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Economic and Programmatic Considerations for Advanced Transportation Propulsion Technology

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After the space shuttle becomes operational, requirements for space transportation will increase, which will lead to the development of shuttle derivatives and new Earth-to-orbit vehicles. Economic and programmatic impacts are considered for these concepts in proposed scenarios which include the space shuttle, a heavy-lift cargo derivative of the shuttle, a unique dual-fuel orbit transfer vehicle, and a small new Earth-to-orbit vehicle in the foreseeable future. Large new orbital transfer and Earth-to-orbit vehicles would be added when needed.

Introduction

THE space shuttle[1] will soon bring spaceflight out of the developmental era, characterized by expandable vehicles and operational complexity, into an era that will be characterized by increasingly routine operations. The emphasis in the space program will shift from the flight itself to applications. Already, thoughts of solar power beamed to Earth,[2] colonies at the Earth-moon libration points,[3] and electromagnetic mass drivers for mining the moon[4] have attracted significant publicity. More subtle movements have begun to support large communications platforms, enzyme growing, and reflectors to beam solar energy to Earth for light and heat.[5]

Some of the proposed applications, and others not yet conceived, will warrant research and development flights; some will reach production. The result will be traffic growth and the need for vehicles more advanced than the space shuttle and the solid-fueled upper stages now being developed. The major milestones shown in Fig. 1 for typical vehicle development—preliminary phase A (PHA) studies, authority to proceed (ATP), and initial operational capability (IOC)—indicate that if a new vehicle is needed by 1995, the technology must be developed in less than a decade. What is not shown is that for certain pacing items, such as advanced propulsion systems, technology development must proceed in earnest almost immediately.

The purpose of this paper is to examine various vehicle options that have been proposed in light of a range of traffic growth. The traffic in the model[6] has been 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 includes 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 flights into specialized orbits—anything requiring a separate Earth-to-orbit flight. Traffic growth rates of 10-20% annually have been considered. A 20% growth rate would be required to reach the traffic level for one solar power satellite per year by the end of the century. A 10% growth rate is considered to be reasonable if no new major programs are started; it is commensurate with the 8.3% growth in air traffic in 1970-1977.[7]

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Space Shuttle and Derivative Vehicles

Figure 2 shows the space shuttle and three derivative vehicles that have been considered. The heavy-lift (HL) derivative results when the orbiter is replaced by a recoverable propulsion and guidance package. Because this concept eliminates a significant portion of the inert mass of the orbiter, the payload mass is greater than that of the space shuttle even though the insertion mass is the same. The liquid booster (LB) derivative would eliminate the expense and potential environmental problems of the solid rocket boosters. Versions of the LB include the twin ballistic system shown and flyback systems. The combined derivative would use the LB and the HL derivative.

The HL derivative would not require propulsion development; it could use essentially the same subsystems the basic space shuttle uses. The question of whether to develop the LB or not is a significant one for the propulsion community. At the very least, the space shuttle main engine (SSME) could be adapted by modifying the nozzle for an expansion ratio of about 35. A hydrocarbon engine would really be preferred for the LB. One of the considerations is whether or not the same hydrocarbon technology would be applicable to other advanced vehicles.

Economic studies for the shuttle and the HL derivative have been made in the past,[6] and more recent results are presented in Figs. 3-5, which include the LB derivatives. The analysis method was described in Ref. 6. The difference between the discount rate and the inflation rate was assumed to be 7%. All costs are given in 1975 dollars. Some vehicle assumptions are shown in Table 1.

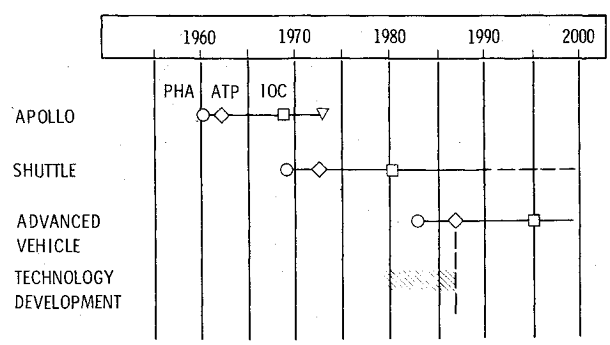

Fig. 1 Advanced aerospace vehicle technology planning.

