High-Energy Orbit Refueling for Orbital Transfer Vehicles

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The payload capabilities and fuel economy of chemically powered orbital transfer vehicles are severely limited by the specific impulse of the available chemical propellants. Midmission refueling of payload-carrying chemically powered orbital transfer vehicles using propellant lifted into high-energy orbits by high-specific-impulse electrically powered orbital transfer vehicles results in substantially higher payloads for a given size of chemical vehicle and in overall propellant savings. For the transport of payloads to geosynchronous orbit, circular and elliptical refueling orbits intermediate between low Earth and geosynchronous orbits each have specific advantages. High-energy-orbit refueling is also advantageous for Earth escape missions and for utilization of lunar-derived propellants.

Nomenclature

COTV	= chemical orbiter transfer vehicle
EOTV	= electrical orbital transfer vehicle
FOTVT	= future orbital transfer vehicle technology
GEO	= geosynchronous Earth orbit
LEO	= low Earth orbit, 400 km nominal altitude
OTV	= orbital transfer vehicle
RO	= refueling orbit

Introduction

In conjunction with a space station, a reusable orbital transfer vehicle (OTV) will play an important role in the utilization of space in the next few decades. This vehicle will be used primarily to transport payloads into high orbits, with transport to geosynchronous orbit (GEO) being perhaps the most common mission. Currently, chemically powered OTV's (COTV) are projected to use long-lifetime, high-expansion-ratio liquid-hydrogen and liquid-oxygen engines, at specific impulses of 480–490 s.[1] Using such COTV's, propellant requirements for GEO transfers are very large and OTV's with a higher specific impulse are desirable. Engines burning hydrogen or hydrogen plus lithium with fluorine represent the most promising approach to higher-specific-impulse chemical systems.[2] The gains to be expected are, however, modest (a 5–15% increase in specific impulse) and the development costs for engines burning such propellants are likely to be high.

High-specific-impulse photovoltaic electrical OTV's (EOTV) offer one way to achieve propellant savings with currently available technology. The study of future orbital transfer vehicle technology (FOTVT)[3] has examined the technology for space based COTV's and EOTV's. EOTV's gave propellant savings when used to deliver cargo to GEO, but the delivery times were very long, preventing the use of EOTV's for time-sensitive or manned GEO missions. The same study considered the use of EOTV's to carry propellant to GEO for midmission refueling of COTV's. This offered some advantages for missions where substantial payloads had to be carried both up and down from GEO, as the COTV could be smaller than for a nonrefueled mission. Suitable missions for refueling were, however, a minority of the missions modeled. Overall, the use of EOTV's in a mixed COTV/EOTV fleet was judged not to be cost effective, relative to an all-COTV fleet.[3]

It is proposed here that the appropriate role of high-specific-impulse EOTV's is not to lift payloads or propellant to GEO, but to lift propellants into orbits intermediate between LEO and GEO for the midmission refueling of payload-carrying COTV's during their ascent to GEO. All payloads to be delivered to GEO are carried by the refueled COTV, so the transfer times remain short. It is shown here that a mixed fleet of COTV's and EOTV's delivers substantially more payload to GEO per amount of propellant used than does a completely chemically fueled fleet. At the same time, the payload that can be delivered by a COTV of a given size is dramatically increased.

The analysis reported here is for vehicles utilizing high-specific-impulse electrical thruster systems powered by an OTV-carried photovoltaic solar power system. Similar arguments, however, also apply to high-specific-impulse OTV's based on other propulsion schemes such as nuclear-thermal, nuclear-electric, solar-thermal, or beamed energy such as laser or microwave.

Vehicles

For the purposes of demonstrating the potential usefulness of high-energy-orbit refueling, three generic OTV's have been assumed (Table 1). The COTV assumed is approximately 80% of the size of the space-based COTV's considered in the FOTVT study, does not utilize aerobraking, has a somewhat better mass fraction (0.9 vs 0.864), but has a lower specific impulse (480 vs 485 s). The EOTV's are thought to represent what might be achievable with 1990's technology and a minimum of developmental work. They are markedly smaller than those assumed for the FOTVT study (100 vs 1600 kWe end-of-life power and 5000 vs 50,900 kg) and have a much more conservative power-to-mass ratio. Efficiencies are derived from Ref. 4 and include losses in the power-processing unit. The 50 kg/kW inert mass includes the photovoltaic power supply, power processors, thrusters, guidance and control, and active refrigeration systems for cryogenic-propellant payloads, but does not include EOTV propellant tanks, which are figured separately for each mission as 15% of the LH_2 propellant mass for EOTV-1 and 1% of the Hg propellant mass for EOTV-2.[4] The solar cell array assumes built-in radiation shielding (FOTVT heavy-shielding option[3]) and is oversized to allow the specified power level to be achieved after the radiation damage of 10

