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Cost Comparisons of Dual-Fuel Propulsion in Advanced Shuttles

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Econometric analyses of advanced Earth-to-orbit vehicles indicate that there are economic benefits from the development of new vehicles beyond the space shuttle as traffic increases. Vehicle studies indicate the advantage of the dual-fuel propulsion in single-stage vehicles. This paper shows the economic effect of incorporating dual-fuel propulsion in advanced vehicles. Several dual-fuel propulsion systems are compared to a baseline hydrogen and oxygen system.

Introduction

SPACE flight began with expendable vehicles which established the feasibility and desirability of space flight, but the usefulness of such vehicles is limited by high costs and operational complexity. The space shuttle,[1] which recently completed approach and landing tests successfully, will soon make space flight significantly more routine and less costly. As shuttle operational capability approaches, potential users are becoming more aware of the potential of space flight to serve mankind and return a profit to the user. Some of the new proposals[2-6] will come to fruition; traffic to space will probably grow steadily in the future. If proposals such as solar power satellites, space industrialization, asteroid mining, or nuclear waste disposal are adopted, traffic could grow rapidly.

These increasing traffic projections indicate the need for future improvements in space transportation beyond the space shuttle. At the same time, technology advancements are increasing the technical and economic attractiveness of improved vehicles. A program has been under way for several years to analyze various vehicle concepts and to determine which technology advancements should be pursued.

One of the technologies being considered is dual-fuel propulsion. Since the initial suggestion by Salkeld,[7] several alternative schemes for incorporating dual-fuel advantages into a vehicle have been proposed.[8-12] Three engine concepts were analyzed in Ref. 10: a series-burn dual-fuel engine, a staged-combustion hydrocarbon engine, and a hydrogen-cooled gas-generator engine. A fourth concept,[11] the dual-expander engine, incorporates parallel burning of hydrogen and hydrocarbon fuels. A linear engine using parallel burning of both fuels has also been studied.[12] Dual-fuel vehicle analyses with the various engines have been done.[13] The results indicate a considerable benefit from the dual-fuel approach.[14]

An econometric analysis has also been performed for advanced vehicles,[15] and the initial results indicate that there will be economic benefits from the development of a new vehicle with a modest traffic growth rate. The purpose of this paper is to extend the econometric analyses to include the dual-fuel vehicles. The results should help in the selection of which dual-fuel engine technologies should be pursued.

Approach

The first step of the econometric analysis was selection of a traffic model; Fig. 1 shows the model used. The traffic was separated into two parts: cargo traffic represented by a yearly mass to orbit, and priority traffic represented by a number of separate flights per year. The cargo traffic represents orbit transfer propellants, materials for construction of large space structures and for space processing, and other items which could be grouped into payloads for a common orbital destination. The priority traffic represents Spacelab flights, crew rotation for manned space construction or processing facilities, and flight into specialized orbits. Traffic growth rates of 10-20% annually were considered. A growth rate as steep as 20% would be difficult to maintain for the period shown, but would be required to reach the traffic rates suggested by solar power satellite studies.[3] The 10% growth rate would be reasonable if no major space projects were undertaken, since it is only slightly more than the world airline passenger traffic growth of 8.3% over the 1970-1977 period.[16]

The second step in the analysis was selection of the vehicles to be considered. Based on previous results,[15] the vehicles shown in Fig. 2 were selected: the basic space shuttle, a heavy-lift derivative of the shuttle, and a new single-stage vehicle. Several versions of the heavy-lift derivative vehicle are currently being studied. The propulsion of the new vehicle is the primary independent variable in this analysis. The costs of the shuttle and heavy-lift derivatives were assumed from published data and estimates of cost reductions with program maturity. The costs of the new vehicles were calculated from the component design data[14] and cost-estimating relationships. The methodology agrees with that of Ref. 13.

