CIRCULATION COPY
SUBJECT TO RECALL
IN TWO WEEKS

UCRL-89252
PREPRINT

EARTHBREAK
A Review of Earth-to-Space Transportation

Roderick A. Hyde

This paper was prepared for submittal to
FESTSCHRIFT

24 May 1983

Lawrence Livermore National Laboratory

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

EARTHBREAK

A Review of Earth-to-Space Transportation*

Roderick A. Hyde

Physics Department, Lawrence Livermore National Laboratory, Livermore, CA 94550

Beyond the Earth lies outer space, a frontier almost without end. Since as a nation and a culture we were born and evolved on a frontier, why aren't we spreading into space, just as our ancestors filled this continent? The widespread view of space as a barren desert is not the reason. First, this view is not correct: space provides abundant energy from the Sun, readily available resources from the Moon and the asteroids, a constant and benign climate (with solar flares as the only hostile weather), and most important of all, plenty of uncontested elbow room. Secondly, it shouldn't matter that some people doubt the value of space; it is never skeptics who pull up stakes and tame frontiers. The reason that those who do believe in the space frontier don't go there, and by flourishing attract others, is simple: they can't afford to.

Freeman Dyson, when pondering the issue of space colonization,[1] looked at the economics of the initial Plymouth and Mormon colonies. Not surprisingly, he found that the cost-to-colonize when expressed in man-years of wages per family (MY/f) was similar and moderate, 7.5 for the Mayflower voyage, and 2.5 for the trek to Utah. Then as now, a family simply can not accumulate more money (lenders look askance at their debtors' heels). For colonization of space to occur, the cost must be no more than about 5 MY/f. In order to convert this to a dollar figure, let's characterize a modern family as 3 people per full wage earner, and suppose an after-tax annual income of 25,000 $/yr. This leads to a figure of $40,000 per head to support colonization. But today the cost of moving from Earth into the Solar System is about 10,000 $/kg. Quite clearly this cost is orders of magnitude more than families can afford; it is this transport charge that precludes space colonization.

What should the cost be? The Mayflower and Mormon efforts required 2 tons of material per person; while it will probably take more to live in space, let's be optimistic and assume this as a reference value. This provisioning will cost money; therefore, assume that only 2 of our 5 MY/f can be spent for transport. We find that the acceptable transport cost

*Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

is only 5 - 10 $/kg, a thousand times lower than the present value. Effective colonization will also require a reasonable volume of transport, both as a means of reducing the cost, and to establish the industrial infrastructure necessary for success. The required value is not clear, so I'll pick a range of 1 - 10 Tg/yr (comparable to that of domestic airtravel, and 2 orders of magnitude below the mass flow via railroads and trucks[2]).

The fundamental reason that transport into space is difficult is that we lie at the bottom of the Earth's gravity well. To escape it requires 62.5 kJ/g of energy, an amount equivalent to climbing 6400 km vertically in a 1 g field (Mt. Everest is $\lesssim$10 km high). Fig. 1 displays a gravity well in energy space, with axes U for potential energy and K for kinetic energy; bisecting the two is the E axis for total energy. An escape trajectory must leave the bottom of the well (K = 0, U = -1), and reach the E = 0 line. The shaded region in Fig. 1 is where orbital ledges are found; we can use them as rest stops, as well as places to store supplies or other escape equipment. The easiest way, in terms of energy, to reach the orbital ledges is to increase kinetic energy, i.e. to jump. This contrasts with climbing routes which increase potential energy, but don't access orbits.

Whichever route it takes to reach the escape condition, a space vehicle will need an energy supply and something to react against. If a vehicle in free space was required to gain 62.5 kJ/g, it would have to be self-reliant and provide both. But it is only because of the Earth that we must gain energy; we should consider getting some use out of it. This can be done by basing energy on the Earth and transmitting it to our vehicle, and/or by using the Earth to react against.

There are other features of the Earth, beyond the depth of its gravity well and its potential as an energy/momentum source, which should be considered. Some of these can impair an escape attempt, but some can be exploited. Our planet has a thick (1 kg/cm^2) gas atmosphere, which impedes the motion of a vehicle travelling through it. Obviously this complicates jumping manuevers from the Earth's surface, but it also acts to raise the height of stable orbits, and by winds to load even stationary structures passing through it. In some situations we can make use of atmospheric drag, and in others can use its mass for resupply.

The steepness of the gravitational potential is often a serious constraint, since until the orbital ledges are reached, enough force must be applied to our escape vehicle to enable it to resist the Earth's gravitational pull. This lower limit on thrust-derived acceleration is 1 g (980 cm/sec^2). Because of this limit, a number of space transportation technologies can only be used after an orbital ledge has been reached, and hence can't be used in the lower half of the well. The Earth is indirectly responsible for an upper limit on thrust

acceleration; we evolved subject to only 1 g acceleration; not surprisingly, we fail if loaded much beyond this level. As a result, systems which develop higher than about 10 g's acceleration cannot be used to transport people.

The Earth rotates; this helps us by supplying an initial kinetic energy, and by admitting orbits which are geostationary. It also means that objects rotating with the planet experience Coriolis forces, which generally hurt, and centrifugal ones, which usually help. Finally, the Earth has a satellite parked high in its gravity well. By virtue of its position in Earth orbit, lunar mass has relatively large potential energy. Since the Moon's gravitational well is only 5% as deep as the Earth's, we should be able to make use of lunar material, both for itself, and for its potential energy.

We can set two bounds on the cost to escape from the Earth. At one extreme is the current Shuttle value of 10,000 $/kg; this is completely unacceptable for space colonization. A much lower bound is set by the energy cost to lift matter out of our gravity well. At a bulk electricity price of 0.02 $/kWhr, this cost is only 0.35 $/kg, a very acceptable value. In our current space transportation systems, the escaping vehicle is self-reliant, providing for itself the mechanism and supplies necessary for escape. To approach the lower cost limit, we should consider the other extreme, where the vehicle receives outside support while escaping the Earth.

Let's start by considering self-reliant systems. The only propulsion device which allows independent operation is a rocket. In general, a rocket consists of an energy supply, reaction mass, and a payload. The energy is used to eject propellant away from the rocket, with the reaction force accelerating the payload. The energy acquired by the payload is kinetic, so rockets use jumping-type escape routes. Energy storage requires mass, the amount of which can be found from its storage density, expressed in kinetic energy terms by a storage speed W. The drawback of rockets is that the energy storage mass and the propellant used late in the burn must be carried along with the payload during the early part of the burn. If the storage speed W is much less than the desired final payload speed V, this drawback becomes severe. In this case it is best to make the propellant and energy storage medium the same, leading to a direct transfer of energy from storage into the propellant. Such a rocket has equal exhaust (U) and storage (W) speeds, with a ratio of final to initial rocket mass given by

$$m_f/m_i = e^{-V/U} \equiv 1/R \tag{1}$$

In some rockets, the energy storage mass is not important, either because W is much larger than V, or because we import the energy from offboard. We can select the exhaust

speed U by the amount of propellant mass used. It turns out that a high U is not necessarily good, since most of the energy winds up as kinetic energy of the exhaust, rather than in the payload. The performance of these rockets is usually governed by the methods chosen to acquire energy and to transfer it to the propellant. Sometimes, this process will lead to a fixed value of U, and our Eq. 1 remains valid. Often though, it is the exhaust power P which is fixed; this occurs when we can only import energy at a fixed rate, or when the energy transfer is indirect and lossy, requiring fixed rate entropy rejection. These rockets involve a tradeoff between thrust and exhaust speed:

$$TU = 2P \tag{2}$$

For most such rockets, the power-to-mass ratio is sufficiently low that if we select a U value which gives a mass ratio R close to 1, the accelerations developed are much less than 1 g. As a result, power-limited rockets are usually restricted to use in the upper half of the Earth's gravity well.

