

PERMANENT – Chapter 3 – Transportation of Earth, Lunar and Asteroidal Materials

Excerpts from a website developed by physicist Mark Prado on issues related to space transportation and resources. [www.permanent.com]

1 Overview – Transport of Earth, Lunar and Asteroidal Materials

The main barrier to space development is the cost of getting there. For example, the current Space Shuttle cost is around \$12,000 per kilogram, and near future rockets are almost certainly not going to be able to deliver for less than \$2000/kg. That is why we are looking at using materials already in space – getting materials from asteroids near Earth and the Moon. After all, the settlers of America didn't bring from Europe all their bricks, wood, cement, food, water, etc. This section explains the differences in transportation costs between delivery from Earth, the Moon, and asteroids near Earth, both theoretically and by practical engineering methods. Different transportation technologies are compared, with an emphasis on practical, near term solutions.

There are two factors that determine the economics of space transportation:

1. Theoretical requirements, *i.e.*, the minimum energy required to go from one place to another due to gravity without considering any other requirements, and
2. Practical means, *i.e.*, the cost of producing and operating vehicles.

The relative weight of these two factors varies, depending on origin and destination.

The effort required to transport a particular payload from one point to another in space is often compared in terms of “delta-v” – the total velocity change you would need to impart in order to go to a different destination. It's not necessary to completely understand what this means, but it is important to understand that this reflects a kind of theoretical minimum, somewhat as if the payload were fired from a gun without the need to launch any fuel propellants for use later. In reality, as the delta-v gets higher, the economics get worse much quicker due to fuel and fuel transport needs.

Some delta-v's are given below, in kilometers per second (km/s) and miles per hour (mph):

- 0.06 km/s (130 mph) from asteroid 1982DB to high Earth orbit
- 2.37 km/s (5,000 mph) from the lunar surface to high Earth orbit
- 7.50 km/s (16,000 mph) from Earth's surface to low Earth orbit
- 10.00+ km/s (20,000+ mph) from Earth's surface to high Earth orbits (*e.g.*, communications satellites)

Getting off of Earth's surface and into low Earth orbit requires so much fuel that rockets must lift off with massive amounts of fuel for later in flight. For example, the Space Shuttle, when sitting on the launch pad, is about 5% cargo, 85% fuel propellants, and 10% vehicle. It's like launching a skyscraper building. The stresses and engineering demands on these vehicles, in addition to safety and economic reliability standards, are so extreme that the costs of manufacturing and operating rockets are exorbitant for launching materials off of Earth's surface.

In comparison, the Apollo lunar lander's fuel tank to launch the astronauts off of the Moon was so small that you could sit on it like a chair, and made up a small corner of the spacecraft. Even in the future, with a heavy lift rocket from the Moon, the stresses will be substantially less than for launch from Earth.

Asteroids have practically no gravity. If your rocket engine fails during launch, there's practically no chance you could crash back down. The vehicle and fuel propellants can be low throughst, low spec, and very small. The equipment for deploying to the asteroid can be configured in low Earth orbit and “docked” to the asteroid, *e.g.*, by a deflating airbag, ratchet-locking springs, or other nonrocketry means if preferred. (For sending a cargo to the Moon, it must be packaged, landed and deployed in the Moon's gravity.) Retrieving asteroidal material is like moving from one orbit to another, which gives tremendous benefits in flexibility, reliability and safety.

Notably, the Shuttle goes only to low Earth orbit. If the cargo in the Shuttle bay is a communications satellite headed for geostationary orbit (a high Earth orbit), as is commonly the case, then the Shuttle's cargo bay consists of one third satellite and two thirds additional fuel propellant. The Shuttle serves mainly as the first stage to get the satellite off the ground and above the atmosphere. Once in orbit, the payload leaves the Shuttle and an interorbital vehicle takes over.

Launch vehicles and the vast majority of interorbital vehicles to date have all been based on chemical rocketry, whereby a fuel is mixed with oxygen and the "controlled, continuous explosion" produces the thrust. For oxygen-hydrogen rocketry, the oxygen makes up between 86% and 89% of the fuel mix.

On the moon, oxygen is easily extracted from lunar soil. Hydrogen is scarce on the Moon except at the poles where it is abundantly available as extremely cold ice. Elsewhere on the Moon, water needs may compete with fuel needs. Rocketry based on powdered metal fuels mixed with oxygen has been developed but needs to be adapted to the lunar mission.

Many asteroids are rich in both oxygen and hydrogen, as well as carbon for alternative hydrocarbon fuels which are more storable and easier to handle. All of these elements are easy to extract from asteroids, using a simple solar oven, for example.

One study put together a design for an initial mission to retrieve asteroidal material. This study determined that a 100 ton spacecraft launched to and assembled in low Earth orbit (and consisting mainly of the fuel propellants to get to the asteroid), could come back to Earth orbit with 10,000 tons of asteroidal material if it gets hydrogen and oxygen from water at the asteroid to use as fuel propellant. This spacecraft is simple and does not involve any radical new technology.

Excess fuel propellants will be one of the first products from asteroidal and/or lunar materials. This will enable rockets on Earth to launch only payloads to low Earth orbit. Separate, "interorbital vehicles" fueled by asteroidal and lunar propellants at fuel stations in high Earth orbit, can come down to bring satellites up to higher orbits, *e.g.*, geostationary orbit, as well as deliver fuel propellants for stationkeeping and maneuvering in any orbit. Rockets on Earth can triple their useful payloads by not launching fuel propellants for the interorbital vehicle.

No longer will satellites be lost in space due to rocket stage failures or decommissioned due to exhaustion of stationkeeping propellants. Lifetimes can be extended, and indeed obsolete satellites can be sold to less developed countries ... though this is getting a bit off the topic of transportation.

Also covered in this section are non-rocketry techniques which are starting to emerge today, as well as techniques further down the road as space becomes more industrialized. However, a near-term project can be based entirely on proven transportation technology. The one technology that is most likely to emerge for asteroidal materials is the steam rocket – not making a fuel propellant but simply heating water from the asteroid to produce steam for interorbital propulsion, as discussed in a section of this section.

2 Theoretical transportation energy requirements

2.1 Moving around in the Earth-Moon System

The Earth is 81 TIMES as massive as the Moon, and asteroids have a trivial mass compared to the Moon. To get from the surface of the Earth or the Moon into orbit around Earth (where space products providing valuable space services will reside) requires energy in two forms:

1. Energy to rise above the surface, *i.e.*, "potential energy"; and
2. Energy to stay up there without falling back down, that is, acquiring the speed to go into a circular orbit, *i.e.*, "kinetic energy". In a circular orbit, gravity is countered by the centrifugal force constantly.

Notably, when the Space Shuttle goes into low Earth orbit about 500 kilometers up, only about 7% of the theoretical energy required goes into lifting it to that height (potential energy). About 93% of the energy goes into accelerating the Space Shuttle to a speed where it goes into a circular orbit (kinetic energy). The total amount of energy (kinetic plus potential) required is often expressed in terms of an analogy – an "energy well", as pictured

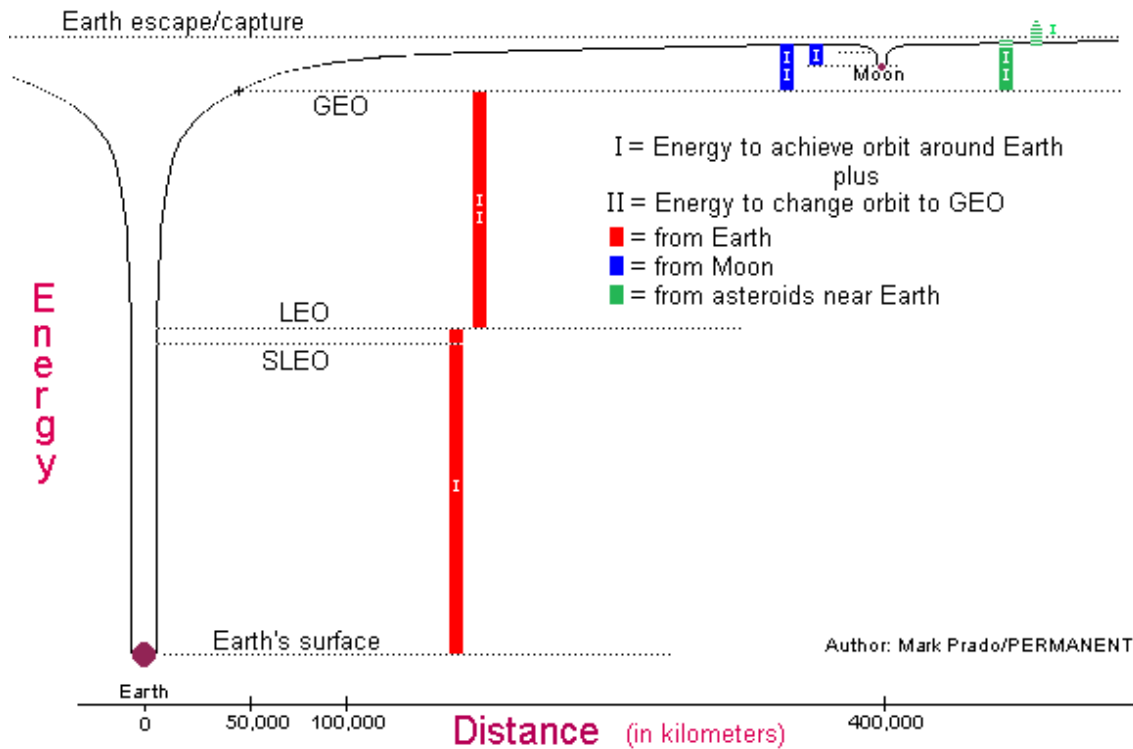


Figure 1: Note on the graph that the energy required to go into “geostationary earth orbit (GEO)”, *i.e.*, “stationary communications satellite orbit”, from the Moon is small, compared to coming from Earth. It will later be shown that the energy required to get material from many asteroids near Earth into geosynchronous orbit is even less than from the Moon.

here, as if each gravitational body represented a hole in the ground like a water well which a cargo must crawl out of. The bigger the planet, the deeper the equivalent well. In the picture below, the vertical “height” represents the energy required to move from one point to the other, whereby the horizontal length represents the physical distances (to scale).

The Space Shuttle can go to about 500 kilometers, and doesn't have the capability to go significantly higher than that, energy-wise. Communications satellite orbit is at 36,000 kilometers. Roughly half the energy to get to geosynchronous orbit is consumed in just getting to an orbital speed. When the Space Shuttle carries a communications satellite up, it brings it only above the atmosphere to the 500 kilometer orbit. From there, the satellite is removed from the cargo bay and then launches to geosynchronous orbit 36,000 kilometers up using its own fuel propellant, which makes up most of the cargo in the Shuttle bay, not the satellite. But this is another issue for another place.

What orbital speeds are we talking about? For low Earth orbit, we are looking at a little over 7 kilometers per second (*i.e.*, about 15,000 miles per hour), for the orbital speed. At this speed, the Shuttle orbits the Earth in about one and a half hours. As a satellite goes higher in orbit where Earth's gravity is weaker, it does not need to go as fast to stay in orbit, and thus one orbit of the Earth takes much longer, *e.g.*, 24 hours for GEO. However, it takes much more energy to lift it up to that orbit.

An orbit used by communications satellites is a high Earth orbit called “geostationary” or “geosynchronous” orbit, where it takes exactly 24 hours for one orbit. Since the Earth rotates once per 24 hours, each satellite stays “stationary” or “synchronized” above one point on Earth. That's why you can point your satellite TV dish to one place and leave it there, rather than having to track the satellite and lose communication if it were to pass over the horizon.

It takes more than 10 times more energy, theoretically, to get into geosynchronous Earth orbit from the surface of the Earth than from the surface of the Moon (that is, a circular orbit). The energy required from asteroids near Earth could be less or more than from the Moon, depending on the particular asteroid's orbital properties. Adding in the heavy vehicle and complexity associated with Earth launch, and launching the fuel for later in the flight, getting materials off of the Moon and especially from asteroids is much easier than from Earth. To escape Earth orbit altogether takes less than 10% more energy than getting to geostationary orbit. Hence, the energy difference between GEO and other bodies besides Earth is often much less.