The third step in the analysis is calculation of the transport cost for each year. In this calculation, the vehicles are compared and the vehicle used for the cargo traffic is the one with the lowest cost per unit of payload mass. For the priority traffic, the vehicle with the lowest cost per flight is used. The costs for the selected vehicle and the traffic projection give the

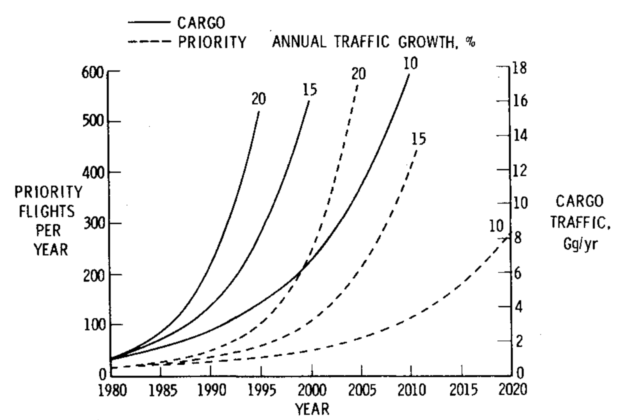

Fig. 1 Traffic growth projections; flights per year are given for a payload of 29.5 Mg.

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Index categories: LV/M Propulsion and Propellant Systems; LV/M Mission Studies and Economics; Liquid Rocket Engines and Missile Systems.

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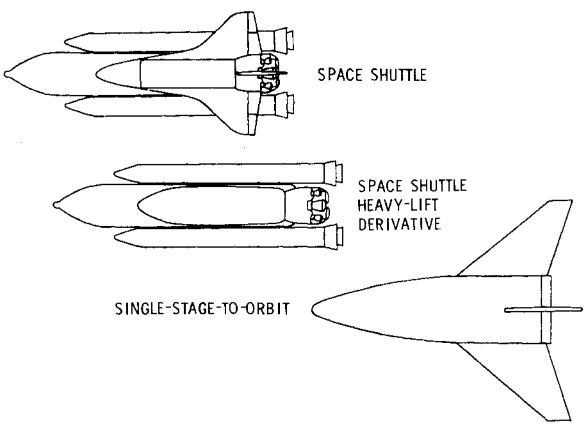

Fig. 2 Vehicles included.

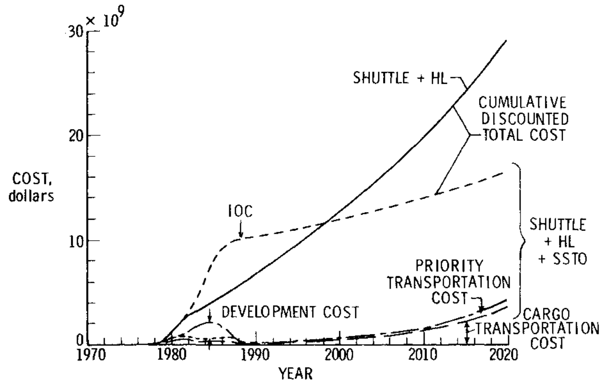

Fig. 5 Shuttle, heavy-lift derivative, and single-stage-to-orbit costs for 10% annual traffic growth.

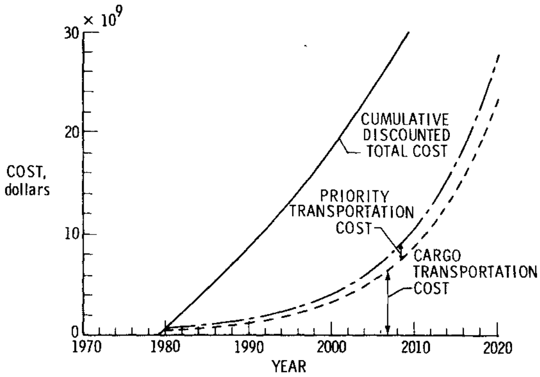

Fig. 3 Shuttle costs with 10% annual traffic growth.

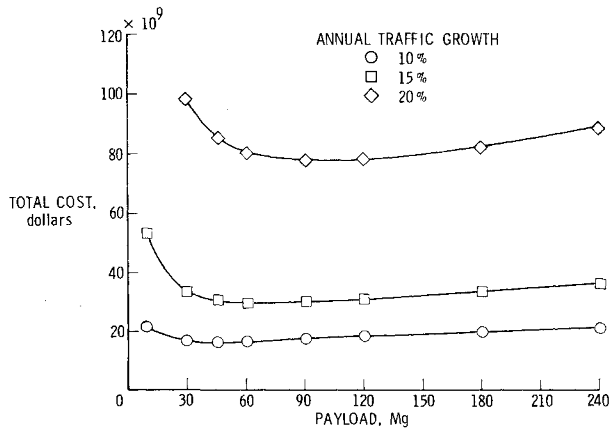

Fig. 6 Effect of single-stage-to-orbit payload on total cost.

