TRANSPORTATION ECONOMICS OF EXTRATERRESTRIAL RESOURCE UTILIZATION

Andrew Hall Cutler
A-021
California Space Institute
University of California at San Diego
La Jolla, California 92093
(619) 452-6044 or 4798

Mari Leilani Hughes
CSR Consulting
P.O. Box 203106
San Diego, California 92120
(619) 284-3760

Abstract

It is assumed that the utilization of space shuttle external tanks as an extraterrestrial resource is economical, as it would be ridiculous to discuss the use of lunar or asteroidal resources if this were not true. Due to the restricted composition and limited nature of this resource, the exploitation of lunar and asteroidal resources is worthy of consideration. Several conclusions can be drawn from a consideration of the economics of mining the moon and asteroids. It is shown that production of lunar oxygen or steel for use in LEO is economically justified in the near future, and is superior to the use of asteroidal resources. Production of lunar hydrogen, if feasible, is not desirable from an economic standpoint until a lunar oxygen producing facility is on line and delivering oxygen to LEO. In determining economic feasibility high mass payback ratios are not particularly important. Low initial capital investment is important. Thus steel for uses such as SDI is a more economical product than oxygen for propulsive or other uses. It is found that optimizing and comparing selected physical parameters such as delta V or I_{sp} does not in general lead to the most economical system. Two major questions are identified which have a major impact on extraterrestrial materials utilization econmics. These are the minimum acheivable ratios of dry mass to loaded mass for the transport vehicles, and the ability to manufacture at the mine mouth. Dry to fully loaded vehicle mass ratios must be less than 6% or so if there is any hope for economical transportation. The ability to perform manufacturing at the mine mouth is probably dependent on human presence for repair.

Introduction

Motivation When studying the economics of extraterrestrial resource utilization the question of which products to manufacture and which inputs to the manufacturing process to import are considered differently than in an engineering systems study. An engineer is concerned with designing a system that works and then with making it more efficient. We are concerned with taking a scientifically possible system and making it economically feasible. This paper will deal with the manufacturing scenario only as it relates to the economic factors of breakeven point (payback period), internal rate of return and mass payback ratio.

The purpose of this work is to understand the economic constraints faced when attempting to design a scheme for extraterrestrial resource utilization which could be economically viable as a private endeavor. These constraints must be understood in order to direct research and reserch policy in fruitful directions. This paper is an attempt to understand and develop a methodology for evaluating the economic feasibility and desirability of various schemes for extraterrestrial materials processing. A standardized methodology to do this is needed to understand the relative merits of varoius proposed schemes and research projects.

Resources Extraterrestrial resources are materials in space which may be used to acheive a desired end or to construct a desired item more economically than can be done using terrestrially derived materials. The moon, near earth asteroids and the moons of mars are typically considered to be possible extraterrestrial resources. Defunct satellites, spent upper stages and space shuttle external tanks may also be considered to be extraterrestrial resources. While the extent of man made resources is far less than that of the natural resources, the man made resources are often far more accessible and far closer to finished form.

For example, there is a large family of asteroids which take zero delta V to reach, have a round trip flight time of minutes, and are exactly where you want them. In addition to this they are composed of liquid hydrogen, liquid oxygen and various aluminum minerals of great engineering utility. A new one is created every time there is a space shuttle launch. These asteroids go by the collective name of "external tanks". Any serious discussion of the economical delivery of products derived from lunar and asteroidal resources to LEO presupposes that the external tanks are being utilized. If it is uneconomical to utilize external tanks, the present authors do not believe there is any sense in discussing less accesible resources which require far more processing to acheive final form as well. With this caveat, external tank utilization will be ommitted from the discussion that follows.

Most economies rest upon the wasteful use of large amounts of inexpensive resources. Materials such as gravel (which would seem of limited utility) are of tremendous importance to any economy. The foundations of factories, homes and roads are laid in gravel and gravel containing concrete. The cost of gravel is the basic determiner of the cost of most goods and services. Using the superior engineering properties of concrete or steel where gravel will do leads to a more attractive engineering system, but to a more costly product. Hauling the gravel from the next county rather than digging a local gravel pit also leads to a costly product. Gravel can profitably be used to make items of fairly low value, while only higher value items can be made from concrete or steel.

For most materials launched into space, cost is proportional to mass, and the proportionality constant is large. The lack of cheap materials seriously retards the growth of the space economy. There are a tremendous number of tasks which cannot be performed profitably due to the uniform high (payload launch) costs of all materials. The role of extraterrestrial resources is to provide an economical foundation of cheap, unsophisticated material on which the space economy can rest. Space operations actually use substantial amounts of unsophisticated materials (e. g. propellants, sheet metal). Since these are expensive to launch into space, space operations are inherently expensive. Using local materials to lower the cost of simple materials makes sense and may also make a profit.

Launch costs dictate that high demand materials such as propellant be manufactured from local resources while the low mass components such as instruments, electronics and engines continue to be imported. Extraterrestrial resources can provide certain unsophisicated materials cheaply. These cheap materials plus their transportation costs determine the base cost of doing things in space, and are the intrinsic limit on the scale of human activities in space. Thus, as in the terrestrial economy, unsophisticated materials should be maufactured as close to the point of use as possible, while the more sophisticated and expensive systems components may be transported long distances without having an adverse impact on system economy.

The use of local resources early in the exploration and exploitation of new frontiers is not new. In the 1500's Balboa and Cabrillo found it easier to sail to Panama, walk across the Isthmus, and build new ships to explore the Pacific coast of America than to sail around Tierra del Fuego. Space resource utilization extends this tradition of using local materials to explore and exploit our new frontiers.

Discussion

Cost Variables There are two figures of merit for the operating costs of a lunar resource utilization scheme. One is the Mass Payback Ratio (MPR), which is pertinent when the product is used by itself at its final destination. Steel plate would be such a product. The MPR is given by:

$$\text{MPR} = \frac{\text{product at LEO}}{\text{fuel \& expendables at LEO}} \qquad [1]$$

MPR as defined in this study only accounts for operating costs, and is unaffected by capital costs. A second figure of merit is the Effective Propellant Multiplier (EPM), which is pertinent for the use of propellant oxygen. Since propellant oxygen must be combusted with terrestrial hydrogen fuel, some hydrogen is consumed running the transportation loop and some is consumed in using the oxygen. All of this hydrogen must be accounted for in calculating the effective payback of the system. EPM is given by:

$$\text{EMP} = \frac{\text{MPR} + \frac{\text{MPR}}{\text{O/F}}}{1 + \frac{\text{MPR}}{\text{O/F}}} \qquad [2]$$

where O/F is the oxidizer to fuel ratio of the engine burning the lunar derived oxygen. Figure I shows the relation of MPR to EPM. It is seen that EPM is not particularly sensitive to MPR. Another way to view this data is as the amount of hydrogen which must be imported as a,fraction of the total LEO propellant consumption exclusive of that used to run the oxygen delivery system. This is shown in figure II.

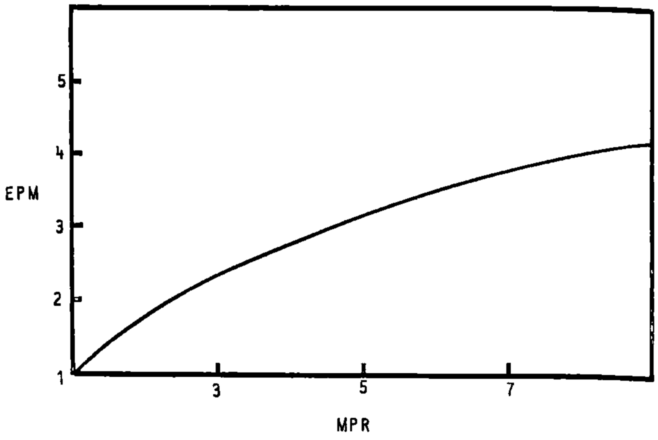

Figure I. EPM versus MPR.

