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Electric vs Chemical Propulsion for a Large-Cargo Orbit Transfer Vehicle

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Techniques for sizing electrically or chemically propelled orbit transfer vehicles and analyzing fleet requirements are used in a comparative analysis of the two concepts for various levels of traffic to geosynchronous orbit. The vehicle masses, fuel requirements, and fleet sizes are determined and translated into launch vehicle payload requirements. Technology projections beyond normal growth are made and their effect on the comparative advantages of the concepts is determined. A preliminary cost analysis indicates that electric propulsion greatly reduces launch vehicle requirements and would be competitive with chemical propulsion if the technology of power generation systems advances to where reusability can be achieved at low cost.

Nomenclature

C_{ETO} = Earth-to-orbit launch cost, \$/kg
C_{FU} = first-unit cost of a vehicle, \$
C_{OTV} = total OTV associated specific cost, \$/kg
C_p = cost of power generation equipment, \$/W
g = acceleration of gravity at Earth's surface = 9.8066 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_{prop} = propellant mass, kg
$\dot{m}$ = propellant mass flow rate, kg/s
N_F = number of flights
N_V = number of vehicles
P = output power of generation equipment, W
P_b = beam power, W
R_m = ratio of startburn mass to burnout mass
t = flight time, days
T = thrust, N
T/W = initial thrust-weight ratio
V_1, V_2 = circular orbit velocities, m/s
ΔV = equivalent free-field velocity addition required to change orbit, m/s
η_p = propellant utilization efficiency
η_T = thruster efficiency
θ = change in orbit inclination, deg

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). The two most likely candidates for the propulsion system of the LCOTV are low-thrust electric propulsion and the higher-thrust chemical rocket. Both candidates have features that make them attractive for this application.

The electric propulsion system has a much higher specific impulse than the chemical rocket and would require less propellant to perform the same mission. A smaller fuel requirement, besides being a benefit in itself, would reduce the payload requirement of the Earth-to-orbit (ETO) launch vehicle, resulting in smaller or fewer vehicles. There are problems associated with the use of electric propulsion. The technology is not mature compared to the chemical rocket. The long flight time due to low thrust requires large numbers of vehicles to handle heavy levels of traffic. In addition, there is a question of the reusability of electric power systems for a number of LEO-GEO round trips.

Chemical rocket technology is very mature and there is little risk in projecting future performance of such systems. Also, the relatively high thrust of chemical rockets eliminates the problems of long flight times. The disadvantage of chemical rockets is the low specific impulse which leads to large propellant requirements. Since the propellant must be delivered from the ground, the delivery of the propellant can be very costly.

Concepts for both electrically and chemically propelled stages for the delivery of cargo from LEO to GEO are developed herein. Using fleet and preliminary cost analyses, the parameters which have the most significant effect on the cost of delivering the cargo are identified. The effect of these cost drivers on the competitiveness of the two concepts is discussed.

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

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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 which sized the LCOTV, whether electric or chemical, determined fleet requirements based on vehicle characteristics and traffic level, and calculated the cost for a LCOTV to deliver the desired cargo based on simple parametric methods. All of these programs are described in the following.

Electric LCOTV Sizing

All of the LCOTV's were single stage and 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. Also, each vehicle was constrained to a given startburn thrust-weight ratio. In the electric LCOTV, the equivalent field-free velocity requirements for orbit change were determined from the equation of Edelbaum,[2]

$$\Delta V = [V_1{}^2 + V_2{}^2 - 2V_1V_2\cos(\theta\pi/2)]^{1/2} \tag{1}$$

where V_1 and V_2 are the circular velocities of the orbits and θ is the difference in inclination.

Using the appropriate values of inclination and circular velocity at the two orbit altitudes considered and adding 10% for various losses results in a value of 6430 m/s for the required change in ideal velocity for a one-way journey from LEO to GEO. From the rocket equation, the mass ratio is

$$R_m = \Delta V / e^{gI_{sp}} \tag{2}$$

and the propellant required for a given startburn mass is

$$m_{\text{prop}} = \frac{m_0}{\eta_p}\left(1 - \frac{1}{R_m}\right) \tag{3}$$

where m_0 is startburn mass and η_p is propellant utilization efficiency, assumed to be 0.85.