Table 1 Vehicle assumptions

	Payload, Mg	Development cost, $B	Recurring cost, $M/flight
Shuttle	29.5	(already paid)	15
HL	60	0.5	15
LB	45	2.0	11
Both	75	2.75	11

The annual costs for cargo and priority traffic grow monotonically with traffic growth using just the basic space shuttle. The annual costs with this system will exceed two billion dollars before the end of the century with an annual traffic growth rate of just 10%.[6] The cumulative discounted total cost grows rapidly (Fig. 3).

The reduction in annual cargo costs due to the HL derivative can reduce the total cost even though there is an increase in the total cost initially because of the development of the derivative.[6] In Fig. 3, the LB development cost is significant, but the total cost is still below that for the shuttle alone after 1990. Compared with the costs for the shuttle alone,[6] the LB reduces both cargo and priority annual costs.

In Fig. 4, the effect of developing all derivatives is shown. The annual costs are lower than for either single derivative with the shuttle, and the total cost is shown to be less than that for the HL derivative with the shuttle.

In Fig. 5, the total costs are summarized for the shuttle and the shuttle plus the derivatives. Since the important question is which scenario has the lowest cost over a significantly long period of time, only the total costs through the year 2020 are shown. Results are shown for all three traffic growth rate assumptions. Either of the derivatives can reduce total costs, and development of all derivatives can reduce costs even more. The magnitude of the total costs, even with all derivatives, indicates the possibility that new vehicles could eventually be developed with even lower annual costs than the shuttle derivatives. It is important to examine the effects of new vehicles on these results before making decisions about shuttle derivative developments.

Effect of a New Vehicle

Figures 6-9 show the results of economic calculations with a new vehicle included. It is a vertical-takeoff horizontal-landing single-stage vehicle with all-hydrogen propulsion.[6] For comparison purposes, the new vehicle in Figs. 6-8 was designed for a 29.5-Mg payload. The development cost was estimated to be about $6 billion, and the recurring cost was estimated at $2.5 million/flight. The results are probably not very sensitive on the scale shown to the type of new vehicle. Figure 6 shows that the new vehicle significantly reduces the total cost. Even for the closest comparison, with all derivatives and an annual traffic growth of 10%, the new vehicle reduces total costs about 15%.

Another significant result shown in Fig. 6 is that the selection of shuttle derivatives has very little effect on the total cost when the new vehicle is included. This conclusion is completely different when the new vehicle is not included. Because of this result and because a new vehicle will surely be developed eventually, the selection of shuttle derivatives may be made on some basis other than cost.

Figures 7-9 show some programmatic effects relating to the shuttle derivative selection. The annual costs are shown in Figs. 7 and 8 with a new vehicle, and the total costs are

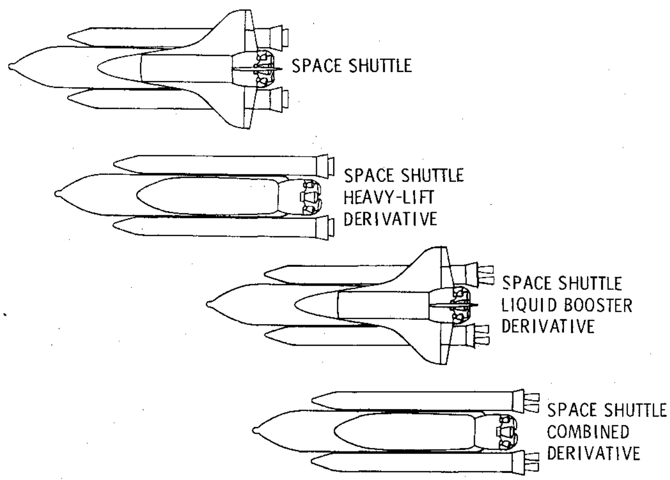

Fig. 2 Space shuttle and derivative vehicles.

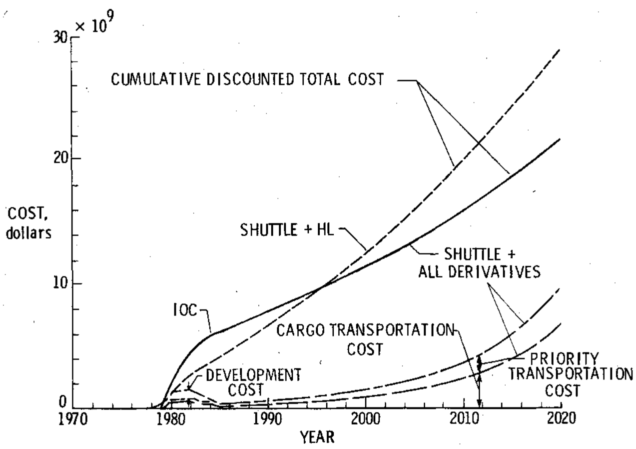

Fig. 4 Shuttle and all derivatives costs with 10% annual traffic growth.

