ADVANCED PROPULSION FOR LEO-MOON TRANSPORT: III. TRANSPORTATION MODEL

Mark W. Henley

General Dynamics Space Systems Division
P.O. Box 85990
San Diego CA 92138

A simplified computational model of low Earth orbit-Moon transportation systems has been developed to provide insight into the benefits of new transportation technologies. A reference transportation infrastructure, based upon near-term technology developments, is used as a departure point for assessing other, more advanced alternatives. Comparison of the benefits of technology application, measured in terms of a mass payback ratio, suggests that several of the advanced technology alternatives could substantially improve the efficiency of low Earth orbit-Moon transportation.

INTRODUCTION

A computer model has been constructed to assess new technology alternatives as implemented in a reference Earth-Moon transportation infrastructure. This transportation model was developed as part of the Advanced Propulsion for Low Earth Orbit-Moon Transportation study performed for NASA Johnson Space Center by the California Space Institute at the University of California, San Diego (*Stern,* 1989). Input for the transportation model has been developed through interaction with participants in this study to determine the mass payback ratio of transportation system alternatives. This mass payback ratio is only a first measure of merit, and has been used in the study as an input to a separate economic model (*Stern,* 1988) that assesses overall efficiency and cost-effectiveness of these new technology alternatives.

The reference transportation infrastructure employs orbit transfer vehicles (OTVs) for orbit-to-orbit transfer, OTV-derived lunar landers for transportation between the lunar surface and low lunar orbit (LLO), and orbital transfer and staging facilities (OTSFs) in low Earth orbit (LEO) and LLO. Technology needed for the reference infrastructure is already in the planning and early development stages (*Bialla and Ketchum,* 1987).

Several advanced technology alternatives are considered in the transportation model. Tether-assisted transportation, wherein a long tether exchanges momentum between an orbital facility and an OTV or lunar lander, is examined for use from facilities in LEO, eccentric Earth orbit, and LLO. Other advanced technology alternatives considered include lunar-derived aerobrakes, laser propulsion, and ion engines as modifications of the reference OTV, and use of a mass driver to eject material from the Moon's surface into lunar orbit. System parameters for configurations using these technologies were determined through the interaction of a team of academic, government, and industry representatives participating in the Advanced Propulsion for LEO-Moon Transportation study, resulting in representative alternative configurations analyzed in the transportation model.

These alternative systems, which use more advanced technology, are compared with the reference transportation infrastructure in terms of mass payback ratio (MPR), the net mass of lunar material delivered to LEO per unit mass of terrestrial material used in the system (*Frisbee and Jones,* 1983). An MPR greater than one is considered to be necessary for the export of lunar material (such as lunar oxygen) down to LEO, which is preferred over the transport of similar material up from Earth. The reference transportation system can achieve an MPR slightly greater than one (the system can deliver more lunar mass to LEO than the terrestrial mass needed to produce and transport this lunar mass). Mass payback ratios for some of the more advanced system alternatives considered in the following pages are high enough to suggest that these technologies should play a major role in future lunar operations.

REFERENCE TRANSPORTATION INFRASTRUCTURE

The reference infrastructure is based upon recommendations of recent studies at General Dynamics Space Systems Division (*Bialla,* 1986; *Bialla and Henley,* 1987), with minor modifications to optimize the system for utilization of lunar oxygen. Figure 1 provides an overview of this reference infrastructure, illustrating

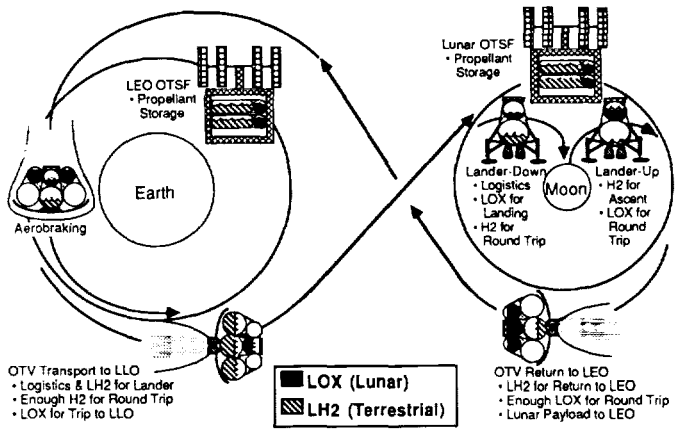

Fig. 1. Reference orbital transfer infrastructure.

the orbit transfer vehicle (OTV), orbital transportation and staging facilities (OTSFs) in LEO and LLO, and an OTV-derived lunar lander.

OTV Concept

The OTV concept chosen for this reference infrastructure is modeled after the modular S-4C concept recommended in recent OTV studies (*Ketchum et al.*, 1988). This space-based, reusable, aerobraked vehicle is illustrated in Fig. 2. The only significant modification of the S-4C for this lunar application is an increase in the aerobrake mass in order to accommodate the large masses of lunar material brought to LEO each time the OTV returns.

The OTV is propelled by two advanced oxygen/hydrogen (O_2/H_2) engines of 22,000 N (5000 lbf) thrust each, with an oxidizer-to-fuel (O_2:H_2) ratio of 6:1 and a specific impulse of 485. This relatively low thrust level minimizes engine mass, but requires a multiple perigee burn trajectory to reduce gravity losses upon departure from LEO. A modification of this OTV engine for lunar lander applications would make use of a significantly higher mixture ratio (well past the stoichiometric ratio of 7.8:1).

The S-4C OTV concept allows variation of the number of tanksets (sets of individual tanks for 0_2, H_2, pressurant, and RCS propellants), with combinations of 1, 3, 4, 5, and 7 tanksets giving the vehicle a wide range of propellant capacity. For the reference OTV, different tankset options have been considered in the analytical model, and the three-tankset configuration has been chosen for the reference OTV. The less efficient one-tankset configuration might be reasonable for use in early, low-mass transport operations required to set up an initial infrastructure, and the most efficient seven-tankset configuration might be preferred for eventual, high-mass transport operations.