Since the thrusters operate continuously, the trip time is the amount of propellant divided by the mass flow rate. The flow rate is the ratio of thrust to specific impulse. Substituting the product of thrust-weight ratio and startburn weight for thrust gives

$$\dot{m} = \frac{T}{gI_{sp}} = \frac{(T/W)m_0g}{gI_{sp}} = \frac{(T/W)m_0}{I_{sp}} \tag{4}$$

The trip time in seconds is therefore

$$t = \frac{m_p}{\dot{m}} = \frac{I_{sp}m_p}{(T/W)m_0} = \frac{I_{sp}}{T/W}\left(1 - \frac{1}{R_m}\right) \tag{5}$$

The components of an electric propulsion stage fall into three categories: the basic spacecraft whose size depends on the volume of propellant, the thrusters, and the power generation and conditioning equipment. The three categories are calculated separately in the sizing process.

The first step in sizing the electric LCOTV was to calculate the masses of the components whose size could be expressed in terms of the volume of propellant, which was assumed to be argon in this study. The program initially uses an estimate of the propellant mass input by the user. The mass estimating relationships were curvefits of data generated by various point design studies of electrically propelled spacecraft. The components in this category included body structure, propellant tank, thermal control system and other systems not directly involved with generating the main thrust and electric power. The masses of these components were summed and a rough estimate of startburn mass was made.

The total thrust required was calculated from the estimated startburn mass and the desired initial thrust-weight ratio. Using the total thrust, the input value of specific impulse and

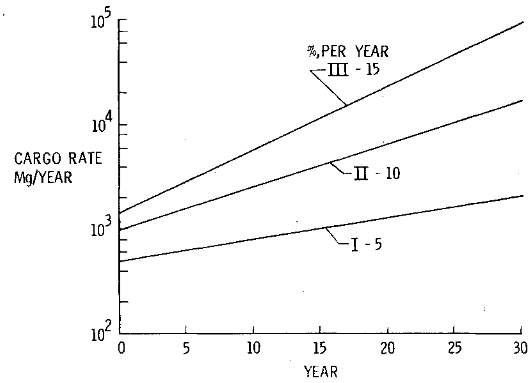

Fig. 1 Traffic level definition.

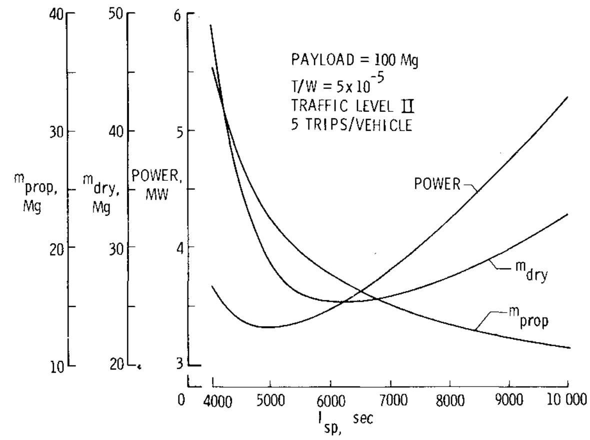

Fig. 2 Effect of specific impulse on electric OTV characteristics.

the propellant utilization efficiency, the number and mass of the thrusters and their efficiency were calculated from data for argon-fueled ion bombardment thrusters presented by Byers and Rawlin.[3] The beam power required was calculated with the equation

$$P_b = (TI_{sp}g)/2 \tag{6}$$

Dividing the beam power by the power conditioning efficiency, assumed to be 0.92 in this study, and the thruster efficiency gave the power required as output from the power generation equipment. The mass of this equipment was calculated from the power requirement based on mass estimating relationships which were curvefits of data for photovoltaic systems from various sources, most notably from the "Forecast of Space Technology"[4] assuming a 1985 technology level.

