the spaceport

PART I: AN ALTERNATE MEANS OF DELIVERING PAYLOAD TO ORBIT

Must space travel be astronomically expensive? *Rockets* are—but here's a new concept that may change our whole view of such things.

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THE FABLE

Everyone knows the fairy tale of the gnome who fell into the burgomaster's well during the summer of 1212 AD and how he got out. Actually he didn't fall in—he was thrown in by the outraged burgomaster. Our gnome, who cobbled shoes for a living, was caressing a lady's foot and the lady happened to be the wife of the burgomaster.

He could see the stars from the bottom of the well. It was cold down there and our gnome wanted to get out. Sometimes the burgomaster's mean servant lowered the well's bucket on its pulley and made him raise countless gallons of water in exchange for a few crusts of bread. Altogether it was a pretty horrible life.

When the servant wasn't around, which was most of the time, he tried to escape. The walls were so slimy he could only climb a few stone levels that way. Once he tried hand-over-hand ascent up his half of the rope but his arms weren't strong enough and the rope was too slippery. He dreamed of sitting in the bucket and pulling himself up but he never had the bucket without the mean servant. His only chance was to make a single leap of twenty meters.

That was going to take energy. Being a meticulous gnome he calculated exactly how much. When the burgomaster had tossed him down the well his velocity of impact had been 20 meters per second as determined from the redness of his belly at splashdown. He massed only five kilograms. Energy is mass times velocity squared divided by two and so he needed 1000 joules of energy to extract himself from his predicament.

He moaned. The most he could put into a really strenuous leap was 50 joules. His lamentations attracted an Irish elf who was taking a day off from bombing pubs in Belfast.

"And how be you?" grinned the elf from the top of the well.

"Exceedingly sorry."

"Now and if it doesn't look as if you'll never get out."

"I will so."

"I'd be betting that you haven't got a thousand joules to your name."

"A thousand joules isn't so much," said the gnome petulantly.

"And the moat around the Lord's castle isn't much to a whale."

The gnome became irrationally defiant. "I don't need a thousand joules!"

"Roofs don't need walls," agreed the elf with a twinkle in his eye.

"Help me," pleaded the gnome miserably, thinking to ask the elf to lower the bucket.

"F*aa*ther in Heaven, I do believe you're sounding like an English gnome. So it's to be *my* thousand joules, is it?"

Suddenly the gnome grew cunning. "I can escape with one joule," he said to whet the elf's curiosity.

"You can't be saying what I'm hearing you saying!"

"But I am."

"Heinlein said, 'There Ain't No Such Thing As A Free Lunch!'" reproved the elf, "and if I didn't know you to be an educated gnome I'd remind you of the conservation of energy."

"One joule," insisted the gnome. Hiding his smile, he added, "I'll show you."

"That I'll be seeing on a sober Saturday night!"

"It will be quick, so you'll have to watch closely."

The elf stood on tip toes, peering over the well wall.

"You'll get a better view from the bucket."

Derisively the elf set the bucket on the wall and perched himself in it. He spat out some apple seeds, ready to wait a few moments while this braggart's bluff was called. The gnome gave a tug at the well rope just strong enough to tumble bucket and elf-cargo over the edge. Down went the fat elf. Up went the skinny gnome hanging onto the rope for dear life.

A FAST OVERVIEW

We stand at the bottom of our gravity well, gazing upwards. We yearn for the stars but right now we would settle for the planets. No one can call us idle dreamers. We have done our homework, and we know what it takes to escape from our well.

A kilogram of mass in orbit around the Earth at a height of 275 kilometers contains some 33 million joules more energy than it does at rest on the surface of the Earth. And, if that kilogram is put there by oxygen/hydrogen/kerosene rockets, another 40 to 60 million joules must be invested in the exhaust gases. That's a staggering energy input, but not enough to stop us. We have built powerful juggernaughts like the Saturn booster to get three men into space for a few days of freedom. We have reached Mars with our unmanned probes and travelled out beyond Jupiter. The sky above us is laced with communication and surveillance satellites.

All this we have been able to do by becoming masters of Brute Force. Soon we will have the Space Shuttle where Brute Force will be tamed into a reuseable package. Yet Brute Force will always remain expensive. It hasn't yet dawned on us that we can reach space for a modest "tug on the rope."

The philosophy of Brute Force is simple minded. It assumes that the energy in the exhaust gases is an unavoidable expense and is not recoverable. It assumes that when we return, the orbital energy of a vehicle can only be dissipated and used to heat the atmosphere. It states as a law that 70 to 100 million joules will be lost every time we cycle a kilogram from Earth to low orbit and back again.

The argument is reminiscent of engineering thought at the time Newcomen invented the steam engine. Steam displaced air in a chamber and was then condensed by spraying to create a vacuum. Air pressure pushed the engine's piston into the vacuum. No one considered the hot cooling water of this cycle as a useful energy source and it was simply run off with the water that was being pumped out of the mine. This practice continued until the mines got so deep that the pumps were consuming the entire output of coal. The Newcomen engine was about two percent efficient. Later engineers learned how to recycle waste heat, and how to use higher pressures and temperatures.

We find ourselves asking a fundamental question about spaceflight. Given that a good part of what goes up will eventually come back down, is it really necessary to waste all the energy contained in the returning mass? Can we somehow devise a scheme that will allow us to use mass dropping into a gravity well to help us lift other mass out? The answer is yes, we can. In fact, there is more than one way.

SOME NEWTONIAN THOUGHTS

We begin our analysis with a small observation whose significance is easily overlooked. While it is very difficult for a rocket to reach true orbit—particularly if it is a single stage rocket—it is easy to reach orbital *altitude*. Modest pre-Sputnik rockets reached heights well above the atmosphere. Merely getting up there is much easier than getting up there with a residual horizontal velocity of nearly eight kilometers per second—how much easier being a function of distance above the Earth's surface.

We must convert motion into *potential energy* to reach vertical altitude. We must generate *kinetic energy* to attain horizontal velocity. And so our story is told compactly by examining the ratio P/E where P is the difference in the potential energy between surface and orbit, and E is the total energy

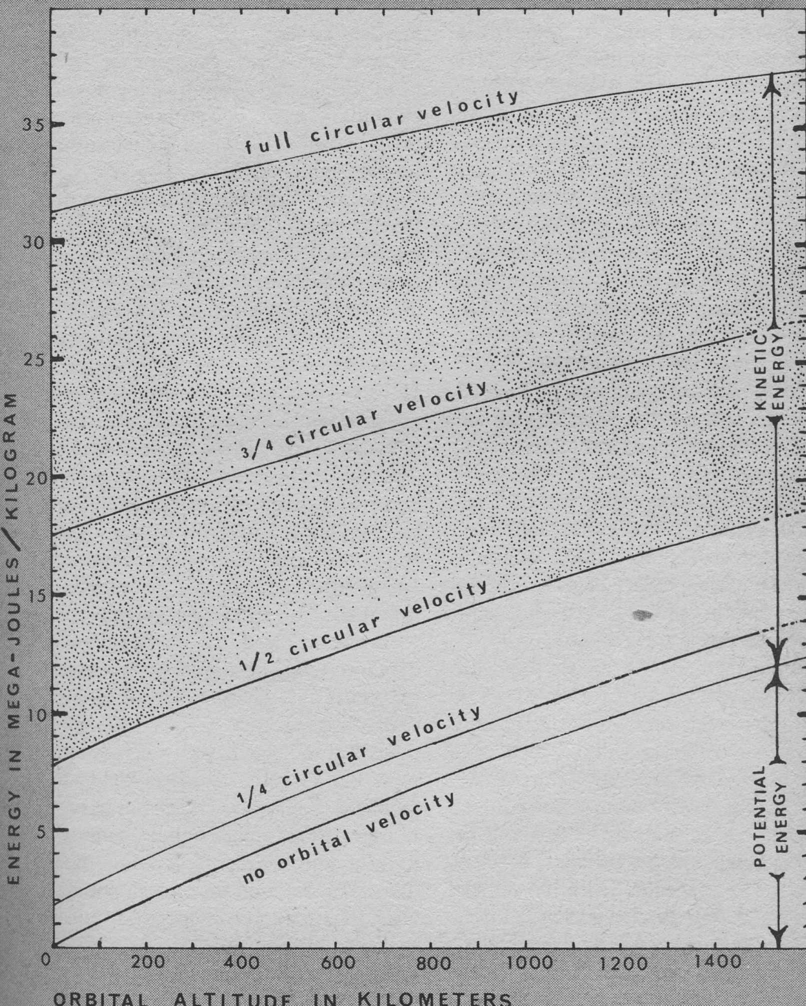


FIGURE 1: Energy Content Of One Kilogram At Various Altitudes And Velocities Above The Earth. Pick an altitude. The vertical distance to each curve represents the energy invested at that altitude in one kilogram moving at the given fraction of orbital circular velocity. The shaded area indicates the portion of the energy supplied by a spaceport receiving payloads at half orbital velocity.

change between sitting on the surface and moving in a circular orbit. This ratio boils down to $P/E = 2h/(2h + r)$ where h is the height of the orbit above the Earth and r is the Earth's radius, 6378 kms.

When h is 275 kms (a 90 minute orbit) this ratio is about 1/12 and tells us that very little of our insertion energy is needed to reach that orbit, most of it being used to attain orbital velocity. On the other hand if we aim for a higher orbit, say $h = r$, the ratio becomes 2/3. Most of our energy must now be used to overcome gravity, only 1/3 of it being used to attain orbital velocity.

Why the fuss? If we don't have orbital velocity by the time we reach orbital altitude we will just fall back down again. This conclusion seems obvious but it is a fallacy. We *can* stay up there and that is the key to a whole new way of viewing spaceflight.

Imagine that at its apogee our vehicle, which we will refer to as a "lighter," suffers an inelastic and non-destructive collision with a relatively massive spaceport already in orbit. The laws of momentum conservation tell us that the vehicle will be accelerated and the spaceport decelerated. The spaceport, with the vehicle attached, will drop to a slightly lower orbit. The vehicle has acquired its orbital energy, not via additional rocket power, but at the expense of the spaceport. Our spaceport is acting as a momentum bank and has just given our vehicle a loan.

If we continue landing vehicles without doing anything to repay these momentum loans, the same thing will happen that always happens in such cases: things will come crashing down around our heads. To remain solvent, then, we must soundly finance our borrowings.