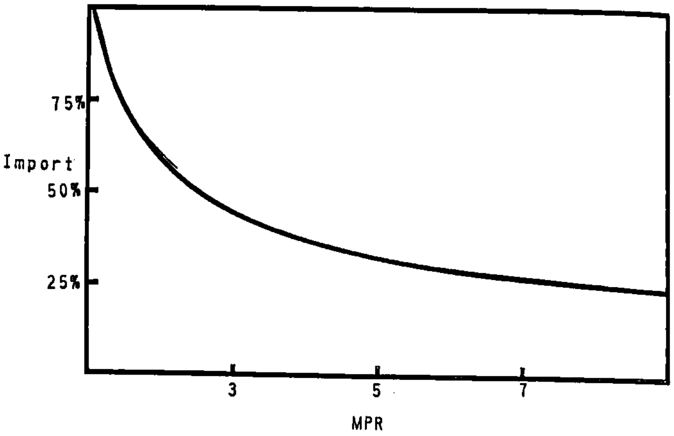

Figure II. The percentage of the total available propellant which must be imported from earth to provide OTV fuel and fuel to return oxygen from the moon versus MPR.

There is a figure of merit describing the capital costs of an extraterrestrial resource utilization system. This is the payback time (PBT). Using the assumption that cost is proportional to mass, this is the time it takes the system to return as much mass to the destination as would have been delivered there if all of the launches to emplace it and operate the transportation system had been used to deliver product instead. This is given by:

$$\text{PBT} = \left(1 + \frac{T_r}{P_1}\right) \left(\frac{\text{MPR}}{\text{MPR}-1}\right) \div U \div O_r \qquad [3]$$

where Tr is the total mass of the emplacement transportation in LEO, Pl is the plant mass, U is the fraction of plant output usefully delivered to the destination and Or is the ratio of plant output mass to plant mass per unit time. The term 1 + Tr/Pl is the mass ratio to reach the site of emplacement for zero tankage vehicles. It is typically 4 to 5 for emplacement of lunar factories.

Economic impact studies vary in the formulae used to calculate costs. It is common to think of costs as a function of the sum of fixed and variable costs or to express them as a function of labor, materials and land. When studying the cost effectiveness of large scale engineering systems, the preferred method is to calculate costs for each phase of the project as in

$$C_e = f(R,A,S,O) \qquad [4]$$

where C_1 is the cost of lunar derived oxygen, R is the total R&D costs, A is the total cost to administer the program, S is the total startup cost, or the cost of emplacing the first lunar factory and O is the cost of operating the factory in a steady state environment.

In order for any scheme of extraterrestrial resource utilization to be economical, C_1 must be less than C_e, where C_e is the cost of earth derived product. The unit cost of earth derived oxygen is well known sice it is merely the cost of procuring the oxygen and shippint it to LEO. Expressed as a formula, this cost is

$$\bar{C}_e = \frac{L}{n_1} + P_n \qquad [5]$$

where $\bar{C}_e$ is the unit cost of earth derived oxygen, L is the cost of a launch, n_1 is the number of units of oxygen launched and P_n is the cost of procuring one unit of oxygen.

In order for any extraterrestrial resource utilization scenario to be economic, the unit cost of extraterrestrial product must be less than the cost of launching that same product from earth. Since we are not concerned with actual cost, but with relative cost, $\bar{C}_e$ is arbitrarily set to 1. Then, for comparison purposes, equation 4 is altered to express unit costs as shown below:

$$\bar{C}_1 = \frac{\left(\frac{R+A+S}{p} + \sum_{i=1}^{p} O \right)}{n_p} \qquad [6]$$

where p is the amortization period and n_p is the number of units of oxygen produced during that period.

For the purposes of this study, equation 6 may be simplified even further by examining each intermediate component. Our scenario minimizes the use of new technologies and maximizes inheritance from present systems. This makes it easier to understand since R&D costs are the most difficult to understand and predict accurately. We also postulate a scenario where R&D costs for the technically risky part of the system (plants to produce oxygen from lunar minerals) is covered by the government. When cost, development time and performance uncertainties are reduced to an acceptable level by government sponsored basic research, private investors will enter the picture. In this case R&D costs charged to the firm involved in extraterrestrial resource exploitation are minimal. Expressed as a range, this is

$$T_r \leq R \geq 0 \qquad [7]$$

where T_R is some yet to be specified total R&D cost.

Administrative costs for large scale engineering systems are more accurately expressed as a percentage of total systems costs. They are not overly sensitive to individual system parameters such as type of propellant or mass of the lunar factory. Therefore in a consideration of relative costs, administrative costs factor out

Start up costs in a system dominated by launch costs such as ours may be expressed as a total mass of the materials to be emplaced to get to a steady state times a cost multiplier constant:

$$S = (m_f + m_{en} + m_{1n}) \times k \qquad [8]$$

where m_f is the mass of the lunar factory, m_{en} is the mass of the LEO orbiting node, m_{1n} is the mass of the lunar orbiting node and k is the cost multiplier. If the LEO orbiting node is the space station, inheritance causes m_{en} to be small or zero.

Operations costs are the cost of running the factory including the cost of delivering the inputs to the lunar surface. A relative measure of operations cost is a function of MPR. Specifically:

$$O = \left(\frac{1}{MPR}\right) \times K \qquad [9]$$

where K is a cost multiplier.

The effect of this treatment (equations 6-9) of the individual cost factors is to define the lower bounds of the unit cost figure as:

$$\frac{1}{MPR} + \frac{m_f + m_{1n}}{n_p} \leq \bar{C}_1 \geq \frac{1}{MPR} \qquad [10]$$

with the upper bound of unit cost being

$$\frac{1}{MPR} + \frac{T_r + \frac{k'}{C_1} + ((m_f + m_{1n} + m_{en}) \times k)}{n_p} \leq \bar{C}_1 \geq \frac{1}{MPR} + \frac{m_f + m_{1n}}{n_p} \qquad [11]$$

where k′ is the administrative cost factor and k is the emplacement mass cost factor.

MPR′s are calculated for each scenario and described below. Start up costs (equation 8) are considered as a part of the payback time calculation.

EPM describes the maximum reduction in operating cost obtainable if the product delivered is liquid oxygen for use as orbit raising propellant. It can be substituted for MPR in the above formulae when condisering the cost of a unit amount of propellant which is composed of terrestrial fuel and extraterrestrial oxygen.

Background The economics of delivering lunar manufactures to LEO has been studied[1]. There have been a large number of studies relating to large scale systems using many new and novel technologies which demonstrate the desirability of space resource based economy[2]. We will discuss the studies which were restricted to currently available and near term technology, and to product demands reasonably matched to the current level of space activities. These studies and the present work can be used to estimate the cost of delivery of lunar derived materials to LEO in the near term[3]. These studies have considered both monetary and physical economics. The physical economic studies describe plant masses, numbers of flights and amounts of material which must be delivered to various places to get a desired amount of material to its destination. These physical economic studies have proven to be more readily interpretable than monetary economic studies. They are also trivially adaptable to variations in assumed earth to LEO launch costs.

Some study results are given in tabular form below[1]:

Study	MPR	CAPITAL
Davis	2.45	437 tons
Simon _et al._	about 3	70 tons
Cutler and Krag[4]	----	80 tons
Cutler	about 3	-------
Frisbee and Jones	2-4	-------

As can be seen, there is substantial variation in the estimates of capital investment. Thus the actual manufacture of oxygen on the lunar surface requires further research to remove technical uncertainty. MPR's are all similar, indicating that these authors perceive an MPR of about 3 as being adequate to make the system arguably economical and hence worthy of study. Since these three studies used significantly different groundrules, direct comparison is difficult.