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 from Eq. (3). 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. The vehicle mass and power characteristics were displayed by the sizing program and saved for use in subsequent analyses.

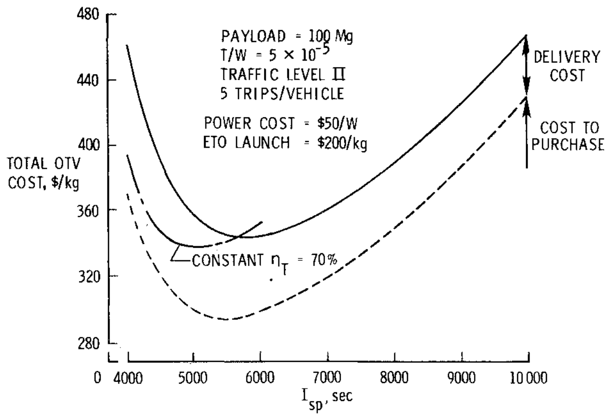

Fig. 3 Effect of specific impulse on electric OTV cost.

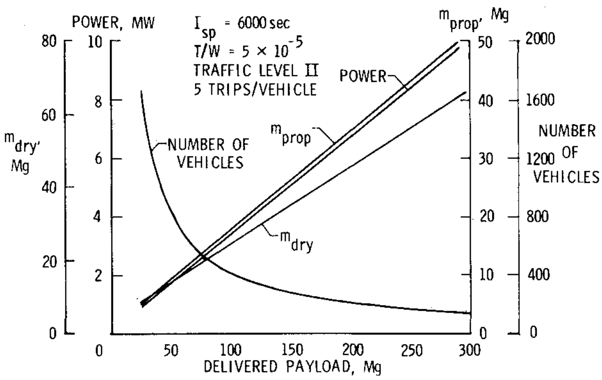

Fig. 4 Effect of payload capacity on electric OTV characteristics.

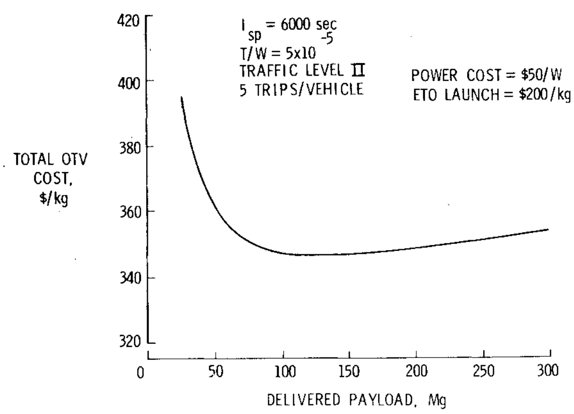

Fig. 5 Effect of payload capacity on electric OTV cost.

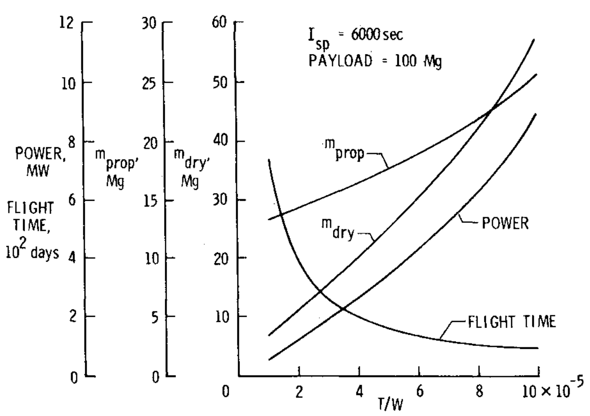

Fig. 6 Effect of thrust-weight ratio on electric OTV characteristics.