The obvious method is to use part of the payload of such a lighter as reaction mass for high impulse rockets mounted on the spaceport. If the exhaust velocity is high enough—as it can be for an ion engine—the fraction of payload mass required can be quite small. Unfortunately our momentum debt is proportional to mass times velocity, while the energy needed to generate this momentum is proportional to mass times the *square* of the velocity. The higher the exhaust velocity of the spaceport mounted engines, the more energy it takes to pay off the momentum debt. And energy costs money.

Ideally we would like to repay our debt by ejecting reaction mass from the spaceport at a *low* velocity. Where is such a large amount of mass to be obtained? If we assume that our reaction mass has to come from the lighter's payload, we have no choice but to use energy gobbling high impulse engines to keep the spaceport orbiting. But there is no law that says reaction mass has to be a fluid you squirt from a rocket nozzle. Consider the lighter vehicle itself as reaction mass.

We can build a long catapult that shoots the lighter out the rear of the spaceport. We know how to do that. The catapult would be a linear synchronous motor—what G.K. O'Neill has dubbed a "mass driver." To achieve the velocities required, it would have to be a long and powerful mass driver, but there is no theoretical reason why it can't be built. The technology is well understood.

Using a mass driver to accelerate returning lighters away from the spaceport allows us to get a maximum of reaction mass without cutting into vehicle payloads. In fact, if the returning lighter is loaded with space manufactured goods, lunar raw materials, etc., of mass equal to its standard payload, then the velocity it needs to kick the spaceport back up to the original orbit is just equal to the velocity it had when it arrived, and the energy needed to effect this return is equal to that which was released while braking on arrival.

Assuming a means to recover and store the braking energy, we have an interesting situation. Aside from covering conversion and storage losses, no net energy input into the system is required. With a steady stream of arriving and returning lighters we can even dispense with most of the energy storage requirement. The arriving lighter and a returning lighter simply exchange velocity and momentum, leaving the arriving lighter in orbit. As a bonus, the returning lighter drops into the atmosphere with only a moderate velocity, continuing the trajectory that the arriving lighter would have followed had it not "landed" at the spaceport.

If there is no cargo for the re-entry leg of the lighter's flight, then the situation is a little different. The mass of the returning lighter is less than that of the arriving lighter so the return velocity required to pay our momentum debt is greater. A net energy input is called for, but not nearly so much as would be asked if the returning lighter couldn't be used as reaction mass. In effect, we only have to pay for the difference between outbound and inbound traffic, which means we only have to pay for what we leave in orbit.

THE SPACEPORT'S LENGTH

How long would the spaceport structure have to be to capture a vehicle nondestructively, that is in a way which can be called "braking" rather than "crashing"? The relevant equation is $s = v^2/2a$ where v is the velocity change, a is the acceleration of the vehicle, and s is the distance through which the change takes place. Suppose our vehicle can tolerate an acceleration of $50 m/sec^2$, about 5 gravities. Its velocity change from standstill to circular orbit at height 275 km is 7740 m/sec and so s must be 600 kilometers. That is a *long* spaceport, about the distance between San Francisco and Los Angeles, or Chicago and Kansas City. It is not impossibly long, but a compromise is in order.

The obvious compromise has our vehicle meeting the spaceport with some horizontal velocity and so we become involved in a trade-off between rocket supplied momentum and spaceport supplied momentum. At one extreme if we want to use a small Piper Cub of a vehicle which has the bare capacity to climb above the atmosphere with no horizontal velocity we will have to build an enormously long and complicated spaceport. At the other extreme, if we like the idea of a short compact spaceport, we have the problem of building and operating a fleet of Gargantuan two stage shuttle vehicles with high mass ratio. (The mass ratio of a rocket is the ratio of the mass at lift-off to the mass at burn-out and is related to the exhaust velocity c and the mission velocity v by the expression $r = e^{v/c}$.)

As a first approximation to an optimal trade-off point we choose the median in which the vehicle delivers half of the orbital velocity and the spaceport delivers the other half. In doing so we have shrunk the length of the spaceport landing track by a factor of four, to 150 kms, and reduced the mass ratio of the shuttle vehicle to the square root of what it would have to be to do the job alone.

MAGNETIC CAPTURE

Even with a 150 km runway, how can a vehicle traveling at thousands of meters per second ever manage to "land"? Obviously it can't depend on wheeled landing gear and mechanical brakes. At the speeds involved, any physical contact between moving surfaces would simply vaporize both surfaces. We have to have some way to arrest the incoming lighters without touching them until they have virtually come to a stop. The problem resolves into two parts: (1) guidance and suspension of the vehicles along the

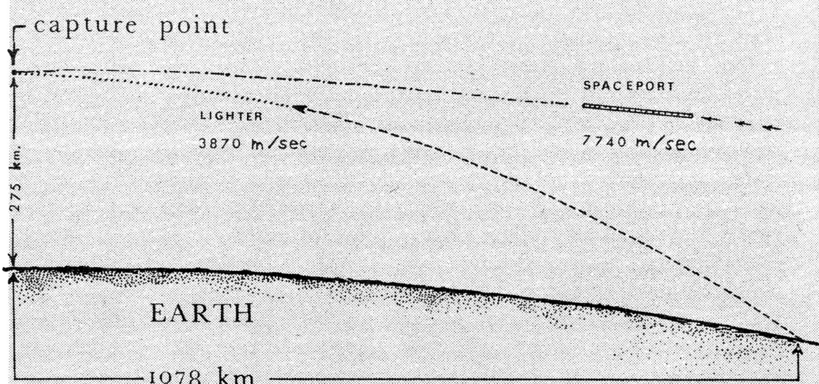


FIGURE 2: Spaceport About To Capture Small Freight Vehicle Called A Lighter. We are looking from the Northern hemisphere toward the equator. Notice that the faster spaceport overtakes the lighter. The one-ton lighter enters the leading edge of the spaceport and is accelerated electromagnetically while the more massive spaceport decelerates slightly. The drawing is to scale; the Earth's radius is 6378 km, the spaceport's length is 150 km, the trajectory of the lighter has an eccentricity of ¾ and a "perigee" of 950 km.

landing track, and (2) braking the vehicles.

If a magnet moves rapidly above a conducting surface, the moving field induces currents in the conductor that create a mirror image of the generating field. The mirror image opposes the generating field and causes a repulsion. This makes for an ideal suspension system, because the closer the generating magnet comes to the surface over which it moves, the closer it comes to its mirror image and the stronger the repulsion. A vehicle using the generating magnets in place of wheels effectively rides on invisible massless springs. They cushion it without ever allowing it to contact the surface of the track. The speed of the vehicle is irrelevant so long as the track is straight.

Superconducting coils aboard the lighter which provide the generating field for the magnetic suspension system also provide the "handles" for braking the vehicle. The principle employed is that of a linear synchronous motor/generator.

When a current flows through a wire in the presence of a magnetic field, a force is exerted on the wire in the direction perpendicular to both the current and the magnetic field. An equal and opposite force is of course exerted on the magnet that generated the field. Normally either the wires or the magnets are connected to a central shaft so that the forces produce torque and cause the shaft to rotate. That is the principle of an ordinary electric motor. But we don't have to use that arrangement. The magnets can be installed in a carrier of some sort, in this case our lighter, and the wires can be arranged along the path of the carrier in the manner of crossties on a railroad track.

When current flows through the wires, a force is exerted between wires and magnets that can accelerate or decelerate the carrier directly, without any need for drive wheels or cogs or whatever. We then have a linear electric motor. If we introduce sensors and switches so that only the wires over which the carrier is passing at any moment are carrying current—a necessity if we want to achieve reasonable efficiency—then the motor is called a linear *synchronous* motor.

Such motors are being studied extensively for rapid train service on Earth and under the name of "mass driver" are being developed for accelerating loads in space. Successful working models of "electric guns" were built more than forty years ago.

Today mass drivers are being considered as devices to deliver mineral ores from the surface of the moon at low cost, and as electrically powered reaction engines for space "tugs." In both of these modes mass drivers accelerate packages that are released near the end of a straight track and fly on at high speed. The idea of using one in reverse to "catch" packages—namely our spaceport lighters—is novel but not at all unfeasible. The principles of operation are the same, except that instead of consuming power, a mass driver operating as a catcher acts as a generator. In fact the power generated in arresting the arriving lighters provides a good part of the power needed to accelerate the returning vehicles along a parallel track. This is the key to the efficiency of the overall system.

TO CATCH A RISING STAR

Our lighter must reach an exact point in space several hundred kilometers from its launch site at the exact moment the spaceport passes with its landing track. If its position and velocity are just right, the lighter will be lined up with the track and will lock onto it, shooting down the track at half orbital velocity, 3870 m/sec, braking furiously to come to a rest at the end of the track. The slightest error, however, and lighter and spaceport will collide, producing a spectacular wreck.

There are several considerations that make the possibility of solving the guidance problem a little less incredible than it might otherwise seem. To begin with, the lighter makes a rendezvous with the spaceport well above the atmosphere in an environment where no random forces disturb its trajectory. There the ideal laws of motion are obeyed with mathematical precision and predictability. Secondly, the accuracy required—while great—is not the kind of accuracy involved in hitting a pinhead at some outrageous distance with a rifle. The lighter is not a passive projectile that must be aimed with absolute accuracy from the start. It is an active vehicle that continuously adjusts its thrust vector according to feedback from a guidance device. Finally, guidance does not depend on human senses and human reflexes, but on precision electronic sensors coupled to high speed computer circuits.

There are basically three elements that make up a guidance and control device: (1) a measurement system that determines where the vehicle is and what it is doing at any given moment, (2) a computational system that looks at the difference between where the vehicle is and where it is supposed to be and figures out what to do about it, and (3) an actuator system that implements the commands from the computational system. The computer and actuator are essentially off-the-shelf technology, while the measurements can be accomplished by predictable developments in multiple beam microwave interferometry.

Range measurements are normally made by timing the travel of a microwave or laser pulse from the rangefinder to the target and back again. Because of fuzziness in the pulse envelope, this method is generally good only to a few tens of centimeters and requires repeated pulses even to get that. With a continuous beam, on the other hand, the phase angle between the return signal and the outgoing signal gives the distance to a fraction of a wavelength—only it is a fraction plus some unknown integral number of wavelengths. If there is a second continuous beam of a slightly different frequency, one gets a set of simultaneous equations that can be solved for the unknown number.

Thereafter, it is only necessary to count interference fringes to have continuous monitoring of the distance to a fraction of a wavelength.

