ADVANCED PROPULSION FOR LEO-MOON TRANSPORT: I. A METHOD FOR EVALUATING ADVANCED PROPULSION PERFORMANCE

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We report on a study to evaluate the benefits of advanced propulsion technologies for transporting materials between low Earth orbit and the Moon. A relatively conventional reference transportation system, and several other systems, each of which includes one advanced technology component, are compared in terms of how well they perform a chosen mission objective. The evaluation method is based on a pairwise life-cycle cost comparison of each of the advanced systems with the reference system. Somewhat novel and economically important features of the procedure are the inclusion not only of mass payback ratios based on Earth launch costs, but also of repair and capital acquisition costs, and of adjustments in the latter to reflect the technological maturity of the advanced technologies. The required input information is developed by panels of experts. The overall scope and approach of the study are presented in the introduction. The bulk of the paper describes the evaluation method; the reference system and an advanced transportation system, including a spinning tether in an eccentric Earth orbit, are used to illustrate it.

INTRODUCTION

In the fall of 1986 we initiated an effort to identify and evaluate advanced propulsion concepts for the transportation of materials between low Earth orbit (LEO) and the Moon. We were looking particularly for concepts that would provide a lower-cost alternative to conventional rocketry in supporting scientific work, colonization, and commercial utilization of the Moon, Mars, and perhaps other planets and the asteroids during the twenty-first century.

We identified six tasks to accomplish the aim of the study.

1. Choose a standard mission and a reference configuration as a basis for comparing the performance of advanced configurations. A configuration is here defined as a complete transportation system between LEO and the Moon.
2. Select a small number of the most promising "pure" configurations incorporating a single advanced component or concept.
3. Define criteria by which to evaluate the performance of the configurations.
4. Describe and model each of the configurations to be evaluated.
5. Describe and model, quantitatively insofar as possible, the evaluation criteria.
6. Evaluate all the configurations.

We chose as the objective of the standard mission to carry lunar material ("paydirt") from the lunar surface back to LEO at a specified parametrized annual rate. This objective, although by itself not sufficient to justify the expenditure for a LEO-Moon transportation system, was chosen because it permitted ready and unambiguous comparison of various configurations. We specified that all oxygen for chemical propulsion was to be of lunar origin, and all hydrogen fuel and repair and replacement parts were to be of terrestrial origin. Aerobraking on return to LEO was to be used whenever advantageous; the aerobrake was assumed to be reusable and of terrestrial origin.

The chosen reference case ("Configuration 0") consists of two kinds of vehicles and three stations (*Henley,* 1988). Both vehicles are powered by reaction engines burning terrestrial liquid hydrogen and lunar liquid oxygen. The first kind of vehicle is an orbital transfer vehicle (OTV). Its functions are (1) to carry liquid hydrogen and other terrestrial logistic supplies for lunar activities from LEO to low lunar orbit and (2) to bring back to LEO lunar oxygen for propulsion and lunar material for storage. The OTV carries a reusable aerobrake for the return trip.

The second kind of vehicle is a lunar lander. Its functions are to carry terrestrial logistic supplies from low lunar orbit (LLO) to the lunar surface and to bring excess lunar oxygen and lunar material up to LLO for transfer to the OTV. This vehicle is fitted out with landing gear, and burns a fuel-lean mix to conserve terrestrial liquid hydrogen.

The first station is an "Orbiting Transfer and Staging Facility" (OTSF) in a low Earth circular orbit at 28.5°. Its functions are to store and transfer fuel, payload, spare parts, and repair tools, and to permit docking and berthing of OTVs for repair, refueling, and load transfer. A second, similar facility with comparable functions is in near-equatorial low lunar orbit. Its docks accommodate both OTVs and lunar landers. The third station is a lunar-oxygen production plant, located on the Moon's surface near the equator. The time frame is 2005-2010. It is assumed that a manned lunar base is in existence by then to establish and support this activity, and that a lunar oxygen pilot plant is available for the emplacement and startup of the configurations.

Six configurations, each incorporating one advanced propulsion component, along with appropriate "conventional" components from the reference configuration as required, have been chosen for detailed evaluation so far. Three of these involve the use of tethers. A seventh configuration, based on solar sails, was eliminated as not suitable for the standard mission in the high-gravity fields prevailing over most of the Earth-Moon trajectory.

Tethers (*Arnold and Thompson,* 1988; *Colombo et al.,* 1974; *Isaacs et al.,*; 1966; *Carroll,* 1985; *Penzo,* 1987) can permit momentum exchange between objects at opposite ends, such as a load and a platform. They become especially attractive if there is two-way traffic, as between LEO and the Moon. In that case, the momentum given up by a platform when loads are picked up and released in one direction can be restored by loads moving in the opposite direction. The three tether configurations are

1. A hanging tether in lunar orbit. In this configuration a very long tether is anchored from a ballasted platform in rather high lunar orbit. It is first deployed toward the lunar surface, so that its tip can rendezvous with a self-propelled lunar load. The tether deployment direction is then changed by 180°, and the load released toward Earth. The procedure is reversed for loads from LEO bound for the lunar surface.
2. A spinning tether in low lunar or Earth orbit. In this concept, a self-propelled load is picked up from below at suborbital velocity, then swung about 180° by the tether before being released. The load thereby gains twice the tangential velocity of the spinning tether. As before, the procedure is reversed for incoming loads.
3. A spinning tether anchored from a massive platform in an eccentric Earth orbit with perigee near LEO ("Configuration 3"). Here an OTV can be picked up in LEO, swung about as above, and released toward the Moon with the same velocity gain. Once again, the platform's momentum is restored upon capture and subsequent release of an OTV traveling in the opposite direction.