In free space, rockets deliver kinetic energy to their payload. In a gravity well, this is still the best way to use them. The fuel used depends on the integral of thrust with respect to time, while the energy delivered is given by the integral of thrust with respect to distance. Clearly this is maximised by traveling as fast as possible, which requires that the energy delivered be placed into kinetic rather than potential form. Hence rockets are best used for jumping-type trajectories. In principle, the escape condition amounts to a speed of 11.2 km/s; this is typically raised to about 12.5 by the gravitational acceleration penalty, and by the need to punch through the atmosphere. Because low thrust rockets slowly spiral away from the Earth, much of their energy goes into potential form. This route through energy space, shown by the dotted line in Fig. 1, requires them to deliver more impulse to reach escape than would a high thrust rocket.

Our current rockets derive their energy from the rearrangement of chemical bonds. Two stable chemicals are burned together in a thrust chamber, producing hot gaseous reaction products. Their thermal energy is then converted to kinetic energy by expansion in a nozzle. The exhaust speed U is bounded in two ways. Full energy conversion by the nozzle is prevented both by its limited physical extent and the ending of expansion by atmospheric backpressure. A more fundamental limitation is the low energy content of chemical bonds. The formation of hydrogen molecules by reaction of free hydrogen atoms would release 218 kJ/g, which with a perfect nozzle results in a U of 20.9 km/s. This is comfortably higher than our 11.2 km/s V, but is unattainable in practice since the hydrogen atoms tend to react before they reach the thrust chamber; current hydrogen

atom storage densities are only about $10^{17}cm^{-3}$.[3] In general, chemical bonds with a high energy potential are not left unexploited by nature, so energy comes from breaking and reforming bonds rather than simply making them. The burning of hydrogen and oxygen molecules to form water is close to the best achievable chemical system, but stores only 13.4 kJ/g; for vacuum burns with big nozzles, this choice results in a U of 4.6 km/s, considerably lower than the escape speed V.

Other ways to store chemical energy can be considered, but in practice are inferior to the existing H_2/O_2 system. The electronically excited state of He is metastable and stores 477 kJ/g but, as with monoatomic H, it apparently cannot be stored in bulk at high density ($\gtrsim 1\%$ of liquid). When we store energy in magnetic fields, or in the kinetic energy of flywheels, we are limited by the stretching of bonds in structural materials. The best commercially available material is Kevlar, but its storage density is only 2.5 kJ/g — a fact that will also haunt us when considering non-rocket options. The current method of using onboard chemical energy, namely direct conversion into hot gas via bond rearrangement, is the best available; however, such rockets will be plaqued by the fact that W is small compared to the required V.

The mass ratio of Eq. 1 forms an optimistic bound, as not all of the final mass is payload. The best chemical fuels are liquids and must be carried in tanks whose mass, along with that of the engines, reduces that allowable for payload. Staging is the common way to cope with this problem; once some fraction of the fuel is used up, its tanks are no longer needed and are jettisoned to avoid having to accelerate them further. This procedure has been required in all present systems, but does raise problems. Simply throwing away the jettisoned mass is unlikely to be economic, while recovering it is complicated by the fact that it is moving and must be stopped. Here the atmosphere can be helpful, since by using drag we avoid the need for rocket fuel.

Are chemical rockets good enough for space colonization? The nation's space transport system now relies on the Space Shuttle. This is a complex, multi-stage, partially reuseable system, which carries 29.5 Mg payload into a low Earth parking orbit. If combined with an expendable H_2/O_2 stage, it could propel a payload of about 12.5 Mg out of the Earth's gravity well. The cost of a Shuttle launch will soon be raised to 70 M$ in order to completely recover operating costs. When the cost of the expendable upper stage is included, we find a cost of 7,000 $/kg launched into an escape trajectory. At the planned level of 40 flights per year, this system could handle 500 Mg/yr. In both cost and mass flux the Shuttle misses our colonization target figures by 3 orders of magnitude.

Advanced chemical systems have been proposed which do much better; see, for instance

[4]. This design reduces tankage effects by scaling up to larger-sized vehicles. It cuts costs by being fully reuseable, and by amortizing fixed costs over a larger throughput. Nevertheless, the system costs 100 \$/kg and delivers 0.1 Tg/yr, thereby missing our cost and volume requirements by over an order of magnitude. The basic problem of chemical rockets is evident even for this advanced system; its escape trajectory payload contains only 1% of the total mass, 8% of the hardware mass, and 5% of the stored chemical energy. These numbers suggest that transport costs can be reduced much further, down low enough for practical colonization, but that to do so will require more efficient vehicles than chemical rockets.

Chemical propulsion might still be acceptable if we could take momentum or energy from the environment. Suppose we continue to store energy onboard, but instead of expelling propellant, react against the Earth, either the atmosphere or the surface. This unfortunately leads to a mass ratio of

$$m_f/m_i = e^{-(V/W)^2} \tag{3}$$

which for the W < V case of chemical storage is worse than that of a rocket. Clearly it is the onboard chemical energy storage that hurts; this can be circumvented by collecting energy in flight. The case where this energy is acquired as electromagnetic radiation, e.g. lasers or microwaves, will be treated later. Various ways of importing energy in the form of chemicals have been proposed. One technique[5] is to burn an onboard fuel with oxygen from the atmocphere. This drastically cuts onboard fuel consumption, but only for the early portion of the burn; payload enhancement is in the neighborhood of 50%. The air-breathing engines used are heavy and must be staged. The increased operational costs associated with this staging, and with servicing the engines, will eliminate much if not all of the gain arising from the payload increase.

A more promising approach to refuelling involves lunar oxygen. Oxygen is readily available in lunar rocks, and because the lunar gravity well is so shallow, this oxygen is easily sent down towards the Earth. The atmosphere can then be utilized to slow it down[6] and insert it into a low Earth orbit. The lunar oxygen is then used to resupply an Earth-launched vehicle, and thus eliminates most of its Earth-originated propellant needs for the orbit-to-escape burn. This resupply is one of several techniques which make transport cheap once orbit has been reached. By only requiring our Earth-based chemical rockets to lift mass halfway up the gravity well, we can achieve costs to low Earth orbit of about 30 \$/kg.[7] In the lunar resupply scheme, we must lift from Earth the hydrogen fuel needed to propel our payload and rocket to escape; this raises the overall cost to less than 40 \$/kg. This value is a huge improvement over current ones, but is still several times

too high for practical colonization. Rockets which use lunar oxygen for an energy supply are an economical form of transport within the upper half of the Earth's gravity well, but chemical rockets are too expensive to use in reaching low Earth orbit. For this phase of the journey, we must either consider nuclear energy, or be willing to accept offboard energy.

A rocket which uses nuclear energy has to transfer it into a separate propellant, which is then expelled at a speed U much closer to the mission speed V than to the storage speed W. The value of U is chosen, within constraints set by the transfer method, to result in good conversion of nuclear energy into payload kinetic energy, as well as a high payload fraction. The energy transfer mechanisms can be characterized by their directness; the fraction of the energy which directly heats propellant without passing through the spaceship's structure. For Earth-to-orbit missions we can't afford to radiatively reject waste heat from our vehicle, so this energy will be thermally transferred to propellant with an exhaust speed limited by the temperature of the ship. I'll discuss three nuclear rockets whose energy transfer mechanism ranges from direct to indirect.