(One item often quoted by others is that it takes about 22 times more energy to launch from Earth and "escape" to infinity (without going into orbit) than to likewise launch from the Moon and escape to infinity. That is a simple comparison for laymen to illustrate the point, and differs somewhat from the more detailed comparison given here which accounts for getting into various useful circular orbits.)

It's important to understand that it takes just as much energy to come down as it does to go up – there's no "free downhill". Coming "downhill" takes just as much energy and fuel in space because there is no friction – you must spend fuel to lower yourself into a circular orbit. (An exception could be "aerobraking", i.e., using the Earth's atmosphere for friction, but no such vehicle has been operated to date except for return to Earth's surface. Aerobraking is discussed in the vehicles section.) Without aerobraking, if you simply brake and fall down in an elliptical orbit, you'll soon be right back at the top of that elliptical orbit and ready for another cycle. To stay at the bottom of the orbit requires that you circularize your orbit when you arrive there by spending more fuel.

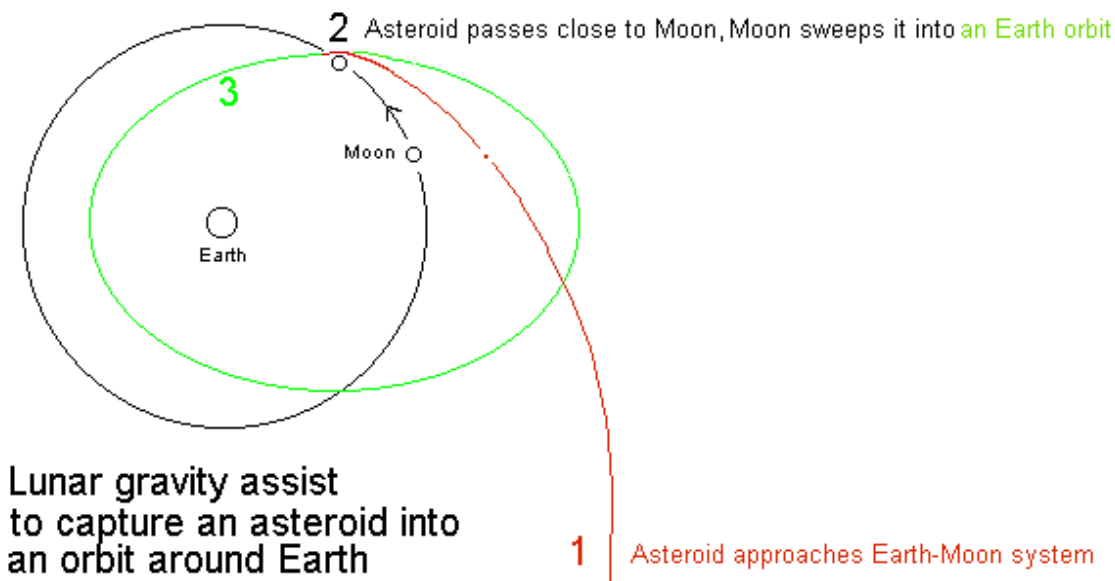
Higher orbits have more potential energy but less kinetic energy. In fact, mathematically, to move from a lower orbit to a higher orbit requires spending two parts potential energy for every one part kinetic energy reduced. Notably, there's no energy shortcut – if you skip going into an interim orbit but just shoot from the surface of the Earth to a high orbit, you don't save anything, theoretically. However, in practical terms, there are differences between trajectories to get into a circular high orbit so that you can spend significantly more than the theoretical minimum. In general, haste makes waste, in terms of energy and fuel spent. The theoretically best trajectory from Earth's surface to any Earth orbit is to first get into orbital space, so that one isn't fighting against gravity's pull back down, and then to spiral up slowly, thrusting perpendicular to the line of sight with Earth (*i.e.*, adding purely centrifugal force). However, this is rarely followed due to economic factors other than fuel launched (*e.g.*, time and complexity, and radiation belt damage factors).

On the graph: "Sea Level Earth Orbit (SLEO)" just illustrates the minimum energy required to "stay in outer space" rather than standing (or crashing back) on Earth's surface – Sea Level Earth Orbit is, say, a purely theoretical orbit just one foot above sea level as if there were no atmosphere or hills to crash into. Energy-wise, Sea Level Orbit represents the 93% kinetic energy to get to Shuttle orbit from Earth's surface, as compared to the 7% to lift up above the atmosphere. The Moon also has a "sea level orbit", or since it has "Mares" instead of "Seas", it has a corresponding "Mare Level Orbit". The entire graph represents the theoretical minimum amount of energy required. However, the more energy required, the more fuel must be lifted for use later. Thus, the rocket size and complexity increase well out of proportion to the theoretical minimum energy required.

Asteroids have no significant escape velocity or "sea level orbital energy", and can be seen as objects already in orbital space. On the chart, they would be located beyond the dashed line above high Earth orbit, energy-wise. Some near Earth asteroids are just a tiny bit above the the dashed line, though most asteroids are significantly above the line. However, an analysis of retrieving asteroidal materials does not lend itself well to the above analysis, largely due to a concept called a "lunar gravity assist", which saves energy by trading orbital energy with the Moon, as discussed below.

2.2 Asteroid Materials Retrieval

The delta-v's for known Earth-crossing asteroids are as low as 60 meters per second (60 m/s), as compared to the Moon's escape velocity of 2,400 m/s. There are many asteroids with required delta-v's lower than the lunar surface. In a probable mission scenario to an asteroid, a large cargo will be launched into high Earth orbit and undergo a gravity assist by the Moon (discussed below) to pick up speed to rendezvous with the asteroid. After rendezvous of the cargo ship with the asteroid, any human presence needed would be sent by a small vehicle on a quick trajectory.



Before we go into specific missions, we should cover a key topic for retrieving asteroidal materials: lunar gravity assists.

2.2.1 Lunar gravity assists for asteroids

Some asteroid enthusiasts humorously see the Moon mainly as an object to offer gravity assists, not to mine the Moon.

A “gravity assist” entails using a fly-by with the Moon to divert the trajectory of a payload and to impart delta-v, saving large amounts of fuel. Almost all NASA probes to other planets have depended on gravity assists, e.g., passing by the Moon and the Earth one or more times on their way out, and sometimes other planets as well for the purpose of gravity assists. For example, Voyager more than doubled its speed when it passed Jupiter.

One or more lunar gravity assists, sometimes in concert with an Earth gravity assist, will be used to:

1. deflect incoming asteroid cargos into a high Earth orbit (or towards another gravity assist), and
2. to brake the asteroid.

A single lunar gravity assist is illustrated conceptually below. The maximum braking the Moon can provide is about 2.2 km/sec, using a “double lunar gravity assist”, whereby the asteroid passes by the Moon coming in, then past the Earth, then past the Moon again going back out. This would divert the asteroid by almost 90 degrees from its original path, and capture it into a highly elliptical Earth orbit. Subsequent gravity assists would insert it into a more circular orbit around Earth after which it would perform final small thrusting maneuvers to achieve its desired destination orbit. Many asteroids require a delta-v of much less than 2.2 km/sec, and require only a single lunar gravity assist (not an Earth gravity assist) to be captured, and optionally additional lunar gravity assists to divert the asteroid into a more circular orbit.

Gravity assists improve the economics of retrieving asteroid payloads, as well as outbound missions, and greatly broadens the number of attractive asteroids. (In this game of “orbital billiards”, we are tapping a gravitational energy source as asteroid payloads exchange orbital momentum with the Moon and the Earth – the asteroid slows down while the Moon speeds up. Because asteroids are so small compared to the Earth and Moon, the effects on the Moon and Earth are so small as to be immeasurable. It would take millions of captured asteroids

to cause any detectable changes in the Moon's or Earth's orbits. It's like measuring the effects of mosquitoes hitting the Empire State Building – significant to the mosquito, but not to the building.)

We probably would not want to bring a complete asteroid in, but instead a series of small cargo containers which are more easily maneuvered and pose no significant threat to Earth. Trajectories are something we know very precisely, well in advance, and there's no need to get too close to Earth. The abovementioned 2.265 km/sec gravity assist maneuver was based on approaching no closer than several thousand miles (kilometers) of Earth's surface in order to allay such concerns. (Some people have proposed using the Earth's atmosphere for "aerobraking", but that's not at all what we are talking about here. We won't ever need to alert any emergency rendezvous team for pure gravity assist maneuvers.) One would expect that a quick response rendezvous team would be set up to protect Earth in the long run against both man-made objects and naturally occurring asteroids and big rocks that pass by Earth. Already, military and civilian telescopes have detected big rocks and sizeable asteroids passing very close to Earth, including skimming the upper atmosphere. If any of these naturally occurring objects had hit Earth, it would cause a natural disaster, possibly to the entire planet, not a man-made disaster. Man-made capabilities can prevent natural planetary damage.

2.2.2 Specific Asteroid Missions

In the late 1970s, many people thought that the ideas of asteroidal materials utilization had so much merit that equipment would be developed and missions would be embarked upon by NASA. This was naive, but it was good that they proceeded with these projections, as they are exemplary. However, some of the dates of the following missions are already past.

The Amor asteroid "Anteros" (1973EC) was projected to have equipment launched to it in late 1992. Rendezvous would happen in 1993 and the equipment would be running at full steam by early 1994. After a delta-v of 1.6 km/sec, the cargo was to be enroute to the Earth-Moon system. It was to arrive in 1995 where two lunar gravity assists and a fuel thrust "capture maneuver" of 0.3 km/sec at orbit perigee would have put it into a circular orbit between the Moon and the Earth. (The 0.3 km/sec could be lowered by a third lunar encounter if so desired, but 0.3 km/sec is so small that it may be worth a little haste.)

The Amor asteroid "Eros" offered essentially the same story. The launch date was scheduled for a year later, in 1993. The delta-v would have been 1.7 km/sec and would've taken two lunar gravity assists and a capture maneuver of 0.3 km/sec.

The investigators thought that further analysis of mission opportunities and trajectories could reduce the delta-v to near 1 km/sec for the above two asteroids. On their shoestring budget, they did a limited number of calculations, and getting a trajectory under 2 km/sec initial delta-v was deemed enough to move onto other issues like analysis of the equipment needed.

In the late 1970s, a few of the newly discovered asteroids were also analyzed for rendezvous, *e.g.*, the Apollo asteroids 1976UA (delta-v of 0.61 km/sec), 1973EC (delta-v of 1.43 km/sec) and 1977HB (delta-v of 1.06 km/sec). These calculations were made using 1970s computers and some remarkably persistent professionals.

Since this 1970s study, using more sensitive telescopes, many more attractive targets have been found, including the asteroid 1982DB, which needs a delta-v of a mere 0.06 km/sec (*i.e.*, 60 meters per second, or 130 miles per hour) to be captured by the Earth-Moon system.

2.3 The L1, L2, L4 and L5 Libration points

There are two points called L1 and L2 on the chart on energy requirements. Their relevance is as follows:

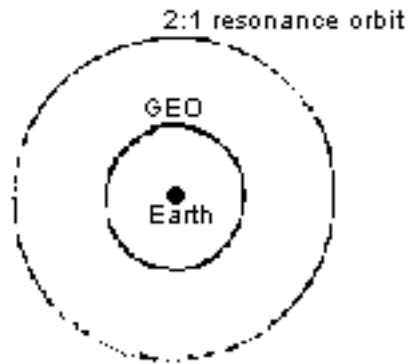
Both L1 and L2 orbit the Earth in the same amount of time that the Moon orbits the Earth. L1 and L2 serve as lunar-stationary or lunar-synchronous points in space, just like communications satellites in geostationary orbit stay above one point on Earth. This is because the Moon keeps one face pointed towards the Earth all the time (*i.e.*, its rotation period equals its orbit period exactly). In other words, if you're on the surface of the Moon and you look up at an object stationed at the L1 or L2 points, it won't move over time. Objects everywhere else in orbital space will move.

The Mass Driver, discussed in the lunar launch section, would shoot payloads to a Mass Catcher located at one of these two points. Lunar material can be shot off the lunar surface and into circular orbit around Earth

+ L2
 • Moon
 + L1

x L4

x L5



+ L3

without being placed in lunar orbit first, and rockets could head there, too. Likewise, a solar power station or giant mirror system at these two points could service the lunar surface during most of the long lunar night by beaming down energy, light and warmth at night, in a longer term scenario. In reality, stationkeeping would be required to keep an object at L1 or L2 due to the effects of the Sun’s gravity. The fuel propellant required for stationkeeping would be small.

