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Propulsion Options for Space-Based Orbital Transfer Vehicles

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A concept for a lightweight space-based orbital transfer vehicle (OTV) featuring thin, spherical, pressure-designed aluminum liquid-oxygen and liquid-hydrogen tanks and a truss structure of composite materials is used as a baseline design for a large-cargo OTV. Vehicle sizing, fleet analysis, and parametric cost analysis are used to evaluate the effects of engine technology, vehicle staging, and high-thrust vs. low-thrust transfer. Results indicate that Earth-to-orbit launch costs and OTV engine performance are strong drivers in orbital transportation cost and that there is no significant benefit in staging vehicles. At the low values of Earth-to-orbit cost representative of advanced launch vehicles, low-thrust and high-thrust OTV's are competitive.

Nomenclature

C	= LEO to GEO transportation cost, \$/kg
C_{ETO}	= Earth-to-orbit launch cost, \$
C_{FU}	= first-unit cost of a vehicle, \$
g	= acceleration of gravity at the Earth's surface = 9.807 m/s
I_{sp}	= specific impulse, s
m_{car}	= total cargo mass, kg
m_{dry}	= vehicle dry mass, kg
m_0	= vehicle startburn mass, kg
m_p	= propellant mass, kg
m_{pay}	= payload mass, kg
n_{DV}	= ΔV split for staged vehicles
N_F	= number of flights
N_V	= number of vehicles
R_M	= ratio of startburn mass to burnout mass
T	= thrust, N
T/W	= initial thrust-weight ratio
ΔV	= velocity addition required to change orbit, m/s

Abbreviations

ASE	= advanced space engine
AVID	= aerospace vehicle interactive design
CAT	= RL10 derivative engine category
ETO	= Earth-to-orbit
GEO	= geosynchronous equatorial orbit
LCOTV	= large-cargo orbital transfer vehicle
LEO	= low Earth orbit
LH_2	= liquid hydrogen
LOX	= liquid oxygen
OTV	= orbital transfer vehicle

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Introduction

WITH the advent of the space transportation system the cost of delivering payloads to orbit will decrease, and the number of users of space will increase accordingly. In the future improvements in space transportation will occur, and it is expected that the utilization of space will increase dramatically. Many innovative proposals have been made to take advantage of the increased utilization. A number of these potential space applications would require the delivery of large amounts of material to geosynchronous orbit. NASA has initiated studies to identify technology requirements for future Earth-to-geosynchronous-orbit transportation systems. These studies are surveyed by Henry and Eldred,[1] who postulate that future space transportation needs will be satisfied by a stable of vehicles, each suited for a particular aspect of transportation.

One element of the stable of vehicles would be a large-cargo orbital transfer vehicle (LCOTV), whose principal task would be to deliver large amounts of nonpriority cargo from low Earth orbit (LEO) to geosynchronous equatorial orbit (GEO). A study comparing electric and high-thrust chemical propulsion systems for LCOTV's showed that the Earth-to-orbit (ETO) launch cost is a main driver for chemical LCOTV's.[2] The current paper investigates the effect of this driver on the comparison between low-thrust and high-thrust LCOTV's.

A low-thrust (initial acceleration $\ll 0.05\ g$) LCOTV would allow the use of small, relatively inexpensive engines. In addition to general-purpose cargo delivery, the low-thrust vehicle could be used to transfer large, lightweight structures from low to high orbits. The gravity losses associated with low-thrust orbital transfer, however, will exact a substantial performance penalty from these vehicles, although this can be alleviated through the use of multiple perigee burns with a corresponding increase in transit time. Also, the technology for high-performance low-thrust rocket engines with long burn time and restart capability is not well advanced compared to that of more conventional high-thrust rockets.

The high-thrust rocket engines provide greater performance and shorter trip times. These engines may also be the same as those used on a priority OTV, which is needed to carry people and priority cargo to GEO. The technology for LOX/LH_2 rockets is mature with one space engine already in existence, the RL10,[3] and component testing in progress on the advanced space engine.[4]

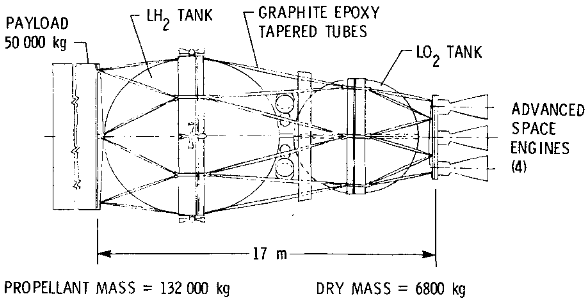

Fig. 1 Space-based OTV concept.