The reference OTV uses a fully reusable aerobrake that is sized as a function of the mass brought back to LEO. The aerobrake is specified to be 13% of the total mass entering the Earth's atmosphere, a factor that is typical of previous OTV designs for return from geosynchronous Earth orbit (GEO).

Modular avionics on the OTV allow modification of guidance and control systems with advances in the state of the art. The modular avionics approach also allows easy modification of guidance as required for an OTV-derived lunar lander.

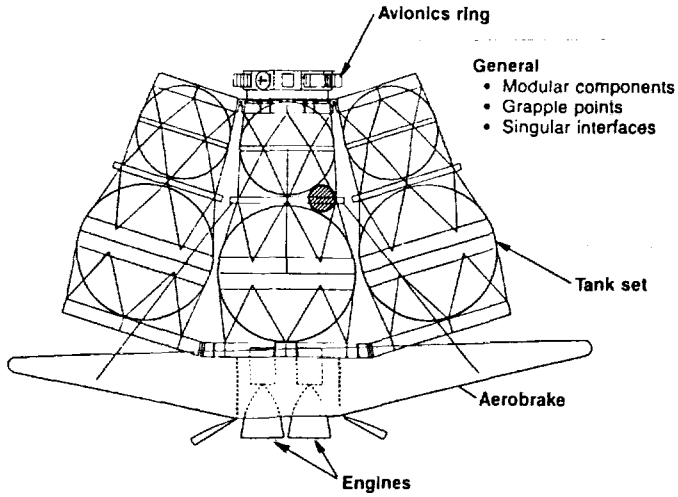

Fig. 2. Reference orbital transfer vehicle.

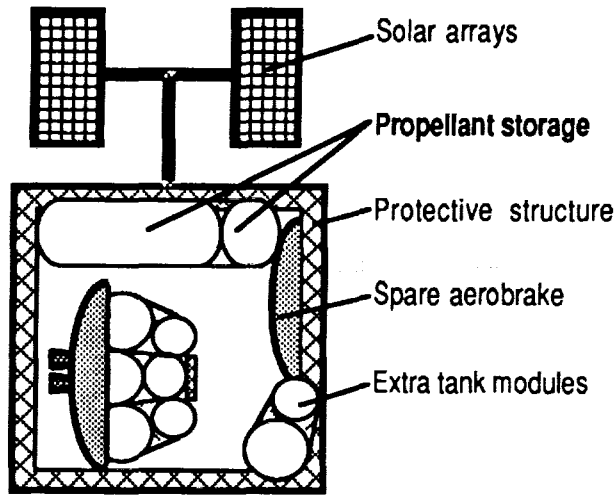

Fig. 3. Representative orbital transfer and staging facility.

Orbital Transportation and Staging Facilities

Two orbital transportation and staging facilities (OTSFs) are used in the reference infrastructure, one in LEO and one in LLO. The OTSF functions include spare vehicle parts storage, meteoroid and debris shelter, and propellant storage. In the transportation model, these facilities are repositories for lunar oxygen and terrestrial hydrogen. With an OTSF present in LLO, the lunar lander can deliver lunar oxygen to LLO while the OTV is in transit between LLO and LEO.

A representative LEO OTSF is illustrated in Fig. 3. Its subsystems are derived from space station hardware and, in this reference case, it co-orbits with the space station at 28.5° inclination and 400-km altitude. Telerobotic operations are expected to be the normal means of maintenance, propellant transfer, and payload processing.

The representative LLO OTSF is similar to the LEO facility in most respects. The lunar facility may use a more advanced solar power system (if derived from evolving space station hardware), and has a larger OTV hangar for multiple vehicles. This facility contains several manned modules, and is expected to evolve with time and eventually serve as a staging base for Mars missions using lunar LOX (*Bialla*, 1986; *Cordell and Wagner*, 1986). More detailed definition of LLO OTSF systems is needed, including design adaptable to later modification by more advanced technology.

OTV-derived Lunar Lander

The reference lunar lander is illustrated in Fig. 4. This configuration is derived from the OTV by substituting landing gear for the aerobrake, and thus has common subsystems and interfaces for propellant handling. More sophisticated avionics packages are substituted for the additional requirements of launch and landing. A single-tankset derivative of the OTV is used for the reference lunar lander, as the thrust from its two engines would be insufficient to lift a larger lander (with full O_2 tanks) from the Moon's surface. The most significant feature of the lander selected

for the reference configuration is the modification of the basic OTV engine for operation at a higher mixture ratio. The purpose of this vehicle is the transport of O_2 from the Moon's surface to LLO, and the return to the surface with logistic supplies and enough H_2 for the next trip up to LLO.

Engine performance as a function of O_2:H_2 ratio (the ratio of O_2 used to H_2 used) follows the trend of the curve in Fig. 5. This curve is based upon the output of a General Dynamics computer program, for one-dimensional equilibrium O_2/H_2 combustion in an engine with a 100-bar (1500 psi) chamber pressure and an area ratio of 400. Higher chamber pressures and area ratios would generally increase the engine's I_{sp}. (Optimal area ratios may actually be lower due to factors such as increased weight and radiative energy losses associated with large engine nozzles.) As the mixture ratio increases beyond the region typical of current O_2/H_2 engines (around 6:1), the I_{sp} (force divided by mass flow rate) decreases. Lunar lander applications can achieve higher MPRs at higher mixture ratios in spite of this decrease in I_{sp}, as the O_2 used is nearly free, while H_2 must be imported from Earth. Oxygen/hydrogen ratios selected for the OTV and the lander were arrived at by trial of various mixture ratio (and corresponding I_{sp}) parameters in the transportation model. The selected O_2:H_2 ratio of 12 for the lunar lander was a compromise; slightly better MPRs would result if the lander engine were operated at a higher O_2:H_2 ratio (>12) for liftoff and at a lower ratio (<12) for landing, but this would require variation in the mixture ratio during flight rather than the somewhat simpler alternative of a constant high mixture ratio. Engine temperatures predicted for this high mixture ratio are actually cooler than those created in conventional 6:1 mixture ratio engines.