A number of conclusions can be drawn from the studies described above. One obvious one is that aerobraking is an extremely desirable technology. Economical delivery of lunar materials to LEO is unlikely without it. Economical delivery of martain or asteroidal materials is not economically feasible without aerobraking under any circumstances likely to hold within the next 50 to 100 years. One interesting aspect of aerobraking is that it is easier to deliver materials to low orbits than to high ones. While the relative difficulty is constant or mildly decreasing as the destination altitiude is increased, the absolute cost per unit mass of material increases with altitude. This means that the absolute cost per unit mass of material increases as altitude increases. Thus extraterrestrial products must be intrinsically more valuable to be sold in higher orbit than they have to be to be sold in lower orbit. Manufacturing systems are typically cheaper per unit material as their total output increases, and preliminary studies indicate this will be the case for startup scale extraterrestrial resource utilization schemes. Delivery of products to low orbit is likely to be economically feasible long before delivery of products to high orbit is. Propulsive braking at perigee for lunar materials delivery becomes cheaper than aerobraking at altitudes over 24,400 kilometers. Delivery costs decrease as altitude increases above this point. Delivery costs to orbits such as geostationary orbit are still much higher than delivery costs to LEO.

Transportation cost is strongly dependent on the fraction of the propellant used for the moon to earth trip which is lunar derived. In general, costs go down as this fraction is increased, even if performance is significantly degraded[6]. Thus partially or fully lunar derived fuels such as silane could significantly enhance economy. Even using current engines it is desirable to burn them somewhat leaner than for optimum I_{sp} in order to increase the performance of earth derived fuel at the expense of lunar derived oxidizer[1]. Transportation system operating costs are determined to first order by the need for fuel on the moon.

Relatively small changes in vehicle dry mass, or tankage factor, can have a large effect on economy. A low order approximation to the partial sensitivity of delivered mass to tankage at constant operating cost is:

$$1 - 2M_rT$$

Operating costs at constant delivery rate go as:

$$1 + 2M_rT$$

Current NASA plans for a space based OTV are not substantially lighter than Centaur, a similar vehichle which has been available for 20 years[7].

The dry mass of most current upper stages is driven by the early need to design for high launch loads and aerodynamic forces. In addition, many systems components are grossly oversized, such as the guidance systems. We assume that "reasonable" tankage factors are below 10%. As subsequent figures show, minimizing vehicle dead weight is very desirable. The relatively mundane task of shaving every pound possible off of the transportation fleet would have significant economic benefit. This would probably have more economic benefit than expending an equal amount of money to raise engine I_{sp}. Since this exercise would be one of starting design with a clean sheet of paper rather than one of research and development leading to an advance in materials or structural engineering, the total cost, cost uncertainty and performance uncertainty are all accurately predictable. Operations in the space environment are more benign than the rather brutal launch from earth's surface that earlier stages had to endure, and there have been significant advances in materials and structural engineering in the last 20 years. Reducing tankage factors significantly should be possible without extensive R&D.

The astrodynamics of travel between the earth and moon are well known, and have some desirable aspects for resource exploitation. Round trip travel times are short, launch opportunities from a given low earth orbit recur every 9 days, and the propulsive requrements are well known and do not vary significantly. The short trip times allow the use of high performance cryogenic propellants at the destination without excessive difficulty and admit the possibility of sending people to repair seriously malfunctioning production equipment. This removes a large technical uncertainty in plant performance. Production losses due to unforseen plant failure are held to a manageable level. This one advantage makes manufacturing on the moon far more feasible than manufacturing at an asteroid or on a martian moon.

Methods Transportation economics for the delivery of lunar manufactures to LEO have been modelled by iteratively satisfying the rocket equations for various burns and maintaining a materials balance. The programs we used to do this are publically available[8]. These programs calculate steady state payback ratios and materials fluxes as a function of amount of material delivered to the destination. These steady state MPR's and fluxes can be used to describe the manufacturing and delivery system's operating costs. Capital costs are simply derived from initial plant costs and easily calculable emplacement costs. In the discussion that follows, we have assumea tnat all costs are directly attributable to the cost of launching material to LEO, this is the basic assumtion that cost is proportional to mass. Thus our cost numbers are lower bounds to the real costs. Our MPR's, PBT's and EPM's do not include interest, administrative costs, R&D, startup costs, or a variety of other costs which are real and non-negligible costs for any system.

We assume a system composed of an earth orbiting transport node (not necessarily the space station), a lunar orbiting transport node, a lunar ascent and decent vehicle, and an earth - moon round trip vehicle. A factory on the lunar surface produces oxygen for product delivery to LEO, and either oxygen or steel product for delivery to LEO.

Delta V's for lunar resource utilization are the apollo 17 delta V's as given by Davis[1]. These are summed[9], and all delta V is assumed to be met by cryogenic propellants. This introduces a very slight overestimate of MPR (about .1%) by ignoring the lower specific impulse typical of RCS propellants.

The economics of asteroidal resource utilization were studied by calculating reasonably straightforward figures of merit, and by inspecting histograms generated from known practical mission opportunities. It is obvious that asteroidal ore recovery is not economically competitive with lunar resource utilization under the assumptions used in this study. Thus further quantitative work was not pursued.

Assumptions The thrust of this study has been to examine how a commercially viable space resource utilization system could start up in the next decade or two. In addition, standard economic practice holds that the greater the desired advance in the state of the art beyond current technology, the greater the estimate of the cost of R & D, and the lower the level of confidence in any cost estimate derived. These two constraints lead to a number of assumptions. We assume that the number of new systems which must be developed has to be held to a minimum. We also assume that automated factories will not be reliable, and that manned missions to mars or an asteroid are not economically feasible in support of a space manufacturing system. This leads to the conclusion that manufacturing on the moon is feasible, while ore must be returned from the martian moons or an asteroid for processing in LEO.

We assume that there are two possible markets which can be served, and that each of them is worth a few billion dollars per year. The first market is propellant for orbit raising. Since about half of the space shuttle's launch capacity is devoted to putting upper stages in orbit, this assumption is justified. The second market is a prospective market for metal plate which would be used to protect military satellites. This market's existence depends on non-economically motivated decisions, however, if it comes to exist decisions on serving it will be driven by economic forces.

Exclusions The relatively small size of the prospective markets makes mass driver based systems uneconomical due to the relatively high emplacement costs. These costs are driven by the large mass of the mass drivers. Relatively light mass drivers (about 10 tons) used to deliver manufactured products to lunar orbit or a lagrangian point in 100+ kilogram sized installments could be a viable part of a lunar manufacturing system. The initial market will not be big enough to support larger mass drivers. Since there is no current art relating to mass drivers actually capable of doing this, substantial R & D would be required. This leads to substantial cost and performance uncertainty.

Several types of electric propulsion systems are at an advanced state, and could be used for major missions without undue investment. Power requirements are not a problem in the context of this study, since any lunar factory will require the development of multimegawatt power systems. The time value of money imposes a large penalty on the use of electric propulsion systems due to their long flight times in the earth moon system. Electric propulsion based transport systems are unlikely to be economcially viable for use in the earth-moon system, and are not considered further.

Delivery of lunar manufactures to geostationary orbit is not considered since the current and near term potential market there can be met most economically by utilizing shuttle external tanks and earth launched materials. After LEO markets are served by the exploitation of space resources the scope of activities in space will expand, the technical risk of using space resources will be diminished, and large markets may develop in GEO.

Lunar Resource Utilization MPR as a function of tankage can be calculated for an aerobraking vehicle using current and advanced hydrogen oxygen engines. This is shown in figure III. The difference in MPR for reuseable versus expendable aerobrakes is shown in figure IV. It is evident that neither advanced propulsion nor a reuseable aerobrake is necessary for economical performance. In fact neither of these enhances performance significantly. MPR's of 3 or 4 are acheivable using the RL - 10 engine and disposable aerobrakes, and these MPR's are sufficient to bring the cost of lunar manufactures to significantly below that of terrestrial products.

