THE INFLUENCE OF LUNAR PROPELLANT PRODUCTION ON THE COST-EFFECTIVENESS OF CISLUNAR TRANSPORTATION SYSTEMS

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It is well known that propellants produced at the points of destination such as the Moon or Mars will help the economy of space transportation, particularly if round trips with a crew are involved. The construction and operation of a lunar base shortly after the turn of the century is one of the space programs under serious consideration at the present time. Space transportation is one of the major cost drivers. With present technology, if expendable launchers were employed, the specific transportation costs of one-way cargo flights would be approximately $10,000/kg (1985) at life-cycle cumulative 100,000 ton payload to the lunar surface. A fully reusable space transportation system using lunar oxygen and Earth-produced liquid hydrogen (LH_2) would reduce the specific transportation costs by one order of magnitude to less than $1000/kg at the same payload volume. Another case of primary interest is the delivery of construction material and consumables from the lunar surface to the assembly site of space solar power plants in geostationary orbit (GEO). If such a system were technically and economically feasible, a cumulative payload of about 1 million tons or more would be required. At this level a space freighter system could deliver this material from Earth for about $300/kg (1985) to GEO. A lunar space transportation system using lunar oxygen and a fuel mixture of 50% Al and 50% LH_2 (that has to come from Earth) could reduce the specific transportation costs to less than half, approximately $150/kg. If only lunar oxygen were available, these costs would come down to $200/kg. This analysis indicates a sizable reduction of the transportation burden on this type of mission. It should not be overlooked, however, that there are several uncertainties in such calculations. It is quite difficult at this point to calculate the cost of lunar-produced O and/or Al. This will be a function of production rate and life-cycle length. In quoting any cost of this nature, it is very important to state the cumulative transportation volume, since this is a very sensitive parameter. Nevertheless, cost models must be developed now to understand fully the interdependencies of a large number of parameters and to provide the best possible data for planning purposes. Without such data, mission modes and vehicle designs or sizes cannot be selected intelligently.

INTRODUCTION

The importance of extraterrestrial production of propellants for the evolution of space flight was recognized rather early (*Stehling,* 1958; *Cole and Segal,* 1964; *Bock,* 1979); but only now does planning for a return to the Moon (*Paine et al.,* 1986; *Ride,* 1987; *Koelle et al.,* 1987) make this proposition an objective that may become reality in the forseeable future.

The Apollo lunar landing program did not include the possibility of using lunar-produced propellants because it was a short-term exploratory mission on a tight schedule with cost being a secondary parameter. Returning to the Moon early next century makes sense only if the goal is to construct and operate a permanent lunar base there that will evolve into a lunar settlement in due course. This will be possible if cost is the primary concern. A permanent lunar base must be affordable!

The acquisition of a lunar base and its operations should therefore be based on using lunar resources to the largest possible extent. Areas where this can be done are production of construction materials from lunar feedstock, using a closed life-support system, and production of lunar propellants employing solar energy. This will necessarily have to be an evolutionary process toward self-sufficiency. The beginning will be modest in nature. Such a process can be analyzed best by a systems simulation. The first results of such studies have shown that progress will not be easy (*Koelle and Johenning,* 1982, 1986; *Fairchild and Roberts,; 1986*).

Among other things, it has become clear that chemical propulsion systems using liquid hydrogen (LH_2) and liquid oxygen (LOX) are hard to beat if lunar propellants become available (*Thomas,* 1984). Even in this case, the largest contribution to the high cost of space transportation in cislunar space is the need to import the fuel (LH_2) from Earth. This accounts for up to 80% of the specific transportation cost in terms of $/kg (*Koelle and Johenning,* 1986). Thus, we should try to find lunar-produced fuels to mix with terrestrial hydrogen without losing too much performance (exhaust velocity). Lunar-produced hydrogen would be ideal, but at present it is uncertain whether this will be ecomically feasible. Another way to reduce the amount of terrestrial hydrogen is to replace some of it by aluminum powder produced on the Moon. This has been analyzed previously and has shown promise (*Bock,* 1979). Recently, R. L. Zurawski has shown that the addition of aluminum to hydrogen will reduce the specific impulse of this mixture only moderately if the aluminum share is held to about 50% by mass. At a mixture ratio of 6:1 (LOX:fuel) the loss is in the order of

17-18%. Using these results, it is now of interest to calculate the potential for cost reduction in a scenario of lunar base development with lunar fuel production.