The rest of this article covers the physics, not the relevancy, of the L1 and L2 phenomenon, as well as the L3, L4 and L5 points, for those who are curious to know. Notably, L4 and L5 are two candidate regions for emplacing industrial facilities in high Earth orbit. Indeed, a famous space advocacy organization promoting asteroidal and lunar materials utilization called itself the L-5 Society. These points are also called the LaGrange points (after their mathematical discoverer) or the “libration points”.

2.4 The physics of L1, L2, L3, L4 and L5

L1 and L2 are two unique points caused by the interaction of the Earth’s and Moon’s gravities. They are also shown in the following chart, along with L3, L4 and L5.

The L1 point is where:

$$\textit{The Earth’s pull} = \textit{the Moon’s pull} + \textit{the orbital centrifugal “force”}$$

When an object placed between them is balanced by two pulls in the two directions, it's as if the object is balanced at the peak of a hill. A nudge one way or the other would cause the object to fall inward towards Earth or outward towards the Moon. (It's actually a little more involved than this in that nothing falls straight down in a three-body rotating system, but you get the idea.)

The L2 point is another place where you can place an object and it will always stay there if balanced perfectly. The cause of the L2 point is:

$$\textit{The Earth's gravity + the Moon's gravity = the orbital centrifugal force}$$

The L3 point is simply the place in Earth orbit opposite the Moon which orbits the Earth in the same period of the Moon. It has no relevant economic potential (unless you never want to see the Moon for some reason).

The L4 and L5 "points" actually denote the centers of two regions – objects will tend to drift around these two points in erratic orbits (appearing to orbit the empty points in a noncircular and nonelliptical shape), without leaving the L4 or L5 region, and without requiring much stationkeeping propellant to stay in the region. The L4 and L5 points are located in Earth orbit 60 degrees in front of and 60 degrees behind the path of the Moon around the Earth. What happens is that when the Moon accelerates/decelerates objects in L4/L5 region, it changes their centrifugal force relative to Earth and hence their orbit around Earth, causing them to climb away from or fall towards Earth, in which case their orbital speed decreases or increases as they climb away or fall towards Earth, and as a result they fall behind or pass up the L4/L5 point and the cycle repeats. (Another way of looking at this is that an object placed at L4 or L5 orbits the center of mass of the Earth-Moon system in one month.) Like everywhere else, the Sun's gravity perturbs objects in the L4 and L5 points so that it's not a perfect picture, but it's fairly close.

In the 1970s, many people saw the L4 and L5 regions as favorable for placing industry to process asteroidal and lunar material, and space colonies as well, because they all stayed in proximity to each other, unlike objects in different orbits outside this zone (unless the latter are all in the same orbit and just strung out in a circular curve), and stayed "close" to the Moon in terms of energy. Whether or not space industry is located at L-4 or L-5 is a minor issue. Space industry could be located in most any Earth orbit. But the L-4 and L-5 points are referenced by many studies as candidate sites, hence their discussion here.

Different studies put the manufacturing facilities in different places, *e.g.*, in a high orbit or an L point. Few put them in a low Earth orbit, due to the energy required to bring asteroidal materials down. Only some finished products come down. Wherever the industry is located, the initial large colonies will be located nearby.

3 Near-Term Vehicles

3.1 Chemical rockets

3.1.1 Introduction to chemical rocket transportation

Rockets are the main propulsion system man has used in space to date. We use rockets to get off of the Earth, to go from one orbit to another, and for satellite stationkeeping and maneuvering. One of the first products to be made from asteroidal and lunar materials will be fuel. This fuel will be used to transport the asteroidal and lunar materials back to Earth orbit, as well as to sell in low Earth orbit for moving satellites around (*e.g.*, from low Earth orbit to geosynchronous Earth orbit). This is a product which is easy to make from asteroidal material, and mostly if not all from lunar material as well.

For example, the Shuttle goes only to a very low Earth orbit. For launching to geosynchronous orbit, much more fuel is needed. Indeed, if a satellite is launched in the Space Shuttle to low Earth orbit and relaunched there to go to geostationary orbit, two thirds of the cargo in the Shuttle's payload bay is fuel and only one third is the satellite. By providing fuel from the Moon and asteroids, we triple the payload capacity to low Earth orbit, thereby allowing larger, more competitive communications satellites and future services. For satellites, we will eventually be able to offer lower overall delivery costs per satellite and make a sizeable profit.

Alternatively, once in space, there are better means of propulsion than chemical rocketry which promise to be significantly less expensive over time for hauling large quantities of goods. However, in a near-term program we could assume that we will be using old fashioned chemical rocketry. It is not necessary to base a near-term

scenario on new propulsion technology, though it may be advantageous to use one of the simpler technologies discussed in PERMANENT for interorbital transportation, *e.g.*, steam rockets or ion drive.

Once we start to industrialize space, we will surely assemble large "space trucks" in low Earth orbit to haul payloads around space much more efficiently, using something else besides chemical rocketry. But for now we could assume we will be using chemical rocketry in the first stage of large scale space development.

A rocket is a device that burns fuel for propulsion. The fuel burn is a chemical reaction between a "fuel" and an "oxidizer". There are three kinds of chemical rocket:

1. Two liquids from two different tanks, *e.g.*, liquid hydrogen (fuel) and liquid oxygen (oxidizer), are piped into the combustion chamber at a high rate using high performance fuel pumps where they mix and combust. An example is the Space Shuttle's main fuel tank, which actually has two tanks within it, a hydrogen tank and an oxygen tank. Two liquids in two different tanks is the most common form of chemical rocketry.
2. Two chemicals are mixed already in liquid form in one tank and just need to be pumped into a combustion chamber where they are heated. This is possible if the two chemicals combust only at high temperatures and mix with each other well at low temperatures.
3. The two chemicals are solid and are not pumped. The fuel is located in the combustion chamber, *e.g.*, a very long cylinder with a thick lining of fuel on the inside, making a long hole in the middle with an opening on the nozzle end (similar to "bottle rocket" fireworks). The two chemicals are usually mixed with a third material which controls the rate of burn. The burn starts on the inside of the cylinder and uniformly (more or less) burns its way out. An example of this are the Space Shuttle's two long, narrow solid rocket boosters which detach after the first few minutes of flight (after which the main fuel tank powers the Shuttle to orbit using two liquid fuels).

Rockets are known to be dangerous. They depend on a controlled explosion. For Earth launch, they depend upon very high thrust due to Earth's strong gravity and the weight of the vehicle plus the payload plus fuel to be used later in flight. This is why the Space Shuttle uses two solid rocket boosters. (It was a solid rocket booster failure that destroyed the Space Shuttle Challenger.) Fortunately, for use in space, rockets are much less dangerous. The thrust required to get off the Moon is very small compared to that on Earth. Moving from orbit to orbit can be done slowly and gently, which is why rockets in orbital space very rarely explode. Launching off of an asteroid is practically the same as doing an interorbital maneuver.

For example, when we launch the Space Shuttle, the cargo makes up only about 2% of the total. The fuel and the vehicle make up the majority. When you look at a rocket on Earth's surface, you're looking mostly at fuel and vehicle, with a little payload on top. In contrast, for the vehicle that lifted the Apollo astronauts off the Moon, the fuel required was so little that it fit in a corner of the vehicle and the fuel tank could have served as a chair.

The key to space development using asteroidal and lunar materials is the ability to make the fuel propellants from these materials, rather than blasting the fuels up from Earth.

The Moon has plenty of oxygen, which makes up 86% to 89% of oxygen-hydrogen rocketry, as since lunar dirt averages 44% oxygen bound into minerals. Extracting this oxygen from lunar soil is fairly simple, and the processing schemes generally aim to produce other useful materials, too. The hydrogen is rare on the Moon except at the lunar poles where it exists in extremely cold form. Many asteroids are rich in frozen water, and oxygen-hydrogen rocket fuel is readily producible. Asteroids are also rich in carbon, too, which can be used in rocket fuels, *e.g.*, hydrocarbon fuels.

Many lunar development schemes propose using substitutes for the hydrogen, *e.g.*, powdered aluminum, which would still be mixed with oxygen for combustion. Aluminum powder based engines have been researched dating back to the Apollo days when NASA planned to develop the Moon, but the technology hasn't been developed yet for in-space applications and indeed has been shelved without an application in today's Earth launch world. The following are details of producing fuel propellants from asteroidal and lunar materials.

3.1.2 Asteroidal fuels

The first step in production of hydrogen and oxygen is extraction of water from the asteroid. All that's needed is to deploy a solar oven, *e.g.*, an array of foil mirrors focused on a tank. Asteroidal material is put in the tank and heated. Water, free hydrogen, compounds of carbon (*e.g.*, carbon monoxide, carbon dioxide, and various hydrocarbons such as methane), sulfur and a few other gases are liberated by the heating. Pipes from the oven lead to a series of very cold tanks in the cold shadows of space, which trap the volatiles in tanks. Since they liquify at different temperatures and pressures, they are easily separated from each other.

This method should produce enough free hydrogen and free oxygen to fuel the return spacecraft. If not, then the water can be split up into hydrogen and oxygen by electrolysis, again an old technology. If desired, hydrocarbon fuels can be collected and used, or manufactured from the hydrogen and carbon. This is all such simple and old technology that little further research is needed to establish this as an option.

3.1.3 Lunar Chemical fuels

With the apparent recent discovery of water in permanently shadowed craters at a lunar pole by the Clementine 1 and Lunar Prospector probes, oxygen-hydrogen rocketry would be feasible from the Moon, which would make lunar resources much more attractive economically. The same means can be used to produce rocket fuel from water as is discussed for asteroids.

(There are tradeoffs in building a big solar oven in zero-gravity around an asteroid vs. the surface of the Moon, plus heat sink issues for the tanks, and rotation of the Moon, but these seem like minor issues. The lunar craters are extremely cold since they never get any sunshine, which calls for research and development on equipment operating in that environment.)

There is considerable research going into producing lunar fuels. The Space Engineering Research Center (SERC) is contracted to NASA to help select <http://scorpio.aml.arizona.edu/lunar.html>; the most advantageous technologies for extracting oxygen and other useful materials for a lunar base, as well as test rocket concepts using hybrid rocket propellants from lunar materials <http://scorpio.aml.arizona.edu/hybrid.html>; (which are sometimes applicable to asteroidal materials as well).

ERC also produced a little laboratory electrolysis plant to produce oxygen from solids, and is progressing towards a space qualified design. "This unit, called MOXCE <http://scorpio.aml.arizona.edu/MOXCE.html>, is capable of producing 0.1 kg of Oxygen per hour and has proven extremely rugged. At this time a second generation plant, called MOXCE2, is under development."

A good theoretical discussion of the performance of various chemical rocket propellants is given in a paper titled *The Power to Go Beyond* <http://scorpio.aml.arizona.edu/nasa1.html>; by the NASA Lewis Research Center, and discusses some lunar (and Martian) propellant alternatives.

Notably, there's an analysis on sulfur-based fuel propellants <http://lib-www.lanl.gov/la-pubs/00326042.pdf>; by Steve Howe of the Sandia National Laboratories. Sulfur is abundant on asteroids (some very high in iron sulfide, aka "troilite"), and might be abundant in spots on the Moon. On some mineralogically interesting asteroids, the sulfur may be the most expendable material.

3.1.4 Launching the first missions with present day Earth rockets

An interesting paper was presented at the 1993 Princeton Conference entitled "Early Lunar Access" (bib-c-S9.htm#1104) on using existing transportation systems to return crews to the Moon before the end of the century for starting a permanent, expandable lunar outpost, using the Space Shuttle, or the Titan IV and/or Ariane V with the Centaur upper stage. The author, Paul H. Bialla of the General Dynamics Space Systems Division in San Diego, California, showed that the only significantly new development is a lunar excursion vehicle, which itself can be a derivative of the Apollo command module. Since the majority of the transportation infrastructure already exists, his approach is low risk and low cost. Since it takes significantly less fuel to go to an asteroid near Earth, we could pack more life support supplies and send people to an asteroid to start materials retrieval infrastructure instead.