Three other configurations incorporating advanced concepts have been examined: laser propulsion, ion-engine propulsion, and mass-driver launch.

In the laser concept *(Kantrowitz,* 1972; R. Glumb, personal communication, 1987) an OTV carries both conventional rocketry and a laser thermal engine. Initially, upon leaving LEO, it is propelled by electromagnetic energy beamed to the vehicle by an Earth-based, high-power infrared laser. The laser beam is focused onto a hydrogen plasma, which is exhausted through a thruster nozzle. The advantage of this concept over a more conventional rocket engine is twofold: The power source (or the oxidant for the hydrogen propellant) need not be carried into space, and the high specific impulse (I_{sp}) derived from this engine results in good fuel economy.

In the ion-engine concept (*Stuhlinger et al.,* 1961) the OTV carries a nuclear electric power source to provide the high-voltage current for ion acceleration. Terrestrial xenon has been assumed as the propellant to be ionized; in practice, lunar argon or oxygen may be more economical. In this configuration, the propellant, as well as the power supply with its massive radiator and radiation shield, must be carried on board (unless solar photovoltaic can substitute for nuclear power), and the thrust is very low, leading to long travel times. Its advantage resides in the very high I_{sp}, leading to manageable propellant loads.

The last configuration incorporates a mass driver (*Chilton et al.,* 1977) for launching packets of lunar material off the Moon's surface. Each packet carries a conventional small propulsion system. Once launched into ballistic orbit, the packets can rendezvous autonomously with an OTSF in low lunar orbit. The launch energy is electrical rather than chemical, and can be provided on the lunar surface either by means of a nuclear power plant or by extensive (but no longer excessively expensive) sheets of amorphous solid-state photovoltaic receptors.

For a more detailed description of these configurations, and of the results of their evaluations, the reader is referred to *Stern* (1989). Some of the results will be stated at the end of this paper.

EVALUATION PROCEDURE

Framework

The evaluation framework comprises two models, a Transportation Model and an Evaluation Model. Two kinds of input are required. Engineering information supplied by technical experts on each configuration serves as input to the Transportation Model. Output of the Transportation Model, along with economic information supplied by evaluation panels, becomes input to the Evaluation Model.

The Transportation Model (*Henley,* 1988) calculates the amount of propellant consumed and the amount of lunar mass delivered to LEO per round trip. From this, one can derive some of the inputs required by the Evaluation Model: the mass payback ratio (MPR), the lunar oxygen plant capacity, and the annual number of round trips required of the OTV and of the lunar lander to satisfy the mission objective. (The MPR is defined as the lunar payload brought down to LEO per tonne of fuel and other supplies that have to be brought up from Earth.) The two models operate independently, and the output of one is fed to the other manually.

The Evaluation Model performs a life-cycle cost analysis of the input data, assuming a venture life and a discount rate. It develops operating costs and capital costs for each advanced configuration, compares these with corresponding figures for the reference configuration, and derives cost-effectiveness measures relative to the reference case from this comparison. Figure 1 shows the flow of information and the relationship between the Transportation Model and the Evaluation Model.

Input data for each configuration come from two sources. Much of the quantitative technical information, such as masses of vehicles and of orbiting or fixed installations, fuel capacities of vehicles, I_{sp} and thrusts of engines, efficiencies and outputs of power sources, and ΔVs supplied by various vehicles or devices, is provided by technical experts or specialists, and becomes input to the Transportation Model. Most of the economic information, whether quantitative or qualitative, is generated by evaluation panels, and is incorporated in the Evaluation Model. This includes estimates of acquisition costs, of technological maturity with its associated development costs and time delays, and of risk of failure and need for repair.

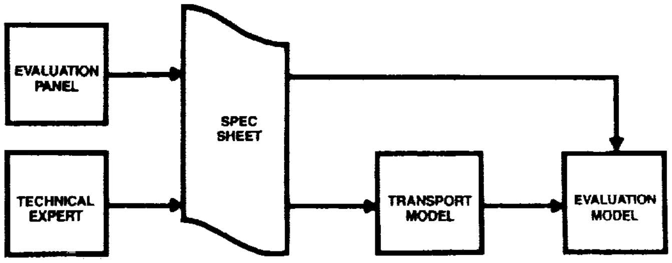

Fig. 1. Information flow in evaluation procedure. This schematic shows the interrelationship between data provided by technical experts and by evaluation panels, and the inputs and outputs of the Transportation Model and the Evaluation Model.

Model Structure

The following ground rules were adopted:

1. Transport from the surface of the Earth to LEO is not considered, but the cost of transport per unit mass between these two nodes is assigned some parametric value $\$\$_0$. All other costs are expressed in terms of this value, insofar as possible.
2. The basic criterion for judging the performance of a given advanced configuration is economic: It is characterized by the payback time or the life-cycle return on investment, which results when the advanced configuration replaces the reference case. The payback time or rate of return is, in most cases, based on a trade-off between savings in operating costs and increased capital costs. The MPR is not a life-cycle measure. It has been retained because it is familiar, and can serve as a coarse sieve to eliminate clearly submarginal schemes.
3. Savings in operating costs are based on improvements in the MPR for an advanced configuration relative to the reference case, corrected for changes in repair and replacement needs.
4. Changes in capital costs take into account transportation as well as acquisition costs of capital installations such as stations and vehicles. Acquisition costs of novel, first-of-their-kind components or subsystems incorporate estimates of their technological maturity. As used in this study, technical maturity is a proxy for the costs of research, development, demonstration, testing, and space qualification associated with the implementation of new technologies.
5. Estimates dealing with repair needs, risk of failure, and technological maturity are quantified with the help of panels of experts. Further details on some of these points are provided below.