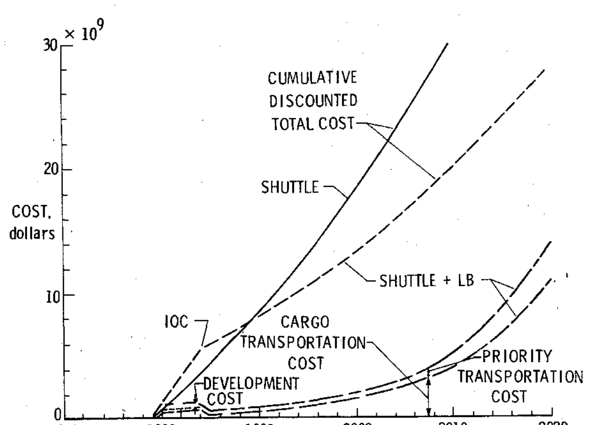

Fig. 3 Shuttle and liquid booster costs with 10% annual growth.

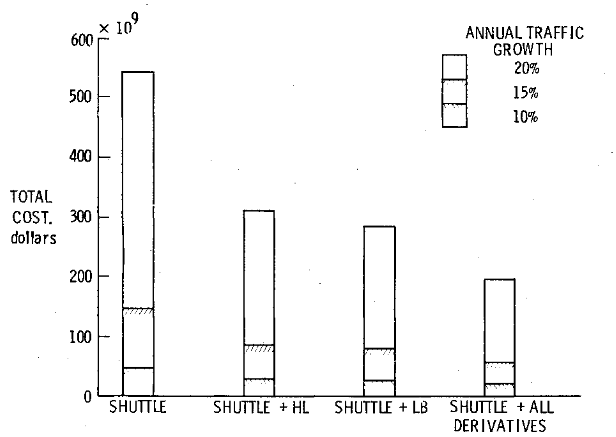

Fig. 5 Summary of total costs through year 2020.

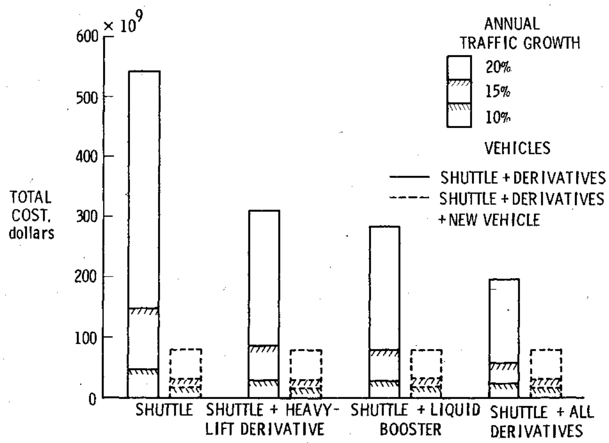

Fig. 6 Summary of total costs with new vehicle costs with 10% annual traffic growth.

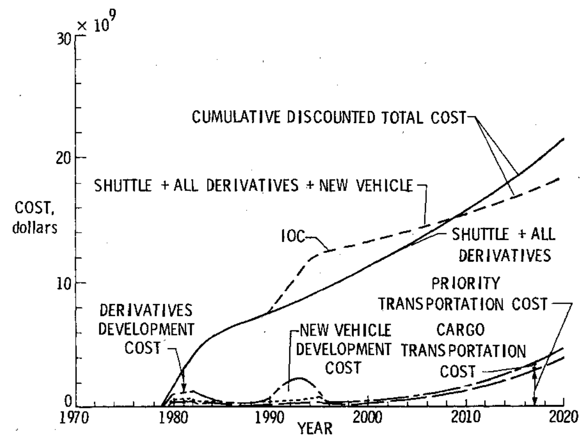

Fig. 7 Shuttle, all derivatives, and new vehicle costs with 10% annual traffic growth.

