THE LAUNCH LOOP

Keith H. Lofstrom

A novel way to get around the expense of rockets for routine space travel.

A Business Trip, 2005

The elevator ride from the ground has taken almost an hour, and the ride to NBC-1, a geosynchronous transmission satellite serving the eastern seaboard, will take another four. That isn't nearly as long as the airplane trip from New York, but at least the plane had windows, and you weren't strapped in and "plumbed." The small cabin that you share with five other passengers has no portholes; you have just a video screen built into the seat in front of you. This is your first trip, so you are tuned into the outside camera system. The screen shows the "Can" you are in, the cradle carrying it, and the slender cables disappearing into the black sky above and the ocean below. The woman strapped into the seat beside you is reading technical reports on her screen, which is configured as a terminal. The man in front is playing a video game. They are apparently experienced space travelers.

There is a queasy feeling in your stomach as the Can slows its ascent; you are nearing west station, now less than three kilometers above you. West station is the terminus of the 120-kilometer-high elevator system, and the start of the 2000-kilometer-long acceleration track that will hurl you into space. As you get closer, you begin to make out details: the light, open structure of west station, its long support pillar, and the small observation cabin on top, bristling with radar and communication antennas. The cradle rack above you holds two other Cans similar to yours, streamlined and covered with heat shields. The rack also holds eight box-like cargo containers, probably from the container ship you saw this morning on your way in.

If the carriers above you are standard five-metric-ton vehicles, your Can should be lowered over the ribbon and launched in about 30 minutes. This is happening to the top vehicle now. The crane has lifted it out of its cradle and is lowering it over the track, carefully positioning it so the magnets in the channel on its belly are on top of the high-speed ribbon. The container starts moving towards the east, picks up speed rapidly, and vanishes into the rising sun.

Getting Out of the Hole

Moving from the Earth's surface to useful orbits requires momentum and energy. By Newton's laws, the momentum must be removed from something else, whether it is rocket exhaust, a beam of light, the atmosphere, or the Earth itself. Energy can be applied in several ways, but the amount of energy that must be turned into payload energy is constant. If the energy is applied less efficiently, more is needed to begin with. This change of momentum and energy can be expressed as a change in velocity, or delta v.

Vehicles are launched to higher orbits in elliptical transfer orbits. At the bottom of the ellipse—at the point closest to the Earth—the vehicle is moving faster than circular orbital velocity at that altitude. A very high delta v is necessary to put the vehicle into this faster orbit. At the top of the transfer orbit (apogee), the height of the vehicle's circular orbit destination, the vehicle is moving slower than circular orbital velocity. Velocity has been lost as the vehicle traveled up out of the gravity well. More delta v must be added to make the orbit circular, but this velocity change is small compared to the delta v needed at launch.

The velocity change at launch time is the largest and most expensive. From the Earth's equator to the Moon, the delta v at the start of the transfer orbit is 10.6 kilometers per second. The transfer orbit to geosynchronous altitudes requires 9.95 kilometers per second of delta v.

An Earth launch system should accelerate a vehicle to transfer orbit velocity without crushing acceleration or dropping it back to the ground. A low acceleration requires a long acceleration path. Accelerating a vehicle to 10.6 kilometers per second at 3 g's requires an acceleration path 1900 kilometers long, almost 5 percent of the Earth's circumference.

The energy is proportional to the mass and the velocity squared; for a one-kilogram mass, a delta v of 10.6 kilometers per second requires the addition of 56 million joules. This looks smaller if measured electrically; 3.6 million joules equals one kilowatt-hour (1000 watts for one hour, and a watt is one joule per second), and one kilowatt-hour costs about 4 cents in the Northwest. That comes to about 60 cents' worth of electricity, and that's why electrically powered launch systems are starting to get a lot of attention.[1]