As in any financial analysis of a venture, there are two main cost categories in the Evaluation Model: operating costs and capital costs. We shall first deal with these two cost categories by assuming that only transportation costs are important. Then we shall address the complications brought about by inclusion of other cost components, such as repair and maintenance, acquisition and development costs, etc.

To begin with, it may be possible to first weed out totally unsuitable configurations based on operating costs alone, for two reasons. First, a configuration whose operating costs are greater than those of the reference case is almost surely not a viable alternative, since it usually also requires additional capital investments. Second, comparison on the basis of operating costs alone gives an accurate picture of on-going costs, once the start-up investment has been made and becomes a sunk cost. It should be pointed out, however, that even if an advanced "pure" configuration is judged nonviable on this basis, it may still have merit if there are net savings in capital costs—a rare situation. More commonly, it may have merit if its advanced component can be combined symbiotically with other advanced components in a "hybrid" configuration.

The transportation-based operating cost can be derived from the MPR obtained from the Transportation Model. This ratio is defined as

$$\mathrm{MPR} = \frac{\text{payload mass emplaced in LEO}}{\text{mass carried up from Earth to LEO}} \qquad (1)$$

For the reference and advanced configurations chosen in this study, which use lunar-produced liquid oxygen (LLOX), the mass that has to be carried up from Earth to LEO consists mostly of terrestrial hydrogen and of "logistic mass," that is, supplies for operation of the LLOX plant. These have been taken into account in the computation of the MPR carried out in the Transportation Model. Other masses of terrestrial origin for installation of vehicles and equipment and for their maintenance and repair have not been included in the Transportation Model. They will be taken into account in the Evaluation Model, as described below.

From the definition of MPR it is easy to show that the yearly mass savings realized with an $\mathrm{MPR} > 1$ is given by

$$\mathrm{OB} = C_s \cdot (\mathrm{MPR} - 1)/\mathrm{MPR} \qquad (2)$$

where C_s is the annual amount of lunar paydirt to be transported from the Moon to LEO and OB is a yearly operating benefit realized from savings in Earth mass when the paydirt is of lunar rather than terrestrial origin. This equation has the right dependence on MPR: If $\mathrm{MPR} < 1$, there is no benefit, but rather an operating loss associated with using lunar, rather than terrestrial, paydirt. Mass payback ratio = 1 is the break-even point. Once $\mathrm{MPR} \gg 1$, its exact value is of minor importance, since the savings in transportation cost (expressed in mass terms) can never be greater than C_s.

There is a transportation-based capital cost to consider, as well. For equipment to be placed in fixed orbits or space locations, such as LEO, lunar orbit, or the lunar surface, this is the cost of emplacement, expressible in units of mass. For example, for the OTSF in LEO, this cost is just its mass. For the OTSF in low lunar orbit, on the other hand, the mass should be multiplied by a factor >1 to account for the additional propellant load required to accompany the facility.

Transportation-related capital expenditures for vehicles must include an allowance for redundancy. This comes about because of the limited payload capacity and finite turn-around time of each vehicle. For example, delivering an annual lunar payload of 2500 T to LEO in the reference configuration, at about 15 T per round trip, would require approximately 4 vehicles, based on a turn-around time of 8 days. This ignores the relatively narrow biweekly windows available for economical travel between Earth and Moon, which may force a substantial further addition to the fleet.

Capital costs and operating benefits can be combined into a single measure of cost-effectiveness by the well-known device of equating the sum of all future operating benefits, discounted to the present, to the initial investment or capital cost. Two measures derived from this equality are particularly useful. In the first, one assumes a "market" rate of return, r, taken at 8% in this paper, and solves for the time, called the payback time, which satisfies the equality. This solution can be expressed in closed form. In the second, one assumes a venture time, fixed at 20 years in this study, and looks for the discount or interest rate, often called the internal rate of return (IRR), which satisfies the equality. This has to be calculated by an iterative procedure, but poses no difficulty for a personal computer. (It should be pointed out that there can be no finite payback time if the annual benefit is less than r times the capital cost. By the same token, there can be no IRR if the cumulative benefits over the venture life amount to less than the initial capital cost.)

So far, only transportation costs have been considered. The complications due to other important cost components must now be addressed. These components include the acquisition cost of capital, the R&D costs of developing the technology for an advanced configuration and bringing it to a state of operational readiness, and the costs of maintenance, repair, and replacement. Their relationship to transportation costs and to the overall measures of cost-effectiveness is represented in Fig. 2.

The acquisition costs of capital for a new configuration can be estimated by experienced space engineers. This is best done by breaking the configuration or system into subsystems and components, many of which are similar to ones already in use or being procured for space applications. The acquisition cost of each component is then estimated in constant-dollar terms. It can be converted to mass units (T) via division by $\$\$_0$ before being added to the transportation cost for that component; conversely, both can be expressed in dollar terms.

The acquisition of a new or advanced component or subsystem, such as the tether-bearing platform and its components in eccentric Earth orbit, or a rocket engine operating at higher-than-conventional oxidizer-to-fuel ratio, poses an additional problem. Clearly, the first embodiment of such a component is much more expensive than the more routine procurement of the fourth or fifth version or copy would be. We have attempted to capture this important cost in a somewhat novel way, summarized here and explained in more detail below.