Table 1 ΔV requirements for low-thrust LEO to GEO transfer

T/W	Two-burn ΔV, m/s	Five-burn ΔV, m/s
.001	5412	5018
.002	5369	4984
.003	5296	4955
.005	5148	4861
.007	5116	4816
.01	5040	4776
.02	4890	4648
.03	4776	4547
.05	4615	4391
.07	4486	4297
.1	4360	4230

Concepts for both low- and high-thrust vehicles are studied herein. Other options studied are improvements in high-thrust propulsion technology, staging vs single-stage vehicles, and expendable vs reusable vehicles. Using vehicle sizing and fleet and cost analyses, the competitiveness of the various options is evaluated.

Method of Analysis

A minicomputer-based computer-aided design tool named the aerospace vehicle interactive design (AVID) system was used in the current study. The AVID system links a number of independent computer programs, each specializing in a particular technology, via a communications data base. A user can interact with each technology module and select the order of program execution. In this way a large number of designs, each with a different set of values for key parameters, can be evaluated, and the designer can easily assess the effect of technology variations on the overall system characteristics. In this case AVID was used to link programs that sized the LCOTV, determined fleet requirements on the basis of vehicle characteristics and traffic level, and calculated the cost for an LCOTV to deliver the desired cargo on the basis of simple parametric methods. All of these programs are described below.

LCOTV Sizing

The vehicles in this study were assumed to be space based; that is, they would be delivered without payload or propellant and would remain on-orbit for their entire liftimes, with the possible exception of the engines, which could be removed and returned to Earth for maintenance. Because of the low acceleration experienced by the fully loaded vehicle and the relaxation of dimensional constraints, the tanks and structure of the OTV can be very lightweight. Such a vehicle, the result of in-house studies, is illustrated in Fig. 1. The spherical aluminum tanks are predominantly pressure designed, while the primary structure consists of tapered graphite epoxy tubes. Preliminary analysis shows that the dry mass of space-based OTV's may be up to 30% less than that of comparably sized Earth-based vehicles.

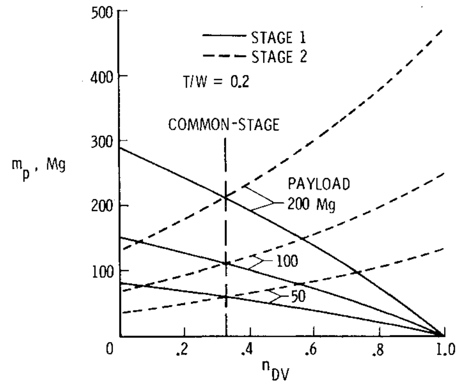

Fig. 2 Effect of ΔV split on stage propellant mass.

Most of the vehicles were sized to deliver a given payload mass from a 500-km circular orbit inclined at 28.5 deg to a geosynchronous equatorial orbit and return with no payload. Some of the LCOTV's were assumed to be expendable; i.e., the vehicle is not returned after payload delivery. Also, each vehicle was sized to a given startburn thrust-weight ratio (T/W), which was a parameter varied in the study.

The velocity requirements for the low-thrust LCOTV are very sensitive to startburn T/W and the number of burns. Ongoing studies are defining this sensitivity and have provided the velocity increments used in this study. The one-way ΔV required for a transfer between LEO and GEO with plane change as a function of T/W is shown in Table 1. Optimal steering was assumed, and the plane change ΔV was distributed throughout the powered portions of the trajectories. Vehicle staging was simulated using ΔV split, n_{DV}, defined as the proportion of the total LEO-to-GEO transfer ΔV that is provided by the second stage. A value of 1.0 for n_{DV} corresponds to a single-stage vehicle. Because of reduced mass due to spent propellant and jettisoned payloads or stages, the return of each stage occurred at high values of T/W, and the ΔV was assumed to be near that for an ideal Hohmann transfer.