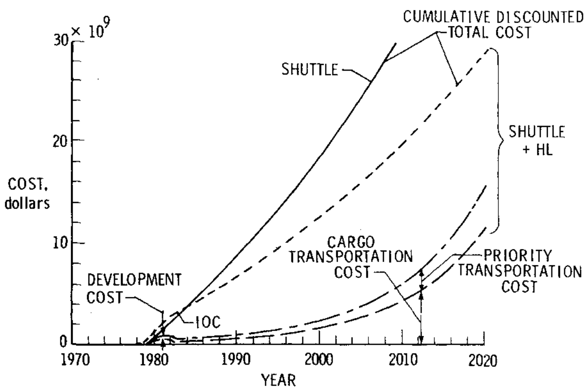

Fig. 4 Shuttle and shuttle heavy-lift derivative costs for 10% annual traffic growth.

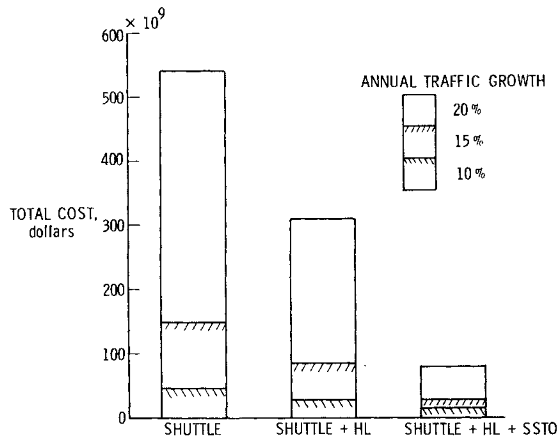

Fig. 7 Summary of total costs.

cargo and priority cost for each year. The development cost for each new vehicle is spread over the six years prior to its initial operational capability.

The fourth step is the summation of the costs for cargo traffic, priority traffic, and vehicle development costs. The annual costs are discounted in this step. A discount rate of 10% was used with an assumption of 3% inflation.

Results with Dual-Fuel

For the remainder of the report, the question of which propulsion systems should be used for a new vehicle will be considered. Only the 10% traffic growth rate and the shuttle payload of 29.5 Mg will be considered.

Figures 8-11 show the results for vehicles with the staged-combustion hydrocarbon engine operated in parallel with a space shuttle main engine modified to have a two-position nozzle. Vehicles were synthesized with the fraction of the sea-level thrust coming from the hydrocarbon engines varying from 0.0 to 1.0. For two thrust fractions, vehicles were synthesized for several values of the fraction of the propellant that is used by the hydrocarbon engines. This variation results from shutting down the hydrocarbon engines at different times during the trajectory simulation.

The solid curves on Figs. 8-10 represent different propellant fractions at constant thrust fractions. The dashed curves pass through points representing different thrust fractions, where the propellant fraction was selected to minimize the ratio of gross mass to burnout mass. These curves will be called the minimum-mass-ratio curves. As can be seen in Figs. 8-10, the minimum-mass-ratio curves do not correspond to the minimum-cost propellant fraction for each thrust fraction. A more complete data set would be required to find the

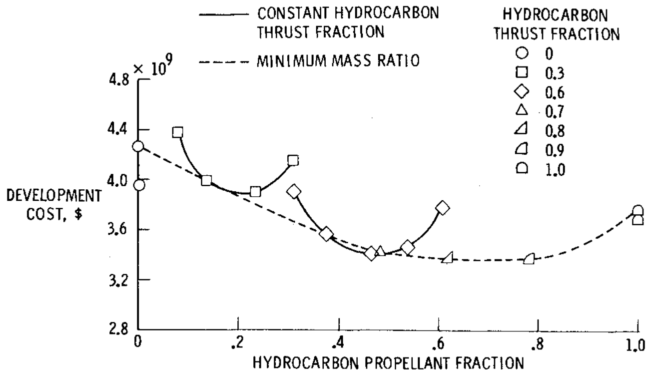

Fig. 8 Development cost for parallel-burn staged-combustion concept.