Technology Development Requirements

The reference transportation infrastructure in this model presumes fruition of certain technology developments for reusable OTVs, OTV-derived lunar landers, space-based OTV accommodations, and the lunar surface base. Key OTV technology in the reference case includes aerobraking, advanced O_2/H_2 engines, advanced avionics, and lightweight structures. Technology for space-based OTV servicing at an OTSF includes telerobotic maintenance, zero-*g* propellant transfer, and automated rendezvous and docking. New technology is also needed for lunar materials processing to produce liquid oxygen propellant for the OTV and lunar lander. In order to use this lunar oxygen most effectively, the lunar lander uses an engine with a high O_2:H_2 ratio.

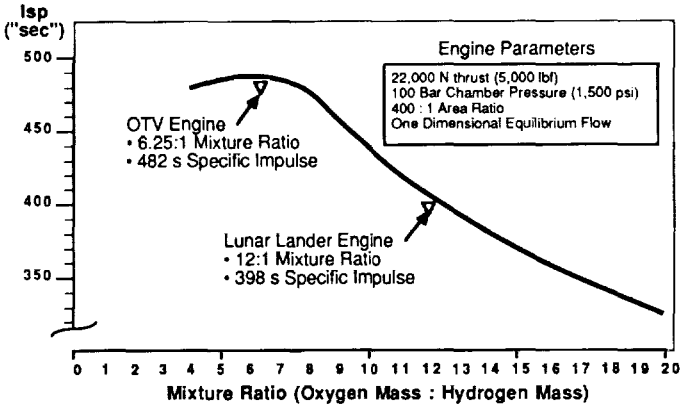

Fig. 5. Engine performance vs. O_2:H_2 mixture ratio.

Modification of a basic OTV engine to operate at a higher mixture ratio for lunar lander applications is considered to be a reasonable evolutionary step for an engine that is still in the early stages of technology development. Engine technology development activities sponsored by Lewis Research Center (such as the use of gaseous oxygen to drive oxygen turbopumps), are relevant to such an increase in O_2:H_2 ratio. Similar high O_2:H_2 ratio and variable O_2:H_2 ratio engines are being studied for Earth-to-orbit applications, where the increase in O_2:H_2 ratio can reduce launch vehicle dry mass (*Martin,* 1987). Small O_2/H_2 engines at the stoichiometric (7.8:1) ratio have been developed and tested for use on satellites (*Stechman and Campbell,* 1973) and on the space station (*Robinson and Rosenthal,* 1986; *Senneff and Richter,* 1986; *Norman et al.,* 1988).

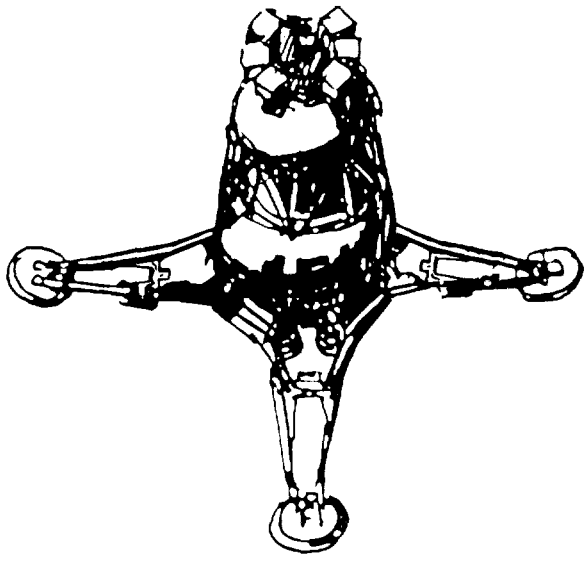

Fig. 4. Reference lunar lander derived from OTV subsystems.

ANALYTICAL MODELING OF TRANSPORTATION INFRASTRUCTURES

An analytical model has been developed to compare advanced technology alternatives against this reference architecture. This model uses Excel spreadsheet software to apply an iterative series of equations to alternative transportation systems. This relatively simple model can easily be modified to consider variations of input parameters, and can be run rapidly on a personal computer.

The analytical model of the lunar transportation infrastructure, which considers separate loops for LEO-LLO and LLO-lunar surface transportation, was illustrated in Fig. 1. The lunar lander: (1) leaves the surface with a full load of O_2 (35,000 lbm) and enough H_2 to reach LLO; (2) transfers excess O_2 to the lunar OTSF (retaining enough to return to the surface) and receives H_2 and logistics mass to make the next round trip and produce the next load of O_2; and (3) returns to the surface to complete this loop. For the reference case, the lander must make approximately seven round trips to the lunar OTSF to transport the O_2 that will be transferred later from the OTSF to fill the three tanksets of the OTV. The OTV loop: (1) leaves LEO with enough

H_2 to make the round trip, enough O_2 to reach LLO, and the payload (hydrogen and logistics mass) required to support the approximately seven lander loops; (2) delivers the payload to LLO and refills oxygen tanks at the lunar OTSF; and (3) returns to LEO with excess O_2. The ratio of this excess O_2 (beyond that required for the next trip up) to H_2 and logistic mass is termed the MPR. This ratio (1.32:1 for the reference infrastructure) is a basis for assessing new technology alternatives to the reference system.