One can look at this additional cost as a development risk with two consequences: it makes development more expensive than mere acquisition cost, and it entails protracted reduction to practice. The more immature and complex the technology, the greater the cost and the longer the time needed for development. Both cost and time have considerable uncertainty associated with them. In this study, we deal with the cost and time aspects separately. We simplify by assigning their effects to the first embodiment only, rather than distributing them over the first few by means of a "learning curve," as happens in real life.

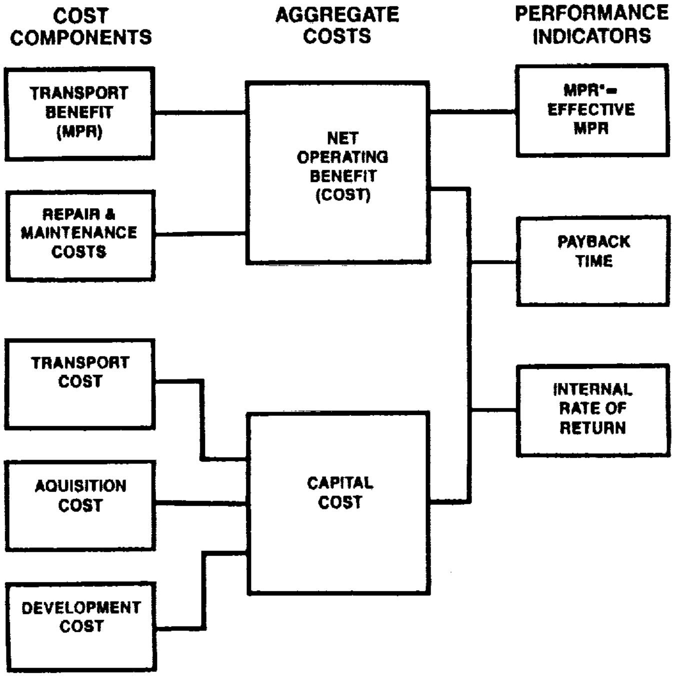

Fig. 2. Interrelationship of cost components. This schematic indicates how the main performance indicators are obtained from various inputs through internal processing in the Evaluation Model.

Briefly, the development cost is estimated by rating the technology readiness at the subsystem or component level; i.e., we list what steps have to be taken to achieve maturity, and evaluate the cost of each step. Development time is arrived at by estimating the time taken to accomplish each step. Delay time is then translated into additional cost (the time value of money) by "discounting" the funds needed for each step forward to the time when operation is to start, with further cost penalties imposed if maturity cannot be expected by the year of initial operation, assumed to be 2005. The effects of technological development and learning are treated deterministically, based on estimates of expected or most probable costs and time delays.

Costs of maintenance, repair, and replacement are aspects of risk of failure in operation, which can be handled as additions to operating costs. After being converted to common (mass or dollar) units, they are summed and subtracted from operating benefits. By equation (2) the revised operating benefit will result in a (generally lower) "effective mass payback ratio" MPR^*.

Panel Evaluation Procedure

Three kinds of input were determined by evaluation panels: acquisition costs, technology readiness ratings, and operational risk estimates. Since these inputs play a crucial role in the outcome of the evaluations, they will be described in further detail at this point. Almost all the data were generated at a week's meeting, held in La Jolla, California, July 5-10, 1987.

One panel of from three to five persons was chosen for each configuration. Each panel included one or two technical experts on the particular configuration. The remaining panel members, including the panel chairman, were experts on other facets of space travel, or were technical generalists. Care was taken to balance areas of expertise to include engineering knowledge and some experience with costs, and to preclude advocates from dominating the decisions.

Table 1 lists technology readiness levels that were used as a basis for the ratings. The definitions are those used by NASA's Office of Aeronautics, Exploration, and Technology (OAET).

Each panel was asked, at the outset, to undertake the following:

- determine the level of readiness, L, of the advanced technology of concern to the panel;
- judge the time, Δt, required to advance the level of readiness, one step at a time, all the way to full operational capability; and
- estimate the cost, R, associated with each step, expressed in units of the final (routine) acquisition cost. In this fashion, the question of complexity was finessed.

The results of this preliminary evaluation step are summarized in Fig. 3 for the cost, expressed as an acquisition cost multiplier R, and in Fig. 4 for the time delay Δt, in years. Although there was the expected scatter of estimates in Fig. 3, some common features emerged. None of the technologies was judged to be of level lower than 3. In almost all cases, the cost per step tended

TABLE 1. Technology readiness levels.

Level 1:	Basic principles observed and reported
Level 2:	Conceptual design formulated
Level 3:	Conceptual design tested analytically or experimentally
Level 4:	Critical function/characteristic demonstration
Level 5:	Component/breadboard tested in relevant environment
Level 6:	Prototype/engineering model tested in relevant environment
Level 7:	Engineering model tested in space
Level 8:	Full operational capability