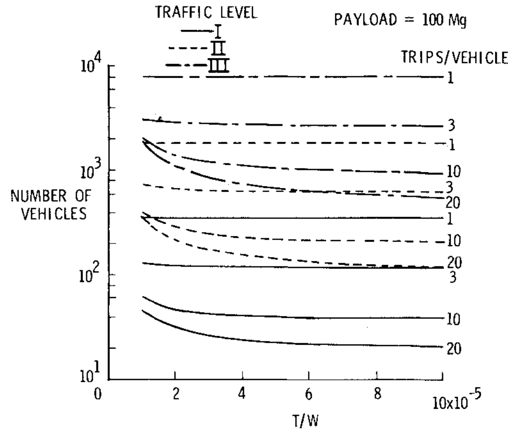

Fig. 7. Effect of thrust-weight ratio on number of electric OTV required to carry traffic.

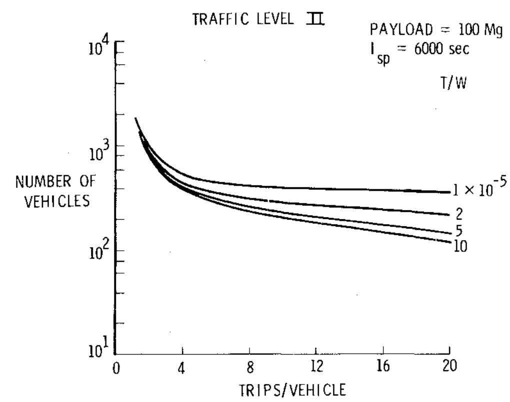

Fig. 8 Effect of vehicle reusability on number of electric OTV required.

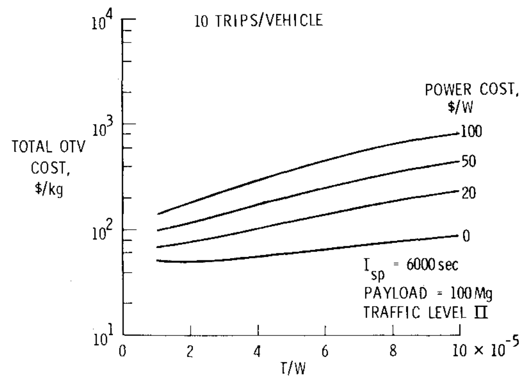

Fig. 9 Effect of thrust-weight ratio on electric OTV cost.

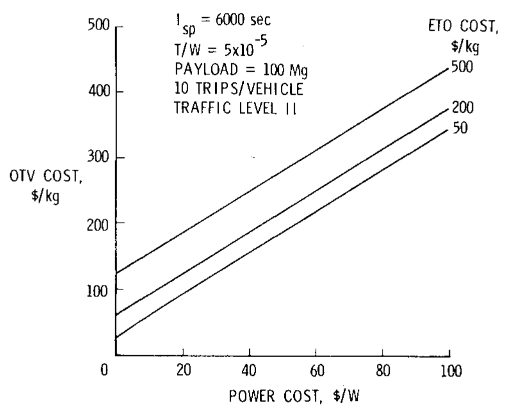

Fig. 10 Effect of power cost on electric OTV cost.

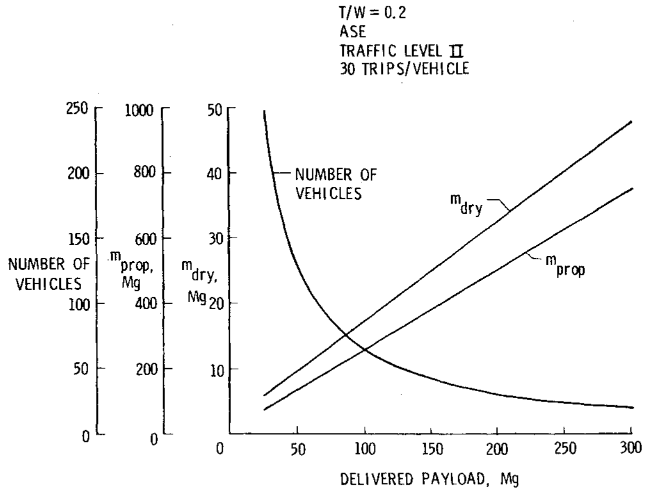

Fig. 11 Effect of payload capacity on chemical OTV characteristics.