A direct transfer scheme called Orion[8] was studied two decades ago and promised much higher performance than the chemical rockets then and now in use. The concept was very simple; small nuclear explosives were surrounded by propellant and torched off behind the rocket. The blast stagnated against a pusher plate which was attached to the vehicle by 'springs'; these smoothed out the impulse so that the payload experienced a steady acceleration. Because the plate and the hot debris were in contact for only a short time, the little heat transferred to the ship was efficiently removed by ablation. Orion was capable of both high U (40 km/s) and greater-than-1 g accelerations, but was killed by the politcal ban on above-ground nuclear explosions. There are two difficulties with reviving Orion to launch colonists: the cost of fission fuel, and the release of fission products. The economic problem is illustrated by a USAF design,[8] which used 0.44 kg of Pu per Mg of payload placed into orbit. When a typical price of 50 $/gm is charged, we find a payload cost of 22 $/kg. This cost can probably be lowered, but only by going to large vehicles and correspondingly large explosions. The release of fission products is a more fundamental concern. Let's assume that our exhaust speed is 20 km/s, and that 1/2 of our final mass is payload. Then if we charge a modest gravity penalty, we find that propellant energy is 7.5 times the final payload energy. Since only the debris heading toward the pusher plate can be used, the actual nuclear energy required is at least twice this: 110 ton of HE-equivalent per Mg of payload put into low orbit. This requires 110 MTon/yr for a Tg/yr colonization rate; regardless of treaties, such an amount of fission product release is not likely to be allowed. It is possible that an Orion type vehicle using pure fusion fuels would be permitted. Such a vehicle would have to employ a fusion explosion ignitor

capable of working within the atmosphere, and use a explosive-propellant module which would prevent release of high energy neutrons (otherwise C^{14} production in the air is too high) while producing little neutron activation in the debris.

By burning the nuclear fuel in an enclosed nuclear reactor, we can eliminate the release of both fissile materials and their products. For Earth launch applications, a high thrust-to-weight ratio is essential, so a reactor is most effectively used as a heat source, thermally transferring its energy to propellant. Conventional reactors use solid materials; this limits the propellant's temperature, and hence its exhaust speed. Both the exhaust speed and the engine's thrust-to-weight ratio are governed by its performance as a solid-gas heat exchanger. Designs with high interface area per volume are best since they permit high power-per-unit-mass operation, and require a lower temperature differential between the fuel and the propellant. The U.S. spent about 15 years developing the NERVA engine,[9] which was designed to exhaust hydrogen at 8.1 km/s, generating a continuous 75,000 lb thrust. While this exhaust speed is much higher than our chemical rockets can achieve, NERVA is useless for Earth launch; because its thrust-to-weight ratio is only 3. It can lift itself, but not fuel and payload. Fortunately, this poor acceleration is not intrinsic to solid core reactors, but came about because NERVA was a relatively poor heat exchanger. An alternate design called Dumbo[10] was studied in the late 1950s; gas flow was through short narrow passages rather than the long wide ones of Nerva, allowing much more effective heat transfer. A Dumbo-based design permits slightly higher exhaust speeds (9 km/s), and much higher thrust-to-weight ratios (50 or more). A quick calculation demonstrates the capabilities of such a rocket: with a 9.3 km/s mission speed, the propellant mass is 64%; allow 11% of the mass budget for tanks (H_2 has low density), and 10% for engines, shielding, and thrust structure. We then find a payload fraction of 15%, which is over 3 times that for H_2/O_2 rockets. Since we have no experience operating nuclear rockets, it's hard to translate this large payload gain into a cost-to-orbit. One limit will be set by the price of liquid hydrogen; based upon either 5 \$/MBtu natural gas, or 20 mills/kWhr electricity, we can estimate this as 2 \$/kg, leading to 8 \$/kg of payload for reaction mass alone. If we scale down the operations costs for chemical rockets by the factor of 3, we find costs to orbit of about 15 \$/kg. Solid core nuclear rockets should therefore lower cost-to-orbit by twofold relative to chemical rockets, but we would like another factor of two gain over this.

Gas core reactors permit higher exhaust speeds, since the nuclear fuel is a plasma at roughly 1 ev. Heat is primarily transfered to hydrogen propellant by thermal radiation, and is not handled by the engine structure. As a result, exhaust speeds of up to 25 km/s are possible. This should increase the payload, and drop the propellant needs enough to

make possible costs to orbit of less than 10 $/kg. Unfortunately, most research on gas core nuclear rockets was stopped 10 years ago, and it's not technically certain that they can work at all, let alone with adequate thrust-to-weight ratios. Most research was done on a coaxial flow concept, with the fuel and propellant in contact. As a result, some fissile fuel, estimated at 0.1% by mass,[11] is exhausted. This is at least an order of magnitude too much, so we must concentrate on the positive containment 'light bulb' technique. In this approach a transparent quartz wall separates fuel and propellant. It was believed that by keeping the wall hot, it would remain transparent while in the reactor. More work is necessary to confirm this, to maximize reactor thrust-to-weight ratio, and to design against the consequences of wall failures, before we can seriously consider using gas core nuclear rockets to support practical space colonization.

Nuclear energy can be efficiently stored on a rocket, but as we have seen, it's not easily used. We have already discussed the limitations of chemical forms of onboard energy storage, so let's now consider a rocket whose propellant is heated by offboard energy. Although microwaves and electrons have also been proposed as energy carriers, lasers are superior, permitting long distance source-vehicle propagation with efficient and compact energy reception at the ship. A number of methods have been proposed for using laser energy to power rockets; I'll discuss one of these, an Avco proposal[12] for direct launch from Earth into high energy orbits. Their rocket is 2 meters wide and 4 meters high, carries 5.4 Mg of water as propellant, and orbits a 1 Mg payload in a 0.5 Mg package. The water is hit by 160 laser pulses per second; each one first vaporizes a thin layer, and then ignites a detonation wave in the blown-off material. This method of converting laser energy to thrust is only 44% efficient, but achieves an 8 km/s exhaust without a nozzle or optics, requiring only a 70 cm expansion skirt. A 1 GW average power CO_2 laser is used, delivering energy to the rocket for 340 seconds, out to a slant range of 1000 km.

The first thing to note is that the rocket is extremely simple; tasks such as steering and propellant injection are done from the ground, by tailoring the laser pulses. The use of pulsed energy relaxs temperature constraints, and allows attainment of high exhaust speeds while using very convenient propellants such as water. The amount of propellant carried and its exhaust velocity are chosen to optimise conversion of laser energy to payload speed; this leads to mass ratios of 4-5. It's striking that laser propelled rockets are much smaller than optimum designs using onboard energy, but require huge (GW size) lasers. This results from two relationships between the size of a rocket and the power required to propel it. One limit, usually the least stringent, is set by the need to overcome the Earth's gravity. The second limit follows from the need to deliver energy to the rocket while it is still within range of the laser. If we include the energy conversion inefficiency, and the

structural mass fraction, we find an energy cost of about 340 kJ/g of payload; and for a 1000 km range, a need for 1 GW/Mg. This power requirement, coupled with the difficulty of building large lasers, drives laser-powered rocket schemes to small sizes. It's probably not cost-effective to reenter, recover, and refurbish such small objects, so the Avco design concentrates on simple, inexpensive expendable rockets.