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Table 1 Characteristics of model orbital transfer vehicles

Parameter	COTV	EOTV-1	EOTV-2
Engine	chemical	arcjet	ion
Propellant	LH_2/LO_2	LH_2	Hg
I_{sp}, s	480	1500	3000
Power, kWe	—	100	100
Efficiency	—	0.36	0.70
Burnout mass, kg	3000	5000 + 15% H_2	5000 + 1% Hg
Propellant, kg	27,000	Variable	Variable

flights. No precise breakdown of the masses involved in the EOTV's is attempted, as the exact design of the OTV is not critical for the first-order mission analyses presented here. For the refueling missions described, the EOTV's are generally heavily loaded (payload mass 100–600% of EOTV dry mass). Under these circumstances, the results are relatively insensitive to the mass assumed for the EOTV's.

Propellants for refueling of COTV's are assumed to be transported by the EOTV in returnable tanks sized at 10% of the total mass of the propellant. The tank mass includes all equipment needed for refueling, as this scales in size with the mass of the refueling propellant payload. An electrically powered active refrigeration system for propellants is assumed as part of the 5000 kg core mass of the EOTV's; therefore, there are no payload propellant losses during transit.

Calculations

For the sake of simplicity, ideal velocities are used without correction for gravity losses during impulse maneuvers, steering losses, etc. Propellant residuals and reserves for off-nominal performance are similarly ignored. No allowance is made for the velocity requirements of maneuvering during rendevous for refueling and refueling is assumed to take place without propellant losses. These simplifications will make all of the payloads quoted in this paper somewhat optimistic and will slightly exaggerate the advantages of refueling. However, the overall conclusions of the study are not expected to be substantially altered by inclusion of these and other factors in more detailed calculations.

The COTV velocities were modeled as standard Hohmann trajectories. Velocity requirements for EOTV transfers between noncoplanar circular orbits were calculated as described by Edelbaum.[5] Given the required velocity and desired payload, propellant requirements and trip times for low-acceleration vehicles were calculated using minor modifications of the equations of Jones.[4]

Refueling

Any reusable space-based COTV developed will have full capability for orbital rendevous and on-orbit refueling, as these capabilities are essential for its normal operation from the space station. It seems reasonable that with careful design, little additional capability must be added to a COTV to allow it to be refueled in midmission in high-energy orbits from propellants placed there by an EOTV. The basic question addressed here is what is the effect of such refueling on both the payload capabilities of a single COTV flight and the "fuel economy" of the combined COTV/EOTV system.

Propellant for refueling is assumed to be carried by a 5000 kg, 100 kWe EOTV with either a hydrogen arcjet or a mercury ion thruster system. At a specific impulse of 3000 s, mercury ion vehicles have the highest efficiency, the lowest tank factor, and the shortest trip times of the vehicles studied by Jones.[4] Mercury ion thrusters represent a relatively mature technology. If spacecraft contamination problems from the mercury exhaust are tolerable, vehicles based on mercury thrusters may be the first choice for an EOTV. For comparative purposes, hydrogen arcjet thrusters operating at a specific impulse of 1500 s have been chosen as an example of another relatively mature technology that could be used in a near-term EOTV. Arcjet thrusters are simple and light and do not require elaborate power conditioning equipment. In spite of a large tank fraction due to the use of a low-density cryogenic propellant, for most missions hydrogen arcjet vehicles have a performance comparable to or better than vehicles based on other electrical thrusters operating at this specific impulse.[4] Other thruster systems (inert gas ion, MPD, etc.) could be considered for an electrical OTV, but these would have similar or longer transfer times.[4]

The definition of optimum size and power for EOTV's must wait until the required missions and the technology available to perform them are better defined. The EOTV missions modeled here range from the delivery of large payloads to low orbits to smaller payloads delivered to high orbits. With the 100 kWe vehicles modeled here, delivery leg times for most of the EOTV missions described in this paper are relatively similar, on the order of 250–350 days. These times could be shortened if the electrical vehicles were scaled up in size to 200 or 300 kWe while keeping the payload constant. However, for the purposes of placing refueling propellant in high orbit, a number of small vehicles with long trip times may be just as effective as a smaller number of larger vehicles with shorter trip times.