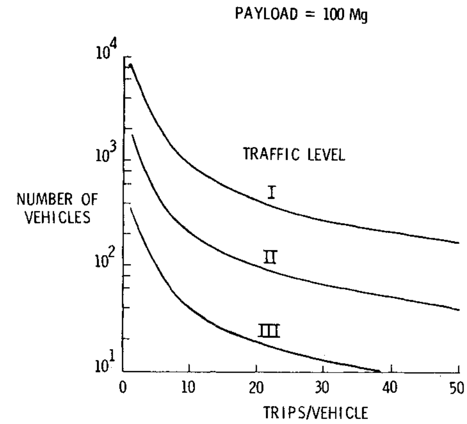

Fig. 13 Effect of vehicle reusability on number of chemical OTV required.

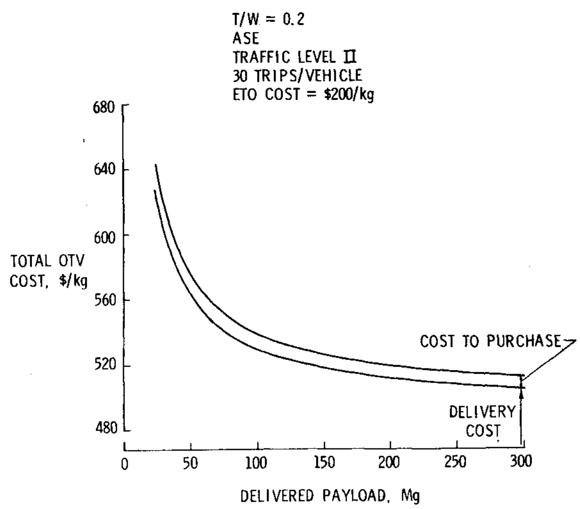

Fig. 12 Effect of payload capacity on chemical OTV cost.

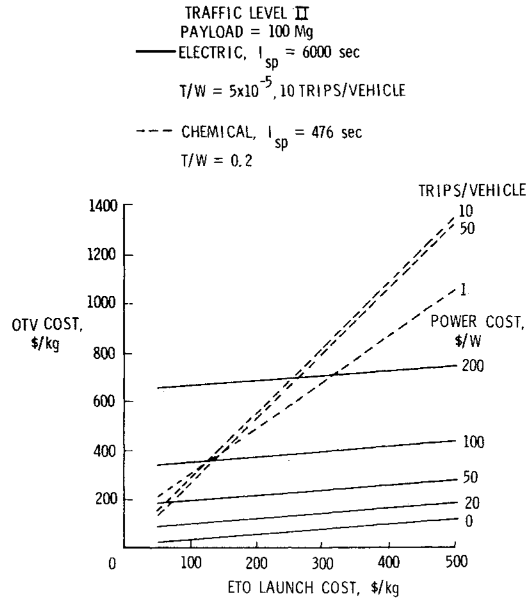

Fig. 14 Effect of ETO launch cost on OTV cost.

Chemical LCOTV Sizing

The chemical LCOTV was a single-stage vehicle powered by a category IIB RL-10 derivative rocket using liquid hydrogen and oxygen as propellants.[5] Except for the engine and thrust structure, all of the vehicle component masses were related to propellant volume. As before, the mass estimating relationships were curvefits of data from a number of point design studies[6,7] and the vehicles were sized in an iterative manner. For the chemical LCOTV, the initial thrust-weight ratio had a constant value of 0.2 throughout the study.