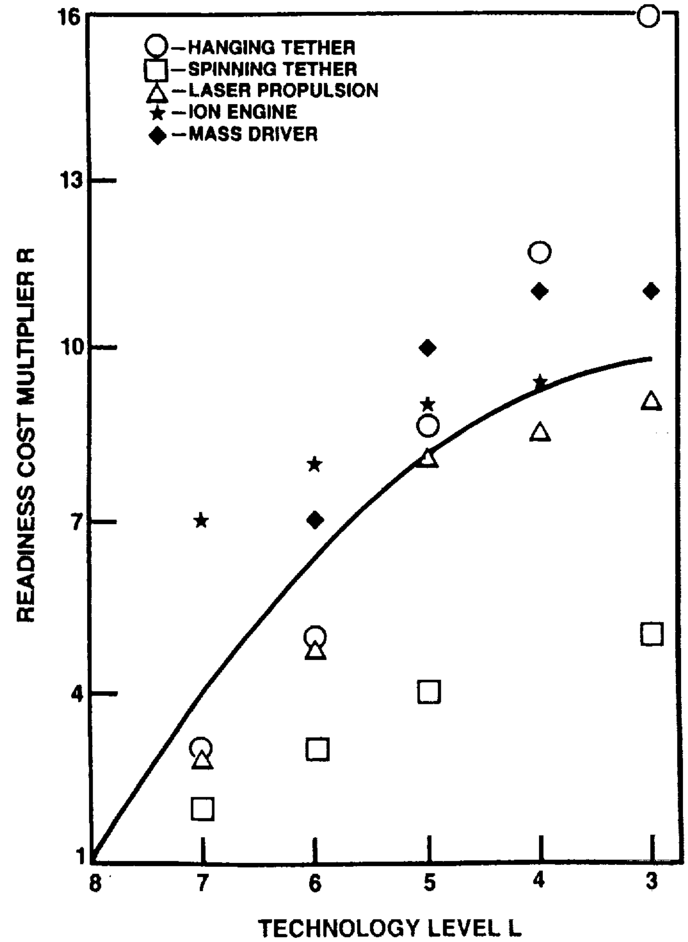

Fig. 3. Technology development cost as function of readiness. The points were obtained from the evaluation panels dealing with five separate technologies. The smooth curve was used as a resulting mean functional relationship.

to increase with increasing level. This is in agreement with the experience that costs escalate as one proceeds from research to development, to prototype laboratory testing, to demonstration. Since the points tended to cluster markedly (except for those of the spinning tether, which were later judged to be too optimistically low), a smooth "eyeball" curve was used as the multiplier for all advanced technologies. The Δt values in Fig. 4 clustered more convincingly about a straight line, which was again used for all technologies. The long delay times for levels 5 and below indicate a high perceived degree of complexity.

Finally, acquisition costs and risks of operation were assigned to each component. Here the judgment of an experienced space engineer on each panel played the key role, since many of the parameters had to be estimated by analogy to present systems and practice. The acquisition cost was intended to reflect the expected "routine" cost of procurement, net of the initial research, development, demonstration, and learning expenditures. Risk of operation was represented in terms of mean expected frequency of replacement or repair, and fraction of total component mass (and dollar value) to be replaced during each repair. For example, it was assumed that in the reference configuration the aerobrake would have to be replaced after 10 missions, but somewhat less frequently in the spinning tether configuration, where it is used to mediate a smaller ΔV.

Model Format

The Evaluation Model was developed on a spreadsheet using the 20/20 (™Access Technology Inc.) software available on UCSD's VAX/VMS operating system. Table 2 displays the input-output section of a run, in this instance, the reference case. Five parameters are inputs from the Transportation Model: MPR, the mass payback ratio based on steady-state payload transportation cost only, here of value 1.31; C_0, the LLOX production required per tonne of payload placed in LEO; C_{10}, the amount of payload put into LEO per OTV round trip; $M_{OTV,F}$, the mass of a fully loaded OTV (as on departure from low lunar orbit toward LEO); and the number of lunar lander trips per OTV trip.

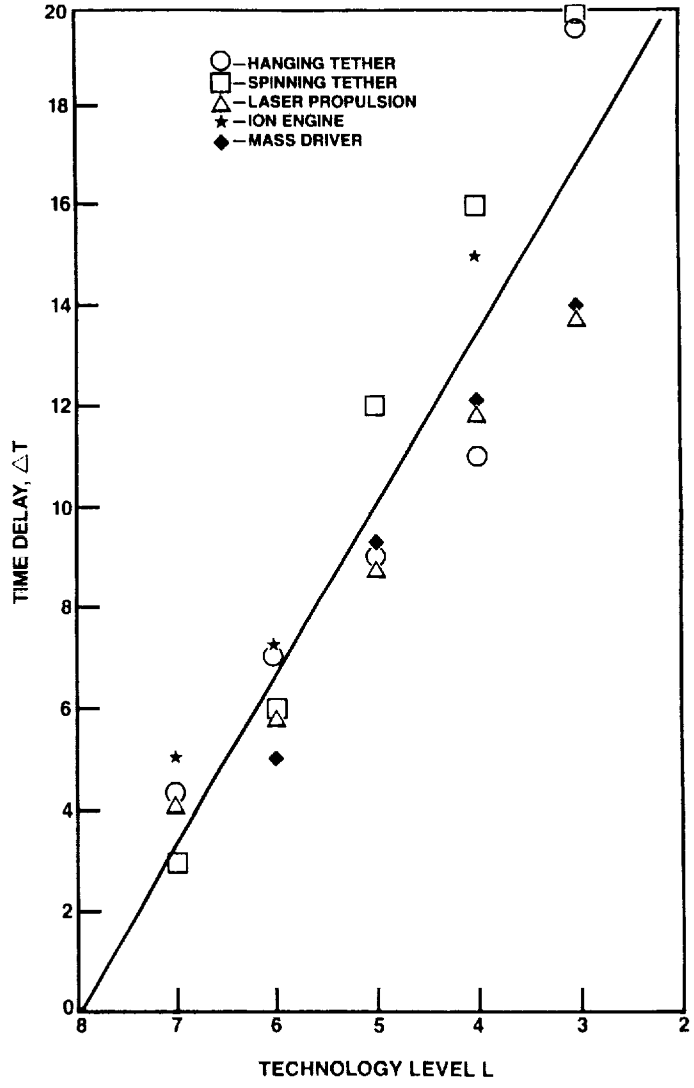

Fig. 4. Technology development time as function of readiness. As in Fig. 3, the points were obtained from the evaluation panels, and the smooth curve represents the adopted functional relationship.