Present rocket launch systems cost much more than this, because of their enormous complexity and the vast amounts of fuel they consume. Most of the thrust a rocket generates lifts the fuel, tanks, and engines it will need later in the flight. A fully loaded space shuttle orbiter weighs 100 metric tons (a metric ton is 2205 pounds, a little more than an English short ton). The assemblage of tanks and solid boosters that lifts from Kennedy Space Center weighs over 2000 metric tons, most of which is fuel. The orbiter, surely one of the most marvelous machines ever built, is nevertheless an incredibly expensive vehicle. Optimistic estimates suggest more than two months between each shuttle re-use, a slow way to pay back a multibillion-dollar investment. The maximum payload is 30 metric tons to low Earth orbit, or 5 metric tons to geosynchronous orbit, a tiny fraction of the launch weight. A shuttle launch costs more than 30 million dollars, and this doesn't include the purchase of the shuttle itself, or the expensive shuttle ground support systems left over from the Apollo program. A greatly expanded space program based on rockets may prove much too costly.

The idea of a fixed structure on Earth or in space, electromagnetically driven and capable of handling many vehicles per hour, is not a new one. The skyhook was suggested by Yuri Artsutanov in 1960, and independently by Isaacs *et al* in 1966.[2] The skyhook is a long cable reaching up from the Earth's surface far into space, its downward weight balanced by centrifugal force as it follows the rotation of the Earth. Artsutanov's idea has been expanded on by others, with tapered cables, rotating cables, and other refinements intended to lower the mass of the system or ease construction.[3] Incredibly strong materials are required that will not be commercially available for many years, making these systems impractical at present. Most designs must be built from orbit, which requires a large existing space launch capability as well.

Mass drivers use moving magnetic fields to accelerate vehicles equipped with electrically conducting coils or shells. In the November 1979 *Analog* Roger Arnold and Donald Kingsbury suggested an orbiting mass driver for vehicle capture, the Spaceport.[4] The Spaceport is an orbiting platform 500 kilometers long that captures vehicles from the Earth or high orbit along its length. Energy is extracted from the velocity difference between the vehicle and the Spaceport and stored in rotating coils. The vehicle is accelerated to the same speed as the Spaceport, and the Spaceport changes velocity slightly. The stored energy may be used to eject vehicles from the Spaceport. The Spaceport has a mass of 50,000 metric tons and must be assembled in orbit, while the vehicles it handles are too small (230 kilograms, or 500 pounds) to transport human beings or larger machines. A Spaceport that can move people must be much larger. While this system may be the most economical in the long term, it would be very expensive to ship up with rockets.

Earth-based mass drivers[5] are capable of reaching orbital velocities, but the Earth's atmosphere is a major problem. If vehicles are launched horizontally, they must travel through hundreds of kilometers of atmosphere before reaching space, and the air drag is enormous. If launched vertically, the accelerator must be very tall and the g forces are much too high for people or complex machinery. Such a system might be useful for some raw materials, but only if people and machinery get into orbit by some other means.

Such accelerators also must handle enormous pulsed power. A five-metric-ton vehicle accelerating at only three g's and moving at eight kilometers per second requires 1.2 billion watts of power from the segment of the accelerator immediately around it. This is the power level of a large power generating plant, and this power-handling capability must be repeated many times down the accelerator. Accelerators such as this could be very expensive.

A good Earth-based launch system should be built from the ground up, operate in vacuum, and deliver energy and momentum to the vehicle without expensive power-handling circuitry.

By Your Own Bootstraps

A ball tossed into the air, a stream of water from a hose, and a planet in its orbit are all governed by Newton's Laws, and follow paths that balance the external forces on them with their own accelerations. An orbit can be viewed as a balance between centrifugal acceleration and gravity; if the centrifugal force is higher than the gravitational force, the orbiting body moves upwards. If a stream of material moves faster than orbital velocity, it will also move upwards, unless extra downwards force is added. This force could be provided by stationary weight somehow "hung" on the stream.

The centrifugal force on the stream is proportional to the velocity squared. A stream moving twice as fast as orbital velocity generates a centrifugal force four times that of gravity, and such a stream could support the weight of a stationary mass three times its own mass. Altitude actually improves the lifting action, which can be used to support long, light structures far above the Earth's surface.