The startburn thrust-weight ratio for all the high-thrust LCOTV's was 0.2. The transfer from LEO to GEO was accomplished with two burns. The first burn provided a ΔV of 2432 m/s, sufficient to take the vehicle to GEO altitude. The second burn provided circularization and plane change with a ΔV of 1768 m/s. For high-thrust staged vehicles, the first-burn ΔV of 2432 m/s was split between the two stages according to the desired value of n_{DV}. The return ΔV for the first stage was essentially equal to its share of the first-burn ΔV, while the return ΔV for the second stage from GEO was 4165 m/s including plane change. A 2% contingency was added to all ΔV's for both the low- and high-thrust vehicles.

For each ΔV the mass ratio was calculated from the rocket equation

$$R_M = e^{\Delta V/gI_{sp}} \tag{1}$$

and the propellant required for any startburn mass was

$$m_p = m_0(1 - 1/R_m) \tag{2}$$

The first step in sizing the LCOTV was to calculate the masses of the components whose size could be expressed in terms of volume of one or both of the propellants. The computer program initially used an estimate of the propellant mass input by the user. The mass-estimating relationships were curvefits of data generated by various point design studies[5-7] and in-house studies of space-based OTV's. Estimates were also made of nonimpulsive fluid losses, such as reserves and residuals, boil-off, start/stop losses, and attitude control propellant. The masses of these components were summed with the payload, and a rough estimate of the startburn mass was made.

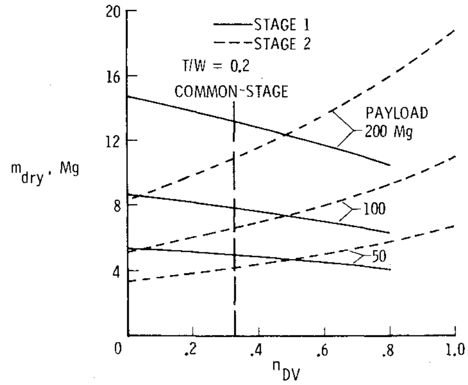

Fig. 3 Effect of ΔV split on stage dry mass.

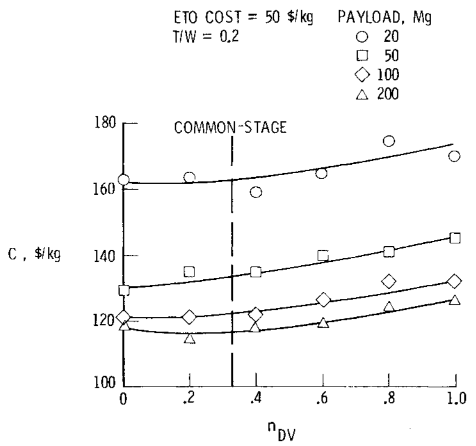

Fig. 4 Effect of ΔV split on orbital transportation cost.

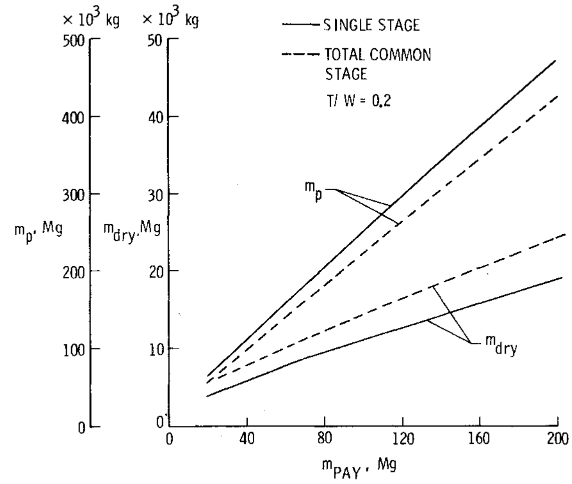

Fig. 5 Effect of payload capacity on vehicle characteristics.