TABLE 2. Input-output section of an evaluation run for the reference configuration.

A	B	C
1		
2	Reference case	Config 0
3		
4		Date: 03-28-88
5		Time: 11:44:40
6		
7	Final results	
8		
9	Operating benefit	-601.398
10	Effective mass payback ratio, MPR^*	0.454
11	Incremental capital cost	10755.518
12	Payback time	-11.541
13	Internal rate of return	No Return
14	Corrected LLOX production per LEO T	6.765
15	Corrected LPD into LEO per OTV trip	14.864
16		
17	Parameters from Transportation Model	
18		
19	Mass payback ratio, MPR	1.310
20	LLOX production per LEO T, C_0	6.130
21	LPD into LEO per OTV trip, C_{10}	16.187
22	Mass of loaded OTV, $M_{OTV,F}$	59.236
23	LL trips per OTV trip	7.260
24		
25	Additional parameters	
26		
27	Annual payload mass to LEO, C_s	500.000
28	Cost of 1 T from Earth to LEO, $\$\$_0$	3.000
29	Interest rate, r	0.080
30	Maximum time delay, Δt	13.600
31	F(r)	0.478
32		

This section shows the main inputs, either assumed or obtained from the Transportation Model, and the main aggregate outputs of the Evaluation Model. Three other input parameters can be chosen at will: (1) C_s, the annual payload mass to be emplaced in LEO; (2) $\$\$_0$, the cost (in M$) of bringing 1 T of mass from Earth to LEO; and (3) r, the interest or discount rate. Δt, the maximum time required for implementation of any component of the configuration, is based on the minimum value of L, as supplied by the evaluation panel (see Fig. 4); it is an estimate of how long it takes to implement the configuration. F(r) is a calculated result which, when multiplied by the maximum Δt, approximates the effective time at which all the development investment can be committed as a lump sum to account for the time value of money.

Seven output results are listed: (1) the operating benefit, (2) MPR^*, the effective mass payback ratio, corrected to include repair costs, (3) the capital cost for the configuration (in T), (4) the payback time, (5) the internal rate of return, (6) the LLOX production required per T of payload corrected for repair, and (7) the corrected amount of payload put into LEO per OTV round trip.

ILLUSTRATIVE RESULTS

We illustrate the evaluation procedure by presenting results for the reference case and for the spinning tether in eccentric Earth orbit. The illustrations demonstrate how the calculations are performed and what kind of flexibility is available for sensitivity analysis and trade studies.

Reference Configuration

Turning first to a discussion of operating costs, the Transportation Model yields an MPR of 1.31. With C_s = 500 T/yr, equation (2) then leads to an annual transportation operating benefit of 118 T (of mass that need not be launched from Earth). From this operating benefit must be subtracted the three yearly repair cost components: the acquisition cost of the repair and replacement parts, the direct transportation cost of lofting their masses to their assigned destinations, and the indirect (opportunity) cost of transporting them.

Table 2 shows the effects of these corrections. The net operating benefit changes precipitously, from +118 T/yr to -601 T/yr, yielding an MPR^* of only 0.454, a negative payback time (i.e., longer than ∞ at an 8% discount rate), and no internal rate of return. Less dramatically, LLOX production required per tonne of delivered payload increases from 6.13 T (C20) to 6.77 T (C14), and load delivered per OTV round trip decreases from 16.19 T (C21) to 14.86 T (C15).

From the complete spreadsheet (found in *Stern*, 1989, and not reproduced here) one learns that repair of the lunar lander alone accounts for over 80% of the total repair cost, based on the repair estimates provided by the evaluation panel for the reference case. These estimates indicate that the five major components of the vehicle must be replaced every 20-30 round trips. Since the lunar lander contributes only about 2 T to the payload for every sortie, 250 sorties per year must be carried out, requiring replacement of the entire vehicle about 10 times annually! Moreover, it can easily be shown that most of this cost (about 90%) is due to acquisition rather than transportation.

Figure 5 examines the repair assumptions. Curve (a) shows how MPR^* would change if all costs per repair incident were multiplied by a uniform factor varying from 0 (no repair cost) to 2 (twice as much cost as in the standard case). The economics of the reference case are evidently very sensitive to this component of the operating cost. For comparison, curve (b) shows to what extent the sensitivity of MPR^* to repair is reduced if lunar lander repair needs are first scaled down by a factor of 10, before the multiplier on the abscissa is applied.

In sum, much of the operating cost is due to lunar lander repair. It will therefore be necessary to take a closer look at the repair assumptions. This will reveal (1) whether they are realistically based on past experience and (2) whether they could be substantially reduced by additional research and development, leading to the utilization of new materials and/or better design. If neither is feasible, service requirements will severely circumscribe the vehicle's routine operation. This in turn may greatly inhibit the establishment and operation of the lunar base and the beneficial exploitation of the Moon itself.