If the moving stream is an iron strip or ribbon, it will be attracted to a magnetic field. Consider an electromagnet with long pole faces parallel to the direction of the moving iron ribbon, as shown in Figure 1. The magnetic flux travels through the coils and into one pole. It then passes up through the gap into the ribbon, across it, and back down through the other gap to the other pole, completing the magnetic circuit. The poles are attracted to the ribbon, attempting to close the gap. The control electronics sense the spacing and adjust the current in the control coils to change the field, and thus the upwards force on the poles.

The magnets, electronics, and poles are called the "track." The track does not need to move with the ribbon. If the magnetic field between the track and

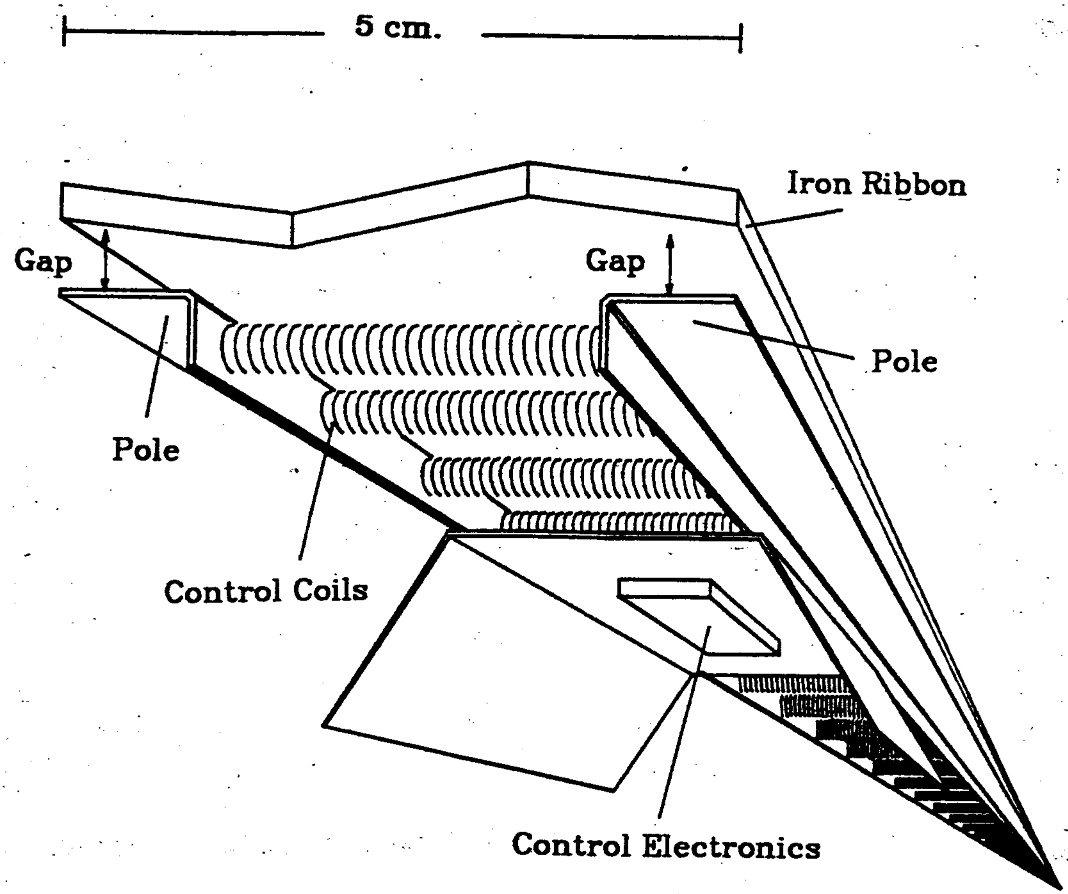

Figure 1—A cross section of the ribbon and track.

ribbon is uniform, the ribbon can move at very high speed without friction between it and the stationary track, even while the ribbon supports the track against gravity. This is a form of "magnetic levitation," which is being considered for high-speed trains, supporting the train cars without the rolling friction of wheels.