The transport cost is governed by three components: the laser, the electrical energy, and the expendable rocket. Let's (reasonably) assume a 20% efficient laser; hence we need 1.7 MJ/g, which costs us 9 $/kg. There is no experience with lasers of GW size, but they probably cost more per watt than power plants; if we assume a 2 $/W capital cost, we must add 3 $/kg to our price. The rocket cost is critical; a unit price of even $10,000 drives our transport cost to 22 $/kg. How can we reduce this price by the factor of 2-4 required to make large-scale colonization feasible? Two avenues exist for reducing the rocket portion of the cost. The first is to simply postulate a lower production cost. These rockets are roughly the size of a small car, and for Tg/yr transport are built in similar quantities. But they are much simpler machines than a car, so it's plausible to assume a unit cost of $2,000. Another route to cost reduction involves scaling up the vehicle size. This should reduce the structure-to-payload mass ratio, and may even make reuse economical. In order to deliver 1 Tg/yr, we require 10 GW of laser capability. Large lasers are most readily built in small modules; by grouping them in 1 or 2 sites instead of 10, we can lift larger unit payloads. Reductions in the energy cost will not be as dramatic. By using a non-constant exhaust speed, and more efficient energy-thrust conversion, we can cut the needed energy to 200 GJ/Mg of photons, ie 1,000 GJ/Mg of electricity. This improves the overall conversion efficiency to 6%, but energy costs still dominate; there are two ways to reduce them further. The first is to find a more efficient laser. A free electron laser should give twice the electrical efficiency, and can be operated at a shorter wavelength. This allows longer range transmission, which permits us to use bigger payloads per launch. The other option is to only thrust into low orbit, and use some other more efficient scheme to reach escape. By reducing the energy that must be transferred while within range of the laser, this option permits us to raise the unit payload size by a factor of two. Laser propulsion costs, assuming cheap expendable rockets, but staying with CO_2 lasers, should be reduced to 10 $/kg for escape, and 6 for low orbit. Whether or not laser propulsion is suitable for large-scale space colonization purposes will depend upon how closely we can attain the assumed values of laser efficiency and cost.

Escaping from the Earth's surface with rockets is a difficult task; the transport costs for the preceding systems are reduced if they only lift payload to low orbit rather than all the way out of the terrestrial gravity well. For laser propulsion the savings is a factor

of two, while for H_2/O_2 rockets it's about 4-fold. We want rocket systems that will carry payload from orbit to escape, but which don't impose these cost penalties.

There is no thrust-to-weight constraint for orbital tugs; this permits us to utilize rockets with high exhaust velocity, and hence low propellant masses, which may be too heavy for Earth launch. Such rockets have two subsystems, one to produce thrust by transferring energy into a propellant, and the other to acquire the energy and dispose of any which was wasted in the transfer process. There are several ways to perform each of these tasks, but the system which is currently best developed uses Si solar cells to power electrostatic ion thrusters; one tug design[13] has a specific mass of 5 g/W. We can immediately see from Eq. 2 that such a tug is capable of only very small accelerations; it pushes itself at 0.0005 g when exhausting propellant at 80 km/s. There are two drawbacks to using low acceleration methods to reach escape: they take a long time; and because they follow a primarily climbing path out of the well, they require a velocity gain of V (the orbital speed) instead of the 0.41V value needed for impulsive jumps. A tug will carry payload out of the well, and then return to low orbit for reuse; the time taken for the mission is

$$\tau = \frac{\alpha V^2}{2}\left\{R^2 - 1 + \frac{m_p}{m_e}(R-1)\right\}/(lnR)^2 \tag{4}$$

where R is the mass ratio from Eq. 1, α is the specific mass in gm-sec/erg, and m_p & m_e are the payload and tug masses, respectively. The transport system is scoped to deliver F gm/sec of payload; so N tugs are required:

$$N = \tau F/m_p \tag{5}$$

We can derive a transport cost for the tug by adding two components: the capital cost of the tugs, and the cost of lifting the propellants from the Earth. For a given trip time, the mass ratio R can be selected to minimise cost. In Fig. 2, we show results based upon a lift cost of 6 \$/kg (laser propulsion), and a material cost of 16 \$/kg/yr (based on capitalization of a 100 \$/kg[13] hardware cost). There is a tradeoff between trip time and cost; to reach 2 \$/kg, we need a 110 day mission (97 going up), with a 55 km/s exhaust velocity. This simple model shows that when long trip times are acceptable, low thrust tugs are a cheap transport system. Pioneers in the past have spent similar times in transit; but I suspect that most people would opt for a swifter system, such as multi-orbit laser propulsion,[14] and send their gear by slow tug.

One of the early consequences of cheap transport off the Earth will be the establishment of lunar bases. It's cheaper to send material from the Moon down to low Earth orbit than it is to lift material into such orbits from the Earth's surface. Escaping the Moon is easy,

and we can exploit either low thrust tugs or atmospheric braking to lower matter down the Earth's gravity well to low orbit. Therefore lunar materials can be used to resupply rockets once they have reached low orbit. One option is to ship propellant for low thrust tugs down from the Moon instead of up from Earth; this will cut tug costs to about 1 \$/kg. Another option has already been mentioned: shipping down fuel for orbital-based H_2/O_2 tugs. These tugs require an oxygen-to-payload ratio of 1.2, and a similar hydrogen ratio of 0.2. Lifting the hydrogen from Earth's surface with laser propulsion will cost 1.2 \$/kg; the lunar oxygen cost will probably raise the total to 2 \$/kg. Hydrogen is present in much of the lunar surface material at near STP density; if we ship it also from the Moon, then tug costs can drop to 1 \$/kg. So once lunar bases are established, fast chemical tugs will become competitive with the slow solar-electric rockets; either will give 1-2 \$/kg orbit-to-escape costs.

Despite today's astronomical cost for space transport, there do appear to be methods which in the future will offer Earth escape costs low enough to permit colonization by families and individuals. Travel within the upper portion of Earth's gravity well can be cheaply done using low thrust rockets and, by using propellants of lunar origin, can be quick as well. Transport from the Earth's surface into low orbit is more difficult, but rockets powered either by gaseous fission reactors or ground based lasers should be economical enough. Note the caveat: gas fission rockets offer high performance, but they're still technically uncertain, and involve unknown operating costs; laser rockets will almost certainly work, but their economics impose challenging constraints on laser efficiency and cost. Even if these schemes work as planned, their costs are just acceptable; there is no fat in them. Unfortunately, costs predicted by paper studies are habitually lower than those actually paid. Accordingly, we should look for more economically robust surface-to-orbit transport systems. We've already considered vehicles which are completely self-contained, such as chemical and nuclear rockets, as well as partially-dependent ones, such as laser-powered rockets. Our search for less marginal transport will center on systems with dependent vehicles, whose energy and momentum are both supplied from offboard.

We can benchmark such transport systems by considering two extreme cases. In one, the payload is flung off the Earth at high speed, while in the other it primarily climbs off the surface. Neither scheme will be adequate for space colonization, but they serve as instructive model systems.

The climbing approach relies on a device called a Skyhook, and was first proposed in the Soviet Union; a good English description of this concept can be found in[15]. The Skyhook is a long rope; one end is anchored on the Earth's equator, while the other is some 150,000 km overhead. The rope rotates with the Earth, and so is acted upon by

centrifugal force as well as gravity. The centrifugal force on the outer portions of the rope can be used to counter the gravitational force on the lower sections, and hence support the Skyhook. To escape from the Earth, a vehicle need only climb the rope, releasing payload at the appropriate height, 47,000 km above the surface. Since this climb can be made with a simple linear motor, and since the vehicle can be returned by simply climbing down the rope, transport costs should approach the pure energy price. The primary difficulty with this concept is that gravitational and centrifugal forces are only globally balanced; the rope is locally supported by varying, and large, tensile loads. The Skyhook will be operated at a constant stress level, the maximum that its material can sustain, so tensile support is provided by tapering its cross-sectional area. The ratio of area at the widest point, which occurs at Earth's geosynchronous radius, to that at the surface is given by

$$e^{0.775(V_E/c)^2} \tag{6}$$

where c is the energy storage speed of our structural material. But, as we saw when considering chemical energy storage for rockets, c is much less than orbital speed V_E. For Kevlar, with a maximum c of 2.2 km/s, our taper ratio is 22,000. In order to achieve practical ratios, we must resort to materials found only in laboratories, such as SiC whiskers having c of 3.3 km/s, or diamond with c greater than 5. Assuming that the necessary multi-kiloton quantities of these materials are available, a Skyhook faces another basic difficulty: it must somehow supply the energy used by a climbing vehicle. The car can't afford to carry its own energy, and laser transmission will yield a system only slightly better than laser rocket propulsion. Power cables are too heavy; so local generation and storage along the rope will be necessary; generation can be either by solar cells, limiting travel to roughly 8 hours per day, or by sending mass down the rope. The Skyhook is not now buildable, but we will later consider an alternative way to support such a rope, as well as schemes that impose less strenuous requirements upon strong materials.