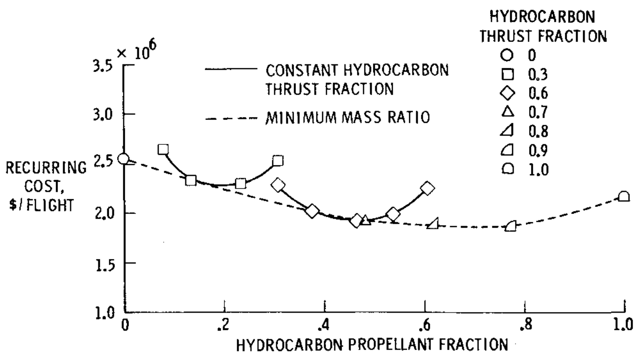

Fig. 9 Recurring cost for parallel-burn staged-combustion concept.

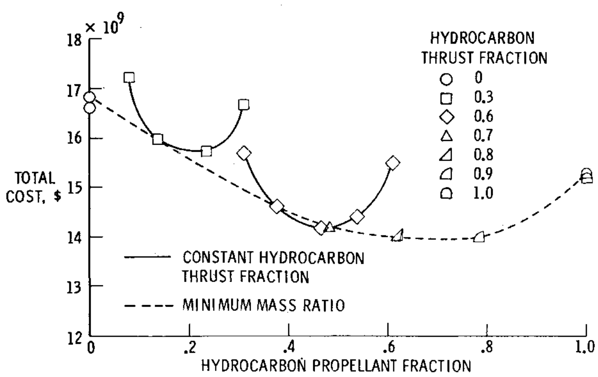

Fig. 10 Total cost for parallel-burn staged-combustion concept.

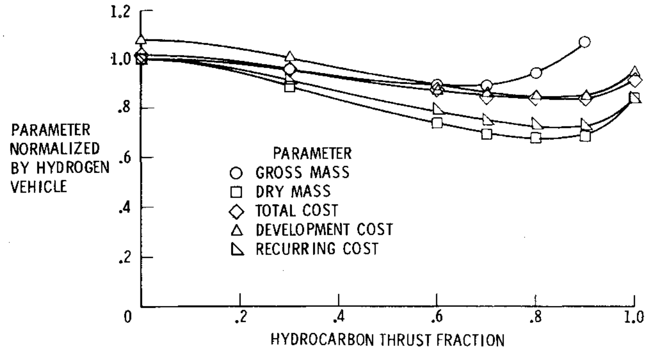

Fig. 11 Summary for parallel-burn staged-combustion concept.

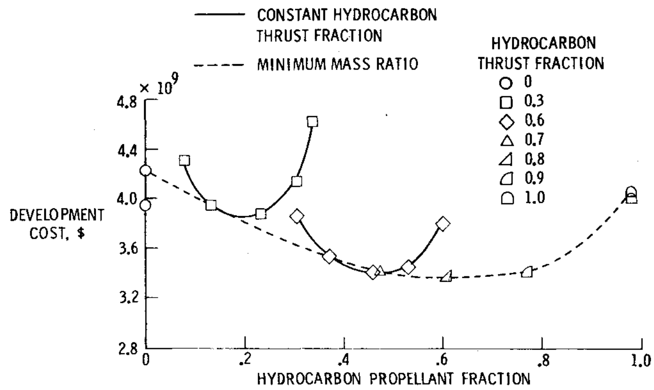

Fig. 12 Development cost for parallel-burn gas-generator concept.

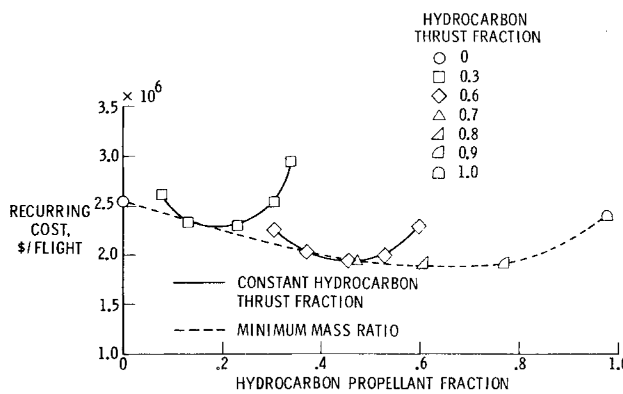

Fig. 13 Recurring cost for parallel-burn gas-generator concept.

minimum cost combination of thrust fraction and propellant fraction, but the minimum-mass-ratio curves show the trends.

