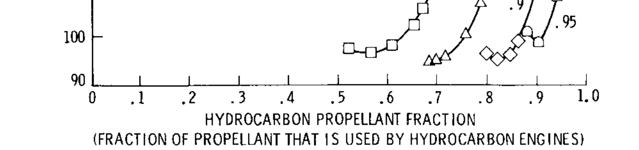

Fig. 1 Optimization of single-stage dual-fuel vehicles.[5]

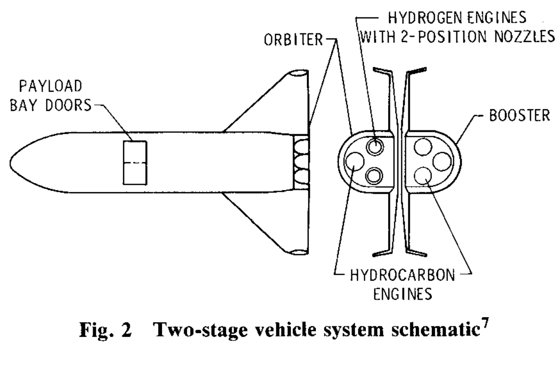

Fig. 2 Two-stage vehicle system schematic[7]

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fluid because it has excellent characteristics as a coolant and as a drive gas to provide pump power. After providing pump power, the hydrogen can also provide some thrust. In some engines, the hydrogen portion of the tripropellant engine can be used separately, so a separate SSME is not needed.

Several tripropellant engines have been designed in the last 6 years. One engine, the hydrogen-gas-generator engine,[9] shown schematically in Fig. 4, could be developed with a minimum amount of technology development. By using a hydrogen-rich gas generator, this engine avoids the technology-development requirements of pure hydrocarbon engines for pump-drive systems with hydrocarbon- or oxygen-rich hot gas streams. The utility of this engine has been shown before.[10,11] As with any engine using a gas-generator cycle, this engine dumps some propellant at low pressure and without complete combustion. (A staged-combustion cycle avoids this dumping and thus has a potential for a higher specific impulse.) This engine has only one mode of operation and is used in parallel with modified SSMEs as shown in Fig. 5.

Another type of tripropellant engine has two modes of operation, as shown in Fig. 6. In the first mode, hydrocarbon fuel is burned in one combustion chamber to provide the majority of the thrust, and hydrogen fuel is burned in a second combustion chamber to provide the rest of the thrust. In the second mode, the hydrocarbon portion of the engine is turned off, and the hydrogen portion of the engine operates alone. This group of engines also has integrated expansion of the hydrocarbon and hydrogen exhaust streams such that the hydrogen exhaust operates in mode 2 with an increased expansion ratio without a mechanical change in the nozzle. Three engines of this type will be considered.

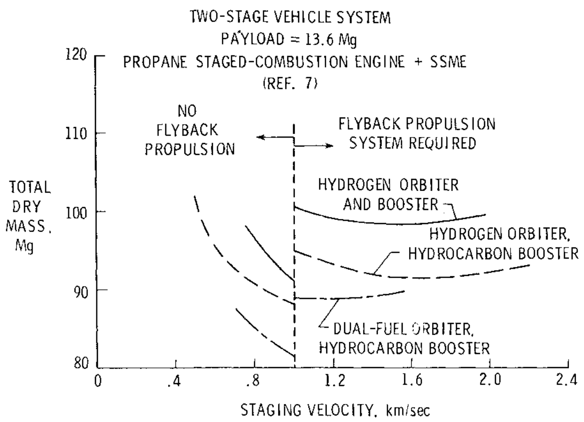

Fig. 3 Effect of dual-fuel propulsion on two-stage vehicle systems.[7]

