LUNAR BASE LOGISTICS

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Abstract

Three types of support tasks, or 'logistics', for a lunar base are discussed with an emphasis on using local lunar source materials to reduce support costs for a base. Using a system of two orbiting tethers as momentum transfer devices, and lunar-derived oxygen plus hydrogen from Earth for propulsion, cargo can be delivered to the lunar surface with a propellant overhead of 5.6% of payload weight. This is 15 times less than a mass driver/OTV/lunar oxygen system and 64 times less than the all-Earth-propellant case. Local construction materials can be separated by composition by dense-gas flotation. Glass fibers and cast basalt from lunar sources can be used as construction materials. Supply of photovoltaic power during the lunar night can be accomplished by heating surface material during the day, then using the radiation from the hot regolith at night.

Introduction

Placing and operating a Lunar Base has frequently been cited as the next logical step in man's exploration and exploitation of space. We shall define 'mission operations' as the end purpose tasks for which we are on the Moon. Examples are scientific research and mining. Logistics is then defined as those support tasks which make the mission operations possible. Three areas of logistics are considered in this paper: transportation, construction, and electrical power. They are considered with the intent of using local Lunar materials to make the tasks easier or more efficient than if only earth-provided materials are used.

Transportation

Chemical rockets launched from the Earth is the only way used in the past to deliver payloads to the Lunar surface. There is a significant drawback to using this method in the future: for each ton of payload delivered from low Earth orbit (LEO) to the lunar surface, 3.5 tons of propellants must be supplied.

For example, assume the task is the delivery of 10 metric tons of cargo to the lunar surface. Hydrogen-Oxygen rockets are the most efficient in use today. We will use the Pratt & Whitney RL-10 engine as an example of this type of rocket.[1] It has a specific impulse (I_{sp}) of 450 seconds. The velocity increments to reach the Moon are listed in figure 1. The all-propulsive case is illustrated in figure 2.

The initial vehicle weight (m_i) and final vehicle weight (m_f) are related by the rocket equation:

$$m_i = m_f e^{(\Delta V / g Isp)} \qquad (1)$$

where g is one Earth gravity (9.80665 m/s^2). For a total velocity increment of 6090 m/s, then the mass ratio m_i/m_f=3.975. If the vehicle (engines and tanks) is 2000 kg, then the total initial mass is 47,700 kg, and the propellant mass to payload ratio is 35,700/10,000=3.57.

From	To	ΔV Required
Low Earth Orbit	Trans-Lunar Injection	3116 m/s
Trans Lunar Injection	Low Lunar Orbit	874 m/s
Low Lunar Orbit	Lunar Surface	2100 m/s
Low Earth Orbit	Lunar Surface	6090 m/s

Figure 1. Mission Velocity Increments.

Lunar Oxygen

The combination of liquid hydrogen and liquid oxygen is the most efficient chemical propellant in use today. It is normally used in a ratio of 6:1 oxygen to hydrogen by mass. Andews and Snow [2] proposed using oxygen from the moon rather than bringing it from the Earth, sinced the oxygen comprised 6/7 of the total propellant, and lifting it from the moon requires less energy than lifting it from the Earth. The transport of the oxygen to Earth orbit was to have been done via an orbital transfer vehicle which used the Earth's atmosphere as a brake to slow down on arrival. Snow, Kubby, and Dunbar [3] proposed a simplified electromagnetic accelerator for the lunar surface to lunar orbit phase of the propellant delivery.

Again consider the example of delivering 10 tons of cargo to the lunar surface. The delivery leg is performed the same way as in the previous example, thus 35.7 tons of propellants are required. 1/7, or 5.1 tons, is hydrogen brought from the Earth. The remaining 30.6 tons of oxygen is brought from the Moon. An aerobraked OTV requires 874 m/s to go from low lunar orbit to trans-earth-injection, plus about 130 m/s of maneuvering after the aerobrake pass through the atmosphere to rendezvous at a space station. The return trip thus takes about 1000 m/s. The aerobraked OTV is assumed to mass 3 tons. The mass ratio of this trip is 1.254, requiring 8.55 tons of propellant for the oxygen delivery. 1.22 tons of this is hydrogen 'supercargo' to be delivered from Earth along with the 10 tons of useful cargo. 7.33 tons is additional oxygen to be brought to low lunar orbit.