3.2 Electric propulsion for inter-orbital vehicles

There are various ways of using electricity to thrust propellants, rather than using chemical explosion as in launch rockets. Electric thrusting of propellants is useful only for interorbital transportation, not launch from the Earth's or Moon's surface. There are two electric propulsion techniques used in space today:

- Some American interorbital satellites today use electric “ion drive” for stationkeeping. Ion drive is a simple and fairly mature technology. Ion drive can just as easily be used as the primary means of interorbital propulsion for delivering cargoes, and has been projected in future scenarios for space industrialization as a competitive kind of reusable interorbital vehicle. The Deep Space 1 probe, launched on October 24, 1998, was the first vehicle to depend upon electric ion drive for all of its propulsion needs, to perform a close flyby of an asteroid.
- The Russians have for at least 10 years been extensively using an electric propulsion technique called a “plasma thruster” which they have begun to market overseas. This thruster has been used on close to a hundred Russian military satellites, but is relatively unknown in the West.

The main advantages of electric propulsion are:

- It uses much less propellant than chemical rocketry (or, from another perspective, it gets much more mileage out of a given quantity of propellant)
- It could use 100/
- It may promise better reliability and simplicity than chemical rocketry

Its main disadvantages are:

- It requires an electric power plant
- It offers only low thrust propulsion, which means a longer time to deliver the cargo

For an analogy, chemical rockets are like express delivery via powerful and fast airplanes, whereas ion drive vehicles in interorbital space are like the big tankers on the oceans which deliver their cargo slowly but cheaply and safely via surface transport and more mundane technology. For missions to asteroids, it is actually advantageous to use a continuous, low thrust vehicle as this greatly expands the “launch window” period in which it is economically feasible to go to these objects, as compared to chemical rockets which impart short blasts of acceleration and deceleration. (This is also called a “thrust profile”.) Whereas chemical rocketry uses a chemical reaction and controlled explosion for thrust, electric propulsion uses electricity to accelerate the propellant out of the thrust chamber. Unlike chemical rocketry, there is no chance for an explosion with ion drive. Ion drive is much safer and a simpler technology, and has no relation to chemical rocketry at all.

Since electric propulsion vehicles use electricity, the vehicle must produce that electricity, typically by solar cell panels. In other words, ion drive vehicles are solar powered vehicles. The DS1 ion drive thruster is a 2.5 kilowatt device powered by a solar cell array.

Many studies into future large scale space industrialization base all interorbital propulsion on reusable electric propulsion vehicles, with chemical rockets being used only to launch material from Earth's surface to low Earth orbit, and from the lunar surface to lunar orbit, where the cargo is transferred to an electric propulsion vehicle for interorbital transport. However, some very conservative “immediate term” studies assume all interorbital propulsion is based on today's chemical rockets, *e.g.*, with oxygen and hydrogen extracted from asteroids or the Moon being used to refill the fuel tanks of the chemical rockets, which means no use of electric propulsion. That's because lunar and asteroidal materials can be used to refuel today's hydrogen-oxygen chemical rockets with no design modifications at all, whereas large scale electric propulsion vehicles would need development of vehicle designs.

For a comparison between electric propulsion and chemical rocketry in the mainstream studies: Chemical rockets consume 8 TIMES as much fuel propellant than electric propulsion for the same service. The cargo-to-propellant ratio from low Earth orbit to high Earth orbit is around 4:1, round trip, with ion drive vehicles refueling in high orbit where lunar or asteroid derived propellants are tanked. In comparison, for today's chemical rocketry used for transporting satellites from low to high orbit, it's a 1:2 cargo to payload ratio (not 2:1, but 1:2), and the vehicle goes on a one-way trip, being discarded afterward. Ion drive ejects its propellant at a speed about 15 times that of chemical rockets, hence imparting 15 times more momentum per unit mass of propellant. However, the ion drive vehicle is heavier than a chemical rocket vehicle due to the electric power plant so that the performance comes down to about 800/

(Notably, in a few studies, the propellant for ion drive vehicles is stated to be pure oxygen from the Moon or asteroidal material. This is a highly questionable assumption. Oxygen presents several problems for ion drive, as discussed later. However, other lunar and asteroid derived propellants should work fine. Also, oxygen should work in the Russian plasma thruster.)

One reason why only chemical rockets have been used in space for propulsion to date (except by the Russian military, addressed later) instead of ion drive is the continued lack of basic infrastructure in Earth orbit – there is no reusable interorbital vehicle service in space at all. To date, the interorbital vehicle has always been launched with the payload and thrown away after it delivers its payload. To date, ion drive has been used only for stationkeeping propulsion once the satellite is delivered and its solar panels deployed. Hughes Space and Communications Company is starting to market an ion drive system as an interorbital upper stage, as covered at the end of this article. Nobody is yet marketing a reusable interorbital vehicle, whereby we just launch up fuel tanks and dock for fuel and payload transfer.

It is hoped that the DS1 mission will stimulate more interest in ion drive and electric propulsion in general, perhaps leading to a commercial venture to offer interorbital services via a reusable interorbital vehicle. These services could include hauling satellites from low orbit to geosynchronous orbit, moving old satellites to new orbits, and refueling and maintenance of satellites in orbit. Future satellites could be designed for interaction with such interorbital infrastructure, though this is a chicken-and-egg situation that must be overcome by broad industry recognition.

The Russian plasma thruster is used primarily on military satellites (*e.g.*, space based radars), and their commercial space program has struggled to get onto its feet after the massive Cold War subsidization of their military program waned. The Russian plasma thruster is a well developed and very efficient engine, and is seen as one of the potentially most valuable exports in their space program. The Russian plasma thruster is seen by many in the Western space program as an unusual technology, but its efficiency and reliability in space for more than 10 years on nearly 100 military satellites makes it a very well proven piece of flight hardware.

DS1 is a step in the right direction to gaining acceptance of electric propulsion in the west, by using ion drive to get from Earth to an asteroid. A big part of the DS1 mission is simply to demonstrate and analyze the ion drive propulsion system in space. DS1 will carry a set of sensitive instruments to analyze the effects of the ion drive's propellant on the spacecraft and its local environment, and how well the drive is working as an engine. It's expected that when this mission is over, its "NSTAR" ion drive engine will be a proven and well understood piece of hardware which can be used by anyone for a primary means of interorbital propulsion.

3.3 Lunar and asteroidal propellants in electric propulsion

The Russian plasma thruster can use most any propellant in the thrust chamber, including oxygen. However, some studies propose using oxygen as a source of propellant for ion drive as well. This is questionable. The main issue is the effects of ionized oxygen with the thruster materials (cathode, neutralizer, filament grids) of the ion drive engine. The thruster would need to either be made of different materials than today's ion drive engines and/or have easily replaceable parts, neither problem being easily solved. A thruster design such as the German RIT10, which uses RF energy instead of a cathode to ionize the gas, may be the best present day design to start to consider for oxygen use. A second issue is that oxygen is not easily ionized, which means lower electrical efficiency. Thirdly, ion drive works best with heavier elements. Overall, oxygen does not look attractive for ion drive interorbital propulsion. (For satellite stationkeeping, the effects of ionized oxygen on the satellite would

preclude its use.)

Xenon is the most popular propellant for ion drive today since it is a heavy gas (high atomic mass) that is easily ionized. Argon and mercury have also been used. Xenon and argon are inert gases which are not expected to be recoverable in useful quantities from the Moon and asteroids. The best candidate fuel for ion drive using lunar or asteroidal materials may be sodium, which is fairly abundant in some nonterrestrial materials, extractable without very much effort, easy to store and handle, and would work well with ion drive – easily ionized, not damaging to the engine materials, and a relatively heavy element.

The Russian plasma thruster is different, and probably could use oxygen. It uses a separate, external cathode discharge and has no grid, so you can run just about anything you want through the thrust chamber, and use about 5/chamber. JPL has done some preliminary work in the area and hasn't found any show-stoppers.

3.4 How an Ion Drive Works

Ion drive thrusters use an electric field to accelerate charged atoms or molecules (*e.g.*, oxygen) to a high velocity as they are expelled out the thrust chamber, thus accelerating the spacecraft.

Ion thrusters generally use a cathode (a negatively charged grid similar to that found in a tv set) to generate a stream of electrons, which form an electric circuit with a positively charged ring - the anode. This stream of electrons is used to ionise the propellant. A small magnetic field is used to aid this process (electrons spiral around the magnetic field lines, increasing the chance of electron-atom collisions). The magnetic field may derive from either a permanent magnet or an electromagnet.

The ionised gas drifts towards an extraction grid system (two or three plates with many small holes in them, held at high voltage) where they are accelerated out of the thruster, so producing thrust. A neutraliser similar to the cathode is used to generate free electrons and balance the overall space charge in the outgoing beam so that the spacecraft doesn't charge itself up.

The electric power comes from a solar cell array. Of course, in orbital space, there is no air drag or weather forces, so the solar cell array doesn't need to be aerodynamic at all. Since the ion drive vehicle is relatively low thrust, the structural strength and mass can be low as well. For example, in a General Dynamics report: "The solar array performance was conservatively assumed for sizing purposes to be 150 watts/kilogram" based on a very conservative assumption of solar cells having only 7%/converting electrical energy into beam kinetic energy was 63/some ion thrusters today produce efficiencies between 70/

Ion thrusters are modular. If you have more cargo or want to speed up your mission or slow it down to conserve fuel, then you can add or subtract thrusters and solar cell array units.

Ion drive engines have long lives, being subject to a much less stressful environment than chemical rocketry. Ion drive engines are also easier to work on, consisting of simple electrical components, in contrast to the high performance mechanical pumps bolted into chemical rocketry.

Ion drive was developed in laboratories in the 1960s, and there were the SERT1 and SERT2 experiments in space which proved that the drive would work in space for long periods of time and deliver significant propulsion to a spacecraft. When the space program shrunk due to poor political leadership after the Kennedy-Johnson era, ion drive was one area that saw research and development wane. However, some private communications satellites in geosynchronous orbit incorporated ion drive into their stationkeeping system once the satellite was delivered there by a chemical rocket and its solar cell array deployed to power the ion drive engine.

The NASA Lewis Research Center is developing a lower power version (about 700 Watts) of the DS1 NSTAR ion drive engine system. However, large scale space industrialization will use larger ion drive engines, or else many low power units together in a modular craft, the latter offering spacecraft security in case an engine or two fail.

In any case, ion drive is looking as if it will become a routine means of interorbital propulsion within the next 5 years for low cost scientific missions as well as some kinds of industrial missions.

3.5 Hall-Effect Stationary Plasma thrusters (Russian-French)

In the 1990s, an electrically powered propulsion technology used by the Russians was marketed outside of Russia, particularly in France. It was kept fairly confidential by those interests, but was referred to by various names,

e.g., the Russian Stationary Plasma thrusters, the Hall-Effect thrusters, and the Russian Anode Layer thrusters. Then came the announcement of the European SMART-1 probe to launch in October, 2002, to demonstrate this technology in a lunar orbiter probe. The home page for SMART-1 is sci.esa.int/smart-1/ but skip over to the subpage sci.esa.int/content/doc/10/2320_.htm for a good description.

The following explanation is a 1990s quote thanks to John Schilling (schillin@spock.usc.edu) of the University of Southern California's Aerospace Engineering:

"The thruster consists of a cylindrical chamber 10cm in diameter with a central spike. Both spike and cylinder are made of ferrous material, and incorporate magnetic windings so as to create a transverse (radial) magnetic field across the exit. The walls are insulated, the base serves as an anode."

"External to the thruster is a separate, hollow, cathode. About 95% of the propellant (currently Xenon or Krypton) is metered into the thruster, and 5% between cathode and anode. As electrons are much lighter than ions, one would expect most of the current to be carried by the electrons, but that same lightness makes it hard for them to cross the transverse field across the thruster exit. Some manage to trickle through anyway and keep the discharge running, but there is always a surplus of electrons hanging around outside the thrust chamber."

"This creates a strong electric field (~100 V/cm) which sucks out ions from the anode discharge region. Being fairly heavy, they don't so much notice the magnetic field, and with the field strength involved they end up moving at 15-25 kilometers per second. They pick up electrons from the accumulated surplus as they pass, not slowing for that any more than they did the magnetic field, and the resulting bulk-neutral plasma proceeds ballistically towards infinity." "Oxygen would be a less effective propellant than Xenon, but it would probably work. You'd still need 5% to run the cathode discharge on, but using 95%"

"The latest edition of Sutton's Rocket Propulsion Elements has a section on the Stationary Plasma thrusters, which is reasonably good."