Figures 8 and 10 have two points at each extreme of the propellant fraction scale. The upper point represents the extreme of the minimum mass-ratio curves and includes the cost of developing both the hydrocarbon engine and the modified space shuttle main engine (SSME). The SSME modifications include a two-position nozzle and technology improvements to increase life. The lower points represent the more realistic case in which only the development cost of the engine being used is included. At the left end of the curve, the lower point represents the all-hydrogen vehicle, and the upper point represents the same vehicle costs plus the cost of developing the hydrocarbon engine. At the right of the curve, the lower point represents the all-hydrocarbon vehicle, and the upper point represents the same vehicle plus the cost of modifying the SSME. The realistic points for the all-hydrogen vehicle are used as a reference for normalizing the data, and the normalized data along the minimum-mass-ratio curve is shown in Fig. 11.

Figure 11 shows that the optimum fraction of hydrocarbon thrust depends on the optimization criteria. The minimum gross mass occurs with 0.65 hydrocarbon thrust fraction; the minimum dry mass is at 0.80. The development cost minimum is at 0.83. The minimum recurring cost is at 0.86, and the minimum total cost is nearly the same at 0.85. The reduction in gross mass is about 10%, and the reduction in dry mass is over 30%. The development cost is reduced 15%, and the recurring cost is reduced 27%. The total cost is reduced 16%, and this percentage would be increased if just the new vehicle costs were included. Shuttle costs are included in all cases, and they dilute the effect of the hydrocarbon propulsion. The impact of this dilution can be seen by referring to Fig. 5. The cost of using the space shuttle and heavy-lift derivative through 1987 is nearly $\$5 \times 10^9$. The new vehicle costs, from looking at detailed numerical output data, are the remaining $\$11 \times 10^9$. A 16% reduction in total cost is about a 24% reduction in the new vehicle costs. The reductions in all the parameters except gross mass are simultaneously possible at a hydrocarbon thrust fraction of 0.80-0.85; if gross mass is

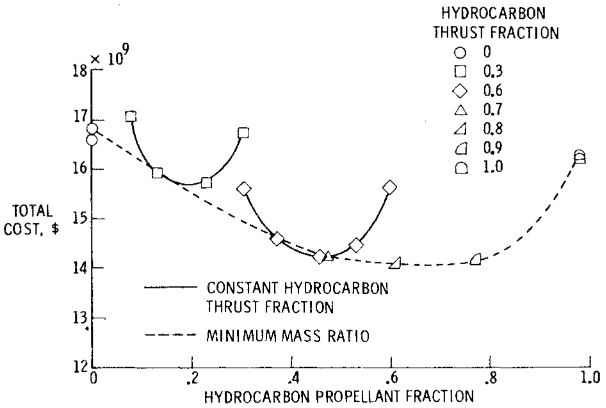

Fig. 14 Total cost for parallel-burn gas-generator concept.

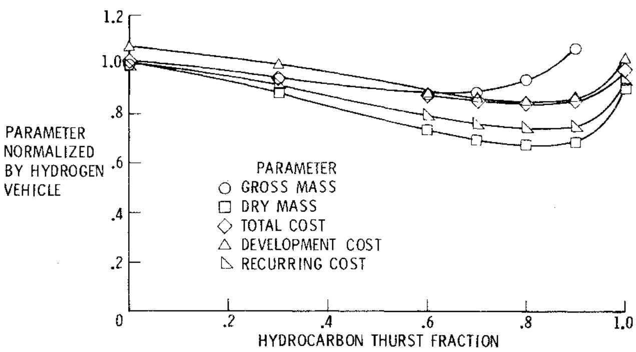

Fig. 15 Summary for parallel-burn gas-generator concept.