At the opposite extreme, are a number of machines which have been proposed for throwing material off the Earth; they supply the launch energy, and transmit the reaction force into the planet. Nuclear explosion driven cannons can be used to hurl very large masses, but let's concentrate on magnetic guns which shoot smaller (Mg-sized) payloads in a more controlled fashion. Two basic varieties of guns have been proposed: DC railguns[16], and synchronous traveling wave accelerators.[17] The projectile in a railgun rides between 2 conducting rails; current flows along one rail, through a plasma arc behind the projectile, and back along the other rail. The magnetic field trapped behind the projectile accelerates it. Railguns have the advantage of their extreme simplicity, but suffer from rail erosion and a rather low efficiency, about 10%. The steps that must be taken to increase this efficiency

involve the deexcitation of a rail section after the projectile has passed, and the recovery of the magnetic field energy stored in the section. These modifications amount to traveling wave excitation and cause the railgun scheme to give up most of its simplicity; once this is done, we might as well consider other traveling wave guns.[17] These guns push projectiles by interacting a traveling wave magnetic field with a dipole on the projectile. This dipole need not be generated by direct current conduction, as in a railgun. By using induction, ferromagnets, or superconductors we can more strongly couple the gun field and dipole, as well as avoid the requirement for physical contact. The projectile will consist of a payload carried by a dipole-generating bucket. After the launch speed is reached, the bucket can be separated from the payload, and decelerated by a reversed gun. This recovers the energy given to the bucket, and because it is recaptured, permits the economical use of superconductors for its dipole. There is no doubt that very efficient magnetic guns can be made in this fashion; I anticipate launch costs of less than 2 $/kg.

Unfortunately, machines that throw payload directly off the Earth have a common problem, completely unrelated to the merits of their technology. They impose an acceleration inversely proportional to the distance over which it acts:

$$a = \frac{V^2}{2L} \tag{7}$$

A 10 km long gun, throwing matter to escape velocity, subjects it to an average acceleration of 640 gees. In order to reduce this to 3 g for personnel use, the gun would have to be 2100 km long. The cost of acquiring and building on so much land would be prohibitive. Even if this were done, the projectile would be strongly braked when it left the gun and started traveling through the lower atmosphere. In addition to causing vehicle ablation, and costing extra launch energy to make up drag losses, the atmospheric drag imposes hundred gee loads. Since high accelerations are inevitable, Earth-based guns are designed to be short and often vertically oriented to shorten path length through the air; payloads will therefore see 500 to 1000 gee accelerations. The usefulness of these guns to space colonization will depend critically upon how large a fraction of the payload flux can tolerate such loads. Clearly people can't, while raw materials such as steel or aluminum can; some manufactured goods should be able to, but how many and with what cost penalty, I don't know. If a substantial fraction of the payload spectrum can tolerate high gee launch, then a mix of Earth guns and laser rockets may form a good transport system. In any event, it's worthwhile to look for systems which offer similar efficiencies and costs, without imposing such acceleration constraints.

In order to achieve long acceleration paths, and to avoid high speed travel through the atmosphere, transport machines must be in space. The obvious way to support them

there is to place them in orbit. A machine in orbit differs from the Earth-based guns just discussed by having a large velocity relative to that which its payload starts with. Consider the collision between a vehicle launched at low velocity from the Earth, and a more massive orbiting machine. First, the collision must take place over a long distance in order to impose acceptable accelerations. Secondly, the collision energy must be handled by the transport machine rather than the payload vehicle; otherwise, we run into familiar energy constraints. The collision can be viewed as inelastic if the vehicle is left in the machine (often with the relative energy being dissipated as heat), or as elastic if it rebounds at a greater-than-orbital velocity. The energy and momentum gained by our payload vehicle comes at the expense of the orbiting machine, and must be restored to it. The advantage of using orbital machines is that it is easier to leisurely supply these quantities to a big object parked in orbit, than to a small one furiously thrusting away from the surface. Let's briefly discuss three systems of increasing scale, shown schematically in Fig. 3A-3C.

The Bolo[18] is a long rotating cable; its lower tip moves slower than orbital speed, while the upper tip moves faster. A payload is launched from the Earth, matches speeds with the lower tip, latches on, and is released half a rotation later; this is essentially an elastic collision with velocity gain twice that of the tip speed. Rotating cables were first proposed[19] in which the lower tip matched speeds with the Earth; this required minimal surface launch capability, but too high a tip speed for available strong materials such as Kevlar. Tip speeds of 2 km/s allow material to be sent to geosynchronous orbit, where a similar bolo can catch it, or whip it to escape, and 3 km/s speeds allow direct escape from low orbit; both of these are within Kevlar's capability. The Bolo loses orbital energy but little rotational energy; restoration of energy is in principle achievable simply by sending downwards lunar material. A nearer term solution would put solar electric thrusters at its center-of-mass. The Bolo then has 3 advantages over a conventional low thrust rocket: it allows short trip times, it burns fuel low in the gravity well (hence using it more efficiently), and it cuts the velocity needed from the Earth launch vehicle, allowing a greater amount to be provided with low thrust systems.

The Spaceport[20] is an orbiting traveling wave magnetic accelerator; it is a more complex machine than the Bolo, but allows greater operational flexibility. A ship is launched from the Earth, intercepts the gun at some relative velocity, and is slowed down by it. Unlike a Kevlar bolo, a magnetic gun can handle full orbital relative velocity, so can permit a very simple Earth launcher. But a 5 gee gun would be 600 km long, so a reasonable tradeoff reduces the gun length to 150 km, while requiring that the surface launch system deliver one half of orbital velocity. The relative collision energy is stored and can be used to reflect the arriving ship, as was done with the Bolo. But there are other

possibilities; the ship can be unloaded, with the empty vehicle discharged at rest relative to the Earth. This makes recovery of the ship more attractive, and can be used to restore the Spaceport's momentum. Energy input is still required, and can be provided either by solar cells, or by braking material shipped down from the Moon. The Spaceport and Bolo differ in the size of payloads they process. The Bolo's use rate is limited by its rotation period, but because it stores energy in strong materials it can handle fairly large payloads at a time. Magnetic guns do not approach Kevlar's energy storage density, largely due to the channeling of energy through capacitors. As a result, payload sizes will probably be an order-of-magnitude smaller than those of a bolo, about 1 to 2 Mg. This can be offset by the rapid processing capability of a gun; ground stations will deploy a string of small vehicles in front of the Spaceport as it passes, rather than one large one. The small payloads will be combined at the Spaceport and sent out of the well either by a low thrust tug, or by a chemical tug using lunar propellants braked by the gun.