When this is done from three different reference points, the lighter's position with respect to the three reference points is known precisely at any time. Of course at these accuracies there are all kinds of correction factors to worry about—transponder antenna characteristics, delay paths within the transponder, orientation of the lighter, and so on, but no fundamental problems.

The use of the position information for guidance is straightforward. Mission control picks the exact time for touchdown and the exact position and velocity vector that the lighter must have. Then the equations of motion are integrated backwards to get position as a function of time for a perfect trajectory. From there it is just a matter of telling the lighter where it is at any time relative to where it is supposed to be. The lighter closes in on the imaginary moving point that represents exactly the free fall trajectory it needs for a perfect capture by the spaceport.

If for any reason the vehicle fails to achieve this moving rendezvous within a given margin of time prior to touchdown, then the contact is aborted. The cutoff could be as much as half a minute before touchdown, giving emergency retros on the lighter plenty of time to kill its upward velocity and keep it well away from the spaceport.

THE LIGHTER

To meet the spaceport at half orbital velocity the lighter needs a mission velocity of about 5000 m/sec. This is typical of an intermediate range ballistic missile. A velocity of 4490 m/sec is required at the Earth's surface to reach 3870 horizontal m/sec at 275 kms. The lighter picks up 410 m/sec by lifting off from Cape Canaveral toward the east—more if it takes off at the equator—but loses about 1000 m/sec to air resistance and gravity.

Assuming a single stage vehicle our mass ratios for this mission would be (about) 5 for oxygen/kerosene propellant, 4 for oxygen/methane propellant, and 3 for oxygen/hydrogen propellant. Mass ratios of 25, 16, and 9 respectively would be required if we intended our lighter to go into orbit without help from the spaceport. Even though hydrogen gives us a lower mass ratio, we prefer more compact fuels like kerosene or methane because they make our vehicle less bulky and reduce our propellant/tankage weight ratio.

It is worth noting that given a mass ratio of 5 we are at the energy optimum for *all* rocket missions in terms of the percentage of energy used that is imparted to the empty vehicle-plus-payload. If our mass ratio is smaller than 5 it means we are using a high exhaust velocity for the mission and since energy is a velocity squared factor, a large proportion of our energy is being bled off into the fast exhaust gases. If our mass ratio is greater than 5 it means we are being prolifigate with reaction mass. Even though our exhaust velocity is low, and each unit of our reaction mass carries away little energy, so much reaction mass is being used that the exhaust gases absorb a large proportion of the available energy. If energy is cheap and reaction mass is expensive we favor high exhaust velocities. If energy is cheap and reaction mass is cheap we may use low exhaust velocities. If energy is expensive we stick as close as we can to a mass ratio of 5.

An oxygen/kerosene vehicle with a mass ratio of 5 is a comfortable one to work with, requiring little new technology over a wide size range. We wish to work the small end because a smaller rocket can be handled by a less massive spaceport. Our baseline design assumes a lighter with a gross lift-off weight of 5000 kg that delivers to the spaceport 500 kg of vehicle and 500 kg of payload.

The simplest design for such a craft is a pointed cylinder seven or eight meters long and one meter in diameter with superconducting coils running around the circumference at axial intervals of about ten cms. If this vehicle proves too clumsy to return to the ground stations, we can go to a folding wing vehicle that flies back to the launch site under autopilot using cruise missile technology now under development. The superconducting coils of the accelerators can be located in triple spines at the rounded corners of a "triangular" cross section, the mates of corresponding drive tracks in the spaceport's mass driver.

Although the lighter is capable of achieving its mission on rockets alone, we can make use of its wings and superconducting drive coils for a mode of operation that would per-

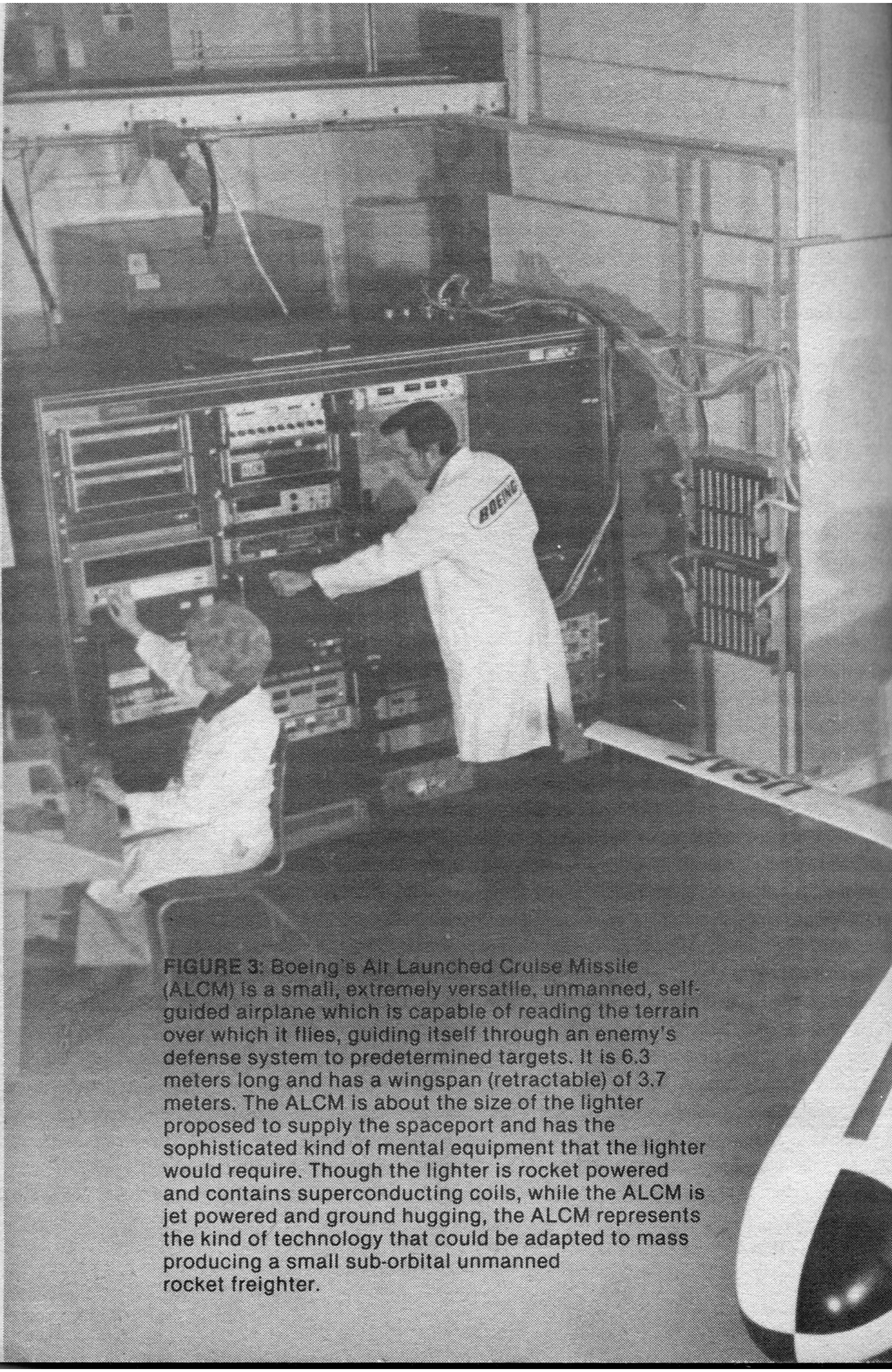
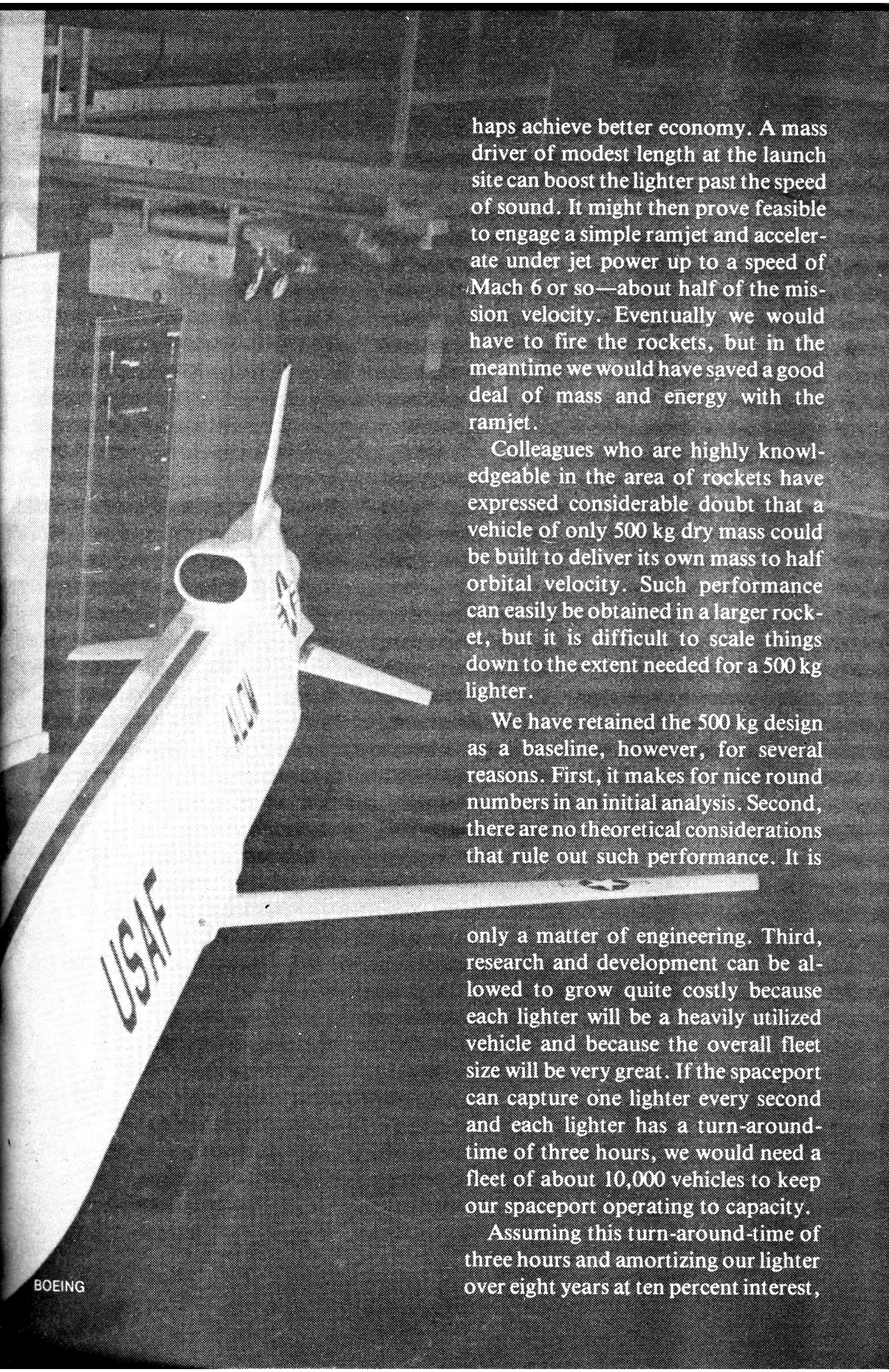


FIGURE 3: Boeing's Air Launched Cruise Missile (ALCM) is a small, extremely versatile, unmanned, self-guided airplane which is capable of reading the terrain over which it flies, guiding itself through an enemy's defense system to predetermined targets. It is 6.3 meters long and has a wingspan (retractable) of 3.7 meters. The ALCM is about the size of the lighter proposed to supply the spaceport and has the sophisticated kind of mental equipment that the lighter would require. Though the lighter is rocket powered and contains superconducting coils, while the ALCM is jet powered and ground hugging, the ALCM represents the kind of technology that could be adapted to mass producing a small sub-orbital unmanned rocket freighter.