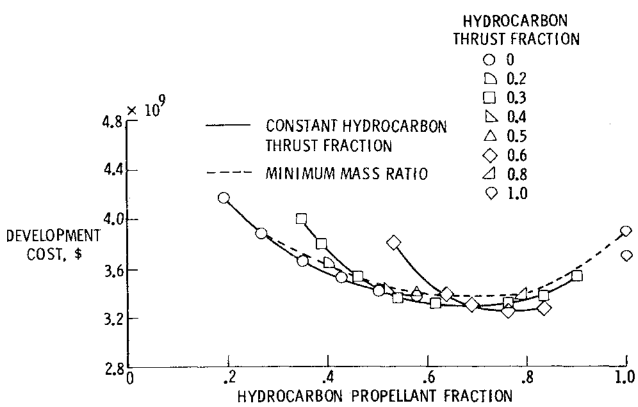

Fig. 16 Development cost for dual-fuel engine concept.

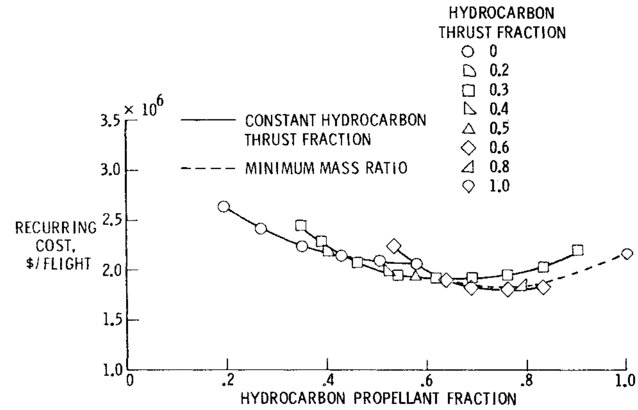

Fig. 17 Recurring cost for dual-fuel engine concept.

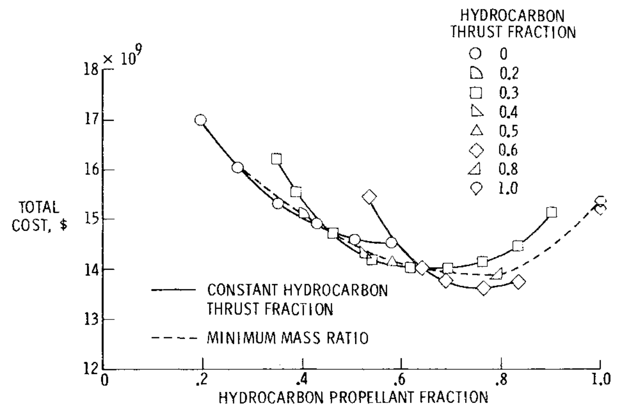

Fig. 18 Total cost for dual-fuel engine concept.

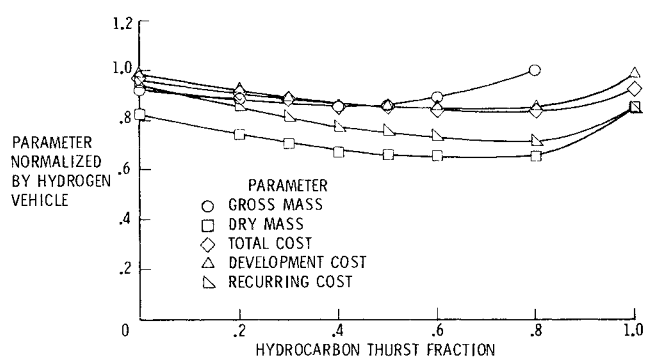

Fig. 19 Summary for dual-fuel engine concept.

important, 0.70 could be chosen without greatly increasing the other parameters.

The final step is optimization of the year of initial operational capability of one vehicle subject to a limit on the earliest year considered possible. The limits used were 1983 for the heavy-lift derivative of the shuttle and 1988 for the new single-stage vehicle.

Results without Dual-Fuel

Figure 3 shows the cost results for the 10% traffic growth rate with only the basic space shuttle included. Even at this modest traffic growth rate, cargo costs exceed $2 billion per year in the early 1990's. Figure 4 shows the effect of including the heavy-lift derivative. The modest development cost ($0.5 billion) is quickly returned in cargo cost savings. Addition of a new vehicle, shown in Fig. 5, increased the total cost during the development period and for a few years after the initial operational capability. The payoff is rapid, and the total savings grow significantly thereafter, even with just 10% annual traffic growth. Both cargo and priority annual transport costs remain low into the next century.