Varying the oxidizer to fuel ratio of the engine from that for optimal performance can increase system economy even though it decreases the specific impulse. This is illustrated in figure V. Lowering the O/F ratio reduces the amount of hydrogen burned to deliver oxygen from the lunar surface to LEO. most of the system transportation costs are related to delivering hydrogen to the lunar surface for fuel use.

The use of tethers to lower outbound delta V from LEO has a beneficial impact on system economy, but is not enabling without aerobraking. This is illustrated in figure VI. Tethers can be used to transfer impulse built up by an electric thruster to a vehicle quickly. They can thus be used to gain the benefits of electric propulsion (high specific impulse) without suffering the drawbacks (high

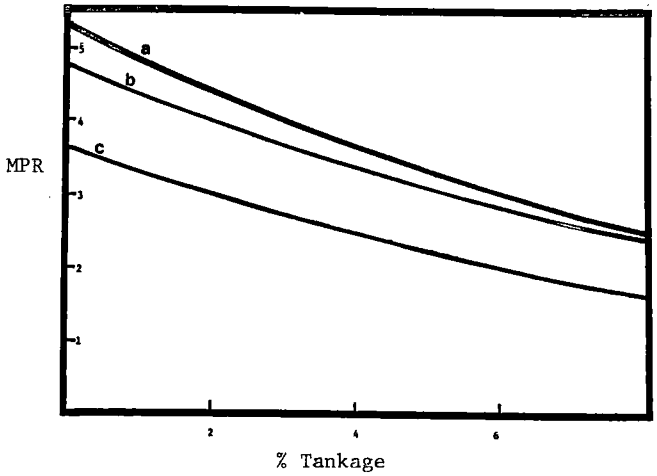

Figure III. MPR versus tankage for a lunar oxygen return scenario with a reuseable aerobrake with a mass of 5% of the braked mass. a) RL-10-II engine operated at O/F = 8.0, b) advanced space engine (I_{sp} = 483, O/F = 6.0) and c) RL-10 engine operated for maximum specific impulse (I_{sp} = 460, O/F = 5.5).

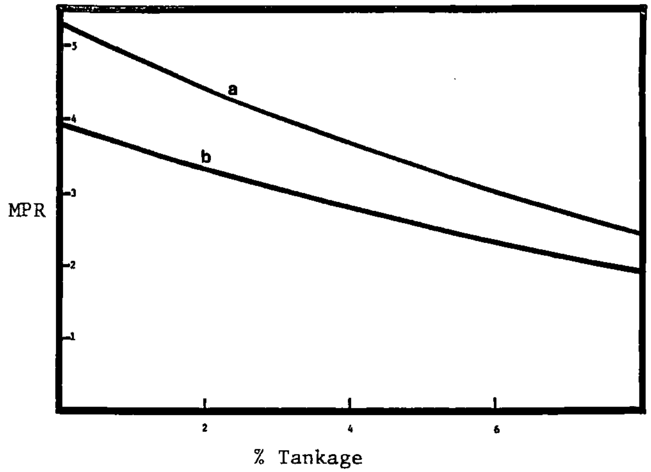

Figure IV. MPR versus tankage for a) reuseable and b) expendable aerobrakes with masses of 5% of the braked mass. Propulsion is an RL-10-II engien with O/F = 8.0, I_{sp} = 440 sec.

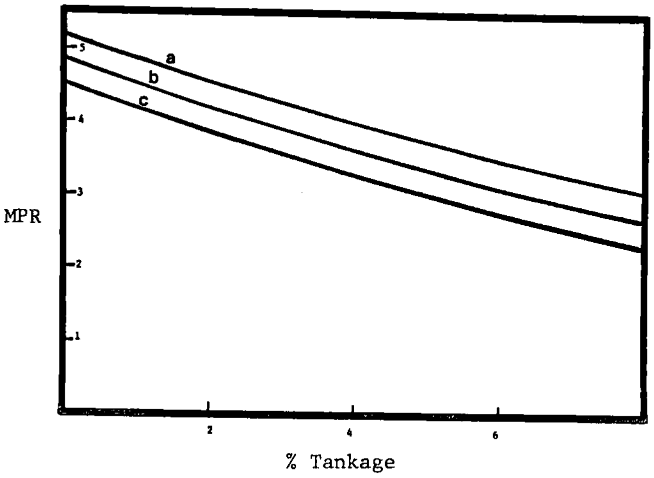

Figure V. Effects of tethered boost from LEO on MPR. A) 1200 m/s, b) 800 m/s; c) 400 m/s. An RL-10-II engine is used with O/F = 6.0, I_{sp} = 460. Aerobrake is 5% of braked mass.

system mass and the economic impact of long mission times). Tethers could conceivably be used on the lunar orbiting transport node. We did not consider this in our model, since the node must then be made relatively massive so that each tether operation does not perturb its orbit too much. This would significantly increase the capital emplacement costs, and require the development of an electric thruster using lunar derived propellant for momentum makeup. Tether operations also take longer and require a longer tether in the lunar gravity field, increasing their complexity and the risk of a micrometeoroid cutting the tether.

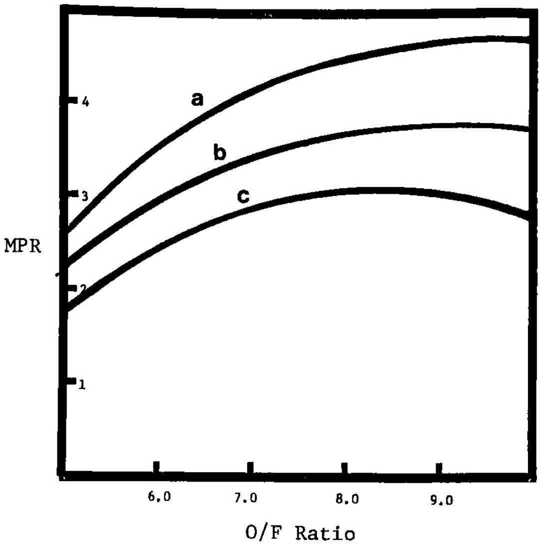

Figure VI. MPR versus O/F ratio for the RL-10-II engine with vehicles of a) 2% tankage, b) 4% tankage and c) 6% tankage. Aerobrake is 5% of braked mass.

The net mass payback times for a factory can be calculated from the ratio of factory mass to output. Estimated specific mass for the production of lunar oxygen is 80 tons of factory to produce 1000 tons per year[4]. Assuming that this factory is emplaced using expendable rockets with the same tankage as the product delivery vehicles, payback times can be generated assuming that all of the propellant comes from earth, or that the oxygen is derived from a previously installed lunar factory, and thus is bought by the investment of a smaller amount of hydrogen. These payback times are shown in figure VII for delivery of oxygen and steel to LEO[10]. The payback time for the second lunar factory is much shorter than for the first, due to the availability of lunar oxygen. Payback times for steel delivery are much shorter than for oxygen delivery. Therefore steel may be a viable product before oxygen is.

Lunar Resource Economics Money has time value since it can earn interest. Typical current time values of money are 18-20% per annum for conservative mining and primary minerals processing investments, and in excess of 30% for more speculative ventures. We must consider mining the moon a speculative venture, since prospective investors certainly will.