We will use an iron ribbon 5 centimeters wide and 2.6 millimeters thick (about 2 inches by 0.1 inches) with a mass of 1 kilogram per meter. If the ribbon is moving at 12 kilometers per second relative to the Earth's surface, and at an altitude of 120 kilometers above it, the upwards centrifugal force is capable of supporting 2.35 kilograms of mass per meter against gravity. The ribbon itself has a mass of 1 kilogram per meter. The centrifugal force can thus support the ribbon and a stationary mass of 1.35 kilograms per meter.

If the poles are 1 centimeter wide, the force per area on the poles will be equivalent to the weight of 70 kilograms per square meter. This force can be generated with a small magnetic field of about 0.04 tesla (a metric unit of magnetic field strength). For comparison, the Earth's magnetic field is 0.0001 teslas, a good permanent magnet generates about 1 tesla, and superconducting magnets can go beyond 20 teslas. This small

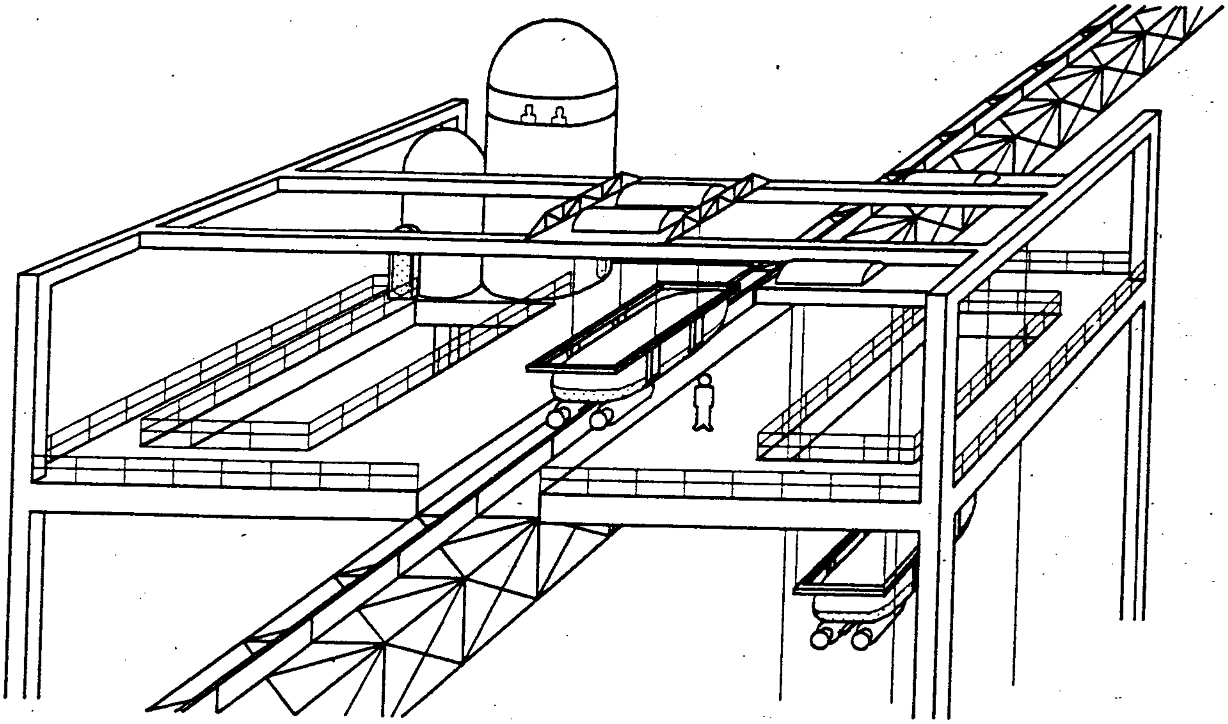

Figure 3—West station, showing a vehicle being loaded onto the track.

forces and wind stresses are relieved by Kevlar® cables running diagonally to the ground. The inclines have a mass of about 5 kilograms per meter, and curve more than the Earth's surface, drooping near the top.

The ribbon reaches the bottom of the inclined section at a 20-degree angle, and is forced to horizontal with electromagnets on a curved ramp. This ramp changes height by 600 meters, and may be cheaper if built in a narrow tunnel under the surface, resulting in the "S" shaped kink shown at the bottom of the incline in Figure 4. Traveling parallel to the Earth's surface, the ribbon passes through a 2-kilometer-long, high-efficiency linear motor. Four of these linear motors, two on each end of the Launch Loop, restore energy removed by friction and vehicle launches.