Refueling at Circular Orbits between LEO and GEO

Without refueling, the payload of the model 30,000 kg all-propulsive hydrogen/oxygen COTV is limited. Starting from a low Earth orbit with an altitude of 400 km, the one-way (stage expended) delivery capability of the OTV is 15,730 kg. If the OTV is to be reused, the payload deliverable to GEO drops to 8400 kg as the result of having to reserve 4325 kg of propellant for the return trip. Adding aerobraking to the vehicle increases the payload deliverable to GEO to approximately 12,000 kg.

Refueling of the nonaerobraking COTV at GEO with propellant carried by an EOTV increases the payload capability back to 15,730 kg by allowing it to exhaust its tanks during the ascent. However, when low-thrust, high-specific-impulse EOTV's are used to deliver propellant to GEO, there are substantial velocity penalties associated with the characteristic low-acceleration spiral orbit used. High-thrust vehicles require a velocity increment of approximately 4200 m/s to reach GEO from a 28.5 deg orbit. The equivalent velocity requirement for low-acceleration vehicles is approximately 6000 m/s. However, the percentage difference between the velocity requirements for low- and high-acceleration vehicles to reach a given circular orbit from LEO becomes smaller as the altitude of the final orbit decreases and is negligible for sufficiently low final orbits. Refueling maneuvers at circular orbits intermediate between LEO and GEO may, therefore, prove attractive as a way of reducing the EOTV velocity penalty.

Refueling takes place by lifting the refueling propellant into a high-energy circular refueling orbit (RO) using an EOTV. The COTV with the payload then leaves LEO and

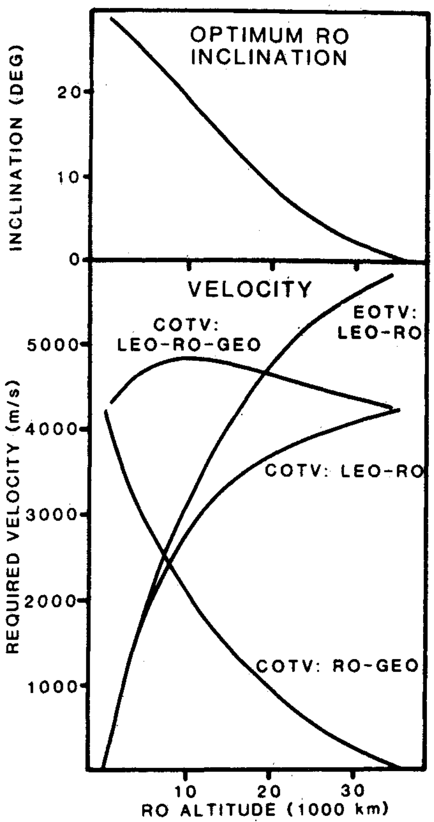

Fig. 1 Refueling in circular orbits: orbital requirements.

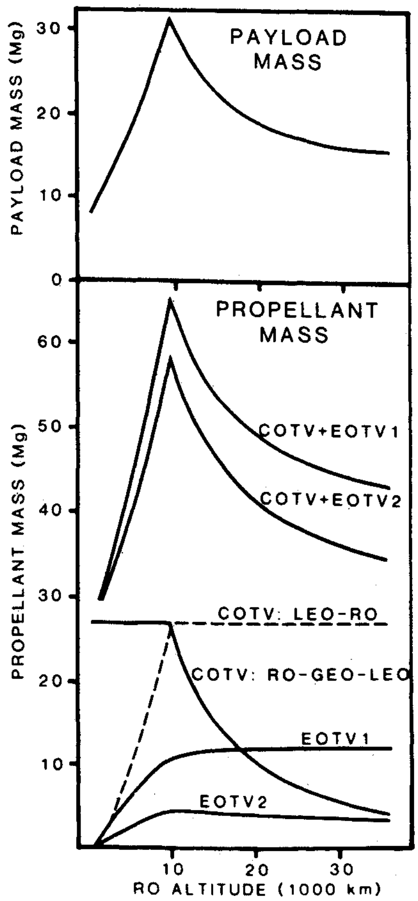

Fig. 2 Refueling in circular orbits: payload and propellant mass.