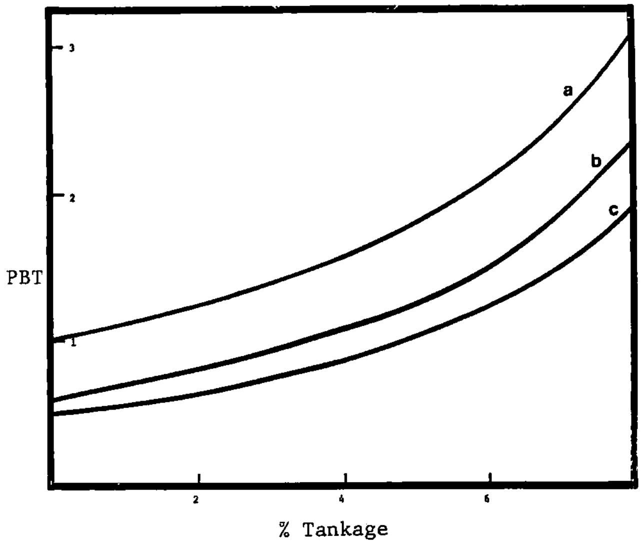

Figure VII. payback time in years versus tankage for a) a transportation loop using O/F = 8.0, emplacement vehicles using O/F = 5.5, oxygen being delivered, b) as for a, with steel being delivered, c) as for a, with the oxygen to emplace the factory being obtained from the moon at the appropriate MPR. Aerobrake is 5% of braked mass.

There are certain simple relations between interest rates and the values we have calculated above. Standard calculation of the internal rate of return is 75% divided by the payback period. This must be higher than the interest rate being paid on the capital in order to make a profit after paying the investors. We see that the payback times in figure VII lead to internal rates of return over 30%, so this investment may be feasible.

The time in years for the principal of a loan to double is about 70 divided by the interest rate. At 20-30% interest, doubling times are in the 2-3 year range. It is not feasible to begin developing essential system components more than 1 or 2 doubling times before initial product delivery commences. This means the extensive development of new technology by a private firm is not economically feasible. In fact, it means that system design, development and deployment will have to occur much faster than has happened previously in the space industry.

A clearer way to visualize costs is to consider delivery of lunar oxygen for propellant use, and look at its impact on a shuttle mission model. Assume that there is a steady state of 24 flights per year. Essentially half of these are devoted to carrying propellant. With a lunar oxygen production and delivery system, 12 flights per year can be cancelled, reducing shuttle wear and operating costs. If the EPM is about 3, four of these cancelled flights must be flown with liquid hydrogen payload to operate the system. This leaves 8 flights per year which are the "profit". In order to keep the system economical, we can only use about 3 years worth of "profit" to install it. Thus emplacing the initial factory and transportation system must be possible within the paylaod constraints of 24 shuttle flights. This can reasonably be expected to put 80-110 tons on the lunar surface.

Using the shuttle, space station and any OTV system as it exists makes use of inheritance from the large R&D expenditures which have already been sunk to develop them. Costs are reduced substantially by avoiding the up front cost and technical risk of developing new vehicles or transport nodes. For instance, an up front cost equal to about 18 shuttle flights is the maximum economic value of developing an SDV which takes 3 years to get into operation after initial R&D, and halves launch costs if the market for launch to LEO remains static in mass throughput. If it remains static in expenditure on launch to LEO (a mass throughput doubling) the allowable expenditure goes up to the equivalent of 36 shuttle flights.

The need for a high internal rate of return makes schemes such as those to extract solar wind implanted hydrogen from lunar soil to provide the fuel to send products on their way to LEO unattractive for startup, because the payback time for such a plant would be 5-10 years unless lunar oxygen were available in LEO to reduce the cost of its emplacement. In terms of shuttle flights, a lunar hydrogen factory can reduce the operating cost of the above system to 0 or 1 flights per year. From the previous discussion, a hydrogen factory must have a maximum payback time of about 3 years to be economical. Thus the value of emplacing the lunar hydrogen factory is 9-12 shuttle flights. This means the factory must have a maximum mass of 30-55 tons. It is extremely unlikely that hydrogen plant mass can be kept below 90 tons[11]. 150 tons is a more likely value. Thus the hydrogen factory must await the availability of lunar oxygen in LEO before it is viable. With lunar oxygen available, 110-150 tons of factory can be emplaced on the lunar surface and have a payback time of 3 years.

<u>Asteroid Accessibility</u> Actual mission opportunities to near earth asteroids have been calculated over the next 25 years[12]. These can be used to make a qualitative statistical study of near earth asteroid accessibility in concrete terms. Figure VIII shows a histogram of number of mission opportunities versus delta V to go to near earth asteroids, and figure IX shows a similar histogram for return from these asteroids. These figures make asteroids look like a far more accesible resource than the moon.

The time value of money makes the asteroids further away than the delta V's indicate. Propellant mass and interest are both costs, and both are exponential. This leads to a relation between the cost of flight time and the cost of delta V as follows:

$$e^{it} = e^{\frac{\Delta V}{I_{sp}\cdot g}} \qquad [12]$$

where i is the interest rate, t is the time of flight, and g is the acceleration due to gravity. The following table illustrates the delta V equivalent of 1 day for various specific impulses and interest rates.

Isp, seconds	320	450	490
	Velocity equivalent of 1 day in meters per second		
i, percent			
8	.69	.97	1.05
16	1.38	1.94	2.10
24	2.07	2.91	3.15
32	2.76	3.88	4.20

Histograms of equivalent delta V's for 8, 16 and 24% are shown in figures X-XII for travel to near earth asteroids. The time is traded off against the cryogenic propulsion delta V's. These figures shows that there are very few mission opportunities where asteroids are more economically acessible than the lunar surface.

There are two asteroids where round trip mission opportunities have been worked out. These are 1982 DB and 1943 Anteros. A plot of the excess delta V over the ideal minimum[12] to go to and to return from these asteroids is shown in figure XIII. Examining the points representing mission opportunities to 1982 DB we note that there is a forbidden region near the origin. Delta V's close to ideal for both going to and returning from this body are not available in the same mission. This makes the economics of ore recovery from this body less attractive than they would seem from a consideration of the ideal minimum delta V's.

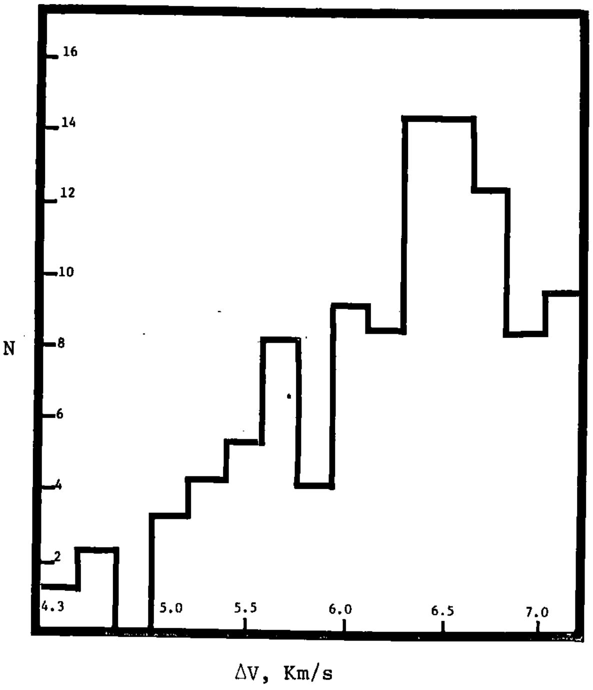

Figure VIII. Histogram of calculated delta V's for mission opportunities to go to known near earth asteroids.

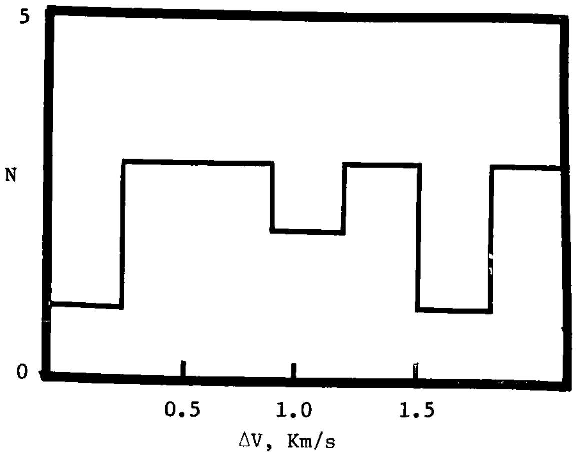

Figure IX. Histogram of calculated delta V's for mission opportunities to return from near earth asteroids. No reserve is kept for aerocapture.