Material on the surface of the Moon is at a higher potential energy level than the same mass in LEO, as illustrated in Fig. 6. If we could construct a "siphon" between the Moon's surface and LEO, mass would flow freely, and if we placed a "turbine" in this mass flow, a tremendous amount of energy would be released. In the reference system, we construct such a "siphon," although it is not very efficient in mass transfer (requiring an input of mass from Earth) or in energy conversion (dissipating energy by aerobraking). Alternative systems that supplement the reference configuration by more advanced technology are generally more efficient in mass transfer and/or energy conversion.

Velocity increments used in the transportation model are also shown in Fig. 6. For an unmanned OTV, much longer flight times might be reasonable, with attendant reduction in its mission ΔV requirements. The altitude and eccentricity of "low" lunar orbit have not been optimized (with corresponding changes in the individual velocity increments) for the reference or alternative infrastructure, but such an analysis would probably result in greater MPRs. Gravity losses for the lander (which transports more mass upward than downward) could be higher in ascent than in descent, tending to exchange the ΔVs attributed to these mission phases.

Hydrogen is the major component of the OTV's payload from LEO to LLO. For cases in which H_2 use exceeds OTV capacity, additional tankage, weighing 10% of the contained propellant, is presumed to be carried to LLO (and left there). The OTV's H_2 tankage is actually oversized for most mission propellant requirements, and thus, if the logistic mass is H_2, it might be carried directly within OTV tanks. For example, production of O_2 by reduction of ilmenite and subsequent water electrolysis (*Gibson and Knudson,* 1985) would use H_2 as a principal reagent

$$H_2 + FeTiO_3 = H_2O + Fe + TiO_2$$

$$2H_2O = 2H_2 + O_2$$

If all the H_2 used in this reaction is not recovered, H_2 might comprise a substantial portion of the logistics mass required for lunar O_2 production. The transportation model assumes that one unit of terrestrial mass must be delivered to the Moon's surface for every 100 units of lunar mass produced on the Moon (O_2 or other useful lunar products). Spare parts for OTV, OTSF, and O_2 production facility maintenance are not separated from other logistics in this transportation model; however, both their unit cost and transportation cost are included in an economic model (*Stern,* 1988), which uses the output of this transportation model.

This LEO-Moon transportation model describes steady-state operations, assuming that the lunar base, including an O_2 production plant, is already established for reasons other than transport of lunar material to LEO (e.g., scientific exploration). The reference infrastructure would initially transport men and supplies for a manned lunar base, and thus "bootstrapping" of the system (to provide for its own development) is not considered. Expansion of the system for higher O_2 production and transportation rates would require a temporary increase in the flow of mass from Earth, with a return to steady-state operation after system expansion is complete.

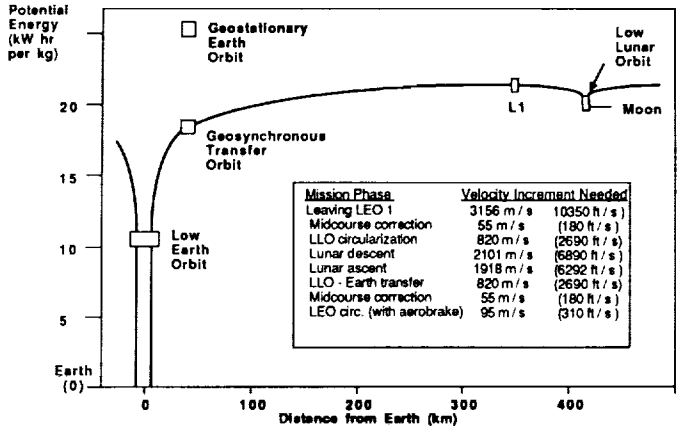

Fig. 6. Potential energy of lunar material.

TRANSPORTATION MODEL RESULTS

The transportation model has been used both in refining the reference transportation infrastructure and in assessing modifications of this infrastructure with more advanced technology. Results of calculations using the transportation model are portrayed in the following charts, with MPR indicated on the vertical axis. While the scale changes somewhat to accommodate the range of results, the reference transportation system's MPR of 1.31 is indicated on all the charts by a dashed line, and a solid line indicates an MPR of one (the limit for practicality of transport of material down to LEO from the Moon, rather than up from Earth).

Reference Infrastructure Refinement

The significance of both the number of OTV tanksets and the high mixture ratio for the lunar lander is illustrated in Fig. 7. As the number of OTV tanksets increases, the system yields greater MPRs. A large improvement is realized by increasing from one to three tanksets, with far less benefit thereafter. The three-tankset OTV configuration is considered to be most desirable, as it achieves relatively high MPRs, yet keeps the total oxygen load (which the lunar OTSF must store prior to transfer into the OTV) at a reasonable level. When the three-tankset OTV is combined with a 6:1 mixture ratio lunar lander, it obtains an MPR slightly greater than one (1.07); however, the use of the 12:1 lander results in a much greater MPR (1.32). The difference between these MPRs becomes significant when one considers that the net gain per unit mass invested in the 6:1 lander case is only 7%, as compared to a 32% gain in the case of the 12:1 lander. The lower-mixture ratio lander is, in fact, marginal for use with the three-tankset OTV, as unforeseen difficulties could easily turn this small mass profit into a net mass loss. Mass payback ratios for the lower-mixture ratio lander configuration improve somewhat as the number of OTV tanksets increases. However, the MPRs for the 12:1-mixture ratio lander also increase by similar increments. The selected reference system, with three tanksets on the OTV and a 12:1-mixture ratio for the lander, is clearly indicated on Fig. 7 by the bold bar.