We now require 37.93 tons of oxygen to be launched from the Moon. The lunar launcher described by Snow et. al. used a 3 kg kick motor for each 100 kg of oxygen launched. This 3% overhead in motors is assumed to be brought from Earth, amounting to 1.14 tons of additional 'supercargo'. 8.34 tons of lunar oxygen transfer vehicles must be returned to the moon from lunar orbit. The mass ratio of this trip is 1.609, requiring 5.09 tons of propellant, and thus 0.73 tons of additional hydrogen 'supercargo' to be brought from Earth. Both supercargoes are only delivered to lunar orbit, and hence carry a delivery mass ratio of 2.470 and a propellant overhead of 1.764.

To summarize this complex flow, for each 10 tons of cargo delivered to the lunar surface, 5.1 +1.22 +1.14 +0.73 +(1/7x1.76) =8.44 tons of hydrogen and kick motors must be brought from Earth, and enough oxygen from the moon to make the system work. This ratio of overhead to useful cargo of 0.844 is considerably better than the 3.57 for the all propulsive case.

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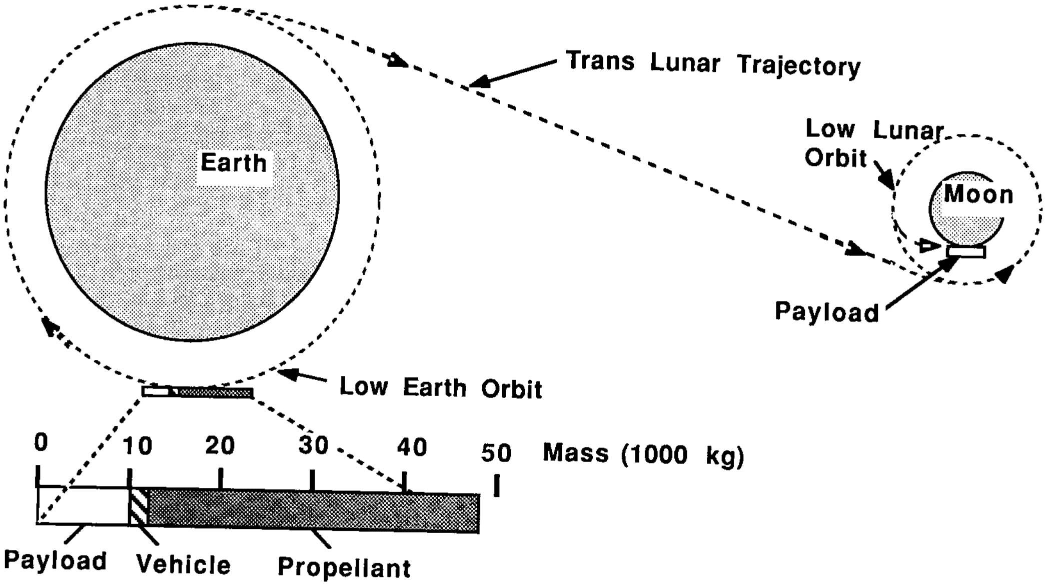

Figure 2: All Propulsive Payload Delivery

Tethers

The idea of using rotating tethers in space for propulsion via momentum transfer to and from spacecraft was first analyzed by Moravec [4]. A system of two rotating tethers, one in Earth orbit and one in Lunar orbit can be used as momentum banks which loan or store momentum to and from a vehicle in transit. The spacecraft begins in Earth orbit at an altitude of 375 km(figure 3). The first rotating tether is in an elliptical orbit with a perigee of 445 km. Since the rotating tether is 70 km long, its tip meets the spacecraft. The tether rotates with a period of 235 seconds, producing a tip acceleration of 50 m/s^2 and a tip speed of 1870 m/s. It is rotating in a vertical plane so that the earthward side is moving slower with respect to the ground. The tether is in an orbit whose perigee velocity is 1870 m/s higher than the circular orbit of the spacecraft, hence the tip comes momentarily to rest with respect to the spacecraft. The spacecraft grabs the tether and rides it for 1/2 rotation, then releases.