The primary assumptions made in this analysis are as follows: (1) A space freighter will be available for the mission leg from the Earth's surface to low Earth orbit (LEO) in a two-stage version or to geostationary orbit (GEO) or alternatively to lunar orbit (LUO) in a three-stage version. The payload capacity to LEO is 360 MT, to GEO and LUO 92 MT. The third stage can also be used as a space ferry between LEO and LUO with refueling at either end (*Koelle and Johenning,* 1986). This cargo ferry has an SSME derived propulsion system with an extended nozzle delivering an I_{sp} of 4600 m/sec. (2) A propellant depot will be stationed in a low LUO to store propellants delivered from the Earth or the Moon. This space operation center can be used for refueling, payload transfer, maintenance, and repair work at a fee. (3) The space ferry and the lunar bus (for transportation between low LUO and the lunar surface) will have a hardware compatibility near 90% of the third stage of the launch vehicle. (4) The main emphasis of this analysis is on cargo transportation; passenger vehicles will probably be smaller in size and depart from LEO to maximize crew safety. It will also use a multiengine vehicle configuration for the same reason. However, passenger flights require propellants for the return flight to Earth that may amount to 50% of the lunar transportation capacity. This will certainly affect the specific transportation cost to LEO and has to be taken into consideration when calculating overall transportation costs.

CASE STUDIES

Several modes of transportation in cislunar space are of interest with respect to the cost-effectiveness of utilizing lunar propellants to obtain an overall picture, specifically: (1) supply of a lunar base with terrestrial products without using lunar propellants; (2) supply of a lunar base with terrestrial products utilizing lunar-produced propellants; (3) supply of an SSPS construction site in GEO with terrestrial materials only; and (4) supply of an SSPS construction site in GEO using terrestrial and lunar sources.

Previous analyses have shown that the following parameters are of primary importance: (1) annual transport volume (MT/year); (2) system life cycle (years); (3) specific transportation cost between Earth's surface and LUO and the lunar surface, respectively ($/kg); (4) production cost of lunar propellants ($/kg); (5) space vehicle hardware depreciation ($/flight); (6) flight operations cost without propellants ($/flight); (7) mixture ratio of lunar propellants to Earth propellants; (8) vehicle payload capability (kg/flight); (9) vehicle state-of-the-art in terms of propellant fraction; (10) RDT&T burden to be shared by this program; (11) vehicle turnaround time between flights (flights/year); and (12) average constructive lifetime (years or flights/vehicle).

The life-cycle cost (LC) of a space transportation system operating as a cargo carrier from the lunar surface (LS) to GEO is comprised of the following elements: C_D (development cost), C_H (vehicle hardware cost), C_P (vehicle propellant cost), and C_L (launch operation costs other than propellants).

The size of the program is determined by the life-cycle cumulative volume of the destination payload. If this is a large space program on the order of 1×10^6 MT or more, the development costs are less than 5% and can be neglected in an analysis of the cost-effectiveness of large-scale lunar propellant production.

If the number of reuses is larger than 100 and the hardware masses of the vehicles to be compared are nearly identical, then the per-flight vehicle hardware costs will be almost the same. Launch operations costs are the costs involved to prepare the space vehicle on the lunar surface, refuel it in LUO, execute a payload transfer (if required), and unload the payload at the destination. These operations will also include maintenance and repair work at these places. These costs should be proportional to the number of flights in first approximation. The difference of vehicle alternatives will appear primarily in the cost of propellants. The cost of lunar propellants produced in quantity should be on the order of $3-10/kg, but the propellants imported from Earth may be on the order of $300-1000/kg, depending on program size.

ONE-WAY CARGO MISSION MODES

One class of missions can be defined as flights with cargo only to be transported from the Earth's surface to the lunar surface in support of lunar base operations. They are relatively clear-cut with respect to velocity requirements and the state-of-the-art. The effectiveness of these missions depends primarily on the cost-effectiveness of the launch vehicles and on the degree of reusability, but not so much on the use of lunar propellants. They are useful, however, as a point of departure and to compare other mission modes in cislunar space.