Orbiting systems tend to have low duty cycles, since orbital machines and ground stations are not always lined up. The need to maintain orbital shape in addition to size can cost another factor of two when solar power is used. As a result, Tg/yr transport fluxes will require many orbital accelerators. As the traffic increases we can carry this process to the extreme and construct a continuous orbiting material ring around the planet. A vehicle braking against this has a very long acceleration path, and so can use the ring to achieve all of its required velocity gain. Because of its size, an orbital ring cannot afford the specific complexity of a traveling wave magnetic gun. The Sky Rail[21] design has an active vehicle and merely uses the ring material to magnetically brake against, dissipating vehicle energy as heat. The ring has no trouble radiating this heat; of more concern is the factor of two efficiency loss, and the question of how to recover the vehicle after it has been brought up to orbital speed — since it must carry the motor, we probably can't afford to throw it away. In addition to accelerating payload, we can use the ring momentum to support two opposite and motionless stations; as the ring material passes each station it is deflected from one shallow elliptical orbit to its mirror, providing upward thrust. The stations are linked to fixed ground sites by structural cables and power lines. Payload is lifted up to the ring by cables instead of rockets. Magnetic motors using Earth-based power are used to reaccelerate the ring as it passes, with the reaction force transmitted through cables to the Earth. Because the variable speed along an elliptic orbit stretches the ring material, only a fraction of its momentum can be used to support the stations. A 1 Tg/yr system will require 2 GW of power to drive the ring; two stations each massing 2000 Mg can provide this thrust, but a 0.8 Tg ring is required to support them. In addition to the difficulty of assemblying this much mass in orbit, and that of recovering the vehicles, rings have a

stability problem. Suppose a station or vehicle is transversely displaced from its proper position; the changed deflection of the ring necessary to reach the new location and then return to course, pushes on the mass in a way that increases its deviation. This is a general instability that will show up in other systems employing high speed mass streams; in the ring we will try to control it via small rockets on the payload vehicles, and with the station cables.

The Launch Loop,[22] shown in Fig. 3D, employs the same propulsion principle as an orbiting ring, but with far less mass. It consists of a high speed (about 12 km/s) iron ribbon which travels along a 2000 km arc above the atmosphere. This length is sufficient to accelerate a vehicle to escape velocity, so the ribbon is then deflected downwards, and descends to the surface at roughly a 15 degree angle. At the surface, the ribbon is deflected to the horizontal, and passes through strong Earth-based magnets which turn it 180 degrees and supply energy to offset that transferred to payload vehicles. The ribbon is then once again deflected into space, and travels back along itself 2000 km, where it is sent through another ground base. So the overall loop length is some 6000 km, there are two ground stations, and either or both of the 2000 km arcs can be used for payload acceleration. There are 4 space stations which do not add energy to the ribbon, but only deflect it; the ribbon momentum change is easily capable of supporting both them and the atmospheric shrouds which protect the ribbon on the inclined sections. This is an Earth-anchored system, so has a high duty cycle, but avoids atmospheric limits by placing the acceleration path in space. The ribbon doesn't have to support the energy feed motors, so it has a smaller lineal mass than the orbital ring, as well as a shorter length. The payload flux is primarily limited by the heat dissipated during vehicle braking, rather than by constraints on longitudinal momentum exchange; a 10 gm/cm ribbon can launch 10 Mg vehicles every 200 sec. These cars climb cables hung from the spacebased deflector stations, are set on the ribbon, and accelerated to speed; by using both arcs, the Loop can launch 3 Tg/yr, which requires (for perfect motors) 13 GW. As with the orbital ring, the vehicles contain motors, and may have to be returned to Earth. Note that the ribbon is traveling at greater than orbital speed; it will be held down by a ferromagnetically suspended, motionless counterweight. This track has a 13 gm/cm mass, and is loosely anchored to the Earth by cables. As a vehicle approaches, the cables are relaxed, deflecting the ribbon-track pair slightly upwards. The vehicle supports itself against gravity by reflecting the mass stream back downwards. The ribbon-track system has two instabilities: a fast one due to ferromagnetic suspension, which can be internally controlled; and the one associated with relative velocity, discussed earlier. This must be controlled by external forces, presumably the ground cables, which also act as a noise source due to wind loading. The Launch Loop

solves the atmospheric travel problem of traditional ground-based guns, but still requires large length ground construction, since it must be built and started up on the ground, only after which it lifts itself into space.

In order to have the high duty cycle of an Earth-anchored machine and yet not require extended surface construction, we must use a vertical accelerator. One way to support such a device is to hang it from an orbital ring;[23] but as we've seen, only the small vertical fraction of its momentum contributes to lift. That being the case,[24] why not use a purely vertical mass flux for support? A stream of particles traveling between ground and space reflectors will push up on the space reflector; we can use this force to support a vertical payload accelerator. Let's illustrate this concept by using it to achieve a more ambitious goal: the dynamical support of a skyhook, which will permit us to carry rather than throw payload away from the Earth.

The Starbridge,[25] illustrated in Fig. 3E, is a skyhook supported by a stream of projectiles traveling both up and down alongside it. A structure with lineal mass m can locally balance its weight by pushing down on a projectile stream νM; if it forces the radial velocity v(r) of the stream to be

$$v\frac{dv}{dr} = -\left(1 + \frac{mv}{2\nu M}\right)\left(\frac{GM_E}{r^2} - \omega^2 r\right) \tag{8}$$

where ω is the Earth's rotation rate, and GM_E its gravitational strength. Several thousand discrete motors tied to the vertical cable are used for this task. Each pushes down on a climbing projectile, briefly stores the energy removed from it, and then uses this energy to push down on a falling projectile. If the motors were perfect and performed this energy transfer without loss, then no energy supply would be required to support the Starbridge. Obviously there will be losses, but the motors can be designed for very high efficiency, as well as for low mass, since motor mass must be included in m. The Starbridge motor stations each consist of an inductive motor coil, a capacitor, switchgear and busbars, and a radiator to dispose of waste heat. The projectiles are inert, non-superconducting, metal loops, which are inductively kicked as they pass through motor stations. Between motor stations, there are Kevlar cables and a ferromagnetic track, which is used to guide the projectiles and to resist Coriolis accelerations. The projectile stream must be reflected at the top and bottom of the Starbridge. This is done with very little loss by a curved and static superconducting track. As projectiles climb the Starbridge, their speed drops, as does the distance between them. This places a limit on the speed at the top reflector; for current designs, the resulting reflection force cannot be resisted by Kevlar cables. Instead a counterweight will be used; this restricts the height of the skyhook to be less than geosynchronous, but allows it to support a large spaceport at its top. This port will be

used to receive and process cargo, which can then be shipped the rest of the way out of the well with either a simple Kevlar skyhook or low thrust tugs.

A specific Starbridge design calls for a 100 gm/cm cable-track mass, ending at a radial position of 40,000 km (95% of synchronous), and supported by 7,500 five Mg motors. There are two complete projectile streams, with a total flux of 83 Mg/sec; the base speed is 13.9 km/s, slowing to 3.6 km/s at the tip. A projectile requires 3.6 hours to complete a transit, losing 0.3% of its energy in the process. Hence, the power required to support this skyhook is 20 GW; with another 20 GW we can send 10 Tg/yr up the Starbridge.

A critical feature of the Starbridge is that it works at any height. First, this means that small versions can be built and tested; the concept, engineering, and reliability can be proved out before a full-scale one is commisioned. Very crucially, it also permits us to build this type of skyhook from the ground up. The Starbridge is extruded: cable, track, and motors are added at the ground, while only the counterweight must be added to in space — using the payload-lifting capability of the growing skyhook. The payload cars can either climb the cables, or react against the projectile stream as the motor stations do. We will use the mass stream to transmit power up the Starbridge. This power is utilized both to makeup motor losses, and to supply energy to the climbing payload cars, thereby solving one of the problems with conventional skyhooks. We can use ground power plants to inject the energy, but another possibility is to hang solar cells along the length of the skyhook. The required cell mass and area are acceptable, the high Q of the projectile stream smoothes out diurnal solar flux variations and, by distributing the power generation capability over the entire structure, we substantially improve overall reliability.