A tether operating at 0.5 of the strength to weight capability of aramid or carbon fibers (which allows for non-structural overhead and a design factor of safety) must mass 12.5 times the spacecraft mass for this mission. Therefore the spacecraft will pick up 3442 m/s relative to the Earth and the tether will lose 298 m/s. The tether is now in a lower elliptical orbit and the spacecraft is in a trans-lunar trajectory with a 30 hour transfer time.

The second tether is in elliptical orbit about the Moon. Since the orbits of the two tethers will be out of phase, the spacecraft must have a ΔV capability of 90 m/s to accelerate or delay it's arrival at the Moon by 1/2 of the orbital period of the second tether. This ensures that the tether will be at the right place in it's orbit when the spacecraft gets there. The spacecraft arrives at the Moon with a perigee velocity of 3200 m/s. The second tether is initially in circular low Lunar orbit at 100 km, with an orbital velocity of 1632 m/s. It has a tip speed of 1568 m/s, and masses 7.15 times the spacecraft mass. The tether slows the spacecraft to 449 m/s horizontal velocity at 50 km above the lunar surface. An efficient landing requires 625 m/s of propulsive ΔV. The tether has gained 384 m/s, placing it in an elliptical orbit.

The total ΔV required to get from Earth orbit to lunar surface is thus 625+90=715 m/s. This requires a mass ratio of 0.162, and a propellant to payload ratio of 0.178. This in turn requires 0.026 times the payload weight in hydrogen to be brought from the Earth, and 0.153 times the payload weight in oxygen to be delivered from the Moon. This oxygen is lifted by the spacecraft on its return trip. It takes off carrying a payload of oxygen equal to the 1.15 times payload landed on the Moon. This requires the same ΔV as the landing, and about the same amount of hydrogen as for the landing. Since the spacecraft is the same mass as it was on the delivery leg (almost), the return trip through the two tethers returns their momenta to their original values. Any remaining differences are assumed to be cancelled by oxygen-ion thrusters on the tethers between spacecraft operations. The specific impulse of the ion thrusters is high enough to ignore this propellant use for this analysis, except to note that it is supplied from the oxygen payload on the spacecraft.

The total requirements are thus 0.056 overhead in the form of hydrogen. 0.15 out of the 1.15 units of oxygen are allocated to the next delivery. There is also one ton of surplus oxygen delivered to low Earth orbit for each ton of cargo landed on the moon. This can be used by other payloads going to other destinations. Thus the tether/lunar oxygen case has 15 times less overhead than the mass driver/OTV/lunar oxygen case and 64 times less overhead than the all propulsive case.

Construction

Separation of small regolith particles by specific gravity could make later material processing simpler by providing more uniform composition feedstocks. One way to do this could be to use high density gas to separate the particles. The feedstock would be placed in a pressure chamber on top of a vibrating plate. The chamber starts at vacuum, then the gas is introduced and the gas density increased until it exceeds the density of the lightest particles in the mix. These will be shaken loose by the vibrator and float to the top of the chamber, where they can be collected. The pressure is then further increased until the next fraction floats. This process continues until all the feedstocke has been separated. If the feedstock consists of single mineral grains initially, in principle it should be possible to segregate minerals by density.