It is well known that the cost-effectiveness of space transportation systems is heavily dependent on the life-cycle cumulative payload volume that will determine the launch rates. These in turn determine the launch cost. Thus, we will investigate the range of 10^5 MT to 10^6 MT of cumulative payload delivered during the system life to the lunar surface. Using a 50-year life cycle, not inappropriate for a lunar base, this translates into 2000 to 20,000 MT per annum or, if delivered in 100 MT units, equivalent to 20 to 200 flights per year. This is not an unreasonable assumption for the annual average of the first half of the next century.

The mission modes investigated here are as follows: (1) For reference, an updated Saturn V vehicle (using SSME in the upper stages called Saturn VI) will be used on an expendable base with direct flights to the lunar surface in a three-stage configuration. The upper and lower limits for the effectiveness are obtained by considering no or full recycling of the landing stage. (2) A reusable space freighter of the Neptune class with an LEO capability of about 360 MT (*Koelle,* 1986) in a two-stage configuration to LEO will be employed. The third stage of this vehicle is an expendable space ferry flying directly from an 150-km injection altitude to the lunar surface in a one-way mission, also allowing full recycling or no recycling on the Moon. There will be no refueling in LEO or LUO and no reuse of the third stage doubling as a space ferry. (3) A fully reusable space transportation system with a two-stage space freighter will be employed between Earth's surface and LEO, a space ferry to be refueled in LUO with propellants delivered by the same vehicle to a lunar propellant depot, and continuing to the lunar surface with enough propellants to return to the LUO station after unloading its cargo on the Moon. No support in LEO will be required because the third stage will function as the space ferry. It can be characterized as a fully reusable system using Earth propellants only. (4) This is identical to mode (3), but with the assumption that lunar-produced LOX will be available either on the lunar surface or delivered from there to the LUO depot by a lunar tanker vehicle. This lunar tanker vehicle is more or less identical to the space ferry (third stage) used for the LEO-LUO leg of the journey. (5) This is identical to mode (3), but with the assumption that all propellants required either on the lunar surface or in LUO are of lunar origin.

Assuming the specific impulse used for all space vehicles to be 4600 m/sec for LOX/LH_2 propellants, the propellant fractions were estimated to be between 0.88 and 0.92 depending on stage size. Velocity increments were close to 4100 m/sec for the LEO to LUO leg, and 1900 to 2000 for the lunar descent and ascent depending on engine burning times.

The results of the calculations are summarized in Table 1 and Fig. 1. It is easy to see that the big improvement comes, as expected, with the reuse of all vehicle hardware. Lunar propellants affect only the last leg and are desirable despite the fact that we have no return payload requirement. This is unrealistic, however, since a lunar base will have crew rotation requirements that will make the use of lunar propellants even more desirable. Thus, we can conclude that the step to have lunar propellants available only for the last leg of a one-way cislunar transportation system turns out to be ineffective. This fits very nicely in any evolutionary development scenario for a lunar base.

PASSENGER ROUND TRIPS

As shown in the previous section, lunar propellants are not decisive for one-way cargo missions because they can be used only for the LUO-to-lunar-surface leg. However, if there is heavy cargo delivered to the Moon, people have to be there to operate these facilities. This lunar crew will have duty cycles of several months or a year, depending on their physical and mental health. It is difficult at this stage of development to make predictions on the length of this duty cycle.