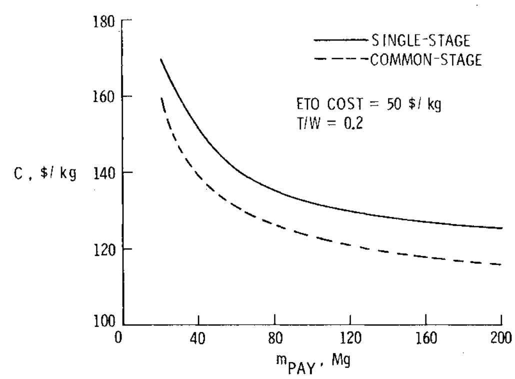

Fig. 6 Effect of payload capacity on orbital transportation cost.

The total thrust required was calculated from the estimated startburn mass and the desired initial thrust-weight ratio. Using the value for thrust, the masses of the engines, thrust structure, gimbal system, and propellant feed system could be calculated.

The masses of all the components were then summed, along with the propellant and payload, to give the exact startburn mass. The initial thrust-weight ratio was calculated using the total thrust and the new startburn mass. If the thrust-weight ratio was not equal to the desired value, within a tolerance, then the process was restarted using the new startburn mass at the point where total thrust was calculated. Once the vehicle was sized to the correct thrust-weight ratio for the given propellant mass, the actual amount of propellant required for the round-trip mission was calculated using several applications of Eq. (2). If the propellant mass required was not equal to the propellant mass used during the component mass calculations, the entire process was repeated using the new value for propellant mass. The vehicle was sized when the propellant mass required and the propellant mass available converged to the same value. For staged vehicles the mass of the second stage was calculated first, and its startburn mass was used as the payload when determining the mass of the first stage. The vehicle mass and power characteristics were displayed by the sizing program and saved for use in subsequent analyses.

Fleet Analysis

The number of vehicles required to handle a given amount of traffic was determined by a fleet analysis. A 30-year scenario was assumed, with a level of traffic from LEO to GEO starting at 1000 Mg per year and increasing at an annual rate of 10%. Using the traffic level, the payload capacity and lifetime of the vehicle, and the round-trip time, the fleet analysis program was used to calculate the number of flights and vehicles required over the 30-year period. With the vehicle and propellant masses provided by the sizing program, the total mass delivered to LEO by the Earth-to-orbit launch system to support the LCOTV was calculated.

Cost Analysis

A simplified parametric cost analysis was performed using the data generated by the sizing and fleet programs. The total specific cost of transporting cargo from LEO to GEO was calculated by dividing the sum of the cost of purchasing the vehicles and propellant and the cost of delivering them from Earth to LEO by the total mass of cargo delivered. The first-unit cost was assumed to be a function of vehicle dry mass. The equation used was a curvefit of data from point designs of various propulsion stages.[5] The equation used for the first-unit cost was

$$C_{FU} = 0.207 m_{dry}^{\ 0.551} \times 10^6 \tag{3}$$

where m_{dry} was the dry mass of one vehicle. A learning factor of 0.90 was applied over the calculated fleet sizes. The cost of the propellant was assumed to be $0.40/kg in all cases.

The cost of delivering vehicles and propellant from Earth to LEO was also an input parameter and was varied from $10 to $50/kg. Therefore, the total OTV-associated cost of delivering cargo from LEO to GEO was

$$C = \frac{1}{m_{car}} \Big[C_{FU} N_V^{\ 0.926} + 0.4 m_p N_F + C_{ETO} m_{dry} N_V + C_{ETO} m_p N_F \Big] \tag{4}$$

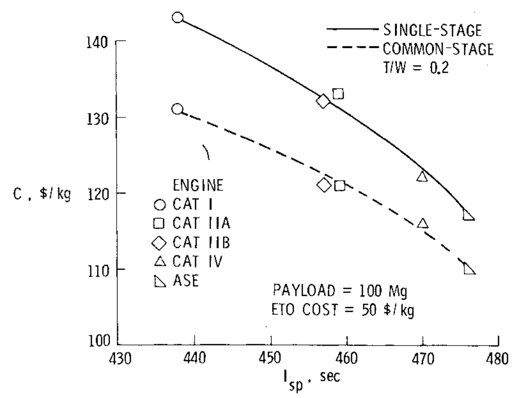

Fig. 7 Effect of engine advancements on orbital transportation cost.