BOEING

haps achieve better economy. A mass driver of modest length at the launch site can boost the lighter past the speed of sound. It might then prove feasible to engage a simple ramjet and accelerate under jet power up to a speed of Mach 6 or so—about half of the mission velocity. Eventually we would have to fire the rockets, but in the meantime we would have saved a good deal of mass and energy with the ramjet.

Colleagues who are highly knowledgeable in the area of rockets have expressed considerable doubt that a vehicle of only 500 kg dry mass could be built to deliver its own mass to half orbital velocity. Such performance can easily be obtained in a larger rocket, but it is difficult to scale things down to the extent needed for a 500 kg lighter.

We have retained the 500 kg design as a baseline, however, for several reasons. First, it makes for nice round numbers in an initial analysis. Second, there are no theoretical considerations that rule out such performance. It is only a matter of engineering. Third, research and development can be allowed to grow quite costly because each lighter will be a heavily utilized vehicle and because the overall fleet size will be very great. If the spaceport can capture one lighter every second and each lighter has a turn-around-time of three hours, we would need a fleet of about 10,000 vehicles to keep our spaceport operating to capacity.

Assuming this turn-around-time of three hours and amortizing our lighter over eight years at ten percent interest, gives a vehicle use-cost per delivered kilogram of 13 *cents* for every million dollars worth of lighter. Boeing has estimated that a low orbit delivery cost of 20 *dollars* per kilogram would allow construction of solar power satellites competitive with coal fired power. So the price of our vehicle will not be a dominant cost. We can afford to put more work into miniaturization than has been justified in the past. We can afford a sophisticated guidance system. We can afford superconducting coils.

ACTIVE CONTROL

One of the largest space structures which has undergone serious analysis is the solar power station. Boeing's design, for instance, masses as much as a battleship, 80,000 tons, and covers an area 22 kilometers by 5 kilometers, about the length and breadth of Manhattan Island. We are proposing a spaceport seven times as long and substantially narrower. Such a long thin structure presents engineering problems.

If we treat the case of the capture of a single lighter we see that energy is available, which can be bled off electrically, and that momentum is exchanged at the moving point of contact. Normally momentum induced capture forces would spread throughout the spaceport from the contact point at the speed of sound in our structure. However, in this case, as the lighter slows to the speed of sound in the spaceport, a shock wave builds up around the lighter that would, unless negated, destroy the interface portions of the spaceport.

The problem can be solved by giving the spaceport an electrical nervous system, electromagnetic muscles, and intelligence enough to respond to the lighter as would a martial arts master. A karate chop will break a passive brick but it will not break the head of an alert black belt samurai.

To prevent lateral buckling, which is a weakness of long structures under compressive stress, we employ an active control system. Any small amount of lateral bending is sensed by this control system. A lateral restoring force is immediately applied electromagnetically that is many times larger than the natural elastic restoring force at the small displacements measured by the sensor. Our spaceport thus has the brains and muscle to simulate "infinite" stiffness.

Another problem is longitudinal waves. To prevent dangerous waves from building up and whipping back and forth through the spaceport we need control over longitudinal springiness. Again the spaceport's brains and electromagnetic muscles allow it to generate waves within itself which can be constructed so as to cancel the waves created by capturing the lighter. Prior to a capture the spaceport gathers itself up into its shortest length, then, just before the lighter makes contact, it starts expanding. Its head sections leap forward to meet the lighter and an anticipatory expansion wave is generated that precedes the lighter down the track. The braking force of the lighter is not directly transmitted from section to section. Rather it serves to kill the leap given to the section by the expansion wave. The spaceport "rolls with the punch" so to speak. There are variations of the strategy depending upon how many lighters are being captured and ejected at any one time.

The control system can also handle the gravitational gradient instability. A long skinny structure in space prefers to align itself with the gravitational gradient—up and down relative to the Earth. The horizontal position is only metastable—like a notions tray carrying a few ball bearings balanced on a knife edge. If the spaceport drifts a fraction off the horizontal position, the gravitational gradient will tend to accelerate the drift in much the same way that it generates tides. Though all sections of the spaceport are tied to a common velocity, once the spaceport "tips," each section is at a different distance from the Earth and so tries to follow a conflicting orbit around the Earth. The low sections are moving too slow to maintain a circular orbit and fall inward, while the high sections are moving too fast to maintain a circular orbit and fly outward. This conflict is only resolved by the vertical position where all the disturbing forces act through the center of mass.

Such a drift from the horizontal can be countered with rockets, of course, but a more economical way is to use the control servos. Orbital motion gives the spaceport a certain angular momentum. Suppose this long structure has a small excess of angular momentum. It is rotating a little too fast for its orbital period, so that the leading edge is drifting below the mean orbital path, while the trailing edge is drifting above. To compensate the spaceport stretches in length. The moment of inertia is thereby increased. The rotation rate is slowed by a corresponding amount, like a skater extending her arms to slow her spin. Now the motion is reversed; the leading edge rises and the trailing edge falls. The spaceport contracts to stop the drift, but leaves its trailing edge low until the gravitational gradient has subtracted enough angular momentum to cancel the original excess. Another contraction and expansion brings the spaceport to the required horizontal position with the proper rotational velocity.

ECONOMICS

Deciding whether a device will work and deciding whether it is economically viable are two different questions. The spaceport is a workable transportation system. But to ask if it will pay for itself poses a peculiar double bind. What the *first* spaceport must charge for freight depends upon its construction costs which in turn depend upon high-cost rocket transport such as the Rockwell Space Shuttle.

Perhaps the best first approximation to make is in terms of the ratio of the delivery cost of freight to the spaceport and the delivery cost of freight to low orbit by rocket. If this ratio is less than one, then constructing a spaceport with rockets will automatically make the rockets obsolete, providing, of course, the charge made by the spaceport to deliver payload will sustain the volume of traffic that the spaceport would have to have.

Using the above ratio we can generate the following inequality

$$MT < 143 \times 10^6 F$$

where M is the mass of the spaceport in tons, T is the average period in seconds between delivery of the 500 kg payloads and F is the fraction of revenues that can be applied to the costs of transporting the spaceport's mass into orbit, amortized over 25 years at 10 percent interest. Immediately it becomes obvious that spaceport mass must be minimized and payload delivery rates kept high.

There are no technical reasons why the spaceport cannot accept payloads around the clock at the rate of one lighter per second; however, we must not expect such a high use-rate initially. First a distributed series of launch sites must be established around the Earth, near the equator. Second, we must have assembled in space enough power generating and storage capacity to maintain the spaceport's momentum balance.

Our baseline design is for a system that receives 1000 kg loads at half orbital velocity (3870 m/sec relative to the spaceport) and returns 500 kg loads at negative orbital velocity (7740 m/sec relative to the spaceport, or zero velocity relative to the Earth). If the arrival and return rates are one vehicle per T seconds, then we require a power input of 8000/T megawatts. Even to handle one lighter every four seconds demands the electrical generating capacity of a Hoover Dam. Where such power will come from will be dealt with in the next article of this series.

What kind of estimates can we get for the spaceport's mass? Assuming that the driver for the return vehicles is adjacent and parallel to the one for the arriving vehicles, it is fairly easy to show that the structure as a whole is under tension. From this we can derive the mass of the main structural cable.

Visualize the stream of braking lighters. They are bunched toward the spaceport's tail according to the following equation

$$x = 3.87t - .025t^2$$

where x is the distance in kilometers from the front of the spaceport and t, in seconds, varies in increments of T. Sixty percent of the braking lighters will be in the last thirty percent of the spaceport, each exerting a force of 50,000 newtons in a direction which tends to pull the tail of our beast. The stream of returning lighters (half as many but twice as fast) are bunched toward the spaceport's front according to the equation

$$x = 0.1\,t^2$$

each exerting a force of 100,000 newtons in a direction which tends to pull on the head. We have a tug-of-war and hence: tension.

The maximum tension

$$S_{max} = 0.83\ Lma/(vT) \text{ newtons}$$

will occur at the center. L is the length of the spaceport, m is the mass of the arriving lighters, a is the acceleration of the arriving lighters, v their arrival velocity, and T the period between arrivals. If we assume the extreme case where T is one second, then S_{max} is 1.6 million newtons. Let this tension load be taken by kevlar cables which have a safe operating strength to weight ratio of a million newton meters per kg, a 2:1 safety factor. Then the total mass of the main tension member comes to 240 tons. That is about ten Space Shuttle payloads, or two payloads for the heavy lift launch vehicle derivative of the Shuttle. To put it in better perspective, however, consider this: when the spaceport becomes fully operational, it will take a mere eight minutes to deliver payload mass equal to this main structural cable!

Obviously the main tension cable will not be the whole of the spaceport's structural mass, or even a very large part of it. Stiffening members, local supports for the drive coils, and the active control structures will add mass at least several times that of the main cable. The various electrical components—particularly the drive coils and power buses—demand many times again as much mass. However, there is no need to detail the mass estimates for these subsystems because the "bottom line" should be clear—the total mass of the system is going to be small compared with its annual delivery capacity.