Turning now to a discussion of capital cost, it should be pointed out that even if the mass payback ratio MPR^* approached ∞, giving an annual operating benefit of 500 T for the case of C_s = 500 T/yr, there would be no net return on investment over 20 years for Configuration 0, since, from Table 2, the capital cost is over 10,000 T (location C11 in the table). That fact, combined with the mission objective (chosen to permit ready and meaningful comparison between configurations rather than to represent a realistic national or private-enterprise goal), dictates the form taken by the benefit-cost analysis. That is, long-run payoffs resulting from establishing a LEO-Moon transportation system are taken as a given in this study, and are not quantified in the evaluation procedure.

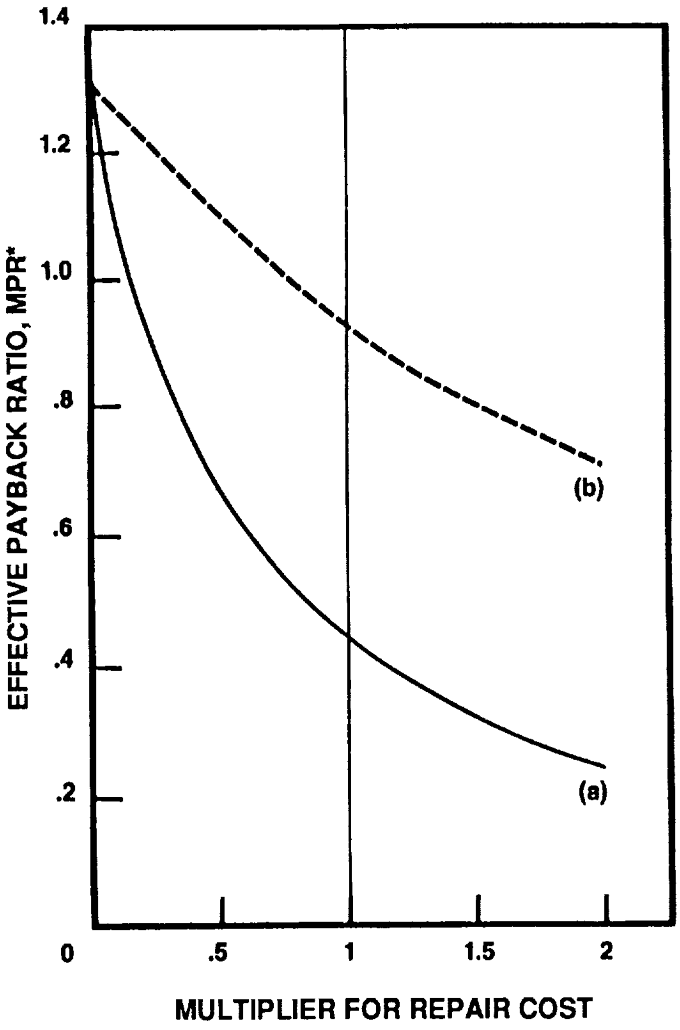

Fig. 5. Impact of repair costs on MPR* for the reference case. Curve **(a)** is obtained by multiplying all repair entries in the spreadsheet by a factor that varies from 0 to 2. Curve **(b)** results when the repair entries for the lunar lander are first reduced tenfold before the factor is applied.

Examination of capital cost components in the complete spreadsheet reveal the following: The stations in LEO and LLO are the major cost items, while the lunar oxygen plant and the two vehicles make only a minor contribution to the total. Moreover, an Evaluation Model in which all technology readiness factors R were set to 1 and all development delays to 0 gives a much-reduced capital cost of ~1870 T. This corresponds to about \$5.6 billion (with $\$\$_0 = M\$3$), which seems reasonable for a complete LEO-Moon "routine version" transporation system. The difference of some \$26 billion should be taken as a first-cut estimate of the cost of bringing the first version of such a system to the implementation stage.

The total capital cost of Configuration 0 is quite insensitive to the assumed value of $\$\$_0$, the dollar cost of transporting 1 T from Earth to LEO, over a range of from \$1 million to \$10 million. It remains at about \$32 billion, with only a slight rise near the high end of the range. This indicates that capital cost is dominated by acquisition cost, not transportation cost. As already mentioned, even for the relatively "state-of-the-art" reference configuration, the development cost dominates the routine acquisition cost by a factor of about 6; the sum of these two components constitutes 90% of the total capital cost, transportation only 10%.

Spinning Tether

Outputs from the Evaluation Model for the spinning tether in eccentric Earth orbit (Configuration 3) are presented in Table 3. In this case, the Transportation-Model-derived MPR (C19) is 3.10, corresponding to an uncorrected annual operating benefit of 338.7 T [see equation (2)]. Repair and replacement costs reduce the benefit by 393.4 T/yr to a net annual loss of 54.7 T, so that the effective mass payback ratio MPR* (C10) becomes 0.90. The degradation of benefit due to repair is almost halved compared to that in the reference case. As already stated in connection with Configuration 0, the low value for MPR* is not in itself very significant in our evaluation.

What is significant is the economic position of Configuration 3 relative to Configuration 0. This is indicated by the operating benefit (C9) of 546.7 T/yr and the incremental capital cost (C11) of 2054 T. Both entries are obtained by taking the difference between corresponding values for the two configurations to be compared. A life-cycle analysis performed by the Evaluation Model indicates that a payback time of 4.6 years or an internal rate of return of 26% can be realized by replacing the reference case by one including a spinning tether in eccentric Earth orbit, even though considerably more development is needed to bring the latter to maturity.

TABLE 3. Input-output section of evaluation spreadsheet for the spinning tether configuration.