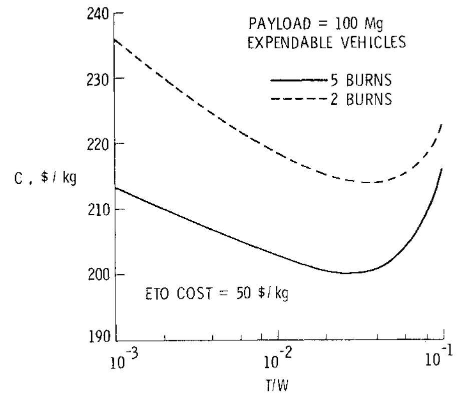

Fig. 9 Effect of T/W on low-thrust orbital transportation cost.

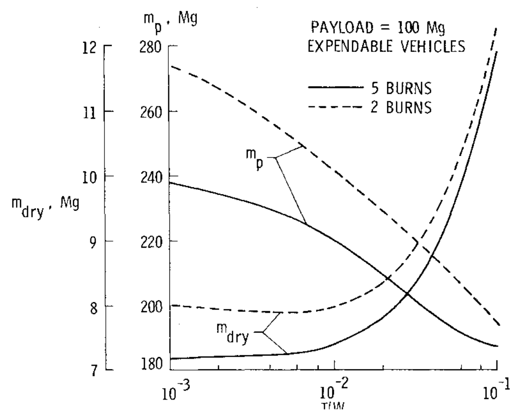

Fig. 8 Effect of T/W on low-thrust vehicle characteristics.

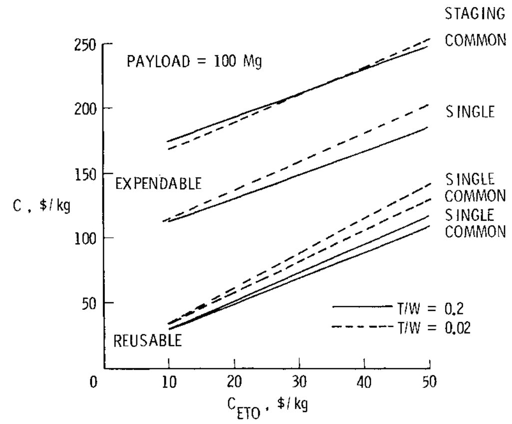

Fig. 10 Effect of ETO launch cost on orbital transportation cost.

where m_{car} was the total mass of cargo delivered from LEO to GEO, m_p was the mass of propellant for one round trip, N_V and N_F were the number of vehicles and the number of flights, respectively, and C_{ETO} was the Earth-to-orbit launch cost.

Results and Discussion

The first option studied was vehicle staging. The LCOTV for this portion of the study was fully reusable and used the RL10 Category IIB engine.[3] The effect of the ΔV split on the relative sizes of the two stages is shown in Fig. 2, which shows the mass of propellant in each stage. With increasing n_{DV}, the mass of propellant of the first stage decreases until it reaches zero at $n_{DV} = 1.0$, which is equivalent to a single-stage vehicle. The second-stage propellant increases with n_{DV} and becomes equal to the first-stage propellant mass at $n_{DV} = 0.33$ for all values of payload. At this point the two stages are virtually identical except for the number of engines and are referred to as common stages.

Figure 3 shows the dry mass of the two stages. Of particular interest are the common-stage values. The dry mass of the first of the common stages is greater than that of the second stage due to the greater number of engines required to give a T/W of 0.2 for the entire mated configuration.

The cost of delivering payload from LEO to GEO is not very sensitive to ΔV split as shown in Fig. 4. The lack of sensitivity holds for all values of payload considered. For all cases the cost of using common stages is less than the cost of using a single stage, but the difference is slight. The lack of smoothness of the curves is probably due to small errors introduced by convergence tolerances in the sizing and by rounding to the nearest dollar per kilogram in the cost model.

The effect of payload capacity on the single-stage and total common-stage vehicles is shown in Fig. 5. The propellant mass for the common stage is less than that for the single stage, while the dry mass is greater. Since the number of vehicles that must be built is also larger for the common stage, it is not obvious which system would be the more cost effective. The results of applying the cost model to these vehicles are shown in Fig. 6. The common stage is less expensive than the single stage, but the difference is slight and may disappear when the complexity of using two stages is taken into account. Another result shown in this figure is that substantial savings can be achieved by going to large-payload vehicles, but increasing the payload beyond 100 Mg shows little additional benefit. For the remainder of the discussion only vehicles with 100 Mg of payload are considered.