Obviously the Starbridge, like the Launch Loop and, to a lesser extent, orbital rings, can fail gracelessly. The Starbridge is designed to operate with only 90% of its motor stations working and to permit at least 5 motors in a row to fail. A power outage lasting several days, physical interruption of the projectile stream, or a control system failure could bring it down. We face the standard velocity instability: a distributed control scheme for short wavelength oscillations has been devised, requiring only internal forces; slower oscillations with multi-kilometer wavelengths will be controlled by thrusters on the payload cars. Since the power generation will also be distributed, either via solar cells, or by the fact that multiple ground power plants would be required, the major threat is physical damage. Orbital debris will be a problem; but if the Starbridge is cut, note that the massive spaceport remains in orbit, and that the cable-track has a sufficiently large surface-to-area ratio to burn up in the atmosphere. The basis for concern with a failure is then an economic one; the Starbridge lifts 25 times its own mass per year, and so should have a short payback time. However, some combination of space debris cleanup and active

defense (perhaps using the projectiles) may be required.

This review of Earth escape transportation techniques is undoubtably — and hopefully — incomplete. Nevertheless, we've looked at enough systems to realize that transport can be made sufficiently inexpensive and extensive to permit practical, large-scale space colonization, and we've seen what types of systems can and cannot do the job. Where do we go from here? Unfortunately, the 'let a thousand flowers bloom' approach won't work. Creating and proving out space transport systems uses up a lot of dollars, and more importantly, time. The Space Shuttle, for example, took a decade to develop and, I suspect, will require a decade of use, before work on a successor system is begun. The next major space transportation system we develop will depend on, and will determine, our interests in space.

If we view space as a place to send missions to, or perform specific tasks in, then we will continue to upgrade chemical rocket systems. The basic problem with mission or task oriented development is that each one must be politically and economically justified, almost always on a stand-alone basis. The tendency is to only seriously consider jobs that can be done within your current transportation system. Those which are marginal or infeasible are either not considered or scrubbed, since to saddle any particlar mission with the development cost of a new transport system will almost surely kill it. Let's consider the current spectrum of space missions. Communications satellites are the big money-makers in space today. They are economical with expendable rockets, did not even demand the Shuttle, and will be satiated for years to come if the Shuttle is mated with a good H_2/O_2 space tug. Straightforward Shuttle derivatives will be sufficient for the development of space stations and space based defense systems. When large space power satellites were found to require advanced chemical rockets to become competitive with terrestrial alternatives, the response was to table the concept. Future chemical rockets can be used to build and maintain large space settlements, but not ones which are economically accessible to the general public. This will leave them with a limited political constituency with which to face the economical challenge presented by robots and teleoperators. So specific space missions will have a hard time even justifying advanced chemical rockets, let alone anything better. Conversely, the missions possible with chemical rockets will at best permit only a slow and uncertain exploitation of space.

The development of the space frontier should be done in the same manner as that of the American West. Once it is opened to large numbers of people, they will do the work, make the decisions, and take the chances necessary to develop it. Accordingly, our next transportation system after the Shuttle should be one that, while being useful for specific tasks and missions, also permits general access to space. Of the systems discussed here, I

would recommend the laser propulsion/Kevlar bolo combination for this next step. This system involves relatively little technical risk, and can become operational at low launch rates. The laser construction and propulsion questions can be answered with small (MW rather than GW) laser modules, which will also be useful for laser fusion and ground-based laser BMD work. An operational system should cluster its laser modules in a few big sites, allowing the launch of both small and Shuttle-sized payloads. The one capability of chemical rockets that this system cannot duplicate is the launching of big individual payloads, but the large cost reduction should more than offset this. As this transportation system is being developed and exercised, work can procede on the more advanced concepts; systems using traveling wave guns, dissipative magnetic braking, or dynamically supported cables can be first built and tested at very small scales. As they are proved out, and the demand for more and less expensive space transport grows, then they will brought on-line, completely opening the space frontier.

REFERENCES

1. Freeman Dyson, Disturbing The Universe, Harper & Row Publishers, (1979)

2. National Transportation Statistics, DOT-TSC-RSPA-80-19, Sept. 1980

3. R.W. Cline, D.A. Smith, T.J. Greytak, D. Kleppner, Magnetic Confinement of Spin Polarized Atomic Hydrogen, Phys. Rev. Lett. V45, 2117 (1980)

4. B. Johenning, H.H. Koelle, Simulation Model for the Operation of Space Freighters, Acta Astro. V8, 1207 (1981)

5. P.A. Kramer, R.D. Buhler, Hybrid Rocket/Airbreathing Propulsion for Ballistic Space Transportation, J. Spacecraft Rockets V17, 334 (1980)

6. D.A. Heald, Economic Benefits of the OTV Program, Acta Astro. V8, 1237 (1981)

7. K. Miller, et al, Solar Power Satellite System Definition Study. Part 2, Volume 5; Operations (Construction and Transportation), Boeing Aerospace Co., NASA CR 151669, Dec. 1977

8. A.R. Martin, A. Bond, Nuclear Pulse Propulsion, JBIS V32, 283 (1979)

9. J.H. Altseimer, G.F. Mader, J.J. Stewart, Operating Characteristics and Requirements for the Nerva Flight Engine, J. Spacecraft Rockets, V8, 766 (1971)

10. B.W. Knight, B.B. McInteer, R.M. Potter, E.S. Robinson, A Metal Dumbo Rocket Reactor, LA-2091 (Los Alamos National Laboratory) (1957)

11. K. Thom, R.T. Schneider, F.C. Schwenk, Physics & Potentials of Fissioning Plasmas for Space Power & Propulsion, Acta Astro. V3, 505 (1976)

12. D.H. Douglas-Hamilton, A.R. Kantrowitz, D.A. Reilly, Laser Assisted Propulsion Research, Progress in Astronautics & Aeronautics V61, 271 (1978)

13. Solar Power Satellite System Definition Study. Volume 6, Phase 1; Space Construction and Transportation, Boeing Aerospace Co., NASA CR 160375, (1979)

14. M.A. Minovitch, Performance Analysis of a Laser Propelled Interorbital Transfer Vehicle, Phaser Telepropulsion Inc., NASA CR 134966, Feb. 1976

15. J. Pearson, The Orbital Tower: A Spacecraft Launcher Using The Earth's Rotational Energy, Acta Astro. V2, 785 (1975)

16. R.S. Hawke, A.L. Brooks, C.M. Fowler, D.R. Peterson, Electromagnetic Railgun Launchers: Direct Launch Feasibility, AIAA J. V20, 978 (1982)

17. H. Kolm, P. Mongeau, An Alternative Launching Medium, IEEE Spectrum, April 1982, p30

18. P.K. Chapman, Cable-Connected Satellites for Inter-Orbital Transfer, available from author

19. H. Moravec, A Non-Synchronous Orbital Skyhook, J. Astro. Sci. V25, 307 (1977)

20. R. Arnold, D. Kingsbury, The Spaceport, Analog p48 Nov. 1979 & p61 Dec. 1979

21. K.A. Brakke, The Skyrail, L-5 News p6 July 1982

22. K.H. Lofstrom, The Launch Loop, L-5 News p8 Aug. 1982, & other papers available from author

23. P. Birch, Orbital Ring Systems and Jacob's Ladders - I, JBIS V35, 475 (1982)

24. R.L. Forward, personal communication

25. R.A. Hyde, L.L. Wood, Jr., J. McCarthy, M. Minsky, The Starbridge: A Skyhook We Can Build Now, Jan. 1981, available from lead author

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government thereof, and shall not be used for advertising or product endorsement purposes.