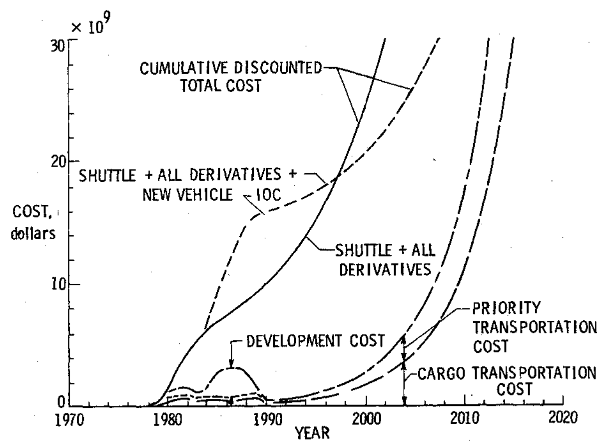

Fig. 8 Shuttle, all derivatives, and new vehicle costs with 20% annual traffic growth.

compared to the same scenario without the new vehicle. With only the HL derivative, the optimum initial operational capability (IOC) of the new vehicle is very early.[6] The IOC was constrained to be no earlier than 1988 in the analysis, and the optimization drove it to this limit. With all of the shuttle derivatives included, the optimum IOC for the new vehicle is delayed until 1996, as shown in Fig. 7, with a 10% annual traffic growth. If the annual traffic growth is 20%, however, the optimum IOC is again 1988, as shown in Fig. 8.

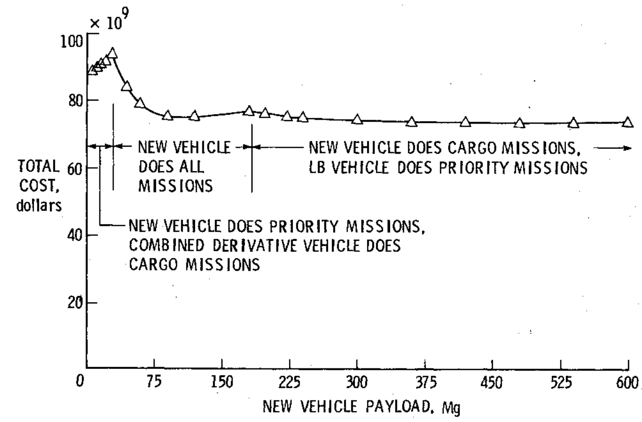

Fig. 9 Effect of new payload on costs for shuttle, all derivatives, and new vehicle: 20% annual traffic growth; reduced shuttle costs.

The optimum payload of the new vehicle can also be influenced by the selection of shuttle derivatives. Results from Ref. 6 showed the optimum payload for the new vehicle to be 45, 60, and 90 Mg for traffic growth rates of 10, 15, and 20%, respectively, when only the HL derivative is developed. In that scenario, the results were rather straightforward because the new vehicle has lower costs for both the priority mission and the cargo mission. The shuttle and the HL derivative can be retired once the new vehicle is developed, and the payload optimization involves only the new vehicle costs. A large new vehicle has a large development cost and a high cost per flight for priority missions, but the cost per unit mass of payload is less than for a smaller vehicle. If all of the shuttle derivatives are developed, however, the results can be significantly different.

The new vehicle could be designed for one of three different payload ranges (Fig. 9). A very small new vehicle would capture the priority missions, and the combined derivative vehicle would continue to do the cargo missions. A moderate new vehicle (30-180 Mg payload) would do all missions. A very large new vehicle, with an optimum payload of about 360 Mg, would capture the cargo missions, and the LB derivative vehicle would continue to do the priority missions. Of the three options, the very large new vehicle results in the lowest total cost. The scenario of a large new vehicle and the LB derivative has been proposed for solar satellite programs.[8] This vehicle combination did not appear as an optimal one in this analysis, however, until the LB cost per flight was reduced from the initial assumption of $11 million to $6 million. With the original assumption, the moderate-payload new vehicle was optimum.

The new vehicle would probably have a new engine. Potential cost savings are indicated in Ref. 6 if various hydrocarbon engines are developed. For large new vehicles, a two-stage design with hydrocarbon engines in the first stage appears promising.[9] Also, a hydrogen engine with greater thrust and longer life than the SSME may be required.