ascends by Hohmann transfer to a rendevous with the refueling vehicle. After refueling, the ascent to GEO is completed by a second Hohmann transfer, leaving sufficient propellant unburned to return the COTV to LEO. Performed in this manner, refueling aids in the transfer of payloads from LEO to GEO and not just in the return of the COTV to LEO, as is the case with refueling at GEO.[3]

The transfer from a 28.5 deg orbit to GEO involves a plane change of 28.5 deg. Figure 1 (top panel) shows the optimum inclination of the RO vs the RO altitude. This inclination was selected in each case to minimize the total velocity requirement for the COTV for Hohmann transfers between LEO and GEO via an intermediate stop at the RO. The lower panel of Fig. 1 shows the impulsive velocity requirements for the COTV for the first (COTV: LEO→RO) and second (COTV: RO→GEO) leg of the trip and the total impulsive velocity for the trip (COTV: LEO→RO→GEO). The total impulsive velocity for the COTV has a value of approximately 4200 m/s if ascent to GEO does not involve refueling at an intermediate orbit. However, refueling at an intermediate orbit involves an additional velocity requirement of up to 675 m/s due to deviating from the simple direct Hohmann transfer from LEO to GEO. Also shown is the low-thrust velocity requirement for an EOTV to reach the refueling orbit (EOTV: LEO→RO). It may be seen that to reach RO's of less than approximately 10,000 km, the velocity requirement for an EOTV is only slightly more than that of a high-acceleration COTV.

The top panel of Fig. 2 shows the payload that can be carried by a refueled COTV from LEO to GEO, as a function of the orbital altitude at refueling. A maximum payload of 31,600 kg is achieved at a refueling orbit altitude of 9700 km. The bottom panel of Fig. 2 shows the chemical propellant requirements for the prerefueling (COTV: LEO→RO) and postrefueling (COTV: RO→GEO→LEO) sections of the mission. For a maximum payload and for refueling at a altitude of 9700 km, a full load of 27,000 kg propellant is required to lift the payload to the refueling point and a second full load of propellant from refueling is required to deliver the payload to GEO and return the COTV. For lower refueling orbits, less than 27,000 kg propellant is needed to reach the refueling point with the indicated payload. The payload in these cases is determined by the capability of the COTV with a full load of propellant on the postrefueling section of the mission. For refueling orbits with an altitude of greater than 9700 km, a full load of 27,000 kg of fuel is required to reach the refueling orbit with the indicated payload. In this case, the prerefueling section of the mission determines the payload capability and the postrefueling section of the mission requires less than a full load of propellant.

For refueling orbits of less than 9700 km altitude, it is assumed that the COTV takes on just enough propellant at LEO to reach the RO and then takes on a full load of propellant. This strategy maximizes the benefits of refueling. Thus, the amount of refueling propellant to be carried by the EOTV to the RO is in all cases equal to the chemical propellant required for the COTV to complete the postrefueling section of the mission (COTV: RO→GEO→LEO).

The lower panel of Fig. 2 also shows the propellant required by each of the two model EOTV's to place the required chemical propellant at the refueling orbit and return to LEO (EOTV-1 and EOTV-2) and the total propellant required for the combined mission (COTV+EOTV-1 and COTV+EOTV-2). The specific payload of the various refueling missions (kilograms of payload to GEO per total kilograms of propellant for the COTV and EOTV) is plotted in Fig. 3 as a function of the refueling orbit altitude. It can be seen that the refueling orbit yielding the maximum payload (Fig. 2, top panel) also yields the most fuel-efficient transfer of payload to GEO (Fig. 3). For this orbit at 9700 km altitude, the payload has increased by a factor of 3.75 over that of an unrefueled COTV, while the total amount of propellant used has increased by a factor of only 2.42 (EOTV-1) or 2.17 (EOTV-2). Therefore, the specific payload increases from 0.311 (unrefueled mission) to 0.479 for the arcjet vehicle and 0.537 for the ion vehicle, an increase of 55 and 73%, respectively.

Failure of refueling will lead to the possibility of the COTV being stranded in the refueling orbit. Optimum refueling orbits are near the upper reaches of the Van Allen radiation belts. Depending on the chosen RO altitude, a permanent manned or unmanned refueling base might offer a safe intermediate destination in the event of a refueling failure.