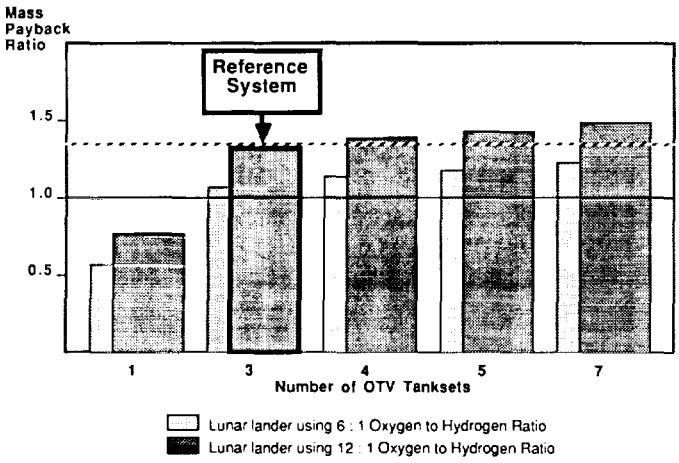

Fig. 7. Sensitivity to number of tanksets and lander O_2:H_2 ratio.

Aerobrake Weight Sensitivity and Potential Production from Lunar Materials

Aerobraking is essential to the success of the reference system, and the mass of the aerobrake is a dominant factor in its MPR. Figure 8 illustrates the sensitivity of MPR to aerobrake mass for the reference OTV, and for alternative configurations that use aerobrakes produced from lunar materials. Aerobrake mass is varied here as a percent of mass entering the Earth's atmosphere. Nominally, 13% of entry weight is used for the reference system's aerobrake, resulting in large aerobrake masses, as the returning OTV's mass (with nearly full oxygen tanks) is relatively large. Multiple aeropass trajectories, with each pass successively lowering perigee, might reduce the aerobrake mass required. If aerobrakes can be produced from lunar materials, substantially larger MPRs may result; the OTV would not have to carry the aerobrake mass from LEO to LLO, but the lander would instead carry the aerobrake mass for the much lower ΔV from the lunar surface to LLO (*Duke et al.,* 1985). If lunar aerobrake manufacture proves to be feasible (for example, using the TiO_2 by-product of ilmenite reduction as a refractory heat shield material), the aerobrake mass could be significantly higher than that of an aerobrake manufactured on Earth, and still be competitive. An expendable lunar aerobrake (discarded at LEO) weighing 25% of the entry mass would still be preferable to the reference system's aerobrake. If the used lunar aerobrake had intrinsic value in LEO (if the mass of the brake discarded at LEO is considered to be part of the payload to LEO), the MPR would continue to increase with increasing aerobrake weight. While the possibility of manufacturing aerobrakes from lunar materials is clearly attractive as a far-term option, the terrestrial aerobrake is retained as a baseline for the reference system.

Tether-assisted Transportation

Alternative systems that use tether-assisted OTV transportation have been emphasized in this Advanced Propulsion for LEO-Moon Transportation study (*Arnold and Thompson,* 1988; *Stern,* 1988). These systems are considered in the model as modifications of a reference transportation facility in LEO or LLO, or as an additional facility in an elliptical Earth orbit (EEO). Tether-assisted transportation alternatives are assumed to compensate for any net imbalance in momentum exchanged toward and away from the Moon through high-I_{sp} propulsion (e.g., ion engines) using propellant from the Moon.

Tether-assisted transportation systems can reduce the ΔV requirements of the vehicles in the reference transportation infrastructure, and thereby increase payload (multiple references). The ΔV supplied by throwing or catching the OTV or lander with a tether is subtracted from the velocity increment needed for a given mission phase. Velocity increments of 500 m/sec (1640 ft/sec) and 1 km/sec (3280 ft/sec) are considered for each tether system alternative. The tether that can throw (release) a vehicle with an initial 500-m/sec velocity, but not catch a similar incoming vehicle, is the least ambitious of the alternatives selected for study, and would be the most reasonable for consideration in "near-term" (early twenty-first century) transportation between LEO and the Moon. Tether-supplied velocity is limited to the maximum velocity increment needed, thus the "1-km/sec" system in LLO would throw an OTV toward Earth at 820 m/sec (2690 ft/sec), the velocity used to escape from LLO. Similarly, 95 m/sec (310 ft/sec) is the maximum increment achievable by system alternatives that catch an OTV for circularization in LEO after aerobraking.

Tether platforms can also provide a means of energy storage (*Arnold and Thompson,* 1988). Consider a platform in EEO with the capability to throw the OTV outward toward the Moon: The OTV uses chemical propulsion to transfer from LEO to EEO, docks with the tether facility, and is thrown by the tether. The momentum given to the mass of the OTV by throwing it at some initial velocity must be compensated by an equal and opposite change in the momentum of the platform in EEO (its mass multiplied by its ΔV). If the platform is heavy relative to the OTV, its resulting velocity change will be small, with little change in its orbital trajectory (a somewhat lower apogee if the OTV is thrown at perigee). Upon returning from LLO, the OTV aerobrakes into EEO, docks with the platform, and is then thrown downward into LEO, at the required remaining ΔV. The momentum of the EEO platform is now changed in the opposite direction

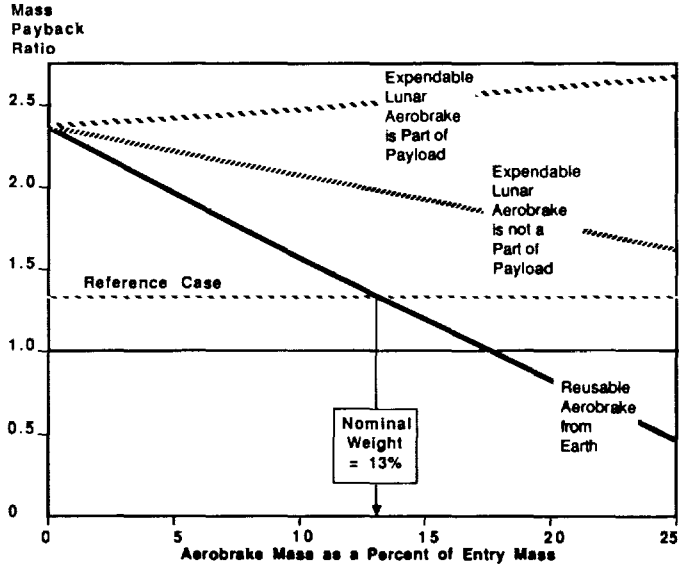

Fig. 8. Reference infrastructure: Aerobrake weight sensitivity.