Two New Vehicles

The development of two new vehicles might be appropriate, as indicated in Fig. 9, one for each type of mission. Figure 10 shows the effect of including two new vehicles with a 10% traffic growth rate. The time-span has been increased to 2050 to properly show the effects of the second new vehicle. Although 2050 is far in the future, the analysis was extended beyond 2020 to show the effect of a second new vehicle that may have an IOC as late as 2010; continuing the analysis too far does not distort the results significantly. Without a small new vehicle, the design payload of the large new vehicle must remain in the 45-Mg range. The reason for this restriction is that a larger vehicle would cost more per flight for the priority

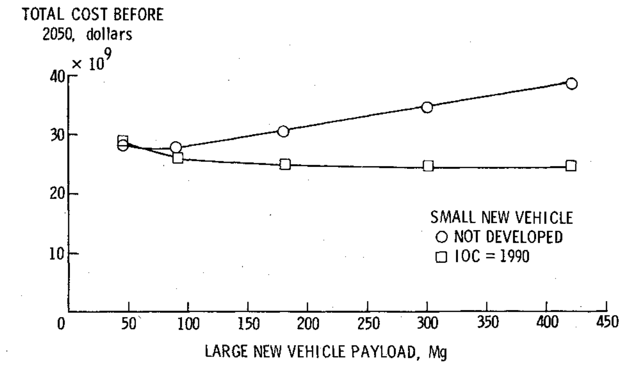

Fig. 10 Shuttle, heavy-lift derivative, and two new vehicle costs: small new vehicle payload of 29.5 Mg; 10% annual traffic growth.

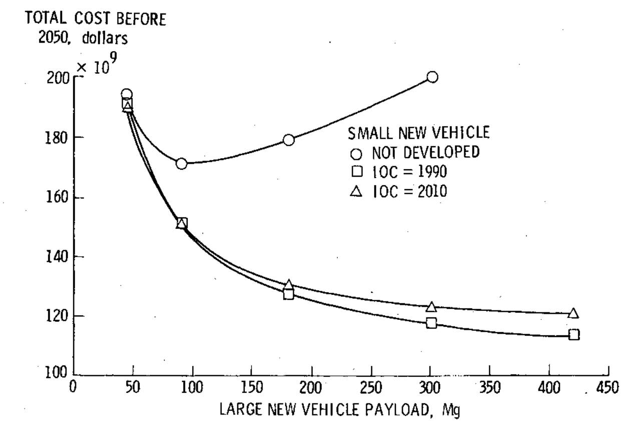

Fig. 11 Shuttle, heavy-lift derivative, and two new vehicle costs: small new vehicle payload of 29.5 Mg; 15% annual traffic growth.

missions and would cost more to develop. With two new vehicles, the small vehicle would handle the priority missions, and the design payload of the large vehicle could be optimized for the cargo traffic. The optimum payload might be about 300 Mg.

The total cost reduction due to the addition of the second new vehicle is only about 15% with a 10% traffic growth rate. With a 15% traffic growth rate, however, Fig. 11 shows that the second vehicle would reduce total costs about 30%.

Another effect that is shown in Fig. 11 is the timing of the new vehicle introductions. The lowest cost results when the small new vehicle is introduced in 1990 rather than 2010. In all cases, the introduction (IOC) of the large new vehicle was optimized. Results with a single new vehicle have shown that the IOC should be quite early. When the small new vehicle is not developed until 2010, the large new vehicle optimum IOC is always in the 1988-1995 range. This timing is not shown in Fig. 11, but it is shown in the tabular output from which Fig. 11 was constructed.

In the scenario with the small new vehicle developed for an IOC of 1990, the small new vehicle has enough capability to do all missions at a lower cost than the space shuttle or the HL derivative. A larger new vehicle with a payload of about 300 Mg would be developed later to reduce the cost of cargo missions. One attractive feature of this scenario is that the payload of the larger new vehicle can be optimized in the future when cargo traffic predictions are much more clearly understood than at the present time.

In addition to the previous scenario where the HL derivative, an early small new vehicle, and a later large new vehicle are all developed, another attractive scenario includes all of the derivative vehicles. In this case, a large new vehicle would be developed and used for cargo, while the LB derivative would be used for priority traffic. Eventually, a small new vehicle might replace the LB derivative for priority flights. This second scenario is only attractive if the annual traffic growth rate is 10% or less and if the LB derivative costs are reduced below the nominal assumption of $11 million per flight.

Orbital Transfer Vehicles

An advanced orbital transfer vehicle (OTV) will soon be needed. One previous concept[10] is for an Earth-based OTV designed for use with a single space shuttle launch. More recently, the use of two space shuttle launches has been considered to place a two-stage Earth-based OTV in orbit.[11] A space-based OTV has also been shown to be attractive.[12] It would require orbital propellant transfer.