We can conservatively estimate the mass of the spaceport to be 50,000 tons plus the solar power arrays. Solar power comes at about 8 tons per megawatt but since the spaceport will be in shadow half the time we will need 16 tons per megawatt and so our total spaceport mass estimate is something like 50,000 + 128,000/T tons, where T is the average interval in seconds between lighter captures. The annual payload delivered will be 15/T million tons. Thus the ratio of yearly-payload to spaceport-mass is approximately 300/(T + 2.5). Even if the spaceport were operating at only one percent of capacity, it would still deliver several times its own mass to orbit every year.

NEXT MONTH

This first article has been a spare overview of the physics of building a system which can provide us with medium cheap access to space. The second article will explore some of the astounding consequences. Medium cheap space travel will allow us to tap into an energy source vast enough to power a space program of a magnitude that even the most ardent space buff has not dared to dream. ■

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Part II the spaceport

Building Energy Cheap Space Transportation

Suitably used, an orbiting spaceport could do far more than pay for itself.

by **Roger Arnold** and **Donald Kingsbury**

SPACEFLIGHT AND ENERGY

Those who saw the Saturn booster lift-off for the moon were awed, and even shaken, by the river of energy that flowed from the nozzles of those five F1 motors as they moved that sky-scraper up off the Earth. That was 42,000 blazing megawatts of power, the equivalent of half of the electrical power being generated by the United States at the time. The Earth trembled.

Since then people have had a gut feeling that it takes *power* to get into space, that spaceflight is an *energy* intensive business too expensive for an energy poor nation like the United States to undertake on a mass scale. That gut feeling, like most gut feelings based on too little experience, is wrong.

(1) Recall the story of the gnome at the bottom of his well who tricked the elf at the top into stepping into the well bucket. While the elf rode the bucket down, the gnome got an energy free ride up out of the well.

(2) Hans Moravec delivered a paper at the twenty-third annual American Astronautical Society meeting in San Francisco titled "A Non-synchronous Orbital Skyhook," which described an energy free way of reaching space. A rimless wheel with spokes "rolls" around a planet, its hub in orbit. If the cage at the end of a spoke brings down as much mass as its counterpart lifts out, we have a "space elevator" that requires no energy input. For Earth such a "wheel" demands materials of greater strength than is practically possible, though of less strength than is theoretically attainable. For Mars or the moon, present day materials would permit us to build such a device.

(3) In last month's Analog we described a method of reaching space which requires substantially less

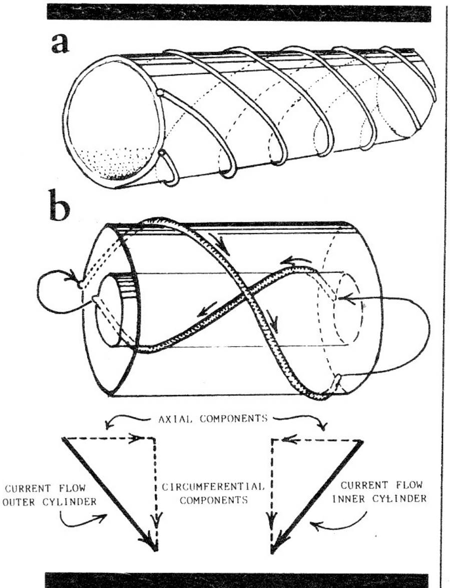
energy than the brute force rocket approach. An orbiting spaceport, long and massive, acts as a momentum bank. Small and single-stage rocket-propelled vehicles called "lighters" are launched from the Earth at suborbital velocity and captured by the spaceport electromagnetically. The momentum exchange between the two slows the spaceport slightly as it drags the lighter into orbit. Later the spaceport regains its lost momentum by electromagnetically shooting the same lighter back to the Earth at high velocity. If the spaceport ejects from its stern as much mass as is being received by its prow, the energy requirements of the parallel mass drivers are small. However, if the lighters leave their payloads in orbit and return empty, the spaceport, to remain in orbit, must have access to a sizeable energy source.

So that we might have a model to generate numbers for us we conceived the spaceport to be a reedlike structure 150 kilometers long containing electromagnetic muscles and electrical senses providing an artificial lateral rigidity and a controlled longitudinal flexibility. The spaceport moved in a 90 minute orbit, 275 kilometers above the Earth's surface at a velocity of 7740 m/sec. Our mass estimate for the spaceport was 50,000 tons plus solar energy generators at 16 tons per operational megawatt.

The Earth-to-spaceport lighters were assumed to have a gross-lift-off-weight of five tons—four tons of oxygen/kerosene propellant, half a ton of dry mass and a half a ton payload—meeting the spaceport at half orbital velocity, 3870 m/sec, and being electromagnetically accelerated at five g's. Maximum delivery rate was assumed to be one lighter per second.

One can question the design presented on various points. Others working with mass drivers have routinely designed for accelerations 100 times greater than the 5 g's we assumed. We chose an exceptionally conservative figure because we found that total spaceport mass was largely independent of the acceleration used. Higher accelerations made for a shorter spaceport, but required an offsetting increase in its mass per unit length to handle the greater forces and power levels. The low acceleration allowed us to minimize the non-payload mass of the lighter. But perhaps a shorter spaceport would be desirable for reducing atmospheric drag. (There are still some traces of atmosphere even at 275 km, as the recent demise of Skylab illustrates.)

Of greater significance is that we may have grossly overestimated the ratio of spaceport mass to lighter payload mass. Designs using homopolar generator-motors (see figure 1) in place of capacitors for energy buffering can apparently reduce by a factor of ten or better the spaceport mass required to accommodate payloads of a given size—or conversely to allow a spaceport of the same mass to handle payloads an order of magnitude greater. That means it would be feasible to operate



with larger lighters and lower arrival rates which allows us the economies that come with increased size such as relaxed mass constraints on the lighter's guidance and control system.

However, at this stage, it is premature to weigh the relative advantages of one design over another. What is important for us to notice is the principle common to all the schemes we have mentioned, whether they be elf-powered gnome-elevators, giant Moravec wheels, or orbiting spaceports. The common and essential principle is the energy exchange between falling and rising loads. The falling cage at the end of the spoke of Moravec's wheel provides the energy to lift the rising cage at the end of an opposing spoke. Similarly, the energy

FIGURE 1. A Rotational to Linear Momentum Transformer Using A Homopolar Design. *(1) Sketch (a) shows a right handed helical winding with a significant pitch. We mount two such cylinders coaxially so that they are free to rotate independently. One has a right handed winding and the other a left handed winding as in (b). (The difference in cylinder size has been exaggerated.) Note the closed current path. The ends of the cylinders are connected through plasma "brushes."*

(2) The current in such helical coils has two components—circumferential and axial, with the ratio between the two a function of the coil pitch. The axial current components are opposed (see b) and cancel each other's magnetic fields. The circumferential components are in the same direction (see b) and reinforce each other's magnetic fields.

(3) Such a configuration can comprise one of many sections of a spaceport, admitting the lighter down the axis of the nested cylinders. The pitch of the windings varies with nominal vehicle velocity through the section—the higher the velocity, the steeper the pitch.

(4) During capture (deceleration), circumferential current is induced by the moving magnetic field of the lighter, but axial components are a byproduct of circumferential current and coil pitch. The lighter's field interacts with the axial current to generate torques which accelerate the two cylinders in opposite rotational directions. The energy liberated by the capture of a lighter is stored as rotational energy in the spaceport's coils.

(5) During ejection (acceleration), the coils are spinning with no current flow prior to the approach of a lighter down the tube. As the lighter arrives, its magnetic field is cut by the rotating coil windings to induce axial EMFs. The induced axial EMFs couple through the pitch of the coil to generate circumferential currents which act to accelerate the lighter. The rotational energy in the coils is converted to the linear motion of the lighter.

generated by the spaceport capture of an arriving lighter is exactly the energy needed to eject a returning lighter of equal mass.

You pay, of course, for your inefficiencies. In the case of the orbiting wheel there will be air resistance on the spokes as they stab into the atmosphere to touch the surface, etc. In the case of the spaceport there will be electromagnetic losses during the capture and ejection of the lighters, and the unrecoverable energy in the rocket exhaust gases required to put the lighters in a position to be captured. But the efficiencies of such linked systems are startlingly better than those of a rocketship which cycles none of its energy.

We may be further astounded to note that we do not necessarily have to pay for the payload we lift into space —*providing* we are bringing back to the Earth, in the context of our linked system, an equal amount of ballast. Indeed, if more mass is falling than is rising our space transportation system can cover its own inefficiencies. *And if the down traffic is great enough we will be generating surplus power!*

Space travel can be had for a negative energy cost. When we obtain a source of ballast out there, spaceflight is going to become cheap.

THE MOON

Strange how we see things. If the moon were a ball of frozen oxygen and oil we would have already created a roaring space industry powered by that largess—but because the moon looks like Nevada and feels like Nevada when we shift it through our fingers, we do not comprehend its potential. Oil when burned releases about 10 megajoules of energy for each kilogram of carbon dioxide formed. Nobody has yet noticed that raw lunar rock is an even better energy source than oil.

The energy potential between the moon's surface and the Earth's surface is 59 megajoules per kilogram of lunar material. That is 25,000 times the energy you get from a kilogram of water passing through the turbines of Hoover Dam. To make another comparison, our best rocket propellant, oxygen and hydrogen, delivers only 13.4 megajoules per kilogram of water created. Raw moon rock contains more than enough energy to break itself down into its constituent elements—when delivered to the Earth. The potential energy in moon rock is so concentrated that if we used it to supply 100 percent of the world's current power needs of about 3.5 trillion watts, it would take *40 billion years* to use it up. The sun won't last that long and the universe wasn't even here that long ago.

We don't propose dropping moon rock through turbines to meet the Earth's *surface* power needs. If nothing else, the Earth's atmosphere makes that impractical. But the resource is there and it *can* logically be used to power low Earth orbit space industry. It can make orbital transportation so cheap that space industrialization becomes commonplace.

The moon can supply the ballast for our returning spacecraft.

There are various schemes for getting mass up off the moon into a position where we can "roll" it down to the Earth. Rocket power we can dismiss. Perhaps the best known method of cheaply lifting mass off the moon is the mass driver of G. K. O'Neill's group. In that scheme a conveyor belt of electromagnetically accelerated buckets dump their loads into space and return for more. A modification of this method is needed, however, when we try to import supplies.