Refueling in Elliptical Orbits

To avoid the velocity penalties involved in a COTV stopping at an intermediate circular orbit during ascent to GEO, refueling in an elliptical orbit can be performed. In the simplest case, this involves using an EOTV to place the refueling propellant in an elliptical orbit with a perigee at the orbit of the space station and an apogee at GEO altitude (a normal GEO transfer ellipse). For a refueled mission, a COTV leaving LEO would place itself into the same transfer orbit as the waiting propellant. During the 5 h or so of coast time to GEO altitude, the COTV would refuel, perform the apogee burn of the transfer, and then deliver its payload. If rendevous and refueling cannot be completed within this tight time constraint, the apogee burn can be delayed until the second or later apogee.

Other elliptical orbit refueling maneuvers are possible and can be characterized by the velocity required to reach them with the COTV. Refueling in a normal GEO transfer ellipse requires a velocity increment of approximately 2400 m/s for the COTV. For refueling at lower velocities, the refueling orbit is an ellipse with a perigee at LEO and an apogee at less than GEO altitude. The COTV then rendevous and refuels, waits until the next or a later perigee to perform a second burn, and adjusts the transfer ellipse to the correct apogee for circularization at GEO. For refueling at higher velocities than those corresponding to a normal GEO transfer ellipse, the transfer orbit must have an apogee at GEO and a perigee higher than LEO. In this case, the COTV performs a full burn to establish a GEO transfer ellipse and then a partial burn at apogee to raise the perigee and match the refueling orbit. After refueling, the circularization is completed by a second burn at GEO altitude.

For the refueling in elliptical orbits described above, no velocity penalties are encountered by the COTV because all maneuvers are performed at either LEO or GEO. The net result of refueling is merely to divide either the first or second burn of the Hohmann transfer into two separate maneuvers, whose total velocity is equivalent to that required in an unrefueled mission.

Figure 4 shows the payload capability of a COTV refueled at various velocities relative to LEO. At the velocity of 2420 m/s noted by the dotted line, only two burns are required from the COTV (the refueling orbit is a normal GEO transfer ellipse). This results in a payload of 37,100 kg, compared with a payload of 8400 kg for an unrefueled vehicle. At lower velocities, two perigee burns are required with refueling in between; at higher velocities, two apogee burns are required with refueling between. The maximum payload of 39,100 kg takes place at a velocity increment of 2320 m/s, corresponding to a refueling ellipse with a perigee at LEO and an apogee slightly short of GEO.

The velocity requirements for an EOTV to reach elliptical orbit have not been clearly defined. The required EOTV velocities depend on whether a continuous thrusting program is used or whether the velocity requirements are reduced by thrusting mainly near perigee. If the latter is chosen, the propulsion available is a complex function of various vehicle design factors such as thruster size, solar array size, and the power output of any propulsion-related battery systems. Perigee thrusting is further complicated by the variable eclipsing of solar power, which depends on orbital parameters and sun position. Because of these complications, specific payloads for elliptical refueling orbits are not calculated here. They are, however, expected to be higher for elliptical orbits than for circular refueling orbits because the COTV propellant dominates the total mission propellant requirements and elliptical refueling orbits do not involve COTV Hohmann velocity penalties. Against this, vehicles utilizing elliptical refueling orbits suffer multiple passes through the Van Allen radiation belts, requiring rapid refueling and eliminating the possibility of a manned refueling base.

Other Missions

While the modeling described in this paper addresses an all-propulsive COTV, refueling during ascent to GEO is also applicable to an aerobraking COTV. A particularly attractive combination for manned missions is an aerobraking COTV refueled in an elliptical orbit having a LEO perigee. If a modest fuel reserve is left after the prerefueling section of a GEO ascent, aerobraking can offer a safe return mode should the refueling fail in any manner. Furthermore, for payloads that are not sufficiently compact or strong enough to survive an aerobraking maneuver, refueling during descent from GEO to LEO allows an aerobraking COTV to

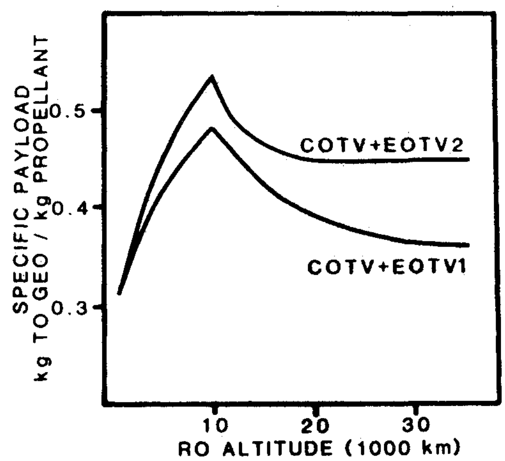

Fig. 3 Refueling in circular orbits: specific payload.