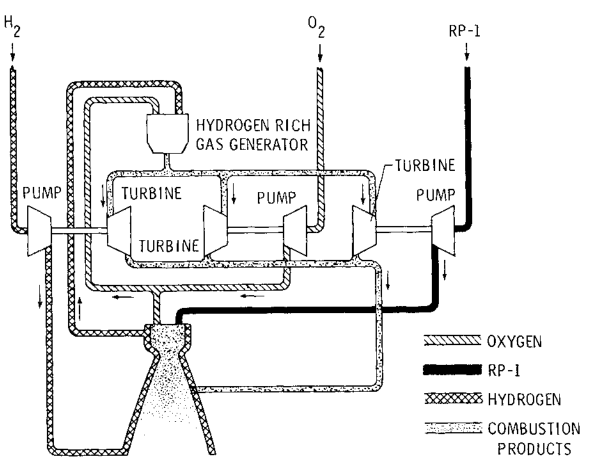

Fig. 4 Schematic of hydrogen-gas-generator engine.[9]

The dual-expander engine,[6,12,13] shown in Fig. 7, uses a central hydrocarbon nozzle and an annular hydrogen nozzle. Each nozzle has a throat so that the streams are supersonic when they meet, which allows the chamber pressure of the chambers to be independent. The selection of liquid-liquid injection in the hydrocarbon chamber allows a high chamber pressure (41.4 MPa, 6000 lb/in.^{2}), which is desirable for good sea-level performance. An oxygen-rich preburner is required, using hydrogen fuel, to extract enough power from the hydrogen part of the engine to drive the hydrocarbon part of the engine with liquid-liquid injection as in a gas-generator engine. Using both hydrogen- and oxygen-rich preburners allows the elimination of the interpropellant seal required in the SSME to separate hot hydrogen-rich gas from oxygen in the oxygen turbopump. Utility of the dual-expander engine has been shown in Refs. 6, 10, and 11.

The dual-throat engine,[13,14] shown in Fig. 8, differs from the dual-expander engine primarily in that the hydrogen and hydrocarbon exhaust streams meet subsonically. This severely limits the pressure in the hydrocarbon combustion chamber (19.3 MPa, 2800 lb/in.^{2}).

The linear, split-combustor engine,[15] shown in Fig. 9, uses the aerospike principle for altitude compensation. At low altitudes, the exhaust streams follow the nozzle contour, and atmospheric air fills part of the base region behind the engine.

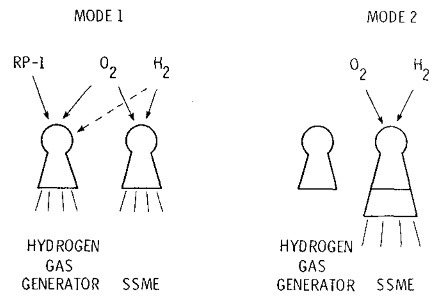

Fig. 5 Operating modes with separate engines.

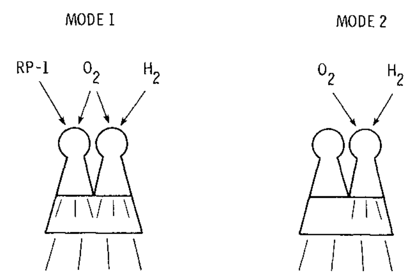

Fig. 6 Operating modes of dual-mode tripropellant engines.

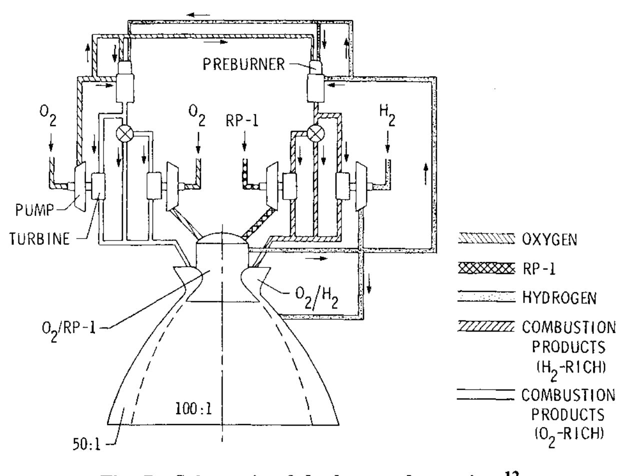

Fig. 7 Schematic of dual-expander engine.[12]