Normally people think of landing on the moon as a vertical maneuver, but a horizontal approach, like an airplane, has distinct advantages. We can build a long "moonport," much the same as our spaceport, directly on the surface of the moon. An incoming ship, moving at the lunar circular velocity of 1680 m/sec, can be stopped by applying three gravities of deceleration along a 48 kilometer length of electromagnetic track. If the ship touches down at lunar escape velocity under the same conditions, we would need a track section twice as long.

As the ship approaches the surface, it is met by a light carrier riding magnetically over the track and equipped with superconducting coils. The carrier moves under the ship, captures it, and then applies the decelerating forces. The considerable power generated by this maneuver is fed into the lunar power grid. During take-off the track ceases to be a generator and acts like a linear synchronous motor, absorbing power.

Structurally the moonport is simpler than the spaceport. Being connected to the enormous mass of the moon, it can handle much heavier loads than can its more ethereal relative. The moonport is mainly limited by its electrical components. A one hundred ton spaceship, moving at lunar circular velocity and decelerating at three g's, is generating enough power to supply greater New York City.

We cannot ignore the moon. Resources and power are there at the headwaters of the mountains of space; the cities are down here at the river's mouth. To reap that wealth we must develop a technology which can extract the energy from a waterfall of lunar material.

INITIAL POWER FOR THE SPACEPORT

When the first orbiting spaceport is built, there will probably be no lunar base to provide a source of energy laden ballast. Even if lunar ballast were available, we would not choose to use it initially. The reason is simple.

To keep the capital investment down, we want a design that minimizes the amount of mass that has to be delivered by expensive rocket. The subsystem to receive lunar ballast and return the ballast carriers to high orbit represents mass that is not essential to the start up operation of the spaceport however much it contributes to the ultimate economy. These lunar mass receivers can be added later at much lower cost as we "bootstrap" to the final configuration.

Once our construction has reached the stage where the spaceport can capture and eject *one* lighter per orbit—a stage far below the capacity it needs for economic viability—we can begin to use the spaceport, instead of rocket shuttles, to supply the material that adds to its capacity. Specifically that means the spaceport can begin operation before almost any of its heavy power equipment has been installed.

How much mass do we invest in power plant to operate our minimal spaceport? And what kind of power will it be?

In last month's article we noted that 7.5 billion joules would be released by a 1000 kg lighter while it was being captured at half orbital velocity, and 15 billion joules would be required by an empty 500 kg lighter while it was being ejected to restore the spaceport's momentum balance. If we allow for a 90 percent conversion efficiency we must have 6.7 billion joules storage capacity to receive the energy from an incoming lighter and have in storage 16.7 billion joules when we want to accelerate the returning lighter.

Suppose we choose flywheels to hold our energy. Assuming a conservative flywheel rotational speed of 208 meters per second, we need 770 tons of flywheels for energy storage to operate one lighter. We also need an energy source to supply the difference between 16.7 and 6.7 billion joules. This translates to roughly a 1.85 megawatt capacity if we intend to handle one lighter per orbit. If we elect to use solar rather than nuclear power we need enough cells to generate 3.7 megawatts since the spaceport spends half its time in the shadow of the Earth. Thirty tons of solar cells at 8 tons per megawatt gives us our required capacity. Thus, for a total investment of 800 tons of power equipment to handle one lighter per orbit, we buy ourselves a payload delivery capability of 8 tons a day.

In one hundred days one lighter can bring up enough flywheels and solar cells so that the spaceport can begin to receive *two* lighters per orbit. With this doubling time it would take only a year and a half to build up to a capacity of fifty lighter captures per orbit, and three months later to 100 lighter captures per orbit. Since this is a geometric progression, we could reach an absurd capacity in very little more time. But long before we run into logistic problems, the clutter of solar cells begins to take its toll.

Solar energy crosses the Earth's orbit at a flux of 1340 watts/m^2, so that 3.7 megawatts corresponds to about 18,000 square meters of 15 percent efficient solar cells, or 75 modular panels 8 meters wide and 30 meters long. 7500 such modules, enough to power 100 lighter capture-ejections per orbit, could be attached along the side of the spaceport at intervals of 40 meters like the legs of a centipede. Since the separation between panels is five times the width of the panels, they

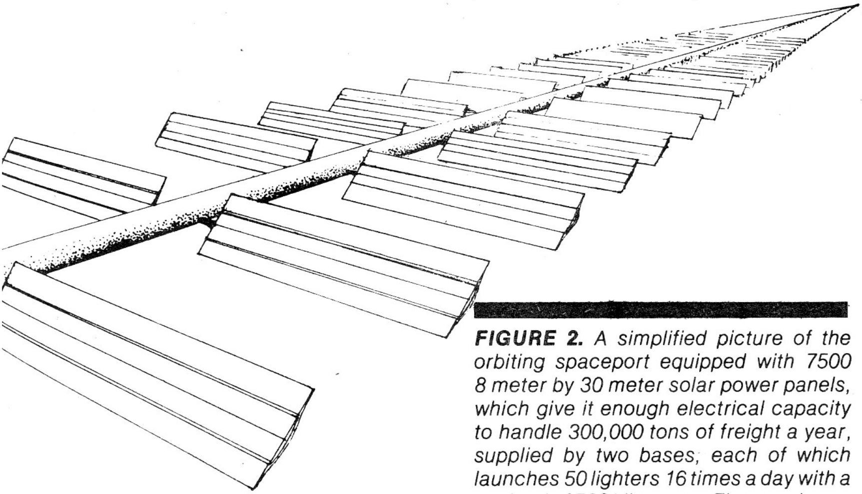


FIGURE 2. *A simplified picture of the orbiting spaceport equipped with 7500 8 meter by 30 meter solar power panels, which give it enough electrical capacity to handle 300,000 tons of freight a year, supplied by two bases, each of which launches 50 lighters 16 times a day with a payload of 500 kilograms. The panels can turn to face the sun. They are not operational at night for 45 minutes of each orbit.*

can rotate to face the sun without shading each other for most of half an orbit.

For greater capacities solar power starts to become impractical and we must look to alternate energy sources like the moon—but note that the spaceport already has a yearly capacity of 300,000 tons and that is well into the region of economic viability.

THE FIRST SPACEPORT

If we wish to begin building the spaceport within the next few decades its starting mass will be transported into orbit by some version of the Space Shuttle. The Space Shuttle itself has a payload of 21 tons for a due east launch. When the two solid rocket boosters are replaced by liquid propellant boosters we can expect a 50-ton payload. The Interim Heavy Lift Launch Vehicle (IHLLV) modification of the Space Shuttle would give us an 85-ton payload and the IHLLV modification with *four* liquid propellant boosters would give us a payload of 160 tons. All for roughly 20 million dollars a launch.

With only modified versions of the Space Shuttle we could expect to put a minimal 50,000-ton spaceport in orbit for a transportation cost of some seven billion dollars. That seems to be a large capital outlay until we see what it will do for us.

Assume that one ground base can launch a group of lighters spread over 200 km of the spaceport orbit. If they arrive at one-second intervals there will be about 4 km between lighters. That is 50 lighters per base per orbit for a yearly capacity of 150,000 tons to low orbit. With only two such ground bases supplying the spaceport we can build 30,000 megawatts worth of solar power stations per year. That power would replace 4 billion dollars *per year* of imported oil at $20 a barrel. The effect is cumulative. The second year we save 8 billion dollars, the third year we save 12 billion dollars.

Of course, one has to spend further money constructing the solar power stations, but money has to be spent *anyway* on power stations whether they be oil, coal, nuclear, or solar. The advantage of solar power stations is that you don't have to pay a billion dollars a year for black lung disease, you don't have to beat your brains out selling to Iran and Saudi Arabia and then flap around like fools trying to restabilize the governments your money has destabilized, and you don't have to finance Libyan terrorists, nor do you have any nuclear wastes to bury. The main side effect of an aggressive solar power satellite project is millions of good paying jobs for Americans.

As we have seen, at Space Shuttle delivery costs we must begin by assembling a minimum spaceport and from there use the spaceport to develop additional capacity. The initial structure will consist of three parallel "tubes"—a generator for receiving the loaded lighters at half orbital velocity situated in close proximity to an accelerator for returning the empty lighters at full orbital velocity, and a lightweight transport tube for delivering captured lighters to various points along the length of the spaceport and to the mouth of the return tube.

The generator and accelerator will lie side by side so that the power produced by an incoming vehicle does not have to be transported over long distances to get to the accelerator and the outgoing vehicles. The mass of the transport tube will be negligible since the power levels it handles are so small compared with the main tubes.

The first spaceport would be constructed in a 90-minute orbit whose point of northernmost transit passes over Kennedy Space Center. It would be desirable, of course, to assemble it in the equatorial orbit where it will eventually be used; however, Space Shuttle operations have been designed for Kennedy, and it is here assumed unlikely that we will undertake to build a new space center on the equator in the next few decades.

The ground bases which service and launch the small lighters can be built as floating platforms. They will have submerged flotation tanks and deep ballast for stability even in heavy seas. The first one will be set up in the Atlantic Ocean southeast of Cape Canaveral, where the southgoing leg of one spaceport orbit crosses the northgoing leg of the previous orbit. From that position you get two launch windows per day instead of just one. This base will be used to check out the spaceport while it is still in its construction orbit.

Once the spaceport has been debugged, it will be moved slowly to an equatorial orbit. The transfer might take as long as a year, using low thrust rockets distributed along the length of the spaceport. The base would be towed at sea and would continue to launch its lighters to supply reaction mass for the transfer rockets. Meanwhile the second base would be built at the equator. Once the spaceport reached equatorial orbit, operations would gradually be built up. Each base would now have 16 launch windows daily.

There would probably be some space manufacturing facilities included in the initial construction, and those would begin operating and returning some products. Most of the traffic, however, would be devoted to beefing up the spaceport's capacity. When the capacity was up to perhaps 100 thousand tons per year, construction would begin on three additional tubes. The first tube would be for boosting payloads to geosynchronous orbit and to lunar altitudes, the second for catching the returning high orbit lighters, and the third for transporting the high orbit lighters between the first and second tubes.

The high orbit lighters would begin to support the construction of solar power satellites and the initial lunar base. The power satellites would be brought on line as rapidly as possible to alleviate American dependence upon oil and nuclear fuels, while the lunar base would be a longer term project aimed at supplying "energy ballast" for the spaceport, liquid oxygen for rocket motors, and cheap raw materials for the mushrooming space industries.