Fleet Analysis

The number of vehicles required to handle a given amount of traffic was determined by a fleet analysis. A 30-year scenario with three different levels of traffic was assumed as illustrated in Fig. 1. Traffic level I starts with 500 Mg of cargo delivered from LEO to GEO each year increasing by 5% each year. Levels II and III start with 1000 and 1500 Mg per year, respectively, and increase at annual rates of 10% and 15%, respectively. 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, with the cost of the power generation and conditioning equipment of the electric LCOTV considered separately. The equation used was a curvefit of data from point designs of various propulsion stages. The specific cost of the power generation equipment for the electric vehicle was an input parameter and was varied from $0 to $200 per watt of output power required. The power conditioning cost was assumed to be one-tenth that for power generation. The equation used for the first-unit cost was therefore

$$C_{FU} = 0.207 m_{dry}^{0.551} \quad \text{for chemical OTV} \qquad (7a)$$

$$C_{FU} = 0.207 m_{dry}^{0.551} + 1.1 C_p P \quad \text{for electric OTV} \qquad (7b)$$

where m_{dry} was the dry mass of one vehicle, C_p was the specific power cost, and P was the power required. A learning factor of 0.95 was applied over the calculated fleet sizes. The cost of the propellant was assumed to be $0.40/k in all cases.

The cost of delivering vehicles and propellant from Earth to LEO was also an input parameter and was varied from \$50 to \$500 per kilogram. Therefore, the total OTV associated cost of delivering cargo from LEO to GEO was

$$C_{OTV} = (1/m_{car})(C_{FU}N_V^{0.926} + 0.4m_{prop}N_F + C_{ETO}m_{dry}N_V + C_{ETO}m_{prop}N_F) \qquad (8)$$

where m_{car} was the total mass of cargo delivered from LEO to GEO, m_{prop} 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 sizing, fleet analysis, and cost programs were run for a large number of combinations of parameters. The following discussion presents a representative sample of results.

Electric LCOTV

The effect of varying the specific impulse of the ion bombardment thrusters on the electric LCOTV characteristics is shown in Fig. 2. Since the power is proportional to specific impulse, the power required and vehicle dry mass, which is dominated by the mass of the power generation equipment, increase with I_{sp}. However, at lower values of I_{sp}, the propellant mass increases rapidly with decreasing I_{sp}, causing the gross mass of the vehicle to increase. More thrust, and thus more power, is needed to maintain a constant thrust-weight ratio. The resulting effect of the two opposing trends is a minimum in the dry mass curve at a specific impulse of 6000s. The effect is similar for a wide range of vehicle parameters.

Calculating the costs associated with the vehicle data from Fig. 2 gives the trends illustrated in Fig. 3. At a power cost of \$50/W, the cost to purchase dominates the OTV cost and the curves follow the same trend shown by the power curve of the previous figure. Because the propellant requirement is small, the delivery cost from Earth to LEO makes up less than 20% of the total. Very low values for power cost should reverse this trend. Some data were generated at a constant thruster efficiency of 70% to see if a thruster technlogy improvement, increasing efficiency at lower values of I_{sp}, would reduce power requirements and cost. As seen in Fig. 3, the cost curve did have a minimum at a lower I_{sp}, but the minimum cost did not change appreciably.

Figure 4 shows the effect of payload capacity on the vehicle. The dry mass, propellant mass, and power are all linear functions of payload, while the number of vehicles is roughly inversely proportional to the payload. The effect of payload capacity on the cost is shown in Fig. 5. The sharp decrease in cost with increasing payload at low values of payload indicates that the number of vehicles required is the dominant effect. As the vehicle requirement levels off at high values for payload, the increasing power required takes effect and the cost starts to increase, creating a minimum at about 100 Mg of payload.

Initial thrust-weight ratio has a powerful effect on electric LCOTV characteristics, as shown in Fig. 6. Increasing T/W requires an increase in thrust and a corresponding increase in power. More power means more weight which in turn means a larger thrust for a given thrust-weight ratio. This cascading effect causes the slope of the mass and power curves to increase with increasing T/W. The flight time is shown to be roughly inversely proportional to T/W [see Eq. (5)] and the curve levels off at values of T/W greater than 5×10^{-5}. It would not be advantageous to increase T/W beyond this value to decrease flight time, since the mass penalties would be large and the reduction in flight time would be small.