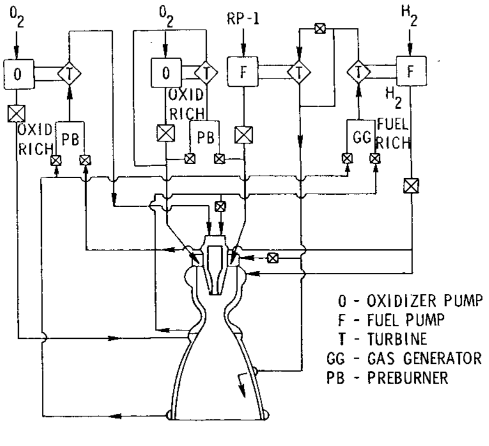

Fig. 8 Schematic of dual-throat engine.[13]

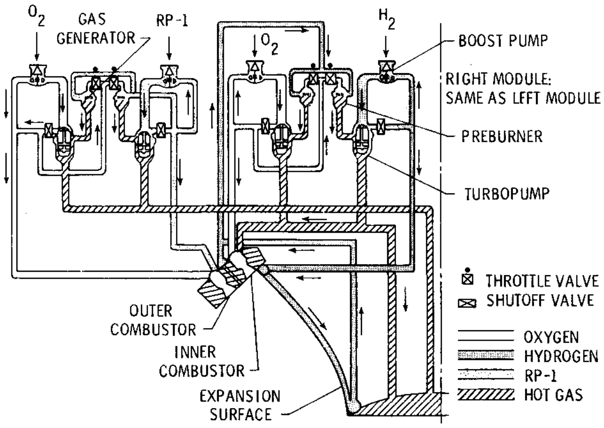

Fig. 9 Schematic of linear engine.[15]

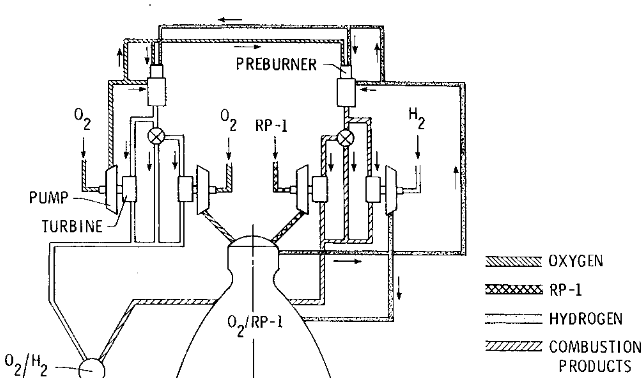

Fig. 10 Schematic of dual-bell engine.

The resulting performance corresponds to that of an engine with a low expansion ratio. At high altitudes, the exhaust flow fills the region behind the engine, so the performance corresponds to a high expansion ratio. The linear engine suffers from the requirement to cool long throat regions in both hydrocarbon and hydrogen chambers. Also, the individual thrust chambers are relatively small. The result is that the hydrocarbon combustion chamber pressure is low (13.8 MPa, 2000 lb/in.^{2}). The mass of this engine is also greater than the dual-expander or dual-throat engines for a given thrust. Utility of this engine has been shown in Ref. 10.

A third type of tripropellant engine which should be considered is the dual-bell engine.[16] This type of engine has not been studied by the engine companies. The dual-bell engine differs from the second type of engine only in that the two exhaust streams may be not integrated. Figure 10 illustrates a dual-bell engine that is identical to the dual-expander engine (Fig. 7), except that the hydrogen combustion chamber and nozzle have a separate bell design rather than being wrapped around the hydrocarbon bell. The advantage of this type of tripropellant engine is that the cooling requirements are reduced. The penalty relative to the dual-expander engine is that a mechanical two-position nozzle is required on the hydrogen bell to provide an expansion ratio change going from mode 1 to mode 2.