3.6 MPD and other electric thrusters

Magnetoplasmadynamic (MPD) thrusters (aka magnetohydrodynamic (MHD) thrusters without the hydrogen association) and other kinds of electric propulsion techniques have been developed but not incorporated on spacecraft yet.

The page on the Southampton University MPD research and development (<http://www.soton.ac.uk/~aef93sa/mpdstuff/>) project describes the basics of the MPD thruster concept, gives a history of the Southampton Univ. Dept. of Aeronautics and Astronautics MPD project, references, and lots of pictures of their MPD thruster research and development, thanks to kind web work by Alexander Fitzhugh.

3.7 Mass driver not considered seriously

PERMANENT gets a lot of e-mail suggesting we cover using a mass driver for interorbital transport. Basically, the mass driver has merit for lunar launch but not interorbital propulsion, compared to alternatives, in a near-term scenario. The moving parts entail considerable risk. Overall, it's too complicated. For more information on a mass driver for lunar launch, however, see the section on long-term propulsion where we have a section on the mass driver [jt-massdr.htm](#).

3.8 Passing through medium Earth orbit radiation belts

A significant problem with interorbital transfer between low Earth orbit and high Earth orbit is the Van Allen Belt of trapped high-energy particles (*i.e.*, radiation) due to the Earth's magnetic field. The Van Allen Belt exists in a middle-level Earth orbit located below geosynchronous Earth orbit and above low Earth orbit. This radiation degrades the solar cells a little bit each time they pass through. This requires repair of the solar cells by an annealing process (heating and recrystallization) after a number of trips. Alternatively, interorbital vehicles could receive beamed power from a satellite stationed in high orbit, as discussed in the section on "Solar Power Satellites". A third option is to use nuclear electric vehicles.

The Van Allen Belt radiation affects only electric vehicles with solar cell arrays which are cycling between low Earth orbit and high Earth orbit. It will not affect cargos being hauled between two different high Earth orbits, or between the asteroids or lunar orbit and high Earth orbit.

3.9 Final words on electric propulsion

To date, the main drawback to electric vehicles has been the need to have an electric power plant. It is most attractive for fuel-efficient stationkeeping of satellites with sizeable electric power capacity, for deep space missions on a low budget which must get the most mileage out of their fuel, for satellites which already have sizeable power plant needs for other purposes (*e.g.*, Russian military space based radar), and in the future as a reusable interorbital vehicle. Notably, DS1 is demonstrating low mass/high efficiency solar panels that will make a 3 kW power plant within reach of most spacecraft. DS1 is not a big spacecraft, and the whole scientific mission which includes studying an asteroid is being accomplished on a nearly record low budget. However, it is debatable if electric vehicles are the most economical means of propulsion for purely scientific missions which don't otherwise need large quantities of electric power. Nonetheless, electric vehicles are attractive for interorbital haulers in a large scale space industrialization scenario.

3.10 Links to other websites on electric propulsion

Hughes Aerospace Company produces the Xenon Ion Propulsion System (XIPS)
(<http://www.hughespace.com/702prods.html>)

which was first used on their previous generation 601 satellites with great success, and is heavily marketed in their current generation 702 satellites. You can also see a diagram of the XIPS (<http://www.hughespace.com/xips.html>). Hughes claims that their latest model of the XIPS is 13 times more efficient than conventional fuel propellant. The following is paraphrased from their web advertisement: XIPS needs only 5 kg of fuel per year for stationkeeping, a fraction of what bipropellant or arcjet systems consume. As a customer option, using XIPS as an upper stage "to help raise the spacecraft into final orbit" can save even more launch mass. Customers can apply the savings in launch mass to launch additional propellant to prolong satellite service life, or to increase the satellite mass to enhance its revenue-generating potential. Or, the savings in mass can be used to shift to a less expensive launch vehicle. They also suggest that using XIPS could allow some customers to add another payload or two to a given launch vehicle.

It's worth mentioning that Hughes' leadership in space communications launched an entire industry communications satellites. Hughes launched the Early Bird satellite more than 30 years ago, the world's first commercial communications satellite. Since 1965, HSC has launched more than 100 satellites, more than 40/satellites currently in orbit – and achieved a 99/record. Hughes has boldly led the way without sacrificing reliability, and this is the case with ion drive as well.

The Italian CENTROSPAZIO (<http://www.centrospazio.cpr.it/Centrospazio2.html>) is conducting research in a variety of electric propulsion systems, including magnetoplasmadynamic (MPD) propulsion, arcjet propulsion, field emission electric propulsion (FEEP), and free electron drift propulsion (Hall thrusters). (Their vacuum facilities are also utilized for other research.)

3.11 Using Cold War Nuclear Missiles to Launch Peacetime Payloads

The Cold War came to an end in the 1980s, and it would be good to make sure it does not come back, at least not with all the ICBMs (InterContinental Ballistic Missiles) currently in launch silos. The Russians are in dire need of foreign cash and exports. Two things they can sell:

1. Launch of ICBMs from silos with the warheads removed, instead putting payloads into orbit; or
2. The rockets and/or engines from some of those ICBMs, to be launched elsewhere.

A typical Russian or American ICBM has substantial orbit launch capability. ICBMs reach about 98% of orbit velocity, and their wartime payloads are heavy. Many have multiple warheads ("RVs") on them (called

“MIRVs” – Multiple Independent Re-entry Vehicles) whereby the ICBM first reaches near-orbit velocities and then a vehicle (called the “bus”) carrying all the RVs, maneuvers around to put each RV onto its own precise target trajectory, releasing the RVs one by one. The total mass of the bus, its fuel, and the RVs is quite substantial.

I ran this past some Arms Control and Disarmament Agency negotiators, but their eventual response was that they didn’t want to add any complications to the disarmament process and wanted as many nuclear missiles turned off as possible in the shortest amount of time. I countered that simple perspective with proper national public relations campaigns, *e.g.*, using ICBMs to launch material as part of a PERMANENT program, a co-operative application that could speed up deep cuts in ICBMs due to broader based public support, even among the resistant conservatives on both sides who respond to nationalistic appeals like the space program. Also, colonies in space change some fundamental psychological paradigms on fighting over a limited Earth.

It’s fairly easy to imagine simply taking off the warheads and putting on useful payload, then launching from the missile silo. However, in the USA at least, there are range safety considerations. The engines of some of them could be taken off and moved to a safe launch site elsewhere in the world, or perhaps the entire rocket could be moved, but that may be prevented by legislation in order to prevent the government from undercutting support for private launchers under development. At the very least, selling the engines to the highest private bidders has not happened yet.

Nonetheless, something can be said for converting our military industries into space development industries, getting rid of the missiles, and putting those personnel back to work on greater things, especially in Russia where valuable rocket scientists are unemployed or underemployed (*e.g.*, selling trinkets on the streets).

The main objection to this scenario is that it could undercut support for developing new launch vehicles elsewhere in the world if the ICBM launch services were sold at under market price. In any case, it’s worth discussion and serious consideration.

PostScript: Since the writing of the above about 10 years ago, there have been quite a few analyses of using both Russian and US missiles for peaceful government and commercial launches, and assessing the potential costs and benefits to the commercial launcher market (*e.g.*, a regulated pricing system, including profit sharing with established launch businesses and their infrastructure suppliers).

4 Mid-term vehicles

4.1 Earth Launch by Present and Emerging Launch Vehicles

There are a large number of present launch vehicles (Shuttle, Ariane, Proton, Titan, etc.) made by various countries which use more or less the same launch technology. There are also current research and development programs using new technologies and techniques for reducing the cost of Earth launch, though there are no serious alternatives to chemical rocket launch in the near future. Covering these topics and issues is beyond the scope of PERMANENT, which focuses on utilizing materials already in space. Launching material up from Earth will be very expensive for the foreseeable future, which is why we need to utilize materials already in space, namely asteroidal and lunar materials. Nonetheless, two things are notable:

1. Current launch vehicles in the research and development phase could be scaled to launch payloads only to low Earth orbit. From there, a fleet of reusable interorbital vehicles would be waiting to lift cargoes up to higher orbits, *e.g.*, geosynchronous orbit. The interorbital vehicles would use fuels or propellants extracted from asteroidal or lunar material. Thus, small rockets could deliver satellites to geostationary orbit in conjunction with a reusable interorbital vehicle using asteroidal and/or lunar propellants.
2. We will need Earth launch vehicles to deliver the first seed industry to space to process asteroidal or lunar materials.

There are several papers on how we can use present day launch vehicles, such as the Titan IV, Proton, or Ariane, and/or slight modifications of the Space Shuttle (*e.g.*, the Shuttle booster but removing the returnable Shuttle and putting on a nonreturnable payload bay), to return to the moon or start to retrieve asteroidal resources. For example, see Andrew Petro’s paper reference (ref-so-5.htm#13). You can get a comparison of costs for Earth launch by present and planned launchers at <http://www.rocketplane.com/comp.htm>.

4.2 Interorbital aerobraking

In space transportation, there is no such thing as a “free downhill” because there’s no friction in space. It takes as much fuel to come down (and insert into a circular orbit) as it takes to go up. An exception could be if we use the Earth’s atmosphere for frictional braking. We do this when spacecraft like the Shuttle return to Earth. The Apollo program entrusted their heat shields and calculations for high speed encounters with Earth’s atmosphere. We’ve just never done this to brake an object in a transfer from one orbit to a lower orbit, whereby the object would pass through Earth’s atmosphere briefly one or more times in order to reduce fuel requirements in its orbital transfer. This would require an “aerobraking vehicle”, which would basically be a heat shield with the payload held safely within.

The heat shield would need to be able to withstand high temperatures and pressures. Unlike the reusable Shuttle, such heat shields may be “ablative”, *i.e.*, allow material to be blown off of them, this material taking away much of the heat as well. Heat shields for aerobraking may be expendable. We may not want to re-use it because that would require we spend fuel to raise it up to another high orbit. The idea is to save fuel this way, not spend it. However, fuel from space resources may become cheap enough to warrant re-use. Or, the heat shield could be used to export products to Earth’s surface. Indeed, one of the applications of aerobraking is sending fuel to low orbit to raise things up to higher orbits. Aerobraking shields can be made from asteroidal and/or lunar materials, as covered in the section on manufacturing refractory materials.

The main issue of aerobraking is safety. We would have to make it very safe so that there is practically no chance we will accidentally cause anything to hit a populated area on Earth, just like we have done for Apollo and every manned spacecraft over the past 35+ years. Objects must be small so that they are relatively harmless if there is a failure. Since the Pacific Ocean takes up almost a hemisphere, objects may aerobrake above that ocean rather than above land masses. A rapid deployment rocket must be available in case an orbital insertion rocket fails after a pass through the atmosphere, or if there’s a bad error on the way towards Earth. Objects can have self-destruct mechanisms if there is any failure at any time, *e.g.*, before entry, after the first pass, etc. For example, the payload can set to self-destruct automatically unless systems are operational and they get the command to not self-destruct. There can be multiple self-destruct mechanisms.

4.3 Interorbital light sails

Like wind, sunlight exerts pressure. This pressure is so “light”, or gentle, that humans don’t feel it. However, in orbital space, if you make a large sail out of thin aluminum reflective material, you can go places without any propellant, merely using the pressure of the sun. However, you need to control your sails so that you go where you want to go.

Going away from the Sun, you tilt the sail at an angle of approximately 35 degrees, since achieving a higher orbit is a combination of being pushed away from the sun and picking up angular momentum (orbital speed at the moment). You can go in towards the sun, too, by pointing your sails at an angle so that you slow down your orbital speed in order for the sun’s (or Earth’s) gravity to pull you inward. Thus, you have flexibility in maneuvering, assuming you have well designed sails.

Notably, going straight out from the Sun is not useful for achieving into a higher orbit, and just makes your orbit more elliptical, passing back through the point where it was when the sail was deployed. The component of force which increases angular momentum is what produces useful changes to orbital parameters.