Once the ribbon is horizontal, and restored to speed by the motors, it must be deflected 180 degrees and sent back the other way. A force of nearly 30,000 metric tons is necessary to do this, equal to two times the ribbon mass per length times the velocity squared. This will be done with the "D" magnets, a magnetic track like that of the launch path, but much more powerful. The ribbon is rotated so that the flat surface is pointing sideways, and the flat surface is pulled toward the magnets, deflecting the ribbon in the horizontal plane. The magnets deflect the ribbon in a 20-kilometer-diameter semicircle, with a force of about 1.5 metric tons per meter and a magnetic field of about 2 tesla. These magnets will weigh about 200 metric tons, and their windings will consume 60 megawatts. They must be firmly an-

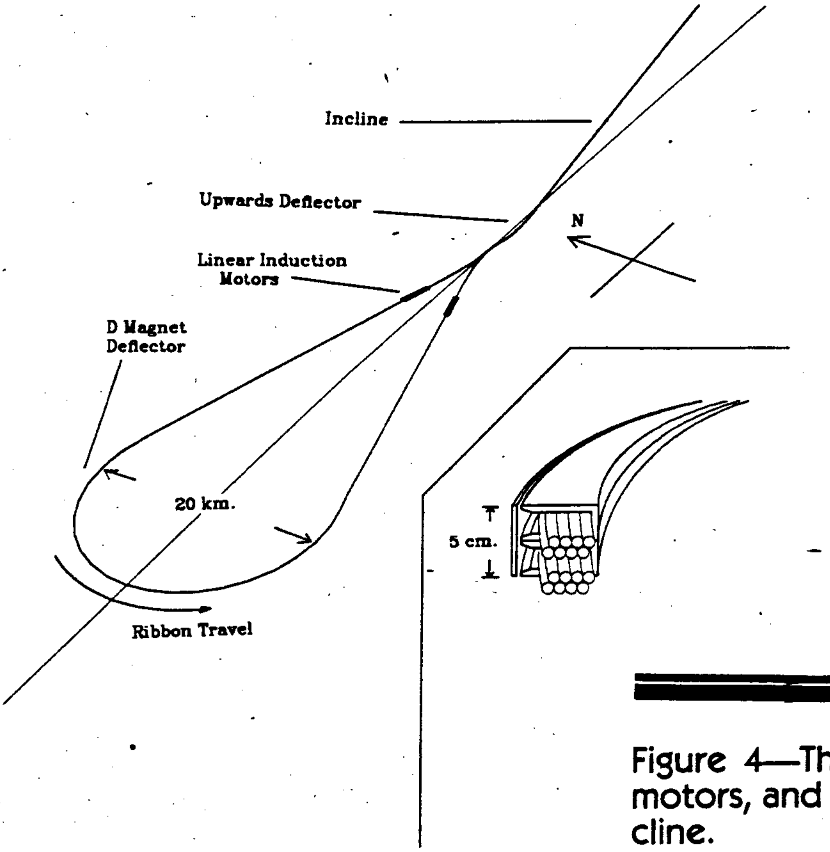

Figure 4—The west end deflectors, motors, and the start of the west incline.

chored to the ground to absorb the deflection stress. With a deflector at either end of the Loop, the Earth itself can be viewed as a giant structural member, holding the ends of the Loop together.

The ribbon changes height from the top to the bottom of the Loop; as it travels downwards, its speed increases by 100 meters per second, causing the ribbon to stretch by 0.8%. Iron will fracture with this much strain, so the ribbon will be built in 1-meter segments, with sliding joints between them. Although this weakens the ribbon along its length, the ribbon is never under tension or compression during normal operation.

The Launch Loop should be located along the equator for optimum launching and weather conditions. Most of the interesting places in space are on or near the plane of the equator and are most easily reached from there. Violent storms and high winds are aided by Coriolis forces, which result from the Earth's rotation. These forces are minimized at the equator, causing milder winds.