Single-Stage Vehicles

Single-stage, Earth-to-orbit vehicles have been analyzed with various tripropellant engines. The methodology has been the same as in Ref. 5. Optimized trajectories were calculated and vehicles sized such that the desired payload of 13.6 Mg could be delivered to orbit. The effect of center-of-gravity location on wing size was not included in the present study.

The results for vehicles using the hydrogen-gas-generator engine are shown in Fig. 11. This tripropellant engine is used in parallel with the SSME. In order to optimize the vehicle, the thrust split between the tripropellant and the hydrogen engines must be optimized. For each thrust split, the propellant split must be optimized. The optimum is at a hydrocarbon thrust fraction of approximately 0.8 and a hydrocarbon propellant fraction of approximately 0.67. A significant reduction in dry mass (from 119 Mg to 93 MG, or 22%) is shown between the optimum dual-fuel vehicle and the all-hydrogen vehicle shown at hydrocarbon thrust and propellant fractions of zero. Figure 11 also shows the optimum envelope curve from Ref. 5 for a propane bipropellant engine used in parallel with the SSME. The tripropellant engine appears to be the preferred engine, since it results in a lower vehicle dry mass and is a simpler engine to develop. A tripropellant engine with propane fuel would probably reduce the vehicle dry mass further. The tripropellant engines were analyzed with RP-1 fuel because a more complete set of data was available.

The results with the second group of tripropellant engines are shown in Fig. 12. For these engines, the hydrocarbon thrust split is fixed by the engine design; therefore, only the hydrocarbon propellant fraction can be optimized. For the dual-expander engine, designs with hydrocarbon thrust fractions of 0.60 and 0.75 were analyzed. The results indicate that hydrocarbon thrust fractions of 0.75 or greater are preferred. The engine analyses, however, identified cooling limits at high hydrocarbon thrust fractions. In Ref. 17, the design with a hydrocarbon thrust fraction of 0.60 was found to be satisfactory in cooling. Higher hydrocarbon thrust factors could not be cooled unless the total thrust was increased or the chamber pressure was reduced. More recent engine cycle designs may have relieved these limits.

The optimum envelope curve for the hydrogen-gas-generator engine has been included in Fig. 12. The dual-expander engine results in a lower vehicle dry mass than the hydrogen-gas-generator engine by up to 19%. Even at a hydrocarbon thrust fraction of 0.60, the reduction is 13%. These reductions are significant and should encourage additional technology development for engines such as the dual-expander engine.

The results with both the linear engine and the dual-throat engine indicate a higher vehicle dry mass than with the simpler hydrogen-gas-generator engine. Some qualifying factors should be considered. The total vehicle base area required is greater for the vehicle with the hydrogen-gas-generator engine and the SSME with a two-position nozzle than for the other tripropellant engines. The linear engine could result in less thrust structure mass and aerodynamic drag than other con-

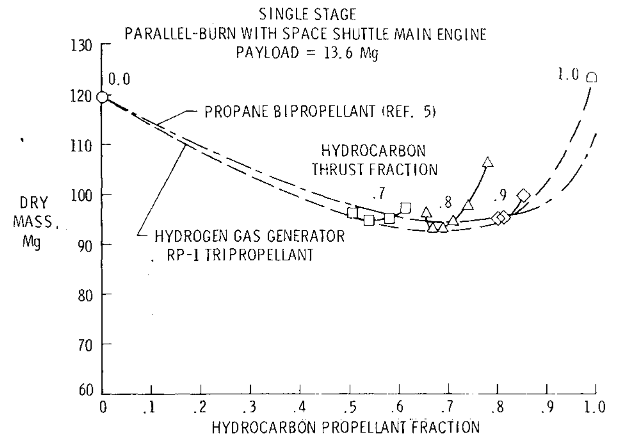

Fig. 11 Vehicle results with hydrogen-gas-generator engine.