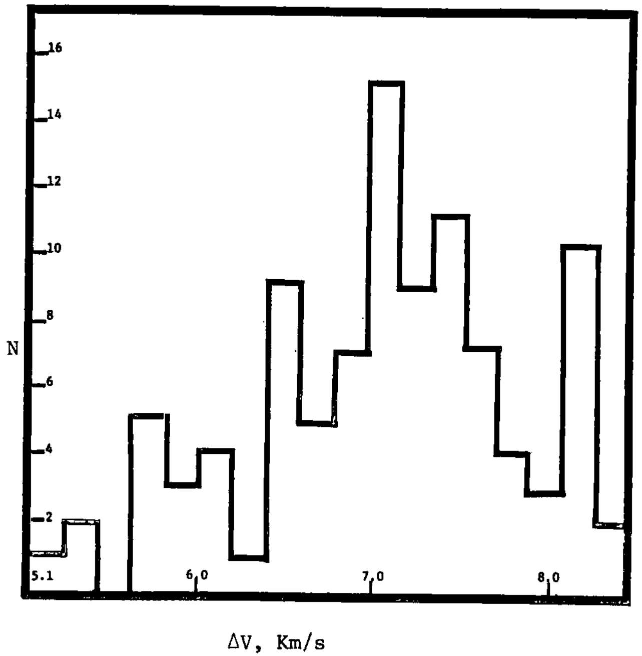

Figure X. Equivalent delta V's for known mission opportunities to travel to near earth asteroids. At 8% interest, 1 day is equal to 1 m/s.

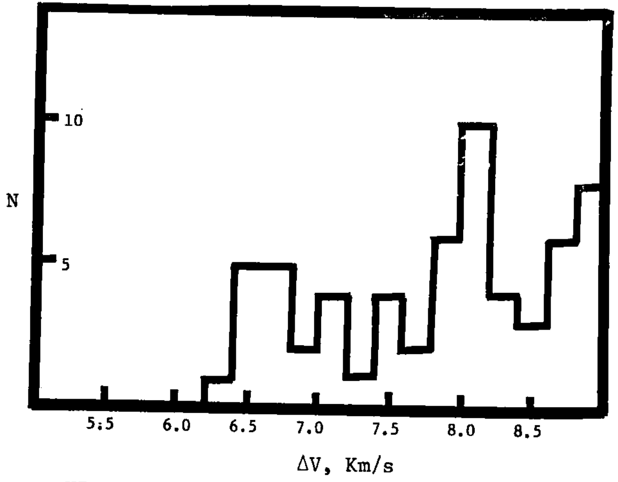

Figure XI. Equivalent delta V's for known mission opportunities to travel to near earth asteroids. At 16% interest, 1 day is equal to 2 m/s.

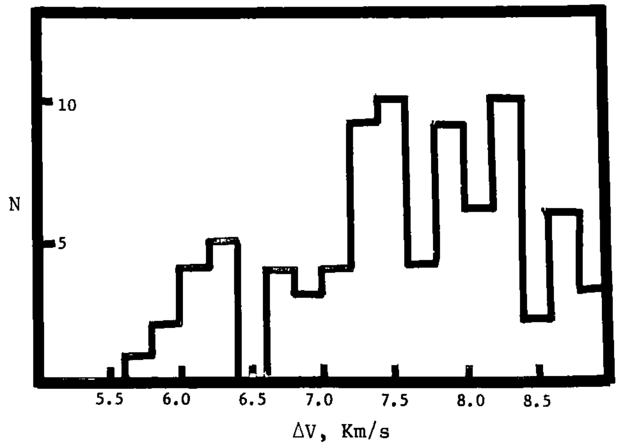

Figure XII. Equivalent delta V's for known mission opportunities to travel to near earth asteroids. At 24% interest, 1 day is equal to 3 m/s.

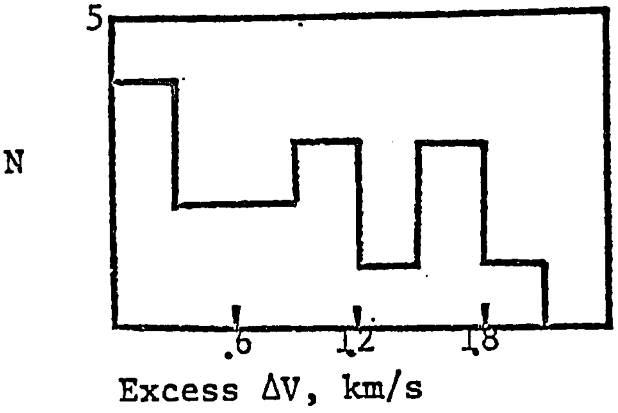

Figure XIII. Excess delta V to return from near earth asteroids. Excess delta V is the delta V for a known practical mission opportunity less the ideal minimum delta V for the best transfer opportunity.

Figures of Merit Figures of merit can be defined which measure the relative economic accessibility of the lunar surface and various asteroids. In any scheme to exploit lunar resources, it is reasonable to assume that all propulsive needs will be met with cryogenic propellants. In going to the asteroids, the deep space delta V's occur months to years after launch. These propulsive requirements could be met with lower specific impulse storable propellants. We can define a figure of merit for comparing the accesibility of the lunar surface and certain asteroids as

$$F = \left\{ \frac{e^{\frac{\Delta V_{ls}}{I_{sp,c} \cdot g}} - 1}{e^{\left(\frac{\Delta V_e}{I_{sp,c} \cdot g} + \frac{\Delta V_s}{I_{sp,s} \cdot g}\right)} - 1} \right\} \qquad [13]$$

where ΔV_{ls} is the delta V to reach the lunar surface from LEO, taken as 6250 m/s; $I_{sp,c}$ is the specific impulse of a cryogenic hydrogen oxygen rocket, taken as 450 seconds, $I_{sp,s}$ is the specific impulse of a storable propellant rocket, taken as 320, ΔV_e is the delta V to leave LEO on the way to the asteroid and ΔV_s accounts for all deep space burns necessary to rendezvous with the asteroid. This figure of merit is greater than one when the asteroid's surface is more accessible than the lunar surface, and is 1.00 when used to calculate the accesibility of the lunar surface. A histogram of number of practical mission opportunities versus this figure of merit is shown in figure XIV. Figures XV and XVI show this figure of merit when one day of time of flight is counted as one and three meters per second, respectively.

An interesting note is that the practical mission opportunities were optimized to minimize delta V, and not resource utilization costs. We can expect some improvement if trajectories are optimized to minimize a figure of merit accounting for the different costs of delta V at different times and for the cost of time of flight. Improvements in economy from this work are not expected to exceed 20%. Again this illustrates that optimizing a physical parameter for optimum system performance does not necessarily increase economy.