MOON POWER

Imagine a time when a mass driver at a small lunar base is progressively stepping up the tonnage it is tossing into space. How can we extract power from this material? Recall that the potential energy difference between the moon's surface and the Earth's surface is 59 megajoules/kg.

The moon revolves around the Earth with a velocity of 1020 m/sec. If mass in the lunar orbit is slowed by 830 m/sec until it is moving at only 190 m/sec it will drop in toward the Earth, accelerating, until it touches the orbit of the spaceport with a velocity of 10,850 m/sec, overtaking the spaceport with a relative velocity of 3110 m/sec. If the spaceport is equipped to capture this mass, much as it captures a lighter from the Earth, two things will happen: the momentum exchange will propel the spaceport outward, and 4.8 megajoules of energy will become available for every kilogram of lunar mass.

Now we have an alternate way of balancing the momentum of our spaceport. The capture of an Earth lighter depresses the spaceport while the capture of a moon lighter raises the spaceport. Momentum balance is achieved when one kg of lunar mass is captured for every 0.8 kg of Earth mass that is picked up at half orbital velocity.

It is important to reiterate that a mass driver acting to capture mass is a *generator* of electricity. Thus if our spaceport is balancing its momentum by *capturing* both lunar and Earth mass it will be a power plant rather than a consumer of power. The spaceport can now increase its capacity to handle freight from the Earth *without further expansion of its solar power facilities.*

How much of the lunar energy are we using? One kg of captured lunar mass supplies 4.8 megajoules, 0.8 kg of captured Earth mass supplies 6 megajoules for a total of 10.8 megajoules per lunar kg. Used in this way 18 percent of the energy held by the lunar mass can be extracted and as such has about the energy density of stoichiometric oxygen/oil. (This energy represents one-fourth of that needed by the rockets to propel our sub-orbital Earth lighters.)

Can we do better than 18 percent? Yes. If we study the case where an empty lighter is launched to the spaceport to pick up raw material that has arrived from the moon—under the constraint of preserving the spaceport's momentum—we find that we can extract energy from the moon rock according to the formula

$$(r/r+1)\,(v-u)^2/2, \text{ in joules/kg,} \quad (1)$$

where r is the ratio of lighter mass to the moon mass it picks up, $v = 10{,}850$ m/sec, and u is the velocity of the lighter relative to the Earth at the time of contact with the spaceport.

Putting u as close to zero as possible increases the energy output. This represents the case when the spaceport is tuned to capture a lighter that has reached orbital altitude with no horizontal velocity. Henceforth assume u to be zero.

Our efficiency also increases when the ratio r is large but that is not as much help as it might seem. We are extracting energy from the moon rock most efficiently when we are bringing in none at all!

Let's take a more practical approach and balance the energy liberated at the spaceport with the energy expended to launch the lighters. We get, for the energy liberated,

$$f(r/r+1)v^2/2 - rx, \text{ in joules/kg,} \quad (2)$$

where r and v are as in (1), f is the efficiency with which our spaceport can extract electricity from kinetic motion (here assumed to be 0.9), and x is the energy per unit mass expended by the rocket motors to put the lighter in a position to be captured.

An elementary calculus maximum-minimum procedure shows that we can extract the most energy when

$$r = v\sqrt{f/2x} - 1. \quad (3)$$

All values are known except x.

To obtain x we make the following considerations. A standard rocket propellant, one part hydrogen to six parts oxygen, contains 13 megajoules/kg, and gives an exhaust velocity of $c = 4400$ m/sec in a reasonable engine. The mission velocity to reach 275 km with no horizontal velocity is about $w = 3000$ m/sec. Thus the lighter's mass ratio is

$e^{w/c} = 2$, which means that $x = 13$ megajoules/kg since we are burning one kg of oxygen/hydrogen to place one kg of Earth mass at orbital altitude. Plugging this value into equation (3) gives $r = 1$.

Thus we obtain the most energy when an empty lighter rises to the spaceport and brings back its own mass in moon rock. Equation (2) shows that this procedure liberates a *surplus* of 13 megajoules for every kg of moon rock we import by rocket! That is like receiving two barrels of oil every time we burn one! Such "magic" is *not* perpetual motion, it is simply a way of tapping into the moon's potential energy.

The details of the packaging of the lunar material so that it can be captured, of the mother ships delivering the packages, and of the appropriate orbits are beyond the scope of this article. There *is* energy in moon rock and it can be utilized. There is so much energy that moon power alone could support a space transportation system vast enough to stagger a twentieth century mind.

THE IMPACT REACTION ENGINE

There is one problem still open. Our spaceport with its swarms of tiny lighters is great for delivering raw materials and small dense payloads to orbit, but it won't handle anything large and bulky. And it won't handle passengers. One solution to this problem is straightforward.

Our design was driven by the need to keep the initial spaceport mass as low as possible. After the spaceport begins operating, however, transportation will be cheap and mass won't be as important. We could then build a much larger spaceport that would accommodate large vehicles at low accelerations. This is an entirely reasonable approach, but it requires that we continue to rely on the Space Shuttle for passengers and large payloads longer than we would like.

An alternative and more interesting solution to the large payload problem involves what we call an impact reaction engine. Let us perform a thought experiment.

Suppose we have a stream of perfectly elastic balls moving with circular velocity c in orbit around the Earth. Suppose we place a massive ship in this stream with velocity u relative to the Earth. Further, suppose that this ship carries a perfectly elastic shield upon which the balls impact perpendicularly. The balls approach the shield with velocity $(c - u)$ and after impact bounce off the shield with reversed velocity, minus $(c - u)$. This bounce results in momentum changes and since rate of change of momentum is force we can calculate the force acting on our ship. The force in newtons is the mass in kg of the balls which bounce off the shield every second times $2(c - u)$ m/sec, and will accelerate the ship in the direction of the stream.

This is the principle of the impact reaction engine. The mass flow against the shield is analogous to the flow of propellant into a rocket

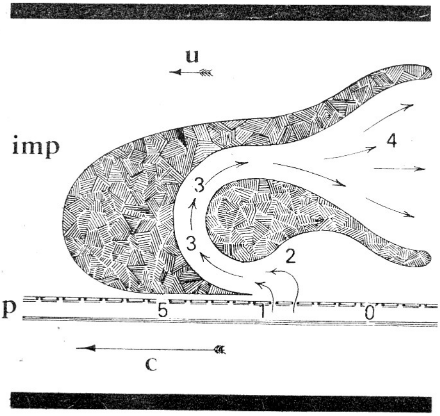


FIGURE 3. *In this schematic diagram of the impact reaction engine (imp), the ship approaches backwards, with velocity (u), the forward end of the orbiting pipeline and magnetic guide track (p) which overtakes it at circular velocity (c). Oxygen at (O) cannot escape because the valves are closed. Oxygen at (1), just prior to the ship's arrival, escapes through rapidly opened valves, where it is captured by the ship's scoops at (2) and swiveled through pipes (3) where it is ejected at (4). After the ship passes, the valves at (5) close. The impact reaction engine exerts a force equal to the mass flow through the engine times* twice *the difference between velocities c and u. Injected hydrogen, carried by the ship, can be used to cool the engine, simultaneously burning with the oxygen to increase the thrust. The oxygen is imported from the moon. The pipeline itself need not be very massive because the ship and pipeline do not exchange momentum while the ship is being accelerated.*

motor—with the exception that an impact reaction engine does not have to carry its propellant with it as does a rocketship. The velocity 2(c – u) is analogous to the rocket's exhaust velocity. The best rocket exhaust velocity we have today is the 4400 m/sec of the oxygen/hydrogen motor. If an impact engine, at rest relative to the Earth, entered a mass flow stream at an altitude of 275 km, its "exhaust velocity" would approach (depending upon the elasticity of the collision) 15,500 m/sec, 3.5 times as great as that from the Space Shuttle's motors! Of course, since (c – u) tends to zero as the impact engine approaches circular velocity, the efficiency of this engine declines drastically at high speeds, a flaw which we shall see can be overcome by marrying the impact engine with the rocket motor.

The impact reaction engine makes an amusing thought experiment, but can it be built? There are no basic physical reasons why it cannot, and there are economic reasons indicating that it could wisely be utilized in passenger and heavy freight transport. Once a moon colony is viable it will be supplying mass to the spaceport both to generate electricity and to balance the spaceport's momentum. If we choose to import plentiful lunar oxygen for this purpose we can not only remove part of its potential energy in the form of electricity by capture, but can also extract a large portion of the remaining energy by disposing of the oxygen to power an impact system.

A basic scheme consists of an oxygen feed pipe and a magnetic suspension track laid parallel to the spaceport and perhaps far longer than 150 km. This need not be a massive structure since it would not have to take any great stresses. The accelerating impact ship exchanges momentum with the oxygen, *not* with the pipeline. Because of this fact, the impact ship, unlike our small lighters, can be quite massive. It can be as massive as a present day commercial jet aircraft like the Boeing 727.

The oxygen intake of the ship rides along the suspension track only centimeters from the oxygen supply jets on the pipeline, which are pulsed for a few milliseconds prior to the passage of the ship. The track and pipe must be extremely straight because, at the speed of the ship, there is no possibility for it to follow bumps and irregularities. But that is why laser beams and active control systems were invented.

As the oxygen is scooped into the vehicle it is guided through tubes in such a way that its direction of flow is reversed through 180 degrees. As we have seen, the force applied by this impact is the product of the mass flow times *twice* the relative velocity between ship and pipeline. At any relative velocity above 2200 m/sec oxygen alone in such a reaction engine will do better than an oxygen/hydrogen rocket —and not be required to carry its own reaction mass.

Some heating through compression and turbulence will occur and there will be boundary layer friction. But the object of the game is to keep as much of the oxygen's energy as possible in kinetic form. That requires that its *speed be maintained* while its *direction is changing*. We can get a worst case estimate of the heating problem by assuming that the oxygen is completely stopped by the impact and then expanded through a rocket nozzle.

Cold oxygen impacting at half circular velocity and brought to a dead stop will only rise in temperature to 4500°K, about five or six hundred degrees hotter than the normal operating range of an oxygen/hydrogen rocket chamber. At these temperatures the dissociation of oxygen into monatomic oxygen is soaking up a great deal of energy. Since we will not be stopping the oxygen, we will not have to deal with such extremes except at very local boundary regions where we can use dynamic insulation with hydrogen to keep the flow surfaces cool.