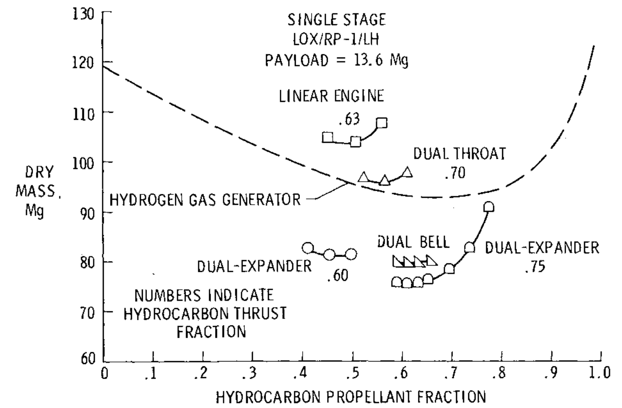

Fig. 12 Vehicle results with tripropellant engines.

cepts. These differences were not included in the current analysis.

The third type of tripropellant engine, the dual-bell engine, yields the results shown in Fig. 12. This engine is similar to the dual-expander engine with a hydrocarbon thrust fraction of 0.75. The thrust and propellant flow rates are identical. The engine mass differs only in that a two-position nozzle is added to the hydrogen bell to provide the expansion ratio which the dual-expander engine gets automatically from the nozzle integration. The extra nozzle mass increases the engine mass 13% and increases the vehicle dry mass about 4%. The characteristics of this engine have been estimated by comparing the engine with the dual-expander engine. No study of this engine has been completed by the engine manufacturers.

Although the dual-bell results are not as attractive as the dual-expander results with a hydrocarbon thrust fraction of 0.75, no other engine (other than the dual-expander engine with a thrust fraction of 0.75) produces such a low vehicle dry mass, even the dual-expander engine with a hydrocarbon thrust fraction of 0.60. In addition, the dual-bell engine will be easier to cool than the dual-expander engine. Figure 13 illustrates the difference. With the geometry of the dual-expander design, the annular throat of the hydrogen chamber is a narrow slit with two long sides. The circular throat of the dual-bell design encloses the same throat area with the minimum perimeter length. The perimeter length for the dual-expander engine is 3.8 times as much as for the dual-bell engine. The wall area that must be cooled is nearly proportional to this area.

The dual-bell results shown should not be confused with previous results, such as those of Ref. 10. The dual-bell engine uses separate bell nozzles but has the cooling and turbopump subsystems integrated to use the unique capabilities of

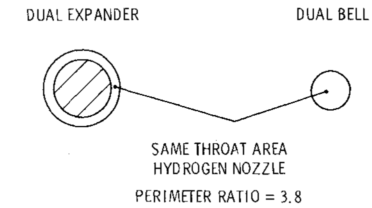

Fig. 13 Throat geometry of dual-expander and dual-bell engines.

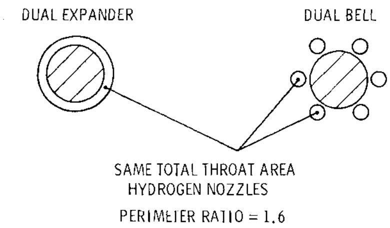

Fig. 14 Throat geometry of dual-bell engine with six small nozzles.

hydrogen to advantage and also use the different chamber pressures to advantage. These advantages may be a significant part of the benefit shown from the dual-expander engine. The mass of the dual-expander engine is low compared to most other engines, and the reason for this low mass is somewhat unclear. The dual-bell analysis shows that the integrated nozzle does not account for the majority of the dual-expander benefit.