A	B	C
1		
2	Spinning tether in EEO	Config 3
3		
4		Date:03-28-88
5		Time:11:49:18
6		
7	Final results	
8		
9	Operating benefit	546.696
10	Effective mass payback ratio, MPR*	0.901
11	Incremental capital cost	2054.477
12	Payback time	4.646
13	Internal rate of return	0.264
14	Corrected LLOX production per LEO T	2.891
15	Corrected LPD into LEO per OTV trip	29.640
16		
17	Parameters from Transportation Model	
18		
19	Mass payback ratio, MPR	3.100
20	LLOX production per LEO T, C_0	2.820
21	LPD into LEO per OTV Trip, C_{10}	30.193
22	Mass of loaded OTV Trip, $M_{OTV,F}$	59,222
23	LL trips per OTV trip	7.260
24		
25	Additional parameters	
26		
27	Annual payload mass to LEO, C_s	500.000
28	Cost of 1 from Earth to LEO, $\$\$_0$	3.000
29	Interest rate, r	0.080
30	Maximum time delay, Δt	17.000
31	F(r)	0.478
32		

The savings for the spinning tether come about because of the reduced fuel load. There are two reasons for this. In the first place, the ΔV that must be supplied by propellant is much reduced, resulting in greater payloads and fewer trips. Equally important, the fewer trips per year lead to smaller repair and replacement needs. For example, lunar lander maintenance requires 604 T/yr in the reference case, but only 301 T/yr in Configuration 3, leading to a mass savings of 303 T/yr, which contributes powerfully to the operating benefit.

CONCLUSIONS

Eight conclusions so far derived from the evaluation procedure described in this paper are enumerated below. The first five flow from the discussion in the paper; for the remainder, the reader is referred to *Stern* (1989).

1. The evaluation method described in this paper permits an objective comparison, based on economic criteria, of the performance of different space systems designed to accomplish a given objective. Here, the method was applied to transporting materials between LEO and the Moon, using either a relatively conventional reference transportation system, or various departures from it incorporating one advanced technology at a time. The method is equally applicable to "hybrid" systems combining several advanced technologies, to transportation systems linking the Earth and other planets or objects in space, or to objectives other than transportation. It is sufficiently flexible and modular to permit extensive "what-if" analyses; it is also helpful in pinpointing high-payoff R&D efforts.
2. Mass payback ratio, as commonly used in space-related studies, is of very limited value as an indicator of good transportation performance, unless reduction of Earth launch mass is the primary objective of the project under consideration, and capital cost is of secondary importance.
3. In our study, the limiting cost for all configurations is their enormous acquisition cost (rather than the launch or transportation cost), especially when research, development, testing, and demonstration costs are taken into account.
4. The cost to repair and replace vehicle and station components must be brought down by almost an order of magnitude if colonization and exploitation of the Moon is to become a reality. This conclusion is independent of configuration, based on those evaluated so far.
5. The spinning tether in eccentric Earth orbit and with the ability to both catch and throw loads or vehicles compares favorably with the reference configuration.
6. Several other advanced configurations, using hanging or spinning tethers, laser propulsion, and mass drivers for lunar launch, also look promising and deserve further investigation.
7. Ion-engine-powered vehicles are somewhat limited for Earth-Moon transport because of their low thrust. Because of their high I_{sp}, however, they may have an important ancillary role to play in "hybrid" configurations. None of the latter have, so far, been evaluated, nor have configurations incorporating nuclear propulsion or solar power.
8. Based on this preliminary effort, it seems likely that one will be able to identify and develop superior hybrid systems combining advanced transportation technologies. These would yield not only high mass payback ratios, but such impressive overall returns as to render obsolete conventional systems based exclusively on chemical propulsion.

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REFERENCES

Arnold J. R. and Thompson W. B. (1992) Advanced propulsion for LEO-Moon transport: II. Tether configurations in the LEO-Moon system. In *The Second Conference on Lunar Bases and Space Activities of the 21st Century,* this volume.

Carroll J. A. (1985) *Guidebook for Analysis of Tether Applications.* NASA CR-178904. 47 pp.

Chilton F., Hibbs B., Kolm H., O'Neill G. K., and Phillips J. (1977) Electromagnetic Mars drivers. *Prog. Aeronaut. Astronaut., 57,* 37-61.

Columbo G., Gaposchkin E. M., and Grossi M. D. (1975) The "Skyhook"—A shuttle-borne tool for low-orbital-altitude research. *Meccanica, 10,* 3-20.

Henley H. W. (1992) Advanced propulsion for LEO-Moon transport: III. Transportation model. In *The Second Conference on Lunar Bases and Space Activities of the 21st Century,* this volume.

Isaacs J. D., Vine A. C., Bradner H., and Backus G. E. (1966) Satellite elongated into a true skyhook. *Science, 151,* 682.

Kantrowitz A. R. (1972) Propulsion to orbit by ground-based lasers. *Astronaut. Aeronaut., 10,* 74-76.

Penzo P. (1987) A low Earth orbit skyhook tether transportation system. AAS 87-436, presented at the AAS/AIAA Astrodynamics Specialist Conference, Kalispell, Montana, August 10-13, 1987.

Stern M. O. (1989) *Advanced Propulsion for LEO-Moon Transport—Final Report.* NASA CR-172084.

Langmuir D., Stuhlinger E., and Sellen J. M. Jr. (1961) *Electrostatic Propulsion,* Vol. 5 of *Progress in Astronautics and Rocketry.* Academic, New York. 579 pp.