Figure 6 shows the effect on the total cost of varying the design payload capability of the new vehicle. Total cost will always mean the cumulative discounted total cost at 2020. The optimum payload is about 45 Mg with 10% annual traffic growth rate, 60 Mg with 15% growth, and 90 Mg with 20% growth. Further results[15] show that two new vehicles might eventually be desirable, with a small-payload (30 Mg or less) vehicle developed first and a large-payload (90 Mg or more) vehicle developed when the cargo traffic level becomes sufficient.

The total costs are compared in Fig. 7 for the three traffic growth rates and the three vehicle scenarios. The heavy-lift shuttle derivative significantly reduces the costs compared to the shuttle alone, and adding the new vehicle yields further significant savings. Vehicles beyond the shuttle will certainly be desirable, even with moderate traffic growth.

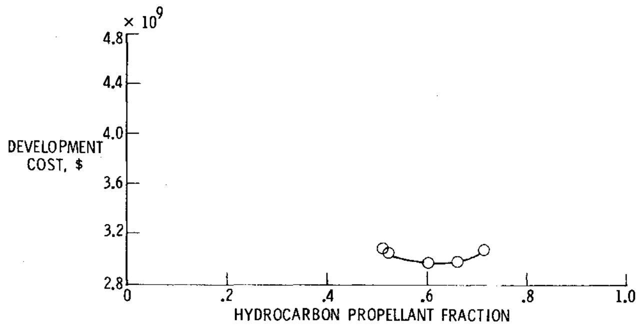

Fig. 20 Development cost for dual-expander concept.

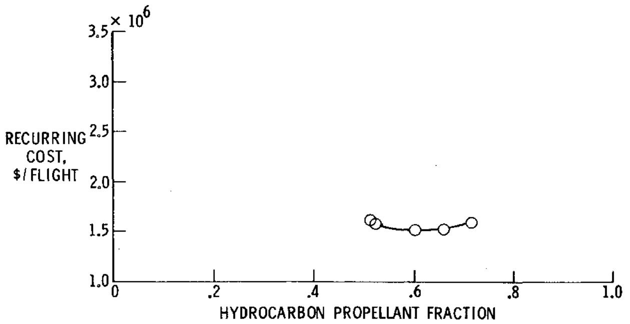

Fig. 21 Recurring cost for dual-expander concept.

The engine development costs used in the analysis are subject to a considerable degree of uncertainty. If the engine development costs were doubled, the development and total-cost curves would be shifted upward an amount equal to the difference between the curves and 1.0 at the extreme left boundary, where the hydrocarbon engine fraction approaches 0.0. The development costs would change significantly, but the total cost would be affected only slightly.

Figures 12-15 show the results with the gas-generator engine. This concept incorporates parallel burn of the modified SSME with a hydrocarbon engine that has hydrogen cooling and a hydrogen-rich gas generator. Since this vehicle needs hydrogen for the gas generator, the point with all-hydrocarbon engines has a hydrocarbon fuel fraction that is less than 1.0. The trends are essentially the same as those of Figs. 8-11.

The results with the dual-fuel engine are shown in Figs. 16-19. In this concept, all of the thrust comes from hydrocarbon fuel at liftoff. Later, the engines that burn only hydrocarbon fuel are shut down. These engines are the same as those used in the parallel-burn concept with staged-combustion hydrocarbon engines. The remaining engines are switched from hydrocarbon to hydrogen fuel, and a two-position nozzle is extended. In these figures, hydrocarbon thrust fraction refers to the fraction of the thrust at liftoff that comes from the pure-hydrocarbon engines. For example, a hydrocarbon thrust fraction of 0.0 would imply that all engines were dual-fuel engines. The curves in Figs. 16-19 do not extend to a hydrocarbon-fuel fraction of 0.0 in the same way that the parallel-burn curves of Figs. 8-15 do. Even when all of the engines are dual-fuel engines, hydrocarbon fuel will be used in the initial part of the flight. In Figs. 16-18, this causes the minimum-mass-ratio curve to end at a hydrocarbon-fuel fraction greater than 0.0. In Fig. 19, this causes the data points at a hydrocarbon-engine fraction of 0.0 to be different from the all-hydrogen reference vehicle. One noticeable difference between the series-burn curves and the parallel-burn curves is the shape of the curves for a fixed hydrocarbon thrust fraction. Starting at the minimum-mass-ratio points and proceeding to the minimum-cost points, the series-burn curves show a greater cost reduction and a greater increase in hydrocarbon fuel fraction.