A figure of merit can be constructed for return to LEO from an asteroidal surface as follows

$$F_r = \left\{ \frac{e^{\frac{\Delta V_{lr}}{I_{sp,c} \cdot g}} - 1}{e^{\frac{\Delta V_r}{I_{sp,s} \cdot g}} - 1} \right\} \qquad [14]$$

where ΔV_{lr} is the delta V to return to LEO from the lunar surface with aerobraking, about 2600 m/s, ΔV_r is the delta V to return from the asteroid to LEO (not counting a circularizing burn in LEO) O/F is the oxidizer to fuel ratio in the engine used to leave the lunar surface, and M_f is the mass fraction of asteroidal material returned to LEO which is converted to processed products. Delivery of manufactured products from the lunar surface to LEO has a figure of merit of 1.00. Accounting for the different factors in this figure in order, the fact that all of the return propellant is earth derived reduces the break even delta V for return from the asteroids to 1/7 to 1/10 of that for return from the moon. The fact that a significant amount of dross is returned with the useful fraction of the ore reduces the allowable delta V by a factor of 2 to 4. The major reason for returning asteroidal ores to LEO is that they contain fractions which are far easier to process than the silicate minerals on the moon. Thus any argument that the silicate fraction of the returned ore will be used as a soruce of oxygen is ill founded, as this might as well be done with the more accesible lunar materials. The above restrict the economical return delta V's from asteroids to a maximum of 200 m/s for break even when compared to lunar resources. 100 m/s is a more reasonable figure. There is only one known mission opportunity in the next 25 years with a return delta V of less than 100 m/s. This is to 1982 DB in 1998 and returning in 2002. This has a return delta V of 83 m/s. The requirements for an extremely low return delta V means that carrying the propellant needed for a circularizing burn afer aerobraking is prohibitively expensive. It also means that there is only one body known which has any possibility of being economical compared to the lunar surface. This is 1982 DB. Due to the previously noted

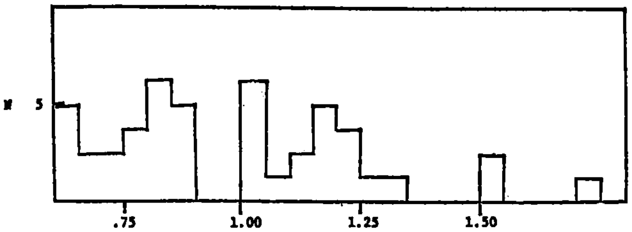

Figure XIV. Accesibility figure of merit for known mission opportunities for transfer to near earth asteroids. The accesibility of the lunar surface is 1.00.

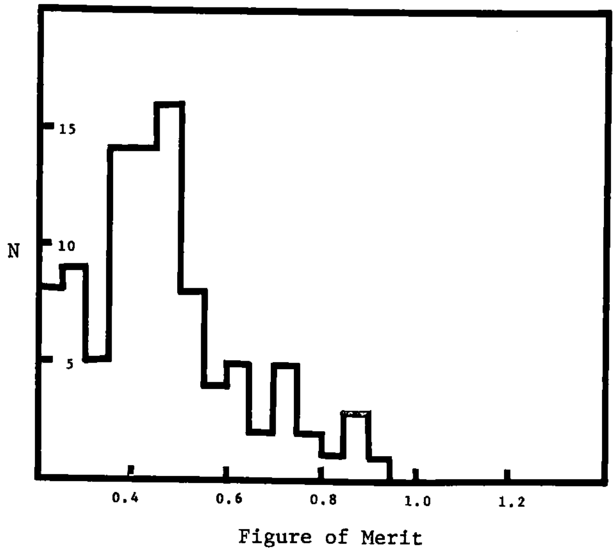

Figure XV. Accesibility figure of merit for known mission opportunities to near earth asteroids at 8% interest (1 day = 1 m/s).

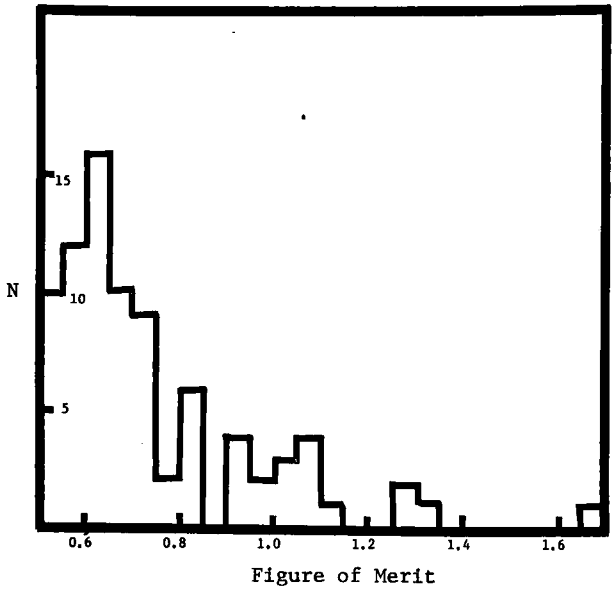

Figure XVI. Accesibility figure of merit for known mission opportunities to near earth asteroids at 24% interest (1 day =3 m/s).

anticorrelation between outbound and inbound delta V's, this is not an attractive target. In addition, it has not been compositionally characterized, and there is only 1 chance in 3 that it has a makeup suitable for industrial processing. Round trip figures of merit ($F_g * F_r$) for 1982 DB and 1943 Anteros are shown in figure XVII for practical mission opportunities in the near future.

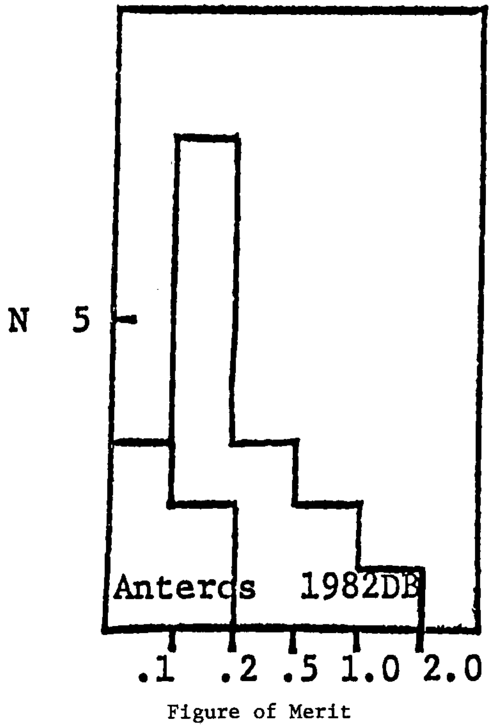

Figure XVII. Round trip figures of merit for 1982 DB and 1943 Anteros. No interest penalty. It is assumed that all returned mass is useful. Lunar resource utilization has a figure of merit of 1.

Various low thrust propulsion systems could make asteroidal ore recovery more economical. There are two questions which must be answered by extensive rigorous work. The first is the minimum delta V required for a low thrust (non-impulsive) transfer from a typical near earth asteroid orbit to earth intersecting orbit. The second is to determine thrust to weight ratios for reasonable near term possible low thrust propulsion systems. These results can be used to calculate the ratio of propulsion system mass to returned ore mass. This mass can be used in formulae similar to those given above to compare a low thrust propulsion based system for the recovery of asteroidal ore to systems for the utilization of lunar resources.

Conclusions

An extraterrestrial resource utilization scheme need not have an extremely low operating cost. In fact, excessive capital investment leading to low operating costs can lead to products which are more expensive than launch from earth with surprising ease. The provision of one or two basic materials such as oxygen or structural metal for somewhat less than current launch costs can be quite profitable if capital costs are kept down. This can start a chain of market expansions and subsequent plant expansions.

Commercial schemes to utilize extraterrestrial resources must pay a realistic rate of return to investors while paying all of their up front costs, such as development of new engines, delivery of the processing facility to its point of emplacement, etc. Govermnment schemes need not do so , but are of limited utility if they do not. For the most part a NASA backed scheme can be viewed as producing a necessary commodity for a lower cost than launching it from earth in order to free up a greater fraction of NASA's budget for other activities and to finance further expansion of the scheme. It is also important to stay within the limits of the capital market the scheme is drawing on. Thus a scheme based on current and near term technology which starts generating income shortly after a relatively small factory is emplaced is very desirable.

Practical mission opportunities indicate that asteroidal ore recovery is less attractive than commonly assumed. Recovery of asteroidal ores is uneconomical using currently available and near term projected propulsion technology. Quantitative engineering studies are required to define the level of propulsion system performance at which asteroidal ore recovery becomes attractive.

Time of flight and the time value of money are important economic parameters which have not been properly accounted for in previous studies. The time value of money renders most schemes requiring long amortization periods uneconomical. It also puts asteroidal resource utilization in a less favorable light than the propulsive requirements would otherwise indicate.