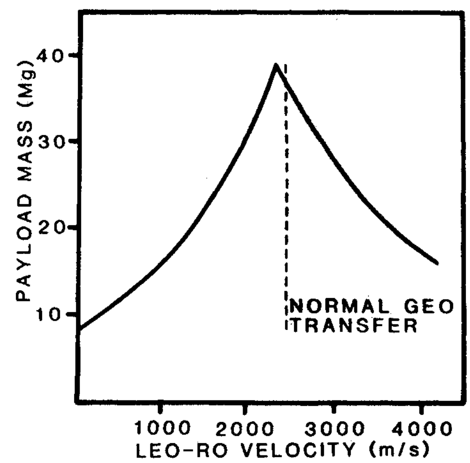

Fig. 4 Refueling in elliptical orbits: payload mass.

perform the GEO to LEO transfer of large payloads in an all-propulsive mode.

Vehicles destined for lunar and planetary missions may also benefit from refueling from an EOTV in a high-energy orbit. The most attractive maneuver is to burn a complete load of propellant, thus placing the vehicle in an elliptical RO with a perigee at LEO. After refueling in the elliptical orbit, a second perigee burn places the spacecraft into the desired escape trajectory. Assuming the establishment of a moon-based supply depot, lunar-derived liquid oxygen might be economically transported from such a depot to an elliptical RO via chemical propulsion (or possibly a mass driver) followed by an aerobraking maneuver. Hydrogen from the Earth would then ascend to the RO by EOTV, which would rendevous with the oxygen-carrying vehicle. A hydrogen arcjet EOTV might be particularly suitable, eliminating the need for active refrigeration of the propellant payload and using boil-off hydrogen as the EOTV propellant. Orbital transfer, lunar transfer, or other vehicles requiring refueling would then obtain propellants from the two vehicles in the elliptical orbit. The net result of this form of refueling would be to retain part of the potential energy of position of lunar-stored oxygen and then to use this energy to achieve savings for chemically powered vehicles ascending from LEO.

Summary and Conclusions

Chemical OTV's offer the rapid transfer of payloads to GEO, but suffer from both low payloads and high propellant consumption. High-specific-impulse EOTV's offer the possibility of low propellant consumption, but suffer from long transfer times and possible radiation damage to sensitive payloads. Using EOTV's to refuel payload-carrying COTV's during ascent from LEO to GEO offers the potential of a mixed fleet that can rapidly deliver large payloads to GEO while consuming less propellant per unit payload than an all-chemical fleet.

Refueling maneuvers can be performed in a variety of ways. Refueling at GEO has the advantage that the OTV can perform a completely normal ascent and payload delivery before refueling. However, the increases in payload mass and specific payload relative to an unrefueled mission are modest, particularly if the COTV is assumed to have aerobraking. Analysis of this option in the FOTVT study has suggested that it has marginal utility.[3] Refueling during ascent using a circular RO has the advantage that the most favorable RO's are at an altitude such that little velocity penalty is incurred by a low-acceleration vehicle ascending to them. The velocities required for EOTV's are approximately half those required for GEO refueling. The refueling propellant is useful for *both* carrying a payload to GEO and returning the COTV. The use of elliptical refueling orbits eliminates the COTV velocity penalty suffered during circular refueling orbits and thus raises payloads. Elliptical refueling orbits are the most easily accessible for lunar-derived propellants and, for safety reasons, are particularly attractive for manned aerobraking vehicles.

The calculations in this paper are only first-order approximations using generic EOTV's that have not been optimized in size, specific impulse, or technology for the missions assigned to them. The results nevertheless suggest that refueling by high-specific-impulse EOTV's may be an attractive way of extending the capabilities of COTV's. The calculations also suggest that relatively small EOTV's based on near-term solar power supplies and thrusters are adequate for refueling operations. For a given mission model, the dramatic increase in payload transferable from GEO to LEO by a given size of COTV brought about by refueling might allow an extensive COTV downsizing relative to the vehicles previously considered.[3] A downsized COTV/EOTV fleet optimized for refueling should be modeled in a more extensive analysis than reported here to determine feasibility and life-cycle costs for future space-based orbital transfer operations.

Acknowledgment

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