The 4% difference in vehicle dry mass between the dual-expander and dual-bell engines shows the value of integrating expansion areas. In addition to the dual-expander approach, Beichel[18] has suggested several other options which could be advantageous. Much useful work could be done defining the relative merits of these options. Engines which are basically the same as the dual-bell engine should be considered with the exhausts of low-expansion-ratio nozzles mixing before expanding further. When some of the combustion chambers are inactivated, the remaining flow would fill the full expansion area. Circular throat designs expanding to a rectangular cross-section before mixing could be useful. Figure 14 illustrates one possibility. Instead of one annular hydrogen nozzle in the dual-expander engine, the hydrogen stream is divided into six nozzles with circular throats. The perimeter ratio of 1.6 indicates a cooling advantage for the six smaller nozzles. From the circular throats, the flow could expand into rectangular nozzles which effectively form an annular nozzle around the central hydrocarbon engine.

Two-Stage Vehicle Systems

The results presented in Ref. 7 indicate that two-stage vehicle systems could result in a lower total dry mass (orbiter plus booster) than the corresponding vehicle dry mass for single-stage vehicles as presented in Ref. 5. The results in both cases were based on propane bipropellant engines and SSMEs. The two-stage vehicles used parallel burn and dual-fuel orbiters. The two-stage vehicles also have lower gross mass and smaller individual vehicle elements. Two-stage vehicles are of interest because of the possible smaller size and mass and also because there is a lower sensitivity to errors in dry mass or propulsion predictions.

Results for two-stage vehicles with tripropellant engines are shown in Fig. 15. The analysis methods were the same as in Ref. 7. Using dual-expander engines on both stages reduces the dry mass 9% from the point shown in Ref. 7 for propane bipropellant engines and SSMEs. Two points are also shown for a combination of dual-expander engines and RP-1 hydrogen-gas-generator engines. The dual-expander engines are used on the orbiter, and the gas-generator engines are used on the booster. This scheme shows a slightly lower total dry mass than that using all dual-expander engines because the gas-generator engines are lighter and require less hydrogen. These factors are advantageous on the booster. Although this scheme reduces dry mass slightly, it is not a realistic approach because two different hydrocarbon engines are required. The results are shown here basically to indicate that using the dual-expander engine on the booster does not result in a large dry-mass penalty.

Summary of Results

Figure 16 shows a summary of the most significant results from this study and Refs. 5 and 7. The total dry mass scale extends to zero to visually present the impact of the propulsion and staging options. The engine used in the vehicles shown include the SSME, the RP-1 hydrogen-gas-generator engine, the dual-bell engine, and the dual-expander engine. The two-stage vehicles used the tripropellant engines in both stages. The single-stage-vehicle dry mass drops rapidly as the propulsion becomes more advanced, going from the SSME with a two-position nozzle to the RP-1 hydrogen-gas-generator engine (used with the SSME) and finally to dual-bell and dual-expander engines. The progression is the same for two-stage vehicles. The propulsion system selection does not affect the two-stage vehicles as much as it does the single-stage vehicles. In both cases, however, dual-fuel tripropellant propulsion technology appears to be worth developing. Note that bipropellant hydrocarbon engines do not appear. For these vehicles, tripropellant engines either provide lower vehicle dry mass or require less engine technology.

The difference between the gas-generator and dual-bell results are sufficient to justify at least some exploratory effort to develop an oxygen-rich preburner, which is the only significant technology step required. The difference between the dual-bell and the dual-expander results are not great, but some effort at nozzle integration is probably worthwhile.

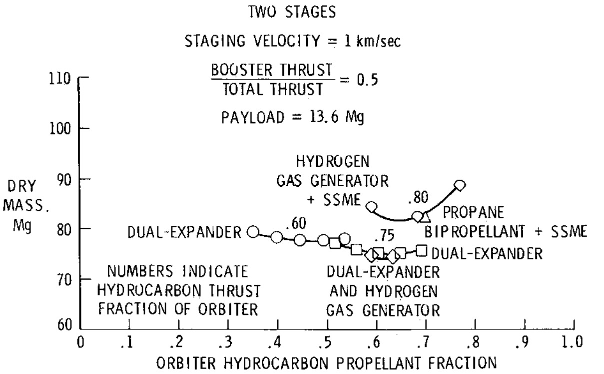

Fig. 15 Two-stage vehicle results with tripropellant engines.