(returning toward a higher apogee if the OTV is thrown at perigee). Energy transferred to the platform by the action of throwing the OTV toward LLO is thereby returned as the OTV is thrown down into LEO.

Similar momentum transfer could be achieved at a tether platform in LEO, which deorbits mass returning to Earth in exchange for upward boosting of OTVs toward the Moon, or at a platform in LLO, which exchanges momentum gained in the downward boost of lunar landers for the outward boost of OTVs returning to LEO. If platforms can be made to catch vehicles as well as throwing them, further improvements in energy storage can be obtained, with additional increases in MPR. While such transfers of momentum do not fully cancel in practice, the net momentum deficit or surplus is substantially reduced.

In a system with an MPR greater than one, the net momentum imbalance will tend to make the tether platform move toward the Moon as the net lunar mass transported by vehicles moves toward Earth. Momentum could be balanced by several methods, including (1) sending additional mass from Earth toward the Moon; (2) throwing vehicles at a lower velocity toward Earth than the velocity at which they are thrown toward the Moon; (3) conversion of orbital energy into other forms (e.g., into electrical energy) via an electrodynamic, conducting tether cutting through geomagnetic field lines; or (4) consumption of propellants at the affected platform.

Platforms equipped for tether-assisted transportation are presumed to use the fourth method noted, with low thrust, high I_{sp} propulsion to cancel any net momentum imbalance. The propellant for such momentum makeup is considered to be a lunar product and, for the purposes of the transportation model, is included as a part of the lunar O_2 produced and transported. Argon in lunar regolith is easily released by heating (*Kirsten and Horn,* 1974), and could be a reasonable propellant choice in place of O_2. An I_{sp} of 5000 sec is presumed for momentum makeup, consistant with the value used for ion engine OTV propulsion discussed later. As the net momentum deficit or surplus is generally small, MPRs are not very sensitive to this selection of advanced propulsion for the facilities equipped for tether-assisted transportation.

Figure 9 contrasts the MPR achieved through tether-assisted transportation from a single facility in LEO, EEO, or LLO. Each case considers two velocity increments supplied in a system that (1) only throws vehicles and (2) both throws and catches vehicles. While any of these alternatives is clearly better than the reference case, several interesting observations can be made through comparison of the alternatives with each other. The LEO tether facility gains little by adding the ability to catch due to the small velocity needed for circularization of the OTV in its low perigee orbit after aerobraking. (Tether-assisted transportation of mass between Earth and LEO has not been considered for the LEO OTSF due to the groundrules of the present study, but would tend to increase its effective MPRs.) The EEO tether facility, in contrast, would benefit considerably from the ability to catch vehicles in addition to throwing them. The increased MPRs for the EEO facility, however, must be traded against the increased operational complexities of such a system. Tether-assisted transportation from the LLO OTSF results in the largest MPRs for any single facility location, as the facility is used to reduce propulsive velocity requirements for the lunar lander as well as the OTV. Here the MPRs achieved by throwing alone equal or exceed those that would be obtained by combined throwing and catching from LEO or EEO facilities. The improvement in MPR that would result from an LLO facility that could catch as well as throw is also far more significant than that for an LEO or EEO facility.

At a high enough velocity, catching and throwing the OTV with a tether may be preferable to aerobraking (*Eder,* 1987). Figure 10 plots the MPR achieved with and without the use of an aerobrake vs. velocity supplied by tether for the case of a tether facility in EEO that can both throw OTVs and catch them. As calculated using the transportation model, the aerobrake becomes a detriment, rather than an asset, if the tether facility can impart a velocity of approximately 1.4 km/sec both in throwing and catching. At low tether-supplied velocities (below 0.7 km/sec), this type of system would be less effective than the reference infrastructure.

Laser Propulsion, Ion Engine, and Mass Driver Systems

Other modifications of the reference infrastructure with new technology could also increase MPR substantially. Figure 11 compares laser OTV propulsion, ion engine OTV propulsion, and a lunar mass driver as modifications to the reference system.

The laser propulsion case, as defined by R. Glumb of TRW, uses a laser to heat H_2 propellant for departure of the OTV from LEO.

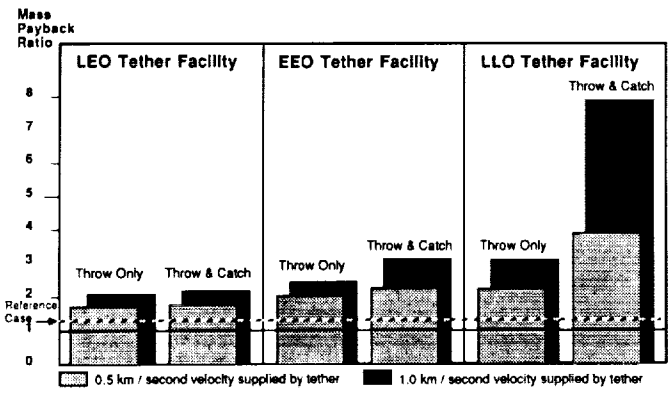

Fig. 9. Comparison of tether-assisted transportation systems.