The following links give information on Light Sails:

- U3P has a nice layman’s explanation of the concept of solar sailing as well as its scientific history, on their beautiful Solar Sails <http://www.ec-lille.fr/~u3p/> website, which also includes animations, images, specific papers and more web links. Also covers Znamya, the Russian in-space solar sail experiments. Multiple language translations. (U3P means Union for the Promotion of Photonic Propulsion.)
- Benjamin Diedrich’s Solar Sails <http://weber.u.washington.edu/~nebrich/solarsails/> page, which includes a great list of web links, books, articles and reports, and people, as well as explanations of the concepts (though not most basic).

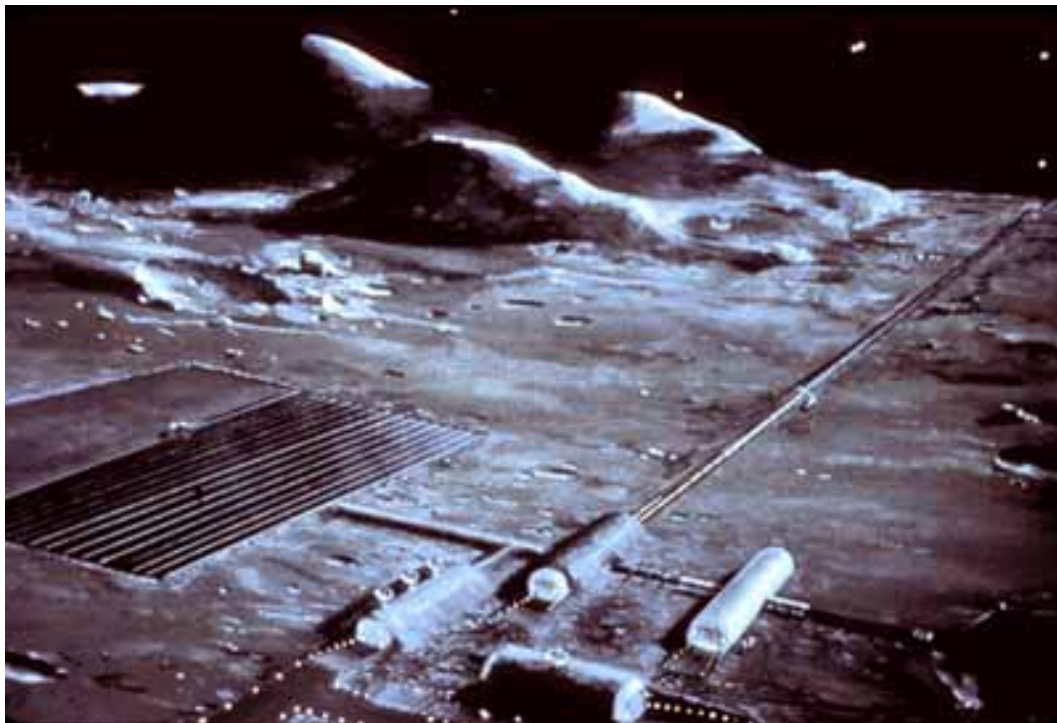


Figure 2: Mass driver on the Moon. Source (SSI) www.ssi.org.

- In addition to the Russian Znamya effort, commercial lightsails could come sooner than expected if the InterWorld Transport's Commercial Solar Sailing R and D Project <http://pw2.netcom.com/~a.differ/index.html> is commercially successful. This is a serious hardware project.
- Manfred Leipold has a Solar Sail page at the German Aerospace Center (DLR) <http://www.dlr.de/solarsail> The DLR has investigated the feasibility of solar sail technology and assessed several deep-space mission scenarios utilizing solar sail propulsion over the last 5 years. Recently, a feasibility study on a low-cost solar sail technology demonstration mission in Earth orbit was conducted cooperatively by DLR and NASA/JPL (Jet Propulsion Laboratory). Currently, a breadboard model of a fully deployable sail structure is being developed for ground demonstration purposes and testing on a co-funding basis between DLR and ESA.
- A UKSEDS (U.K. Students for the Exploration and Development of Space) page entitled The Microlight Solar Sail <http://www.gbnet.net/orgs/seds/sail.html> talks of past and potential student projects. (SEDS is Students for Exploration and Development of Space.)
- The physics of solar sailing <http://caliban.physics.utoronto.ca/neufeld/sailing.txt> is also discussed in a page by Christopher Neufeld (Canada).

4.4 Lunar launch by Mass Driver

The “mass driver” is a “catapult” tube which launches materials from the lunar surface to a Catcher/Collector, perhaps near a factory in orbit near the Moon. The mass driver is like a gun without the explosive gunpowder. It is powered by electricity, producing magnetic fields to accelerate cargoes through an accelerator tube. No fuel propellant is required for lunar launch, and there's no big vehicle to launch. The mass driver shoots a large number of small payloads, continuously, rather than an occasional large payload.

The mass driver will eventually become the main means of supplying material from the Moon to industry in orbital space, though not in the early years of space development. It can help preserve the lunar environment by reducing the creation of a tenuous atmosphere from rocket fuel propellants, and it saves on the consumption and costs of producing fuel propellant. It can be argued that the mass driver can ship materials in much larger volumes than is feasible by chemical rocketry, and at lower costs per unit mass.

The “mass driver” has been a popular lunar launch concept, largely due to promotion, research and development by the Space Studies Institute (SSI). A laboratory prototype of the accelerator section has been built and tested successfully by SSI.

Powered only by electricity, it is a solar powered launcher using the principle of electromagnetism to magnetically accelerate a payload equipped with a magnetic bucket to escape velocity.

It has been argued that the mass driver is a relatively inexpensive and automated device to create a stream of material at the rate of up to a few small packages per second, depending upon design. Total amount of material deliverable each month could dwarf any feasible lunar or Earth launch capacity by rocketry, in terms of tonnage of payload launched.

As it is covered most prevalently in the literature to date, minerals mined and processed are packaged in a thin glass/fiberglass bag easily manufactured using lunar materials. The bag is made to conform to the shape of the bucket so that the bucket assumes the stresses during acceleration, whereas the package contains the minerals after acceleration and snapout from the bucket.

By the time the payloads climb up out of the Moon’s gravity well, they have lost most of their velocity and are travelling slowly. At this point, the orbital-based catcher collects them. The payload material’s momentum carries it through the funnel-shaped catcher into a collector bag. After the bag fills up, it is detached from the funnel and is replaced by an empty bag.

The mass driver accelerator tube would be less than 200 meters (600 feet) long and probably about half a meter wide, though downrange trajectory correction equipment will probably be worth the cost. The mass driver would fit into only one Shuttle cargo bay, disassembled, not including power plant, material handling apparatus, and fuel for delivery. The electric power plant size determines the launch RATE, not ability – a small rate initially, increasing permanently with more power modules and support apparatus.

Unfortunately, the mass driver is feasible to operate only on the Moon, because it needs vacuum. A mass driver operating on Earth would cause meteoric friction heat to such hypervelocity payloads and great physical stresses, at the dense bottom of Earth’s atmosphere (ocean of air) as they left the catapult tunnel. Secondly, the air would aerodynamically deflect such objects in unpredictable ways which would disperse their trajectories. Thirdly, an operable mass driver on Earth would require a long vacuum tunnel (much longer than on the Moon, since the escape velocity is higher). Fourth, the air would create hypersonic sonic boom shockwaves that would be loud for a long distance. Fifth, individual payloads would have to be massive enough to punch through the atmosphere in an acceptable way. Such massive payloads demand a lot of the catapult as well as the orbital based catcher/collector. In contrast, the Moon has no air and low gravity.

The orbital-based Catcher/Collector would be located in lunar-stationary orbit (the “L-2” or “L1” point), where it would collect the stream of numerous small payloads after they slowed down in climbing up in the Moon’s gravity well. Various catcher/collector designs exist.

Pollution of space should be avoided, so the containment of material is important. If a package misses the catcher, it should return to crash on the Moon, not orbit Earth. This must be built into the trajectory design.

A number of bottom-line facts about the mass driver for space transportation:

- It is a relatively simple and automatic device to operate.
- There is little significant mechanical contact between parts *e.g.*, no fiery fuels, no hi-speed fuel pumps, no rubbing components, no lubricants, etc.)
- The mass driver operates at humanly temperatures.
- Maximum forces are measured in hundreds of pounds, not thousands of tons. (Rockets lift ONE payload of several tons plus fuel and vehicle, for a few minutes each month, whereas the mass driver lifts only a kilogram or so at a time but for the whole month.)

- The mass driver can potentially catapult thousands of tons per month. That would take numerous rockets of revolutionary size launched per month.
- The catapult-to-payload ratio is about 1 : 10,000 over its lifetime. Each rocket has about a 1 : 1/2 vehicle-to-payload ratio at best, plus a 1 : 1/50th fuel-to-payload ratio.
- The mass driver requires no fuel propellants, and is “fully reusable”.
- The mass driver is made of a small variety of parts, all simple and repeated in a modular way which expedites simple replacement and maintenance using a small stock of spares in case of a small failure. It is a lightweight device, which makes stockpiles of spare parts are relatively inexpensive; all of which are attractive features of a device operating in a remote place like the Moon.

The mass driver, as you can see, is an entirely different kind of launching device.

With the advent of space-based industry and the demand for products and materials, the small step of basing a mass driver on the Moon will be a giant leap for the eventual low cost transportation of material to space, and will make the Moon more competitive as a source of materials compared to asteroids.

However, it is my opinion that the mass driver will not be used until large scale space infrastructure has been established. It is my opinion that a successful, privately funded investment into lunar materials would need a strong case for the reliability of the mass driver before it would use or invest in development of a mass driver over chemical rocketry. If the mass driver in its popular implementation – pull-only with no magnetic levitation guide strips – were put on the Moon and something went wrong with the launch so that the bucket coil scraped along the wall of the tunnel at anything near its terminal velocity (2.4 km/sec), the mass driver could sustain major damage, delaying delivery of material for a significant time unless there were good repair infrastructure already emplaced. This is a risk issue for private investors. Before the mass driver is developed further, a good, peer reviewed case must be made for its reliability. Notably, a safer, more robust design may be more attractive, e.g., using magnetic levitation guide strips, even if it’s significantly less efficient and more expensive.

In comparison, chemical rocketry has its risks in terms of rocket engine failure. Regarding the latter, rockets for launching off the Moon are significantly safer than rockets launching off of Earth because the Moon’s gravity is much less. The lower gravity has a compounding effect: rockets on Earth have far more fuel than payload (e.g., 50 times more fuel weight than payload) – fuel for later in the flight – which means the Earth rocket must launch a much heavier mass than its payload. The rocket engines on the Moon need not be the very high performance ones as on Earth, and the stresses are much less.

Work to date has emphasized the mass driver acceleration coils, in order to reduce the size of the acceleration section to, say, 160 meters. No laboratory work has been performed yet on any other element, e.g., assuring the precision required to hit the Mass Catcher in orbit, though many paper studies have been performed. Notably, many designs call for the buckets to be recycled, which would reduce the cost of manufacturing bucket coils for every payload or returning bucket coils from orbit to the Moon, e.g., by chemical rocketry. If this approach was adopted, the bucket coils would need to be recycled, which gets into the very risky business of diverting high speed objects into a deceleration tunnel in a precise way, and decelerating them properly. One alternative is to launch large payloads so that manufacturing or returning bucket coils becomes economically feasible, which goes counter to many designs of mass driver to launch small payloads and keep the launch tube short and lightweight. I’ve not seen a good analysis of potential failure modes or remedial actions.

In the long term, a mass driver is preferable in order to preserve the Moon’s environment. The Moon has sufficient gravity to retain an atmosphere, and chemical rocketry launches could create a significant atmosphere which would take many years to dissipate if we were to later cut back dramatically on rocket operations on the Moon.

Explanations of the mass driver as developed by SSI are on the following pages. However it’s worth noting that I have worked on electromagnetic launchers for the Pentagon in the Star Wars/SDI program (largely reviewing and assessing the different concepts for SDIO decisionmakers), and there are a few interesting alternatives to the prevalent “coaxial” mass driver developed by SSI.

4.4.1 How the mass driver works

The mass driver works by the magnetic attraction between electromagnets. One electromagnet is the bucket coil, and the other electromagnets are the drive coils.

What is an electromagnet? Electric current in a coil of wire always produces a magnetic field, called an electromagnet, which behaves basically just like a bar magnet, except for the fact that an electromagnet can be made to be stronger than a bar magnet by increasing the electric current through the coil.