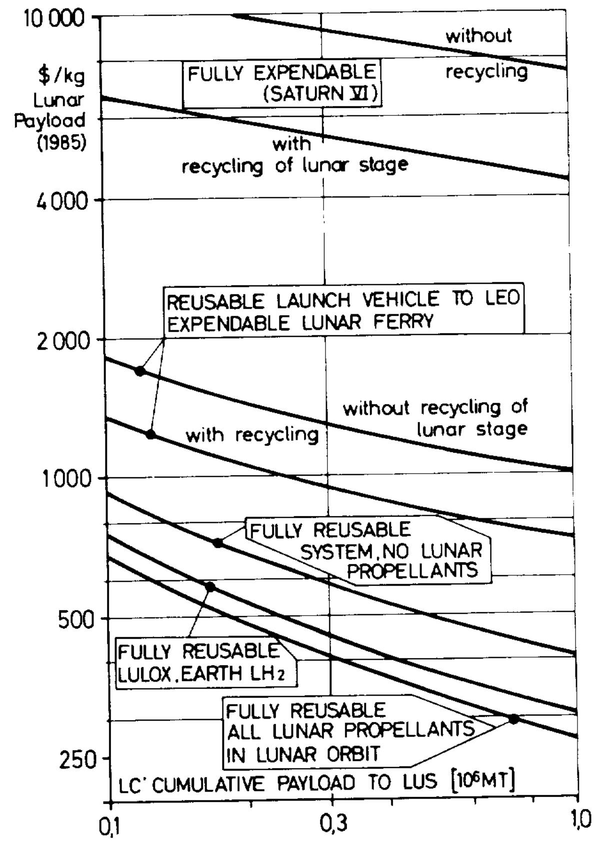

Fig. 1. One-way cargo flights, Earth's surface to lunar surface.

TABLE 1. Comparison of one-way mission modes.

Parameter		Dimension	Saturn Expendable (1)	Reusable Launcher Expendable Ferry (2)	Fully Reusable System; Earth Propellants (3)	Fully Reusable System; Lunar LOX (4)	Fully Reusable System; All Lunar Propellants (5)
			Mission Mode				
Ferry launch mass LEO		MT	140	360	360	360	360
Payload to LUO		MT	—	120	112	120	120
LUBUS launch mass LUO		MT	—	—	360	206	225
Payload to LUS		MT	20	70	195	100	120
Stage mass left on LUS		MT	14	28	—	—	—
Total cost per flight:		10^6 $					
at 0.1×10^6 MT - LC			229	128	177	75	81
at 0.3×10^6 MT - LC			186	93	112	44	49
at 1.0×10^6 MT - LC			151	72	78	30	32
Specific payload cost		$/kg					
at 0.1×10^6 MT - LC			6735	1310	910	753	672
at 0.3×10^6 MT - LC			5465	945	573	440	406
at 1.0×10^6 MT - LC			4438	734	402	301	263
Growth factor LEO to LUS		MT/MT	7.00	5.14	5.05	3.32	2.76
Growth factor with salvaging			4.12	3.67	—	—	—
Reduction of cost	0.1	%	100	19	14	11	10
With respect to	0.3		100	17	11	8	7
reference case (1)	1.0		100	16	9	7	6
Cost effectiveness of	0.1	%	—	—	100	83	74
lunar propellants	0.3		—	—	100	77	71
with respect to case (3)	1.0		—	—	100	75	65

Consequently, a lunar base will require a certain number of passenger round trips per annum as a function of facility size, production rates, and the growth rate of the lunar infrastructure. Previous studies (*Koelle,* 1982, 1986) have resulted in some relevant estimates for crew rotation requirements. A lunar base with a crew of about 500 persons indicates a relationship of 1 man-year for about 20 MT facility mass, a mass flow of lunar products of about 100 MT per man-year, and, with a one-year stay-time, 500 passenger round trips per year. Imports from Earth have been estimated to about 5 MT per man-year.

With such figures in mind, we have now to determine the cost burden of the crew rotation and its influence on the overall operation without and with lunar propellants. It is obvious that we have to transport people to the lunar surface with a manned spacecraft that can use the available lunar bus or a smaller special vehicle. In the case of Earth propellants only, we have to refuel the leg to LUO, and after arrival in the LUO propellant depot we have to take enough propellants on board to fly back to Earth or, alternatively, to the LEO station with the help of an aeroassist brake maneuver. Preliminary calculations indicate a lunar suface mass equivalent of about 4 MT per passenger flight in case of Earth propellants only. Translated into cost this amounts to about $\$1.25 \times 10^6$/round trip (1985) at the given volume. If lunar liquid oxygen (LULOX) were available, the mass burden would be reduced by about 40% and the price for one round trip will be on the order of $\$0.5 \times 10^6$/round trip, in the case of a fairly large lunar base.