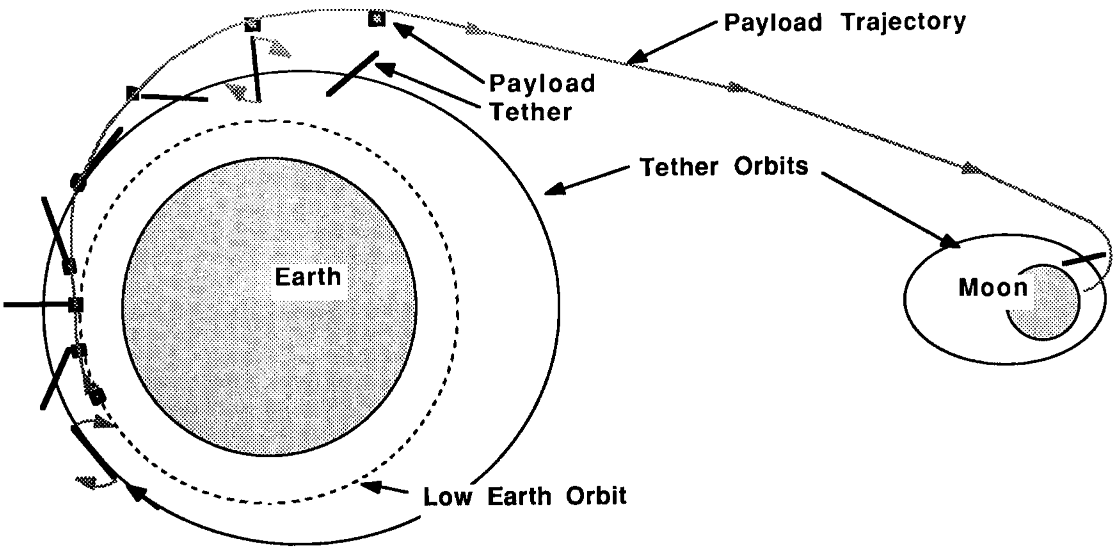

Figure 3. Two tether system.

The gas for this operation should be dense and have a low boiling point. An initial survey of candidate compounds gives the following as potential working gases:

Compound	Boiling Point (K)	Density (kg/m^3)
Selenium	958	4200
Iodine	457	4930
Mercury Iodide	627	6100
Mercury	629	13600

Further study is needed to determine chemical compatibility with the feedstock, contamination effects on later processing steps, and loss rates during the operation.

Lunar Mare basalts cast in regolith 'sand' molds can be used as compressive members in structures to expand an initial base. Glass fibers made from surface material can be used as tension members. Its properties of the cast basalt and glass fibers are expected to be better than concrete and reinforcing steel, respectively, leading to a composite which is expected to be better than steel reinforced concrete. This composite can be made from all local materials using sunlight as an energy source. One characterisitc which would make a reinforced composite easier to manufacture is a fiber with a melting point higher than the basalt melting point. This would allow casting the reinforcing fibers directly in the composite material.

Electrical Power

Storage of energy by heating lunar surface regolith to its melting point in situ, then exposing a photovoltaic array to the radiating pit would allow using photovoltaics during the Lunar night, eliminating the need for complex, costly, and heavy storage systems such as fuel cells or batteries. The heat capacity of the lunar regolith is estimated at 1.6MJ/kg from ambient to 1700K [5], and the bulk density of the regolith is 1500-1800 kg/m^3. Thus the heat storage capacity of the regolith is 2.4-2.9 GJ. Two weeks of power use at 100 kW requires 121 GJ. Thus a volume of regolith 4-5 m in each dimension should be sufficient.

The regolith would be heated during the day by a concentrating reflector. A covering that reflected the infrared and visible radiation from the hot regolith back would prevent large-scale radiation to space. The regolith would be brought to or near the melting point. It would be insulated by the surrounding regolith, which, being particles separated by vacuum, is an excellent insulator. During the night an opening in the reflective covering would direct the visible and infrared energy to a photovoltaic array a small distance away. The distance provides the array with sufficient view of the night sky to radiate residual heat away. This keeps the array cool enough to work efficiently. The vast bulk of this energy storage system is made up of regolith, which is available without any processing at all.

[1] Brown, J., "Orbit Transfer Vehicle Engine Study, Final Report" prepared by Pratt &Whitney Aircraft Group for NASA George C. Marshall Space Flight Center under contract NAS8-33444, 31 July 1980.

[2] Andrews, D.G., and Snow, W.R., "The Supply of Lunar Oxygen to Low Earth Orbit," Space Manufacturing IV, Proceedings of the Fifth Princeton Conference, May 18-21, 1981, AIAA, New York.

[3] Snow, W.R., Kubby, J. A., and Dunbar, R.S., "A Small Scale Lunar Launcher for Early Lunar Material Utilization",Space Manufacturing IV, Proceedings of the Fifth Princeton Conference, May 18-21, 1981, AIAA, New York.

[4] Moravec, H., "A Non-Synchronous Orbital Skyhook", J. Astronautical Sciences, Vol 25, No. 4, Oct-Dec 1977, pp. 307-322.

[5] Williams, Dr. R. J., "Handbook of Lunar Materials", Lunar and Planetary Sciences Division, NASA Johnson Space Center, Houston, May 1978.