By proper orientation of the poles, a bar magnet and an electromagnet can be made to attract or repel each other. Similarly, two electromagnets can be made to attract or repel each other and hence accelerate towards or away from each other. Which side of an electromagnet is the north pole depends on whether the electric current is clockwise or counterclockwise through the coil of wire.

The mass driver works by two electromagnets being attracted to each other and hence causing acceleration. One coil is smaller than the other, and passes through the center of the larger coil. The larger coil is the “drive coil”, anchored down to be stationary, and the smaller coil is the accelerated “bucket coil”. The mass driver is a tunnel of numerous drive coils accelerating a bucket coil. The bucket coil pulls a bucket of material with it.

The drive coils are not always turned on. Each drive coil must turn off its electric current when the bucket passes through its center in order not to slow the bucket coil back down on the other side by the same attractive force. Secondly, each drive coil turns on only when the bucket coil is close enough to feel the pull significantly (in order to save power), and turns off when the bucket coil reaches about the center of the drive coil. Thus, each drive coil gets only a pulse of current, when the bucket coil is closely in front of it, and must be off when the bucket coil is behind it.

The bucket coil always has current. What the bucket coil “sees” as it travels down the tunnel of drive coils is a series of dead drive coils each of which suddenly turns on quickly when the bucket is very close, and then turns back off by the time the bucket coil passes through the exact center of the drive coil. This happens for each drive coil in sequence as the bucket flies down the tunnel of drive coils, picking up more and more speed.

This version of “coaxial” mass driver is called a “pull-only” mass driver, because the bucket is pulled by magnetic attraction but is not pushed by magnetic repulsion. Other versions exist, such as pull-push, which we won’t consider here. With the pull-only mass driver, no mechanical guidance means is needed to keep the bucket from crashing into a drive coil because the pull-only magnetic field of the drive coils strongly forces the bucket to levitate along the center of the drive coil tunnel. The drive coils are side by side; in fact, and the next can turn on before the previous one turns off.

The technical details of the mass driver won’t be discussed in this nontechnical brief (e.g., drive coil kilohertz halfwave power pulsation, capacitors, bucket current induction, etc.). Suffice it to note that a prototype mass driver accelerator tube was built and tested successfully by the Space Studies Institute of Princeton, N.J., with lunar duty as its objective, and produced an acceleration 1,800 times Earth’s gravitational acceleration. A lunar-based mass driver accelerator can be built using present-day off-the-shelf technology, but other parts of the mass driver need to be developed.

4.4.2 Operating the mass driver on the Moon

After lunar soil is excavated, transported, refined using simple conventional means, packaged, weighed, and made to be of precise weight (e.g., added molten glass weights). The packages are loaded into buckets with bucket coils. The buckets are emplaced in a special device in front of the first drive coil, and current is induced in the bucket coil.

The drive coils are fired in sequence, with the aid of “electronic eye” sensors to trigger the drive coils and monitor the location of the bucket for adjustment in timing if necessary. The drive coils induce further current in the bucket coil. After the bucket leaves the accelerator section, it is travelling at lunar escape velocity. Even though the mass driver is horizontal, the bucket and payload would not fall to the ground because of its high speed and the Moon’s curvature and low gravity. Immediately after the acceleration tunnel is a payload snapout and bucket diversion section, where the bucket is magnetically decelerated to separate it from the payload (which isn’t decelerated and hence leaves the bucket behind) and to make the decelerated bucket fall downwards in the

lunar gravity to a lower tunnel track to get out of the way of payloads coming behind it. Magnetic levitation guide strips will be required here.

The bucket is then decelerated magnetically on the lower track and returned on a parallel track to be reloaded with another payload. The mass driver's deceleration section converts the bucket's momentum back into electrical energy as it slows it down, by "regenerative braking", using the same fundamental principle as electric generators. In fact, the decelerator is a generator while the accelerator is a motor (a linear motor instead of a rotational motor). By getting electrical energy back out of the bucket's momentum, the overall efficiency of the mass driver remains between 70% and 90%, depending on the details of the design. In the deceleration section, the bucket requires magnetic guide means to prevent it from striking a drive coil. The well known principle of magnetic flight (*i.e.*, passive magnetic levitational guide strips) would prevent any mechanical rubbing.

Very important is the need for payloads leaving the mass driver to have precisely the same velocity so that they all go to the same place in orbit and so that the catcher/collector can be of reasonable size. Very small variations in speed or significant lateral velocity can make payloads miss the catcher/collector. Thus, it is desirable to have a way of correcting trajectories after payload snapout from the bucket.

Downrange trajectory correction stations are possible for a horizontal mass driver. Several methods have been proposed for both trajectory determination and correction. Trajectory determination can be done by radar or laser ranging. Trajectory correction may be achieved by electrostatic means, or puffs of air, or by striking the side, front, and/or back of the payload with a low power laser or particle beam to boil off a thin layer of the payload's outer skin to create an action-reaction impulse sufficient to prevent the payload from missing the catcher/collector in orbit.

It's important for the mass driver to maintain consistency so that payloads all go to the same point. It may not be necessary to predict that precise point in advance and then try to adjust the mass driver, but it is important that the mass driver be consistent wherever it may be firing payloads. Once the mass driver starts shooting payloads, it may be necessary to move the catcher to adjust for design imperfections in the mass driver. In other words, instead of putting the catcher at the ideal point and then working to make the mass driver shoot that point, we would just shoot the mass driver and then move the catcher to where the stream of payloads is going. Further, as the sun slowly moved relative to the Earth and Moon, the stream of payloads would also slowly shift, requiring the Mass Catcher to follow the stream. Thus, what is most important is that the mass driver be consistent in producing a narrow stream.

The catcher could be located at the so-called "L-2 point" or "L-1 point in orbit, as discussed in the section on Lagrangian libration points. In short, the L-1 and L-2 points in orbit are stationary relative to the Moon's surface so that the mass driver is always shooting at the same point. The L-2 point acts kind of like the top of a gravitational hill that isn't very steep, so that one doesn't have to be stationed at the absolute balance point on top to be sufficiently stable for economical stationkeeping.

The propellant needed for station-keeping and maneuvering would not be very large. The payloads would arrive at about 70 meters per second, so they push the catcher around a bit. For example, it has been proposed that a stationkeeping device shooting slag pellets out at a velocity 30 times the incoming payload velocity (*i.e.*, 2100 meters per second) would theoretically be able to compensate entirely for this momentum transfer at a 1 to 30 ratio of propellant to payload. As for polluting space with propellant pellets, the ejection speed of 2000 meters per second easily escapes the Earth-Moon system, and does not add significantly to the quantity of rocks naturally populating space. Of course, slag pellet shooters aren't our only option, and gaseous propellants are much more efficient since they have much higher exhaust velocities.

It has also been proposed that the catcher be stationed in a lunar-synchronous position whereby it would fall down towards the Moon except for the thrust produced by the incoming packages impacting it.

For technical information on the mass driver in particular, one may wish to contact the builders of the laboratory prototype lunar mass driver, The Space Studies Inst., P.O. Box 82, Princeton, N.J., 08540, (609) 921-0377, [ssissi.org](http://www.ssi.org) and <http://www.ssi.org>

4.5 Long-Term Transport

4.5.1 Tethers in a Vacuum

Tethers are a general topic area with multiple applications for propulsion and electricity generation. In the future, the PERMANENT website will discuss these concepts further. In the mean time, here are some links:

Tethers Unlimited, Inc., performs R&D on tethers. See www.tethers.com ;<http://www.tethers.com>;

A 1999 Scientific American article covers R&D to that point in time, at www.sciam.com/1999/0399space/0399beardsley ;<http://www.sciam.com/1999/0399space/0399beardsleybox3.html>; (Robert L. Forward and Robert P. Hoyt)

4.5.2 Laser Launch from Earth

The fundamental concept is a vehicle using the air around it for propulsion rather than carrying all its fuel with it, and getting the energy from a ground-based laser.

More information can be found by following leads in a 1999 Scientific American article at <http://www.sciam.com/1999/0>

The Lightcraft Technology Demonstrator website of the Air Force Research Lab is at www.pr.afrl.af.mil/technology/light ;<http://www.pr.afrl.af.mil/technology/lightcraft/ltd.html>;

A few keywords used in association with this work are: “lightcraft”, “laser propulsion” and “microsatellites”. Current research is for propulsion of very small objects.

5 Fuel Propellants - Storable, and Hypergolic vs. Ignitable by Mike Schooley

5.1 Using liquid oxygen (LOX) in space

It has been proposed by numerous sources that lunar, asteroid and/or comet materials could be mined and used as propellants to re-fuel satellites, fuel orbital transfer vehicles and to fuel deep space probes. Since oxygen is a gas above -297.6F (162R or 90K) it takes a very large low pressure tank or a very heavy high pressure tank to store an appreciable volume at normal Temperatures. Therefore oxygen is normally super-cooled to its liquid form commonly referred to as LOX. There are three problems associated with using LOX in space. First is commonality, second is boil-off losses, third is ignition problems and fourth is propellant tank scale, which is related to the boil-off issue.

5.2 Comonality

I am not aware of any space craft or satellite that uses LOX as a propellant, but to make sure, I searched Mike’s Satellite Library at “<http://leonardo.jpl.nasa.gov/msl/>”. I searched 164 satellite and space craft types. I found no systems that use LOX. The most common was Hydrazine (N_2H_4) monopropellant, followed by cold gas and bipropellant (N_2H_4 and N_2O_4). The deep space probes, which have the highest delta V requirements, generally use bipropellants. This is surprising since LOX has a higher specific impulse, which means less propellant mass is required for the same level of performance. LOX is the premier oxidizer for fuelling launch vehicles, but in a launch vehicle the propellant is all consumed in a matter of minutes and long term storage is not an issue. However, for satellites, which require small intermittent pulses of thrust over their design life of up to 15 years, long term storage is critical. Therefore, there is currently no demand for LOX in space, since no space craft currently use it. We can also state that the requirements for LOX in the near term will continue to be low since rocket engines that burn LOX and provide low thrust, high reliability and long life do not exist today and would take several years to design, build and test.

Space Station Freedom was designed to use Hydrogen and Oxygen propellants, however it was to be stored as water and separated by electrolysis as needed. After separation the Hydrogen and Oxygen were to be stored in gaseous form under pressure. With the switch to the International Space Station, the propulsion function has been moved to the Russian station modules and the propellants are Unsymmetrical Dimethyl Hydrazine (UDMH) and Nitrogen Tetroxide (N_2O_4).

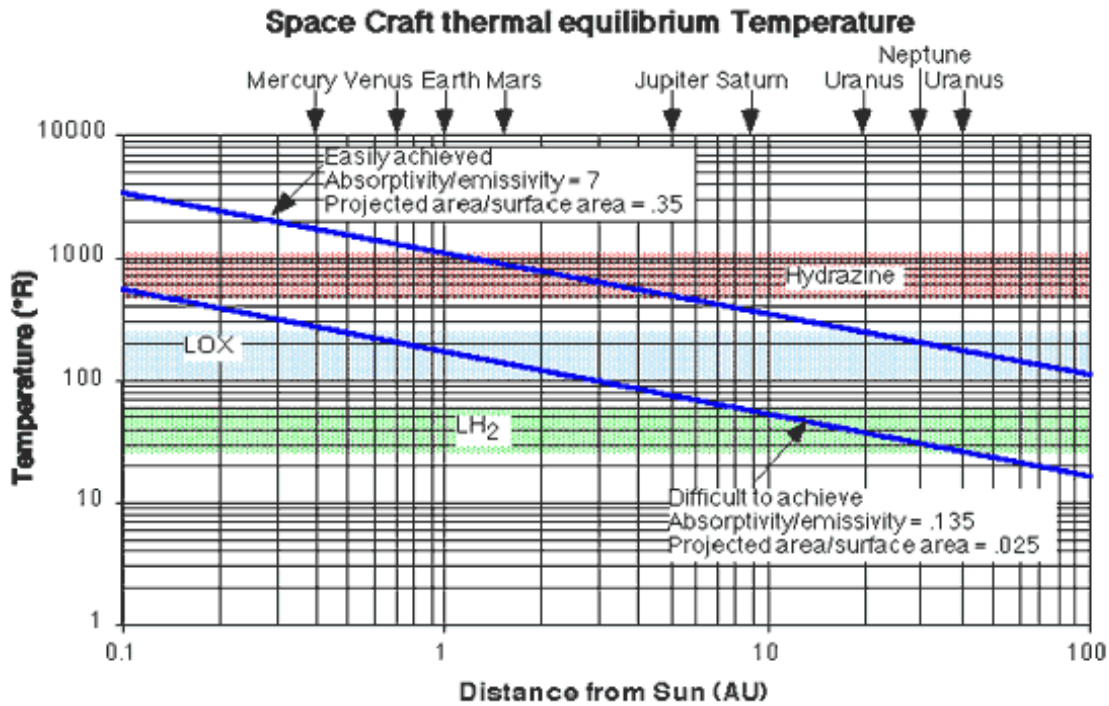


Figure 3: From the graph, you can see that Hydrazine, the most common satellite fuel, is easily storable at Earth and Mars distances from the sun. It also appears that with very careful space craft design, LOX could be stored at Earth distance from the Sun. However, the first figure assumes that the tank is not close to the Earth. The next figure (from reference 1) provides the thermal equilibrium Temperature of a well insulated spherical tank with an effective radiation heat shielding, orbiting at 2 to 9 Earth radii.