Since these figures are preliminary in nature, there will be variables with respect to base size and mission modes employed. The size of the passenger transporting spacecraft will be another factor influencing the round-trip price. A more detailed scenario for the evolutionary build-up of the lunar base is required to come up with more precise figures.

TRANSPORTATION COSTS FOR LUNAR EXPORTS

Exports presently envisioned from a lunar factory are feed-stocks, construction materials, LOX, and selected products that are not labor intensive. The place where these could be used is the GEO for manufacturing and assembling space solar power plants (*Koelle,* 1987).

The transportation task would be carried out by a space ferry vehicle that would be refueled in LUO. The fuel may come from the Earth (LH_2) or partly from the lunar surface (such as aluminum powder). The LULOX and fuel would arrive in LUO by special tanker flights (*Matijevic,* 1987).

Thus, we would like to compare the following mission modes: (1) A space freighter that operates from Earth with Earth-produced propellants without the assistance of lunar resources. This brings up all cargo required in GEO. The launch vehicle is a fully reusable three-stage vehicle taking off from a near-equatorial launch site in a direct flight mode bypassing the LEO station (*Koelle,* 1986). This mode is the basis for comparison of the effectiveness of a lunar-supported logistic system. (2) A lunar-based space ferry serves the legs from the lunar surface to LUO and after refueling there, the leg from LUO to the GEO. It takes return propellants along to GEO for getting back to LUO where it is refueled again. In this mode, the LH_2 comes by tanker flights from the Earth space port directly to the LUO propellant depot, and the LOX is delivered to LUO from the lunar surface by a special tanker ferry of the same size as the cargo ferry. (3) This is the same as mode 2 except that 50% of the fuel is lunar-produced aluminum with a loss in performance (3900 m/sec instead of 4600 m/sec). (4) The lunar-based ferry receives all propellants from lunar resources, assuming that hydrogen and oxygen can be produced by lunar factories in sufficient quantities at acceptable prices. The space ferries themselves and their spare parts are supplied by Earth manufacturers, however. Maintenance and repair services are offered at all transportation nodes (lunar surface, LUO, and GEO). This mode represents the most optimistic operational conditions for space vehicles using chemical propellants.

The assumptions used to make the calculations are as follows: (1) life cycle payload deliveries to GEO = 0.3 to 3.0×10^6 MT; (2) 100 reuses for each ferry vehicle; (3) initial mass of space ferry in LEO or LUS = 360 MT; (4) exhaust velocities = 3900 to 4600 m/sec respectively; (5) single-flight payload capability to GEO from Earth = 90 MT; and (6) empty space ferry vehicle with heat shield = 35 MT.

The results of the calculations are presented in Table 2 and Fig. 2. At the lower end of the payload spectrum we have values of about $550/kg for mode 1 and about $150/kg for mode 3, using a great amount of lunar-produced propellants. For the higher payload volumes we obtain specific transportation costs of about $260/kg and $70/kg respectively. This shows the attractiveness of employing lunar propellants for ferrying lunar exports to GEO.

SUMMARY

The production of propellants from lunar resources is the most valuable commodity that can be produced on the Moon. This is obvious because it will cost about $10,000/kg during the build-up of a lunar outpost to deliver lunar facilities, consumables, and return propellants. This analysis indicates that the introduction of fully reusable systems can reduce the specific transportation cost from Earth to the lunar base to $2000/kg and at large volumes even close to $1000/kg. The use of lunar-produced oxygen in such a space transportation system has the potential of getting the transportation cost down to $500/kg or less. The gain of hydrogen production on the Moon is modest in the case of one-way transportation, but very important for return trips when rotating lunar crews. Using aluminum, even at reduced engine performance, promises to cut the round-trip costs to less than half.