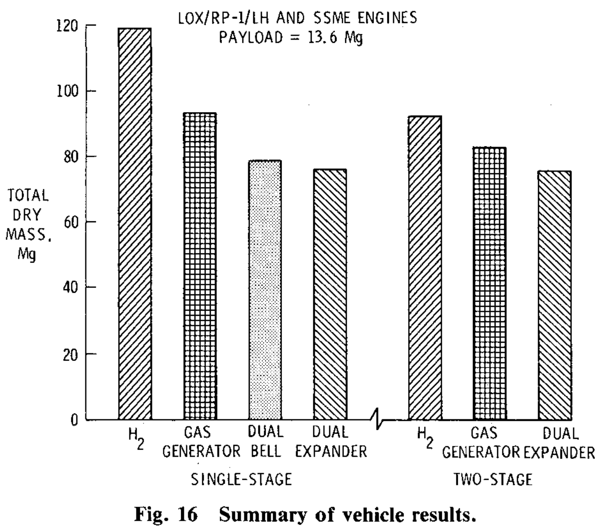

Fig. 16 Summary of vehicle results.

The difference between single-stage and two-stage vehicles is quite large with hydrogen propulsion. With near-term dual-fuel propulsion, the differences are reduced. With the dual-expander engine, the vehicle dry masses are practically the same. The two-stage vehicle system analyzed requires the development of technology for parallel burn and crossfeed. This technology development could be eliminated if the single-stage vehicle concept were selected.

Technology Implications

Several implications for the development of propulsion and vehicle technology should be considered, based on the results of this study. If tripropellant engines are developed rather than bipropellant hydrocarbon engines, there may be no need for some technology developments. Hydrocarbon or oxygen cooling could be used only in the less critical areas of tripropellant engines, such as the outer section of the nozzle rather than in the throat region, as required in bipropellant engines. Hydrocarbon-rich preburners may not be needed. Hydrocarbon pump discharge pressures can be limited to slightly greater than the combustion chamber pressure.

Several technologies will be needed or useful. Injectors for liquid-liquid combustion at high chamber pressures appear in the hydrogen-gas-generator engine, the dual-bell engine, and the dual-expander engine. Oxygen-rich preburners provide a significant vehicle benefit by allowing the design choice to go from the hydrogen-gas-generator engine to the dual-bell engine. An additional vehicle benefit is possible with nozzle integration, which is the difference between the dual-bell engine and the dual-expander engine. Although not specifically addressed in the results presented in this paper, it is clear from Ref. 5 that engine mass reductions and subcooled propane fuel rather than RP-1 would lead to vehicle benefits. Composite materials technology may lead to significant engine mass reductions. The technology for handling subcooled propellant needs to be developed. Propane combustion characteristics need development.

This study did not attempt to specify whether future Earth-to-orbit vehicles should be single- or two-stage systems. The results shown in Fig. 16, however, do indicate that single-stage vehicles become significantly more attractive as propulsion technology is advanced. Some technologies, such as crossfeed, are not required if the single-stage approach is selected. Many technologies, such as composite materials and control of a vehicle with an aft center-of-gravity location, become more important for single-stage vehicles.

Conclusions

This study of the effects of tripropellant engines indicated the following conclusions for the vehicles analyzed:

1) Tripropellant engines (in some cases with separate Space Shuttle Main Engines) can result in lower vehicle dry mass than bipropellant hydrocarbon engines with separate Space Shuttle Main Engines.

2) The dual-expander engine is the most effective tripropellant engine in reducing vehicle dry mass if the cooling requirements can be met at a high hydrocarbon thrust fraction.

3) The dual-bell engine can yield a low vehicle dry mass with lower cooling requirements than the dual-expander engine.

4) With the dual-expander engine, the total vehicle dry mass is nearly the same for single-stage or two-stage vehicle systems.

5) Development of the technology needed for tripropellant engines should proceed.

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