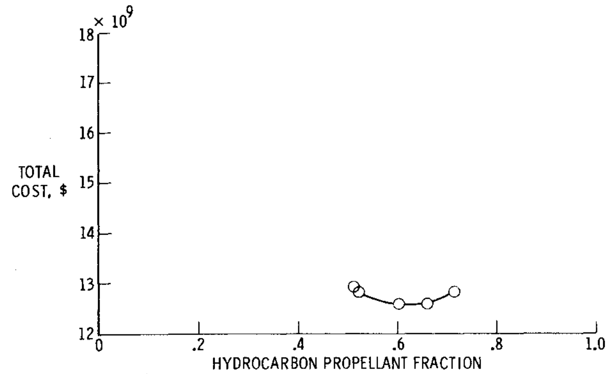

Fig. 22 Total cost for dual-expander concept.

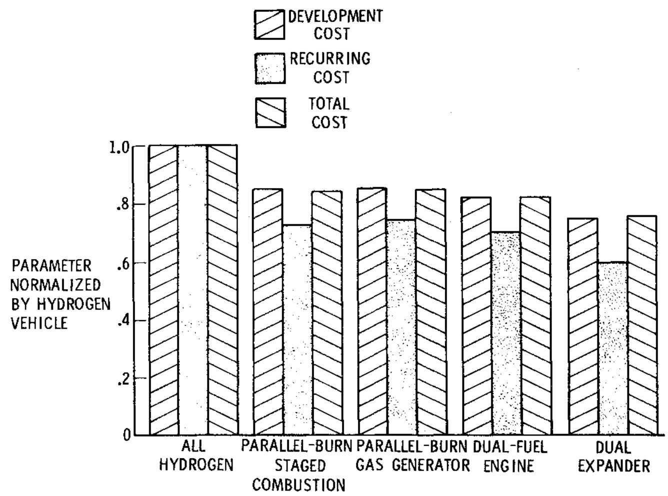

Fig. 23 Cost comparisons of concepts.

Figures 20-22 show the results with the dual-expander engine. This engine burns both hydrocarbon and hydrogen fuel at liftoff; later, the hydrocarbon part of the engine is shut down while the hydrogen portion continues to operate. Because the nozzle exit area that is initially used by the hydrocarbon exhaust can later be used by the hydrogen exhaust, there is a high expansion ratio for the later part of the flight, and a two-position nozzle is not used. Only one hydrocarbon thrust fraction, 0.75, was considered; some variation is possible with the engine concept.

Figure 23 shows the cost comparisons of the various engines. The dual-expander has the greatest potential to reduce costs, but it also requires significant technology advancements. These technology advancements should be pursued now to reach a state of technology readiness, such that the full potential of dual-fuel propulsion is available when a decision must be made to develop a new vehicle. Even without the dual expander, the other dual-fuel concepts show significant cost reductions from the all-hydrogen vehicle. The dual-fuel engine vehicle has slightly lower costs than the parallel-burn staged-combustion vehicle. The parallel-burn gas-generator vehicle is slightly more expensive, but it also has the simplest technology and the lowest engine development cost.

Conclusions

This study of the economics of advanced Earth-to-orbit vehicles using dual-fuel propulsion has indicated the following:

1) Advanced vehicles will be economically attractive in the near future with moderate traffic growth.

2) The optimum fraction of hydrocarbon engines is greatest for minimum-cost vehicles, slightly less for

minimum-dry-mass vehicles, and significantly less for minimum-gross-mass vehicles.

3) Of the hydrocarbon engines considered, the dual-expander engine has the greatest potential to reduce costs, but technology advancements must be pursued now to reach a state of technology readiness before development is required.

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