Launching Vehicles

The Launch Loop is a large stable structure, reaching from the Earth's surface into space. How is this device used to launch vehicles?

There are two common forms of magnetic levitation:[6] one is based on the attraction of magnets to other magnets or ferromagnetic materials such as iron; the other uses the repulsion between a magnet and induced currents in a conductor.

The attractive levitation process theoretically consumes no power, but is unstable and requires power for stabilizing electromagnets and control circuitry. This process is used in the track support and end deflection magnets, where large forces must be generated with minimum power dissipation.

Vehicles are supported and driven by repulsive levitation. Repulsive levitation uses the eddy currents induced in a conductor by a rapidly changing magnetic field. The eddy currents generate a reverse magnetic field, pushing the originating magnet away. The eddy currents dissipate heat, which appears mechanically as drag between the conductor and the generating magnet. Drag is desirable between the ribbon and the vehicle, as it provides the force to accelerate the vehicle.

This version of the Loop is designed to launch 5-metric-ton vehicles. Payload containers have strips of magnets on their bottom side designed to generate a lift of up to 5 metric tons and a drag of 15 metric tons, accelerating them at 3 g's. Rocket motors on the bottom of the payload container will provide additional delta v when the vehicle is at the top of its orbit, at apogee. The center of mass of the payload, container, and rockets is on axis with the ribbon, with stability provided by magnetic damping and small rocket thrusters.

Re-enterable payload containers, as shown in Figure 5, are equipped with a lifting shell, a heat shield, and parachutes for reentry of human cargo if the Loop fails. Insurable, inanimate payloads will not need this protection, and will probably burn up if they accidentally re-enter.

The heat removal by the ribbon from

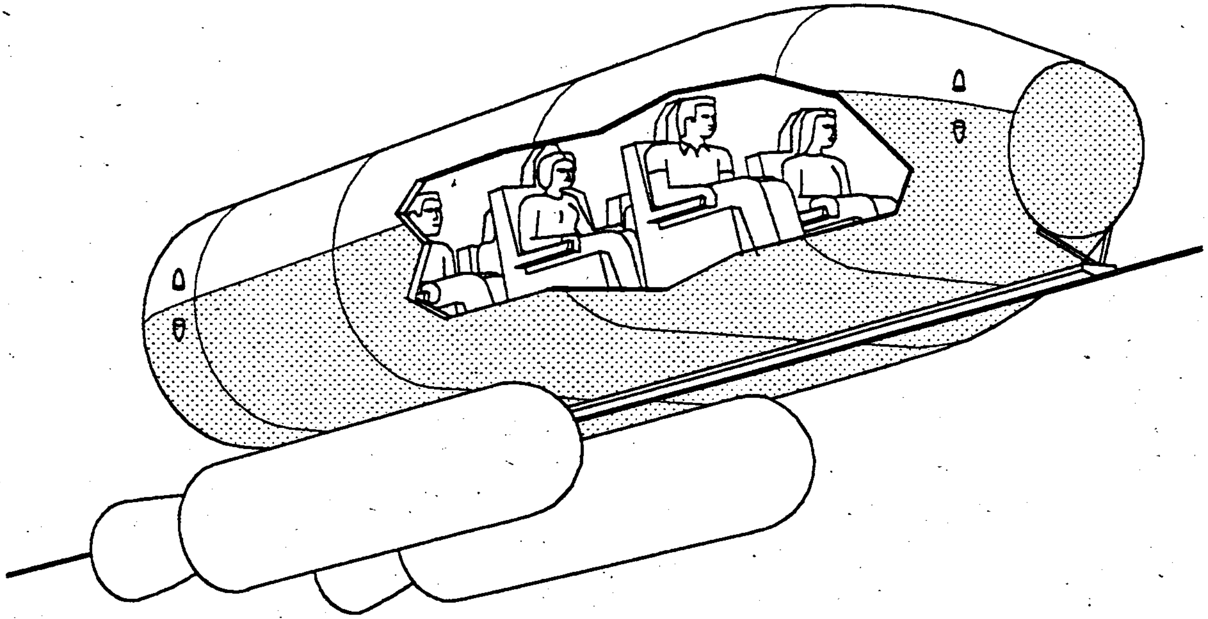

Figure 5—A typical five-metric-ton passenger vehicle, with magnets, rocket motors for apogee orbit insertion, and a heat shield for accidental reentry.

the vicinity of the vehicle determines the maximum force the vehicle can put on the ribbon. A drag force of 15 metric tons results in almost 2 billion watts of heat carried from a vehicle near rest; this heats the ribbon from 400 to 620 degrees centigrade. Iron loses its magnetic properties above 770 degrees centigrade, its Curie temperature.