If and when the delivery of raw materials and feedstock to the GEO construction site of space solar power plants develops into a major market, the production of lunar propellants becomes even more important. This analysis indicates specific transportation cost from the lunar surface to GEO on the order of $300/kg at a cumulative payload volume of 0.3×10^6 MT using LULOX only, which comes down to about $150/kg using a 50:50 Al/LH_2 mixture if the aluminum is produced on the Moon. At cumulative life-cycle payload volumes of 3.0×10^6 MT from the lunar surface to GEO, the specific transportation cost may be reduced to $70/kg. This assumes an average ΔV value of 3000 m/sec for the LUO-to-GEO leg. This analysis made the additional assumption that there are no other demands on the launch vehicle and space ferry, which is a conservative assumption. Consequently, there is some hope that the specific transportation cost from the Moon to GEO may be as low as $50/kg (1985) in a high density market. This would be only about one third of the specific transporation cost of an equivalent mass from the Earth's surface to GEO. This difference might determine whether or not space solar power systems become economically feasible.

TABLE 2. Comparison of lunar surface to GEO mission modes.

Parameter	Dimension	Mission Mode: ES-GEO-ES; Earth Propellants	LUS-LUO-GEO and Return; LULOX/ Earth LH_2	All Lunar Propellants LUS-LUO-GEO and Return; LULOX/50% LUAL	All Lunar Propellants LUS-LUO-GEO and Return; LULOX/ $LULH_2$
Ferry launch mass LEO Ferry launch mass LUS	MT	360	360	360	360
Payload to GEO	MT	90	154	107	135
Cost launch vehicle per flight	$10^6$$				
at 0.3×10^6 MT - LC		41.8	43.5	(146)	(146)
at 1.0×10^6 MT - LC		28.1	27.0	(70)	(70)
at 3.0×10^6 MT - LC		21.6	18.3	(43)	(43)
Cost of ferry per flight	$10^6$$				
at 0.3×10^6 MT - LC		7.0	7.4	13.0	13.2
at 1.0×10^6 MT - LC		3.5	5.2	9.8	10.1
at 3.0×10^6 MT - LC		1.8	4.2	7.7	8.1
Lunar-produced propellant per flight	MT	0	191	541	486
Cost per flight mission	$10^6$$				
at 0.3×10^6 MT - LC		48.8	50.9	13.9	16.6
at 1.0×10^6 MT - LC		31.6	32.2	11.3	11.7
at 3.0×10^6 MT - LC		23.4	22.5	8.6	9.1
Specific transportation cost to GEO	$/kg				
at 0.3		542	331	150	123
at 1.0		351	210	106	87
at 3.0		260	145	80	67

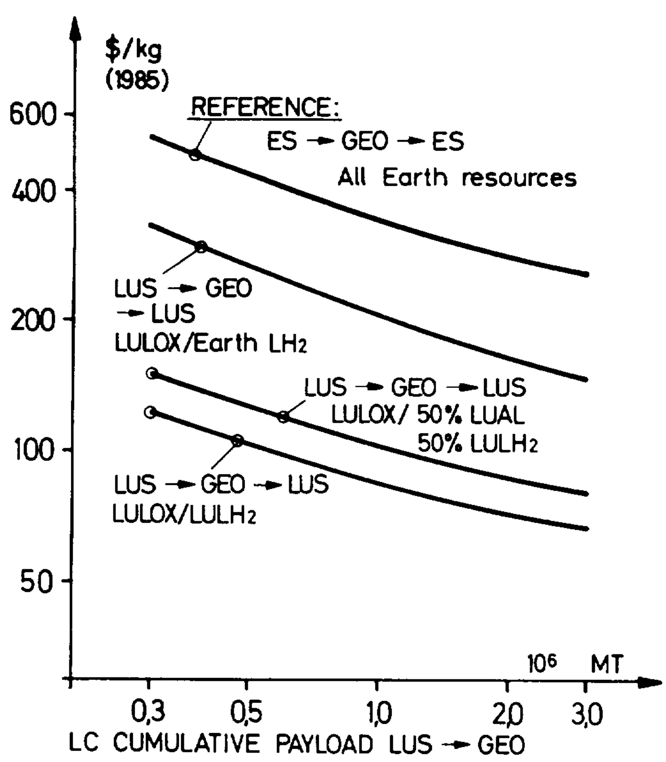

Fig. 2. Specific transportation cost of cargo from lunar surface to GEO.

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