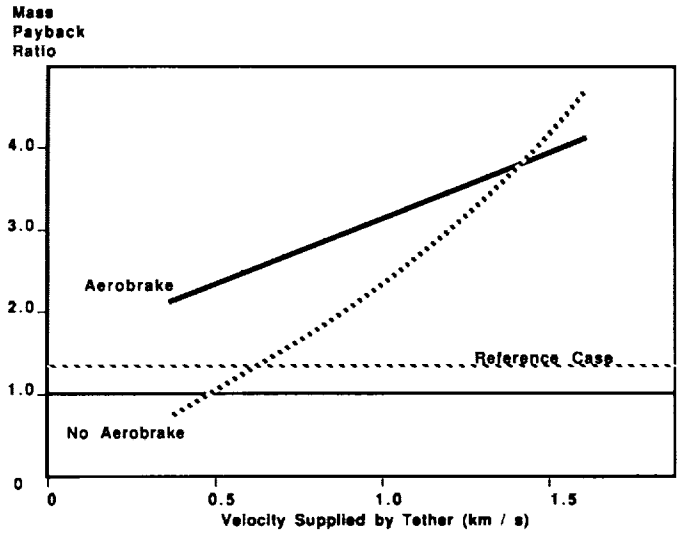

Fig. 10. EEO tether system: Aerobrake vs. no aerobrake.

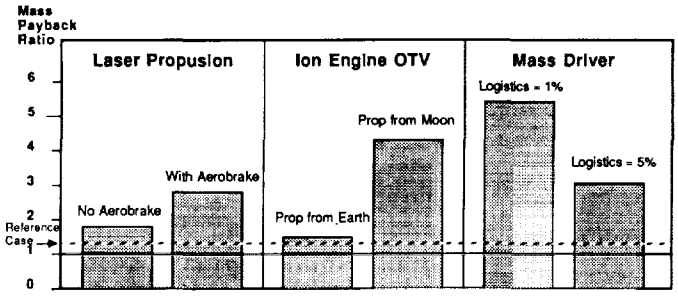

Fig. 11. Laser propulsion, ion engine, and mass driver systems.

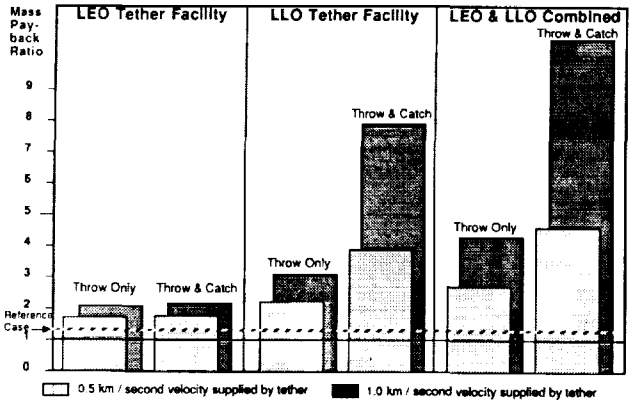

Fig. 12. Combined tether-assisted transportation in Earth and lunar orbits.

The propulsion system of the reference OTV is retained for use in the vicinity of LLO. This alternative results in a relatively high MPR if the aerobrake is retained, but a somewhat lower MPR if the aerobrake is relinquished in favor of carrying additional H_2 for laser propulsion in return to LEO.

An OTV equipped with an ion engine, as defined by Ralph Lovberg of UCSD's Physics Department, also achieves a very high MPR, provided that its propellant is supplied from the Moon. This vehicle has a large mass, no aerobrake, and low-thrust ion engines. The low thrust of the vehicle substantially increases the effective mission ΔV, as well as the mission duration. Use of an aerobrake in conjunction with ion engine propulsion was not considered, due to the presumption that a large power supply would be needed. Nuclear power safety implications or large, fragile solar cells could prohibit aerobraking. (For the purposes of the transportation model, OTV transportation reached LEO rather than being limited to a higher, "nuclear safe" altitude, which would have required a separate vehicle for intermediate transportation to LEO). If aerobraking were feasible, the mission duration and ΔV requirements for ion engine propulsion could be reduced substantially, with a corresponding increase in MPR.

A mass driver situated on the Moon would also result in a high MPR. Two cases are considered here through the transportation model, with logistics mass taken down to the Moon by the lander equaling nominal (1%) and increased (5%) fractions of lunar O_2 produced. An increase in logistics mass may be warranted, as the mass driver (as defined by Hu Davis of Davis Aerospace) launches O_2 payloads with apogee kick motors attached for self-circularization in LLO, and these motors are presumed to be imported from Earth. Propellant required for the collection of O_2 payloads in LLO would also result in an effective increase in logistic mass requirements.

Combined Tether Systems in LEO and LLO

Combined systems, where hanging or spinning tethers are used at two tether facilities in LEO and LLO, have been selected for investigation by the working groups involved in the Advanced Propulsion for LEO-Moon Transportation study. Hanging and spinning tether facilities are identical as evaluated in the transportation model. Results for this case would apply equally well to the use of swinging tethers, which may be another reasonable alternative.

Figure 12 illustrates the LEO and LLO systems alone (as they were shown in Fig. 11) and the combined system of tether-assisted transportation from both LEO and LLO. The MPR improves substantially through the combination of two similar or identical systems in LEO and LLO. The development cost of two such facilities should be a relatively small increase over that for a single facility to be placed in either LEO or LLO.

CONCLUSIONS AND RECOMMENDATIONS

The results produced by this LEO-Moon transportation model suggest that advanced technology can significantly improve the potential for lunar resource utilization in LEO. The reference LEO-Moon transportation infrastructure, using aerobraking OTVs, lunar oxygen, and high-mixture-ratio lunar lander engines, can deliver slightly more lunar mass to LEO than the mass of propellants and logistics needed from Earth for transportation and lunar oxygen production. New technologies of tethered momentum transfer, lunar material aerobrakes, laser OTV propulsion, ion engine OTV propulsion, and lunar mass driver use all have been seen to increase the efficiency of the reference system in bringing lunar mass to LEO.