Lunar resource utilization could be economically pursued in the near future. The major stumbling block is the lack of a plant with low performance and cost uncertainty to produce oxygen from lunar materials.

Lunar hydrogen production is unlikely to be economically viable until after a lunar oxygen plant has been in operation for several years.

As was alluded to in our discussion of prior work, a general methodology to evaluate schemes for extraterrestrial resource utilization is needed. At the moment, no standardized method exists for researchers to compare their schemes on a common basis. They are not able to evaluate the effects of specific innovations on various manufacturing schemes. Each prior study calculated costs differently and set up a different manufacturing scenario without isolating the economic effects of each system component. Thus quantitative comparison between these studies is not possible. Each new study must transverse the same ground rather than having each succeeding research effort build on the last.

Recommendations

Research leading to accurate masses for plants to manufacture oxygen from lunar materials should be pursued vigorously. This reserch must be experimental in nature if large cost and performance uncertainties are to be avoided.

Minimum propulsive requirements for economical recovery of asteroidal ores should be determined, taking due account of the time value of money.

Unusually accesible near earth asteroids should be spectrally characterized to make discussions of asteroidal ore recovery more concrete.

The assumptions regarding human presence on the moon, but not on the martian moons or on asteroids should be examined.

Some standardization of economic cost calculations as applied to extraterrestrial resource utilization should be developed and adopted by researchers in this field to make comparisons between scenarios possible. It is further recommended that a user friendly computer-based methodology to evaluate the economics of various extraterrestrial resource utilization schemes should be developed and made available to workers in the field of extraterrestrial resource utilization as a way of acheiving this standardization.

Preliminary design studies should be performed to determine acheivable dead mass or tankage factors are reasonably acheivable using state of the art materials and manufacturing processes only.

Accurate methods of asessing R&D costs must be developed before private investment is possible. All R&D costs which cannot be predicted accurately will have to be borne by the government.

Aerobraking should be developed and demonstrated, as it is unlikely that extraterrestrial resource utilization will be possible without it, and there will be substantial cost and performance uncertainty until a flight demonstration has occurred.

Acknowledgements

The authors would like to aknowledge insight and helpful discussion provided by J. A. Carroll and A. R. Wolff.

References and Notes

1) There have been four sets of work similar enough to the present work for significant comparison to be made. These are:

H. P. Davis, Lunar Oxygen Impact Upon STS Effectiveness, Eagle Engineering report #EEI 83-63 and

M. Simon, A Parametric Cost Model for Evaluation of Space Resource Utilization Technologies paper presented at the symposium on Lunar Bases and Space Activities in the 21st Century, Washington, DC October 29-31 1984, and personal communications relating to further work, and

R. H. Frisbee and R. M. Jones, Transportation, section 7 of Research on the Use of Space Resources, W. F. Carroll, ed. JPL publication 83-36, and

A. H. Cutler, Transportation Economics of Lunar Oxygen utilization in LEO, abstract presented at the symposium on Lunar Bases and Space Activities in the 21st Century, Washington, DC October 29-31 1984, and Transportation Economics of Lunar Oxygen Utilization, paper presented at the 3rd Cal Space Investigator's Conference, La Jolla, CA May 3-4 1984:

One very interesting paper which deals with a system reasonably comparable with that in the present paper, but in which it is difficult to break out the costs the way we are trying to is

D. G. Andrews and W. R. Snow, The Supply of Lunar Oxygen to Low Earth Orbit, Pg. 173, Space Manufacturing 4, proceedings of the 5th Princeton/AIAA Space Manufacturing Conference, 1981:

There are two early papers which point out the desirability of lunar derived rocket propellants. The first of these gives an adequate cost model for considering the case in which both hydrogen and oxygen are manufactured on the moon. These are

R. J. Salkeld, Economic Implications of Extracting Propellants from the Moon, J. Spacecr. Rockets, 3, 254 (1966), and

D. M. Cole and R. Segal, Rocket Propellants from the Moon, Astronautics and Aeronautics, October 1964, pg. 56.

2) There have been a variety of studies describing scenarios for the utilization of lunar resources which would require extensive R&D, long amortization times and an extremely large initial investment. A large body of this literature is contained in the Princeton Space Manufacturing Conferences, various addenda to the Lunar and Planetary Science Conferences, such as Lunar Utilization, D. R. Criswell, ed, Lunar and Planetary Institute, 1977, and in varous NASA contract final reports dealing with solar power satellites.

3) A timeframe from now to about 2010. This was the determination of the. NASA/ASEE summer study Technological springboard to the 21st Century, held in La Jolla, CA June-August 1984.

The space program has been around long enough that some historical perspective is now possible. Examining timelines presented in studies from 1960-1980 makes it quite obvious that bold estimates of future growth in space are common and incorrect. Scaling current expectations by comparing those expressed in the 1960's to the reality that happened indicates that 2000 or 2010 is a reasonable date to expect space resource utilzation to begin on the modest scale discussed in this paper.

4) A. H. Cutler and P. Krag, A Carbothermal Scheme for Lunar Oxygen Production, to appear in the Proceedings of the symposium on Lunar Bases and Space Activities in the 21st Century, held October 29-31, 1984 in Washington, DC.

5) M. Simon, personal communication.

6) D. R. Criswell, A Transportation and Supply System between Low Earth Orbit and the Moon Which Utilizes Lunar Derived Propellants, Paper presented at the Third Cal Space Investigator's Conference, may 3-4, 1984, La Jolla, CA.

7) L. P. Cooper, Propulsion Issues for Advanced Orbit Transfer Vehicles, NASA TM 83624.

8) T. Duvvuri and A. H. Cutler, Programs to calculate the operating parameters of lunar materials transportation systems, available from A. H. Cutler at the California Space Institute, A-021, U. C. San Diego, La Jolla, CA 92093.

9) The delta V's used in this work are (in meters per second) 4266 for LEO to LLO, 2101 for LLO to lunar surface, 1926 for ascent from the lunar surface to LLO, and 900 for transfer from LLO to LEO with aerobraking. The first 3 numbers are essentially those for the apollo 17 mission, while the 4th is a minimum number consistent with patched conic orbits.

10) Steel is assumed to be a byproduct of oxygen manufacture, since the production of oxygen on the moon requires the production of some reduced product, and iron is the most thermodynamically accesible one. About 3.5 times as much iron as oxygen is produced, which leaves excess iron which cannot be transported to LEO due to a lack of lunar oxygen. Even if a lunar oxygen factory does not produce iron, meteoritic and native iron can be collected from the lunar soil by a device far lighter than that needed to produce the approximately equal mass of oxygen needed to transport the iron to LEO.

11) Thermogravimetric analysis data collected by Gibson et al. (A compilation of this data is available from Dr. Gibson at Johnson Space Center, houston, TX 77058) can be used to estimate engineering systems requirements for lunar hydrogen production. These lead to a plant mass of about 156 tons to produce 63 tons per year of lunar hydrogen, which is about the amount of hydrogen fuel needed on the moon to run a system to deliver 500 to 600 tons per year of lunar materials to LEO. The hydrogen extraction system estimate assumes that 50 ppm of hydrogen is recoverable by heating to 700°C, supplying 200°C of the temperature rise electrically, and retorting for 2 hours in a pressure tight vessel.

12) E. Helin, N. D. Hulkower and D. F. Bender, Icarus, 57 42 (1984); and N. D. Hulkower and D. J. Ross, Acta Astronautica, 10 133 (1983); and the following JPL internal memos by N. D. Hulkower: 312/82.32124; 312/82.3-2126; and 312/82.3-2155; and 312/82.3-1958; amd 312/82.3-1933; and a JPL internal memo by C. L. Yen, 312/83.3-2233. Ideal delta V's for return from 1982 DB and 1943 Anteros were provided by J. S. Lewis at the University of Arizona at Tucson.