5.3 Boil-Off

When liquid propellants are stored at Temperatures above their boiling-point they vaporize. If we contain the vapors in the tank, then the pressure increases with Temperature. Since the tank weight increases with design pressure, a pressure relief valve is generally provided to prevent the tank from over pressurizing and exploding. When the relief valve releases the pressure, some of the propellant escapes from the tank. This lost propellant is referred to as boil-off loss. Propellants have been generally classified as “storable” or “cryogenic” based on whether they remain a liquid throughout the normal terrestrial Temperature range or if they are only a liquid at “very low” Temperatures, however these definitions are not applicable to storage in space. Figure 1 (from reference 1) indicates the thermal equilibrium condition of a well insulated cylindrical propellant tank with effective radiation heat shielding assuming a distance to any object (planet, moon, asteroid, ...) greater than 10 planet radii. The upper and lower curves represent the range of practical designs. The upper limit of each propellant Temperature band assumes a manageable overpressure and the lower limit is defined by the propellant freezing point.

Another alternative is to actively control the propellant Temperature, cooling it when the temperature exceeds the boiling point and heating it if the temperature drops below the freezing point. In the past space craft designers have avoided cooling systems when ever possible due to weight and reliability issues.

5.4 Ignition Problems

Spacecraft and satellites are required to start and stop their rocket thrusters hundreds or even thousands of times over their design life. To eliminate the ignition system as a possible failure, designers prefer to use hypergolic propellants, which means the propellants spontaneously burn when they are combined. Table 1 below defines which common propellant combinations are hypergolic.

Space Craft thermal equilibrium Temperature in near Earth orbit

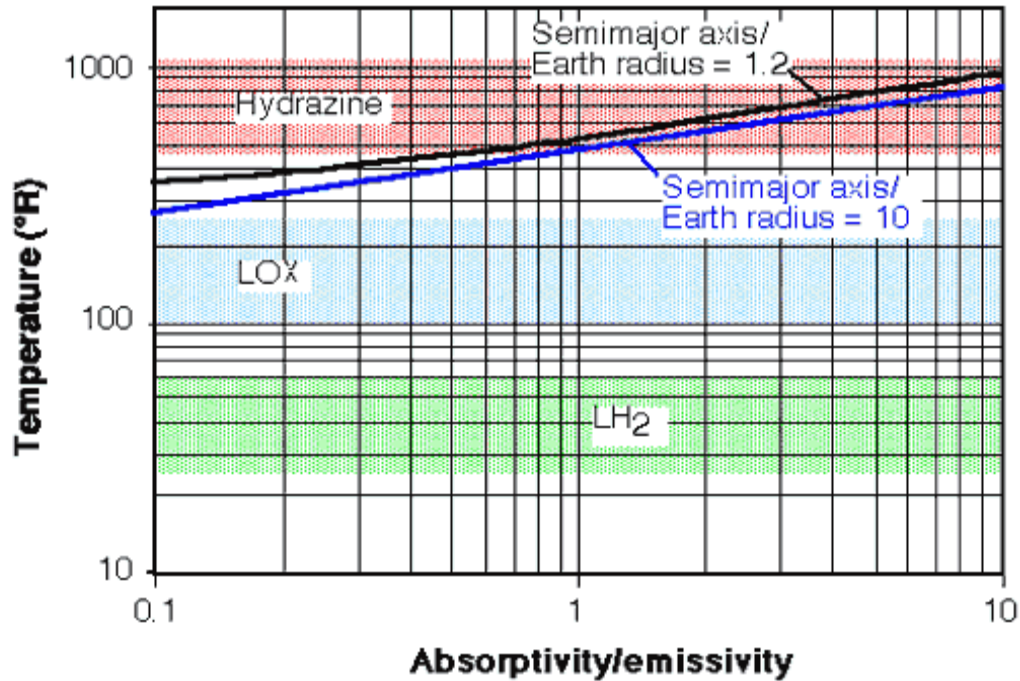
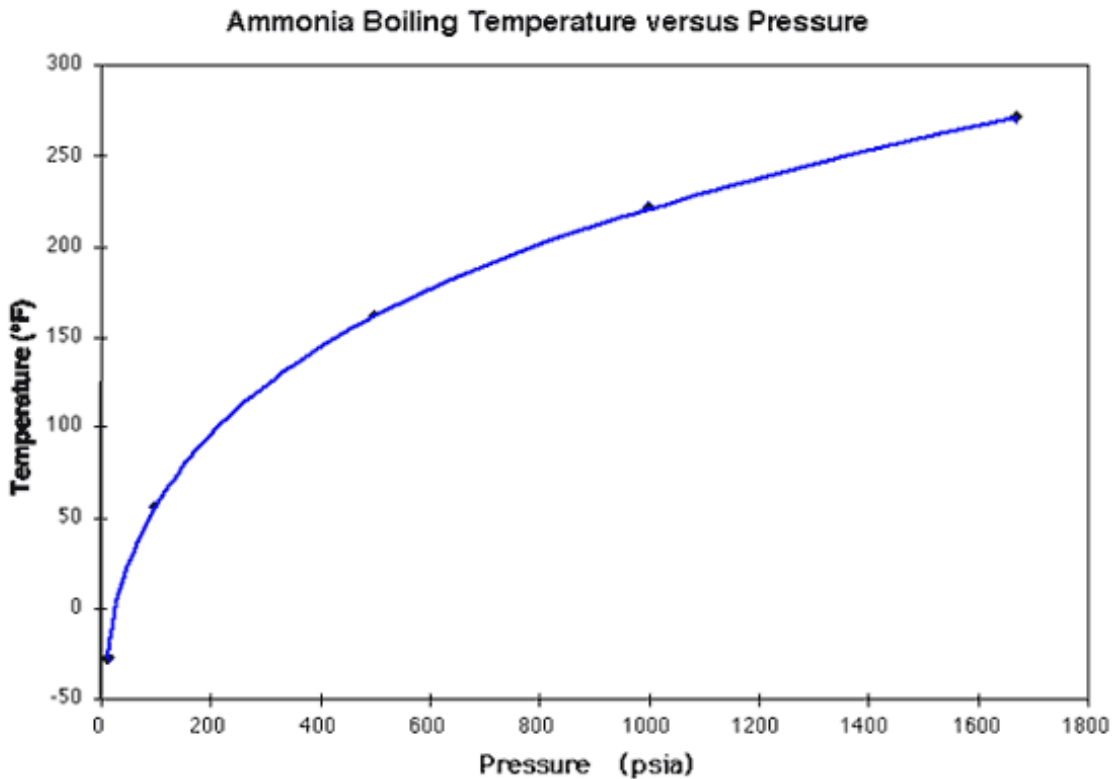


Figure 4: Figure 2 shows that in Earth orbit, the added energy received from the Earth makes LOX storage very difficult. To make matters worse, in actual designs, additional heat sources must also be considered. Heat is also conducted into tanks from onboard electronics, heated compartments such as manned spaces and from solar panels. In addition, heat is gained by radiation from rocket plumes.

	LOX	Peroxide	Nitric Acid	Nitrogen Tetroxide	Combust.
O₂	H₂O₂	H₂NO₃	N₂O₄	Init. ClF₂	
Ammonia (NH ₃)	No	Yes	Catalyst	Catalyst	Yes
Aniline (C ₆ H ₅ NH ₂)	Yes	No	Yes	Yes	Yes
Ethanol (C ₂ H ₅ OH)	No	Yes	No	No	Yes
Hydrazine (N ₂ H ₄)	No	Yes	Yes	Yes	Yes
Kerosene	No	Yes	No	No	Yes
Liquid hydrogen (H ₂)	No	Yes	No	No	Yes
Methyl Hydrazine (MMH)	No	Yes	Yes	Yes	Yes
Unsym. Dim Hydrazine ([CH ₃] ₂ N ₂ H ₂)	No	Yes	Yes	Yes	Yes

Note: The table above shows LOX is not hypergolic with any common fuel. This means that an ignitor will be required, which on engines that are required to fire many times can be a big reliability issue.



5.5 Scale

When boil-off conditions exist, the scale of the propellant tank, which determines the surface area to volume ratio, directly effects the boil-off rate. Large tanks, with a high volume to surface area ratio loose a small percentage of their propellant in a unit of time. A small tank, with a volume to surface area ratio will loose a much higher percentage of its propellant in the same unit of time. Launch vehicles with large cryogenic tanks and short storage time can use cryogenic propellants with negligible boil-off losses, however satellites with small propellant tanks and long storage time requirements would have unacceptable propellant burn-off with cryogenic propellants.

5.6 Conclusion

Satellites do not currently use LOX and will not use LOX for the foreseeable future. LOX is not storable without expensive and heavy cooling systems in Earth orbit. LOX could be used at about Mars orbit and deeper into space. When boil-off does occur, large tanks with high volume to surface area ratios minimize the rate of loss due to boil-off.

On the positive side, we can use oxygen to produce the oxidizer of choice. Many space craft with high total impulse requirements utilize Nitrogen Tetroxide (N_2O_4) and Hydrazine (N_2H_4) bipropellants because the higher delivered specific reduces the space craft launch weight and this propellants combination is hypergolic. If we obtain Nitrogen from asteroids, or import it from Earth, we can combine it with Oxygen to produce Nitrogen Tetroxide. By weight Nitrogen Tetroxide is almost 70% Oxygen and 30% Nitrogen. If we import Nitrogen from Earth, in what form should be transport and store it? Liquid Nitrogen has a lower boiling point ($-320^\circ F$) than liquid oxygen ($-298^\circ F$). Ammonia (NH_3) is an obvious choice, it has boiling point of $-28^\circ F$ and a freezing point of $-107.9^\circ F$. By containing about 200 psi of vapor pressure we can increase the boiling point to $100^\circ F$ as shown in figure 3:

For every two ammonia (NH_3) molecules that we convert to Nitrogen Tetroxide (N_2O_4) we liberate 6 hydrogen atoms. We can also combine two ammonia molecules to produce Hydrazine (N_2H_4) and liberate 2 more hydrogen atoms. All these 8 hydrogen atoms can be reacted with 4 extraterrestrial oxygen atoms to produce 4 water molecules (H_2O).

The mass balance based on molecular weights is: The ammonia makes up 34.7% of the weight of the inputs and the oxygen makes up 65.3%. The propellants make up 63.2% of the outputs with water constituting 36.8%. It is interesting to note that the water produced exceeds the weight of ammonia that is imported. Although this does not appear as attractive as using liquid oxygen from space and imported hydrogen where only 11% of the propellant mass must be imported, Nitrogen Tetroxide (N_2O_4) and Hydrazine are easier to store for long periods and they are currently in use in space.

Another useful fuel to produce in space is Unsymmetrical Dimethylhydrazine [$(\text{CH}_3)_2\text{NNH}_2$], also known as UDMH, is used on the Russian MIR space station and will be used on the International Space Station. Because of its use on Space Stations, UDMH probably has the highest demand of any fuel in space. Unfortunately, until we locate sources of Nitrogen in space, only the Carbon appears to be readily available.

Reference 1 "Handbook of Astronautical Engineering," McGraw-Hill Book Company, Inc., 1961, Edited by Heinz Hermann Koelle.