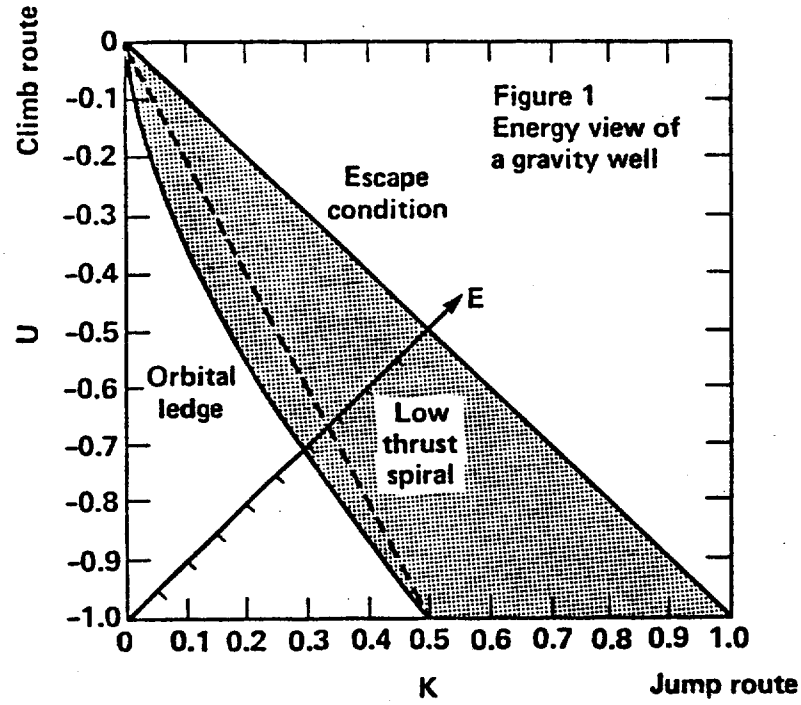


Figure 1
Energy view of
a gravity well

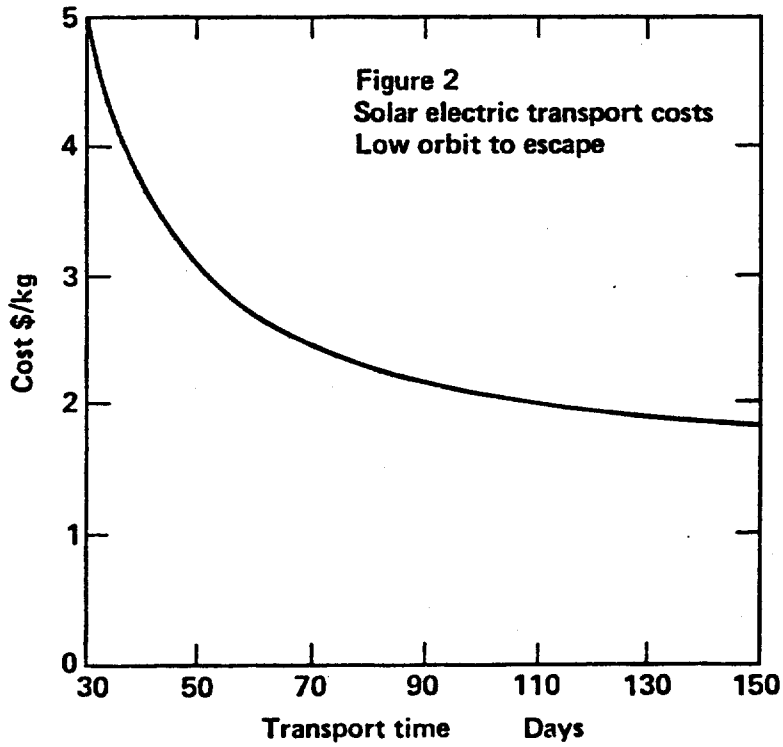
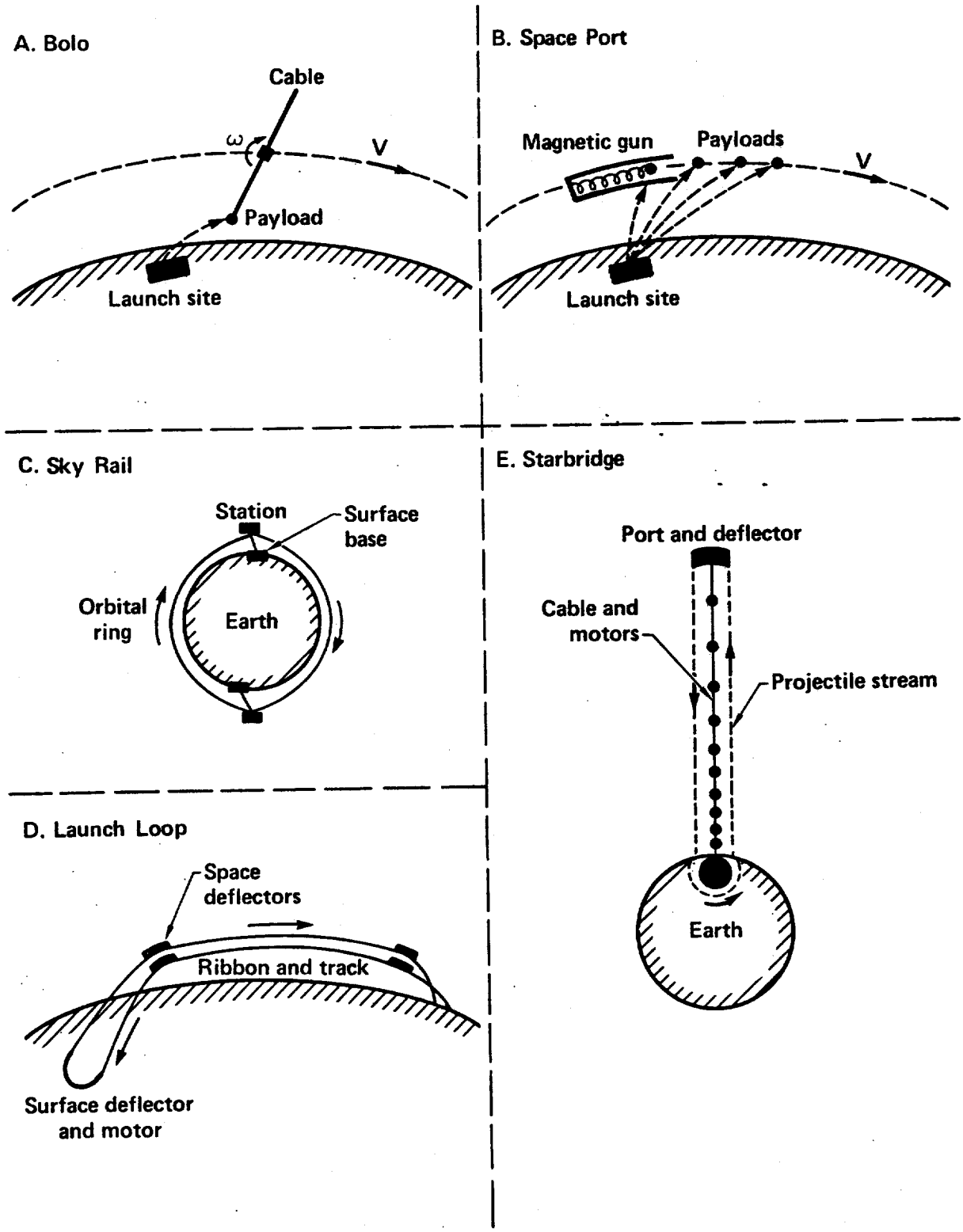


Figure 2
Solar electric transport costs
Low orbit to escape

Space transport machines