In order to reap the benefits of such advanced technology, continuing research and development is needed. High-mixture-ratio lunar lander engines are important for efficient use of lunar oxygen, and deserve consideration in ongoing technology development activities. Conceptual design studies of LEO-Moon transportation systems should consider modifications over time as new technologies mature. Further investigation of advanced technology is necessary in the near term as an input to preliminary design for early LEO-Moon transportation systems. Continued consideration of such advanced systems is recommended to provide the groundwork for their eventual implementation in transportation between the Earth and Moon, as well as in regions beyond cislunar space.

Acknowledgments. Credit is due in several respects for assistance in development of this transportation model. Many of the participants in the Advanced Propulsion for LEO-Moon Transportation study made useful contributions in defining the reference configuration and advanced alternatives to be studied. R. Ford's performance calculations for high O_2:H_2 ratio propulsion were an important input to the reference lunar lander definition. W. Thompson provided guidance and insight into potential operations using tethers for momentum transfer. H. Bonesteel, M. Felix, A. Schneider, and M. Stern are thanked for their comments on earlier drafts of this paper. The research reported here fulfilled part of the requirements for a Master of Science degree in aerospace engineering at the University of California, San Diego. General Dynamics Space Systems Division assisted in related tuition expenses, computer resources, and arrangements for presentation and publication of this paper.

REFERENCES

Arnold J. R. and Thompson W. B. (1988) Advanced propulsion for LEO-Moon transportation: II. Tether configurations for the LEO-Moon system (abstract). In *Papers Presented to the 1988 Symposium on Lunar Bases and Space Activities of the 21st Century*, p. 10. Lunar and Planetary Institute, Houston

Bialla P. H. (1986) The diversity of roles for orbital transfer systems. 37th Congress of the International Astronautical Federation, Paper No. IAF 86-116, Innsbruck, Austria.

Bialla P. H. and Henley M. W. (1987) The space-based OTV and the establishment of the next launch site. 38th Congress of the International Astronautical Federation, Paper No. IAF87-196, England.

Bialla P. H. and Ketchum W. J. (1987) Key technologies for orbital transfer vehicles. *Proceedings of the 24th Space Congress*, Cocoa Beach, Florida.

Bock E. (1979) *Lunar Resources Utilization for Space Construction, Final Report.* Contract NAS9-15560.

Cordell B. M. and Wagner S. L. (1986) Strategies, synergisms, and systems for the mannned exploration of Mars. 37th Congress of the International Astronautical Federation, Paper No. 14F-86-320, Innsbruck Austria.

Cordell B. M., Varnado C. L., and McClain C. (1988) Implications of the NASA lunar initiative for a typical space transportation architecture (abstract). In *Papers Presented to the 1988 Symposium on Lunar Bases and Space Activities of the 21st Century*, p. 59. Lunar and Planetary Institute, Houston.

Duke M. B., Mendell W. W., and Roberts B. B., (1985) Strategies for a permanent lunar base. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 57-68. Lunar and Planetary Institute, Houston.

Eder D. (1987) Lunar base logistics. Paper presented at the Manufacturing in Space Conference, Princeton, New Jersey.

Frisbee R. H. and Jones R. M. (1983) An analysis of propulsion options for transport of lunar materials to earth orbit. 19th Joint Propulsion Conference, Paper No. AIAA-83-1344, Seattle, Washington.

Gibson M. A. and Knudsen C. W. (1985) Lunar oxygen production from ilmenite. In *Lunar Bases and Space Activities of the 21st Century* (W. W. Mendell, ed.), pp. 543-550. Lunar and Planetary Institute, Houston.

Ketchum W. J., Maloney J. W., and Pea L. (1988) Servicing and maintaining a lunar transportation system in LEO (abstract). In *Papers Presented to the 1988 Symposium on Lunar Bases and Space Activities of the 21st Century*, p. 135. Lunar and Planetary Institute, Houston.

Kirsten T. and Horn P. (1974) ^{39}Ar-^{40}Ar dating of basalts and rock breccias from Apollo 17 and the malvern achrondrite. In *Soviet-American Conference on Cosmochemistry of the Moon and Planets.* NASA SP-370.

Loftus J. P. and Brashear W. L. (1985) Beyond low Earth orbit—An overview of orbit to orbit stages. 36th Congress of the International Astronautical Federation, Paper No. IAF-85-141, Stockholm, Sweden.

Martin J. A. (1987) Space transportation main engines for single-stage vehicles. 23rd Joint Propulsion Conference, Paper No. AIAA-87-1941, San Diego, California.

Norman A. M., Briley C. L., and Evans S. (1988) Space station propulsion system test bed. 39th International Astronautical Federation Congress, Bangalore, India.

Robinson P. J. and Rosenthal S. E. (1986) A proven 25 lbf H_2/O_2 thruster for space station auxiliary propulsion. 22nd Joint Propulsion Conference, Paper No. A1AA-86-1560, Huntsville, Alabama.

Senneff J. M. and Richter G. P. (1986) A long-life 50 lbf H_2/O_2 thruster for space station auxiliary propulsion. 22nd Joint Propulsion Conference, Paper No. A1AA-86-1404, Huntsville, Alabama.

Stechman R. C. Jr. and Campbell J. G. (1973) Water electrolysis for Satellite Propulsion. AFRPL-TR-72-132.

Stern M. O. (1988) Advanced propulsion for LEO-Moon transportation: I. Overview (abstract). In *Papers Presented to the 1988 Symposium on Lunar Bases and Space Activities of the 21st Century*, p. 233. Lunar and Planetary Institute, Houston.

Stern M. O. (1989) *Advanced Propulsion for LEO-Moon Transportation, Final Progress Report.* NAG9-186, California Space Institute, Univ. of California, San Diego.