The effect of engine performance on orbital transportation cost is illustrated in Fig. 7. Substantial cost reductions can be realized by selecting the advanced space engine over the current technology RL10. This saving will be offset somewhat by the development cost of the new engine. For the traffic level assumed, including the development cost would add $2 to $3 per kg to the ASE case. Increasing engine performance also decreases the gap between the single-stage and common-stage vehicles.

The principal application of low-thrust-engine OTV's may be to deliver large, acceleration-sensitive structures. The OTV would not be recovered. Figure 8 shows the mass characteristics of the low-thrust expendable LCOTV's and the effect of varying T/W. The characteristics of the low-thrust propulsion system are from in-house studies at NASA Lewis Research Center. Since, from Table 1, the ΔV requirement increases as T/W decreases, the amount of propellant required also increases. However, a substantial reduction in propellant mass results when the number of perigee burns increases. Using five burns increases the transit time to 16 hours compared with the 12 hours required for a two-burn transfer at $T/W = 0.01$. For values of T/W less than 0.01, the dry mass is not sensitive to T/W. The decrease in engine mass counteracts the increase in propellant tankage. The dramatic dry-mass increase at high values of T/W is due to increased engine mass, since the low-thrust engines have more mass per unit thrust than the high-thrust engines.

Applying the cost model gives the results shown in Fig. 9. For low values of T/W, the cost of delivering the propellant from Earth to LEO dominates, and the LEO-to-GEO cost decreases with increasing T/W. At high values of T/W the cost of purchasing the vehicles dominates due to the increased dry mass, and the LEO-to-GEO cost increases with T/W. An optimum occurs at a value of T/W of about 0.02 for the five-burn case.

Figure 10 shows the effect of Earth-to-orbit launch costs on all the concepts considered. At these low values of ETO cost, expendable vehicles are not competitive since their cost is dominated by vehicle purchase. The slopes of the expendable vehicle curves are shallower than for the reusable vehicles, which indicates that for high launch costs the expendables may be less expensive, a result also shown in a previous LCOTV study.[2] The curves for the reusable vehicles show that the high-thrust LCOTV's are slightly less expensive and less sensitive to ETO costs than the low-thrust vehicles and that for very low launch costs the differences among all the reusable concepts virtually disappear. The selection of any one concept over the others must be based on factors other than those considered in this study.

Conclusions

A computer-aided design capability was used to analyze various options for the propulsion system of a large-cargo orbital transfer vehicle. One option, staging of the vehicles, did not show a significant cost benefit. To reduce costs, the vehicles should have a delivered payload capacity of 100 Mg and a new high-performance engine should be developed. The dominant factor in orbital transportation cost for chemical LCOTV's is the Earth-to-orbit launch cost and for low values of this cost, high-thrust and low-thrust reusable vehicles are both competitive.

References

[1] Henry, B. Z. and Eldred, C. H., "Advanced Technology and Future Earth-Orbit Transportation Systems," AIAA Paper 77-530, May 1977.

[2] Rehder, J. J. and Wurster, K. E., "Electric vs Chemical Propulsion for a Large-Cargo Orbit Transfer Vehicle," *Journal of Spacecraft and Rockets*, Vol. 16, May-June 1979, p.129-134.

[3] Cuffe, J. P. B., "RL10 Derivative Engines for Space Tug," *1974 JANNAF Propulsion Meeting Proceedings*, Vol. 1, Pt. 1, Oct. 1974.

[4] Diem, H. G., "Advanced Space Engine for the Orbit Transfer Vehicle," IAF Paper 77-101, Oct. 1977.

[5] "Future Space Transportation Systems Analysis Study," *Transportation Systems Reference Data*, Vol. 3, Boeing Aerospace Company, NAS9-14323, Dec. 1976.

[6] "Orbit Transfer Systems with Emphasis on Shuttle Applications 1986-1991," NASA TM X-73394, April 1977.

[7] "Design and Systems Analysis of a Chemical Interorbital Shuttle," Vol. 2, Pt. 1, Rockwell International, NAS8-27670, May 1972.