The number of vehicles required for a given traffic level depends on the flight time or the corresponding T/W and the vehicle lifetime, defined as the number of round trips one vehicle can make. Figure 7 shows the effect of T/W on the number of vehicles required and confirms an earlier result that using a T/W higher than 5×10^{-5} has no advantage. The effect of vehicle lifetime is shown in Fig. 8. The number of vehicles required is nearly inversely proportional to vehicle lifetime, assuming that there is no degradation of the power generating equipment, which is a major technology advancement.

The relationship between OTV cost and T/W and vehicle lifetime is illustrated in Fig. 9. Both parameters have a strong effect with the cost always increasing with T/W and always decreasing with longer vehicle lifetimes. The effect of power cost is isolated in Fig. 10. The linear relationship is to be expected, since, for LCOTV of this size, the cost of power generation equipment dominates the cost of the vehicle. The Earth-to-orbit launch costs have a small effect since the OTV-associated mass required in orbit is small.

Chemical LCOTV

The effect of payload capacity on chemical LCOTV characteristics shown in Fig. 11 is similar to that shown for the electric vehicle. The dry mass and propellant mass vary linearly with payload and the number of vehicles required is inversely proportional to payload. Comparing Fig. 11 with Fig. 4 shows that the mass of propellant required by the chemical LCOTV is about 10 times as great as for the electric vehicle for a payload of 100 Mg. Because of the short round-trip flight time (about 7 days) of the chemical vehicle, the number of vehicles required is also considerably less. The cost relationship closely follows the number-of-vehicles relationship as shown in Fig. 12 and, as in the case of the electric LCOTV, the cost curve levels off above a payload of about 100 Mg. The relationship between purchase cost and delivery cost is the opposite of that seen for the electric vehicle in Fig. 3, since the much greater mass of propellant increases the mass that must be delivered by the ETO system and the smaller number of vehicles reduces the purchase cost.

As in the case of the electric vehicle, the number of chemical LCOTV's is inversely proportional to vehicle lifetime. This is illustrated in Fig. 13 which isolates the effect of vehicle lifetime. Comparing this figure with Fig. 8 clearly shows that the longer flight time of the electric vehicle adds substantially to the fleet size requirement.

The comparison between electric and chemical LCOTV's and the effect on the comparison of two technology impovements is shown in Fig. 14. The improvements are reductions in ETO launch cost and power generation cost. The dashed curves show that reducing the ETO cost has a large effect on the chemical LCOTV cost, since that vehicle's cost is dominated by the cost of delivering the large amount of propellant required. Using the vehicle only once shows a benefit for large ETO cost, since the propellant mass is substantially less for a vehicle that does not have to make a return flight. Since delivery cost is only a relatively small part of the cost of the electric LCOTV, the ETO cost has little effect, as shown by the solid curves. Thus, for large ETO cost, the electric vehicle shows an advantage. In the future, however, large traffic levels may not be possible without a substantial reduction in ETO launch costs and the relative position of the chemical and electric LCOTV is less clear, but low cost and high reusability for power generation equipment may give electric propulsion a place in future space transportation.

Conclusions

A computer-aided design capability has been developed for analyzing both electrically and chemically propelled orbit transfer vehicles for use in advanced space transportation. Using this capability to study vehicles for delivering large amounts of cargo from low-Earth orbit to geosynchronous orbit, it was shown that improvements in several technology areas greatly affect the comparison of electric and chemical LCOTV for this mission. Since the chemical LCOTV cost is dominated by the cost of delivering its propellant from Earth to orbit, future studies should focus on reducing the propellant requirement and the ETO launch cost. On the other hand, the cost of the electric LCOTV is dominated by the cost of purchasing the vehicles and in particular the cost of the power generation system. It is therefore less sensitive to the ETO launch cost and may show an advantage if ETO launch cost is not reduced substantially. For low ETO cost, the electric LCOTV would be competitive if the technology of power-generation equipment is advanced to the point where a high degree of reusability can be achieved at lost cost.

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