Launching a 5-metric-ton vehicle to 10 kilometers per second removes 600 billion joules of ribbon kinetic energy, of which 350 billion joules is turned into heat, for an energy efficiency of 41%. The initial Loop will be driven by a 500-megawatt gas turbine power plant. Sixty megawatts will be used for deflection magnets, and 40 megawatts for auxiliary equipment, leaving 400 megawatts to drive the motor. About 70 megawatts will be lost to air friction and drag in the ribbon, leaving 330 megawatts to restore the energy used to launch vehicles. This can restore the energy used to launch a 5-metric-ton vehicle in about 30 minutes. This is equivalent to 240 metric tons per day, or 87,000 metric tons per year.

The energy storage capacity of the Loop will allow it to launch at high rates for short periods with less than full power plant capacity. Power plants may be brought on and off line as necessary; the Loop can store energy for days. More power plants can be added, and more vehicles launched per hour, until the Loop reaches its thermal limit. This Loop limits at 4 billion watts (4 gigawatts), allowing the launch of 115 metric tons per hour, or 1 million metric tons per year. It may be years before even one Launch Loop is used at full capacity.

System Startup

The system is stable once it's going, and it can launch a lot of payload, but how is it started up? The ribbon must be started on the ground from a standstill, and accelerated without stretching it too much. The ribbon sections normally above the atmosphere are now in it, and must be protected from air drag. The east and west stations must be lifted to altitude.

The Loop is started flat on the ground. The ribbon is levitated at rest by the D magnets, and is held *underneath* the inverted tracks in the launch path. The launch path is surrounded by a temporary vacuum sheath, to be stripped off later. When the ribbon is first started moving, it is stretched by the pull of the motors and compressed after leaving them. This is a slow process, as the ribbons cannot be pulled too hard without breaking the joints between ribbon segments.

Once the ribbon is moving fast enough, the electrical generators are brought up to full power. To get the 6000-metric-ton ribbon moving at 12 kilometers per second requires 120 gigawatt-hours of energy. The Loop will need almost two weeks to get up to speed if this energy is put in at a 400-megawatt rate.

When the ribbon is finally moving at 12 kilometers per second, the stations and the launch path may be raised from the surface. At the start, the inclines have zero length, and the launch path is 500 kilometers longer than normal. The anchoring cables on the stations pull them toward the center, and the structure slowly rises. During this time, air traffic must be guided over or under the Loop; once the Loop is up, only the ends will pose a hazard to navigation.

As the system rises, the launch path in the center gets shorter and the inclined sections get longer. At the stations, the inclines are extended by welding together new sheath over them, while sheath is cut away from the launch path. This is performed in long vacuum chambers running the length of the stations; while the ends of the chambers are not tightly sealed, they are long and equipped with powerful pumps, so that a high vacuum can be maintained where the sheath is opened.

The Loop may have to be re-erected a few times per year. Control failure on too many segments of track, ultra-high winds, meteoroid impact, vehicle magnet failures, and other problems may cause Loop failure. The major portions of the system must survive the loss of the ribbon, the kinetic energy of the ribbon must be safely dissipated, and the system should be quickly restorable to service.

The moving ribbon stores 120 million kilowatt-hours. This amount of energy would be produced in heat by the combustion of 10,000 metric tons of oil (modern oil tankers carry 550,000 metric tons). If the Launch Loop fails, this energy is lost, and the ribbon should be dumped out in a harmless way. Releasing it at the top of the Loop will throw it away from the Earth at escape velocity, creating a cloud of space junk in solar orbit. From the inclined sections of the D magnets it will be thrown into the atmosphere or onto the ground, in line of sight with the Loop. The Loop should be operated in unpopulated areas. A lost ribbon can only land near the equator, and must be slowed to just below orbital velocity by air friction to do so. This much air friction would harmlessly vaporize the ribbon.