As the relative speed of ship and pipeline falls, so does the performance of the impact engine. The declining thrust can be compensated by adding ship supplied hydrogen to the reaction, the hydrogen doing double duty as a coolant. By the time the ship has stopped we will be using the standard 6 to 1 oxygen/hydrogen mix ratio and will have dropped down to an exhaust velocity of 4400 m/sec.

The performance of such a ship makes it worth investigating seriously. If we could build a hybrid rocket-impact vehicle that reaches orbital altitude and half circular velocity by means of oxygen/hydrogen rockets, and then achieves the second half of its velocity through impact acceleration, it will go into orbit starting with a gross-lift-off-mass only 3.5 times its final mass—an easy design criterion for an oxygen/hydrogen vehicle to meet.

For those who want to do some quick back-of-the-envelope calculations themselves, the formula to compute the mass m needed to change the velocity of a ship of mass M from u_o to u_f is:

$$m = (1/2)M[\ln(c - u_o) - \ln(c - u_f)] \quad (4)$$

where c is the velocity of the oxygen supply pipeline and ln is the natural logarithm. If we carry hydrogen and burn it with the impacting oxygen, the equation is slightly more complicated and does *not* give an infinite m when $u_f = c$!

THE OPEN END

At about the time the construction begins on the three tubes to launch and receive high orbit lighters, the gas supply pipe and track for the large impact vehicles can be installed. The advanced versions of the current Space Shuttle should be ready for commercial retirement at this point and it is not necessary to wait until lunar oxygen is available to phase in the impact powered ships. They can be operated with oxygen imported from Earth by the lighters. This is not as economical a procedure as using lunar oxygen, but quite a feasible interim approach. The impact ships will deliver cargo not easily packaged in the half-ton size and will transport people.

As the lunar mining operations get started, the arresting tube for the in-

FIGURE 4. *An empty lighter which meets the spaceport at the given velocity (x-axis) can return with a ballast of lunar rock and show a net energy profit (y-axis) without changing the spaceport's momentum. The curves are for lighters powered by oxygen/hydrogen and oxygen/kerosene. The numbers along the curves indicate the optimal mass of lighter needed to bring in a unit mass of lunar ballast. The curves terminate where momentum considerations no longer allow the return of the lighters. Slightly different assumptions were made in the body of the article for the sake of round numbers. The above curves were based on the assumptions:*

(1) The mission velocity needed to attain capture velocity 7740k m/sec is $u = \sqrt{5.17 + 59.9k^2}\,10^3 + 500$ *m/sec.*

(2) A kilogram of rocket propellant contains E joules, where $E = 13 \times 10^6$ *joules for oxygen/hydrogen and* $E = 10^7$ *joules for oxygen/kerosene.*

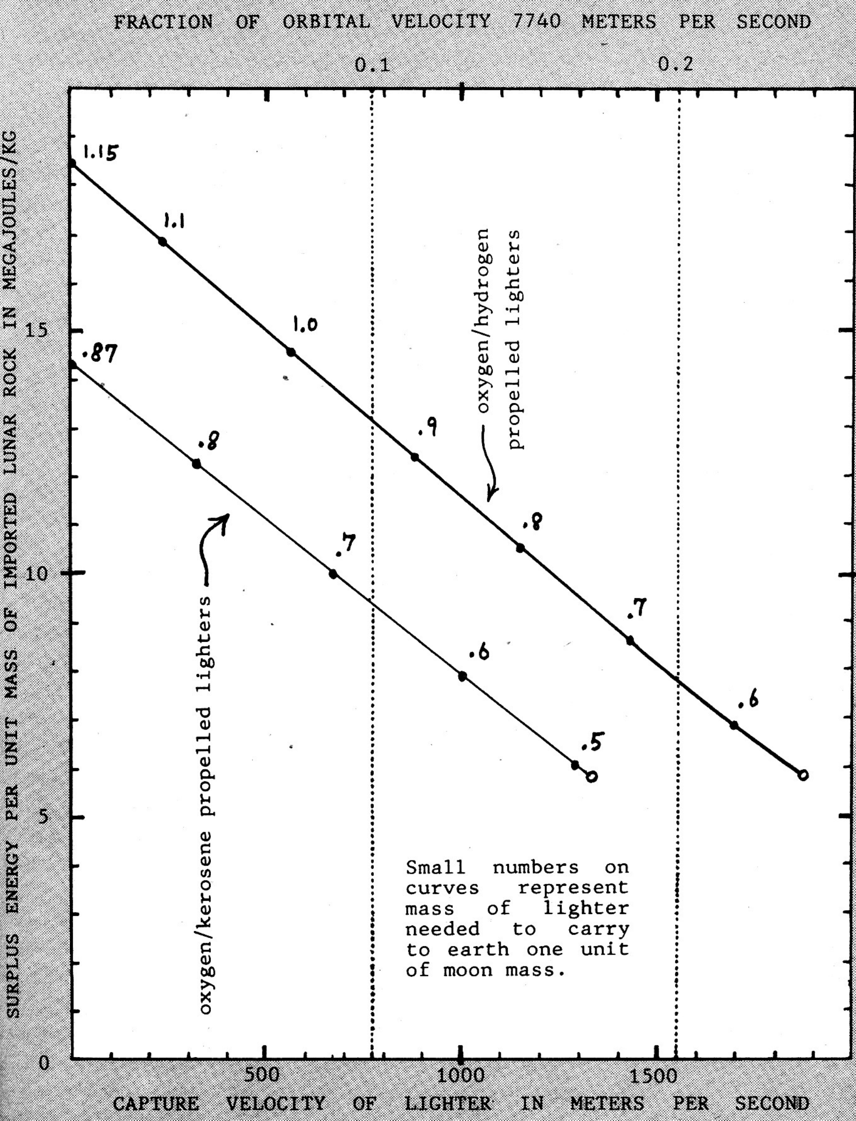
(3) The effective exhaust velocity is c, where c = 4400 m/sec for oxygen/hydrogen and c = 3000 m/sec for oxygen/kerosene.

(4) The energy cost to put a unit mass of lighter in a position to be captured by the spaceport is $X = E(e^{u/c} - 1)$.

(5) The spaceport is 90% efficient at converting between kinetic energy and electrical energy.

(6) The energy released is determined by formula 1 from the body of the article.

(7) The transactions are constrained to leave the momentum of the spaceport unaltered, thus the lighter plus ballast are returned to the Earth at velocity (10,850 + 7740kr) / (r + 1) m/sec, where r is the ratio of lighter mass to lunar ballast.


FRACTION OF ORBITAL VELOCITY 7740 METERS PER SECOND
0.1
0.2
SURPLUS ENERGY PER UNIT MASS OF IMPORTED LUNAR ROCK IN MEGAJOULES/KG
0
5
10
15
1.15
1.1
1.0
.9
.8
.7
.6
.87
.8
.7
.6
.5
oxygen/hydrogen propelled lighters
oxygen/kerosene propelled lighters
Small numbers on curves represent mass of lighter needed to carry to earth one unit of moon mass.
500
1000
1500
CAPTURE VELOCITY OF LIGHTER IN METERS PER SECOND

coming high orbit lighters will be beefed up to handle loaded rather than empty vehicles. With more mass coming down to balance mass going up, engineers can tune the Earthside receiver to handle arrival velocities closer to full orbital, giving better launch economies.

We have reached a take-off point.

In "Space For Industry," one of John W. Campbell's more famous editorials written at the beginning of the space age when rockets were just becoming popular, he said, "We're never going to get any engineering use of space until we get something enormously better than rockets...something that can lift and haul tons with the practical economic efficiency of a heavy truck." He made the obvious point, "Heavy industry has always developed where three things were available; cheap raw materials, easy access to markets, and cheap energy supplies." The spaceport is something enormously better than rocket transport. It has nearby lunar raw materials which can be shoved downhill and tapped for energy, and it has available solar power satellites and large, light mirrors to concentrate solar energy. Even the metals and water and carbons of the asteroid belt are not that far away, all downhill to the markets. The markets? The spaceport sits within a 90 minute glide of any point on Earth.

More and more manufacturing facilities will inevitably mushroom along the spaceport as material and power become cheaper. Freight capacity will soar. The spaceport itself will be generating thousands of megawatts and asking for customers.

At the beginning of the next century we may begin to see heavy industries like steelmaking moving into space with the energy and ore. Steel will begin to face heavy competition from lunar aluminum and titanium as well as exotic alloys. Today the saying is: "If it can be done on Earth, it will be done on Earth." Tomorrow the saying will be, "If we can do it in space, let's do it there." Try to find land these days to build a new steel mill or a new power plant or a new telescope. Try to buy into somebody else's water, or take over somebody else's recreation area. It is going to get worse. In the future, space may be *the* place to get things done. Why not? The resources are there and the energy is there, and with space comes access to all markets. As a bonus, politicians like Proxmire loath it.

The single most important concept we need to make real in our minds is that spaceflight is not going to remain expensive off into some vague indefinite future. Today's technology applied on the proper scale is good enough to make it cheaper than jet flight. All we need is to take that intangible decision to use what we already know.

Let the Earth be healed. We can plant trees again, and stock the rivers for fishing while the chemical plants brew in space and the forges of the smelters consume the solar heat they lust after, closed away in their self contained environments that do not touch what they were not meant to touch. Let the Earth heal while we mine the moon and build the catapults that will fling us beyond Mars.

CONCLUSION

Of course, it doesn't look easy now. We are city dandies and space is a fierce steep river that winds up through the tallest mountain range that mankind has ever faced. It is a bootstrap operation. We need that energy glutton, the Rockwell Space Shuttle, and we need far more of them than we have scheduled for production. We need more rockets and bigger ones just till we get a foothold, till we can get the flow started from moon to Earth.

Then we can be a rich commercial nation again, with full employment, doing what we love to do, those conjuring tricks that no one else seems fast enough to keep up with, while we sell to the rest of the world the high technology that will make them prosperous, too, and save them from the kind of primitive industrial machine that has half-killed *us*.

Why turn back to smoggy coal? Why complain when others make shoes and television sets better than we do? We have already passed through that phase and are ready for the next adventure. We are uniquely capable of creating the kinds of jobs that no one else can create. We can make space travel cheap just like we made ground transportation cheap, just like we made air travel cheap. We can be the generation that makes America great again. Remember the American Way?

All it takes is looking at a problem as if it has never been looked at before. ■

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