A dual-fuel OTV has been proposed that would use one space shuttle launch.[13] Another dual-fuel concept has been designed to use one basic space shuttle launch and one HL derivative launch.[14] The loaded oxygen tank and the engines would be lifted by the HL derivative, and the remainder of the vehicle and the payload would be carried by the space shuttle. The components would be joined in low Earth orbit (LEO) and complete the trip to geosynchronous orbit (GEO) and return. The entire empty OTV and payload would be returned in the space shuttle payload bay. This concept has a much greater payload capability than any other Earth-based OTV for comparable launch costs.

There is some question about the value of dual-fuel propulsion in an OTV. The factors that make dual-fuel propulsion attractive for Earth-to-orbit vehicles, which are discussed in Ref. 14, apply to the OTV, but their importance is greatly reduced. Any difference in the gross mass or dry mass of an OTV designed for a given payload due to incorporating dual-fuel propulsion is likely to be small. The importance of dual-fuel propulsion for an OTV is in the volume reduction. In the particular concept described in Ref. 14, the empty OTV and payload could be returned in the space shuttle payload bay. If an all-hydrogen OTV of the same payload capability were used, some tanks would have to be expended.

The question of wether or not to recover an OTV is a complex one. If the space shuttle is the Earth-to-orbit vehicle, the cost of propellant delivered to orbit is so great that recovery of an OTV is not worthwhile for missions involving delivery to GEO. On the other hand, recovery of the OTV is worthwhile for round-trip payloads such as manned sorties. When the HL derivative vehicle is used, as proposed here for the near future, recovery is more likely to be worthwhile for delivery missions due to the lower cost of propellants delivered to orbit. When fully reusable Earth-to-orbit vehicles are developed, recovery of the OTV will definitely be worthwhile for most missions because the cost of delivering propellants to orbit will be greatly reduced. The proposed OTV concept can be used in an expendable mode when justified and adapts well to recovery or even space basing in the future.

All of the OTV proposals would probably require new or modified engines. A new hydrogen engine is being considered

Table 2 A reasonable scenario

System	IOC	Some capabilities
Space shuttle	1980	Spacelab, LEO satellites, unmanned upper stages
Heavy-lift derivative	1983-1987	Low $/kg to LEO, large and heavy payloads
Dual-fuel OTV	1986-1990	Construction and maintenace of large GEO platforms
Small new Earth-to-orbit	1988-1995	Reduced $/kg and $/kg to LEO
Cargo OTV	?	Reduced $/kg to GEO
Large new Earth-to-orbit	?	Reduced $/kg to LEO

for the all-hydrogen OTV concepts in ongoing efforts. Hydrocarbon and hydrogen engines or a tri-propellant engine would be required for the dual-fuel concepts.

A Reasonable Scenario

Table 2 shows a reasonable scenario for development of space systems over the next two decades or more. The dual-fuel OTV shown in the table was evaluated in Ref. 14, and it has been included to complete the scenario. Although this is not the only reasonable scenario, it appears to satisfy programmatic constraints, to allow for capability increases as needed, and to minimize transportation costs. Propulsion developments required in this scenario are the dual-fuel OTV propulsion, the small new Earth-to-orbit vehicle propulsion, the large new Earth-to-orbit vehicle propulsion, and the cargo OTV propulsion.

One assumption used in this analysis is that future payloads will have densities equal to that of the space shuttle design payload (100 kg/m^3). Another assumption is that payloads can be adapted to the vehicle maximum payload and volume constraint. It is possible that a new vehicle will have to be sized for some particular payload volume or mass even though that design is not optimum economically. It is not possible to include all such possibilities in the analysis, and the probability of such constraints is small. Future space operations will surely include deployable and erectable systems, and the shuttle HL derivative can be used for unusual situations, if needed, even after a new vehicle is developed.

Conclusions

Economic and programmatic analyses of possible future Earth-to-orbit and orbit-transfer vehicles have led to the following conclusions:

1) Including a new Earth-to-orbit vehicle in future plans significantly affects the selection of shuttle derivative vehicles.

2) A reasonable scenario for future vehicles includes a heavy-lift derivative of the space shuttle, a dual-fuel orbit-transfer vehicle, and a small new Earth-to-orbit vehicle. A cargo orbit-transfer vehicle and a large new Earth-to-orbit vehicle could be added, as needed, depending on traffic growth.

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