System Costs

The Launch Loop can launch vehicles very cheaply, but how much will it cost to build one? As the first prototype of a new kind of launch system, it could be very expensive. Fortunately, however, most of the main components are commercially available or are easily mass produced, and their costs may be calculated.

The beginning power plant will use 11 United Technologies 56-megawatt dual FT4 gas turbine power plants, costing $77 million. Structural material costs include $5 million for 200 metric tons of Union Carbide Thornel® carbon fiber and $25 million for 1000 metric tons of DuPont Kevlar® aramid fiber. The magnets and control systems will use $3 million for 1500 metric tons of copper wire and $16 million for 400 metric tons of formed Alnico 8 magnets. The control electronics and motor drivers will cost around $60 million. These identified costs total less than $200 million.

Unknown costs include sheath and track manufacturing, and the upward deflectors on the ends. If the Loop is built on land, many square kilometers of land must be purchased; if at sea, floats and anchoring cables are needed. Vacuum pumps, storage tanks, security systems, housing, and a myriad of other details must be included.

The first commercial Launch Loop may cost 1 billion dollars (a guess), and be used at 30% capacity with a 500-megawatt generator (26,000 metric tons per year). If this system was paid back in one year as a high-risk venture it would cost $50 per gross kilogram (including 6 cents per kilowatt-hour for turbine fuel). Later, launching 750,000 metric tons per year with 4 gigawatts power capacity, 5-year amortization, $9 billion capital cost, and 1.3 cents per kilowatt-hour fuel cost, the cost per gross kilogram is $3. At this cost, labor and vehicle systems will probably dominate net payload cost. Total Launch Loop system cost will probably be well below that of Earth-to-high-orbit rocket systems.

Conclusions

The Launch Loop described here was designed for launching 5-metric-ton vehicles to geosynchronous, LaGrange, and lunar destinations, but other applications are possible. Increasing ribbon speed to 16 kilometers per second lowers near-Earth efficiency, but increases Loop range to Mercury and Jupiter.

Loops may be constructed off Earth, for launching from other bodies or vehicle capture in orbit. For example, the 1500-meter-per-second delta v needed for geosynchronous orbit circularization could be provided by a capture ribbon 120 kilometers long, accelerating vehicles at 1 g. This would make apogee boost motors unnecessary, allowing more net mass per vehicle. Momentum may be restored to the capturing system with high-efficiency ion engines, or payload capture from higher orbits.

Loop structures may even be built in evacuated pipes on the Earth's surface, and used to transmit power. A ribbon with a mass of 1 kilogram per meter moving at 8 kilometers per second carries 250 billion watts of power, and perhaps 20 billion watts can be added or removed as necessary. Energy can be put into the ribbon, transmitted 5000 kilometers, and taken back out with less than 1% loss.

We are now building a 3.7-meter-across, racetrack-shaped, 170-meter-per-second model of the Launch Loop, and are planning larger experiments. It may take 15 to 20 years to scale up to a commercial Loop. At present, this project is funded out of our salaries and savings, and is being put together with volunteer labor; motivated, technically competent volunteer help would be appreciated. A more extensive paper is available on request from the author at P.O. Box 1538, Portland OR 97207.

A Business Trip, Continued

The wait is nearly over; the overhead crane is moving over to lift your Can off its cradle and onto the ribbon. The ribbon is so thin, it's hard to see, extending into the distance. You are reminded of the Loop on NBC-1, which you are going up to help complete. With the new orbital Loop, vehicles can be captured from Earth without onboard rocket engines, pulled up to the speed necessary for geosynchronous orbit by the Loop and the mass of the space platform itself. You will be installing the large ion engines that launched ahead of you, which will be used to restore the momentum removed by arriving vehicles.

This is only a temporary measure. Materials are being accumulated on the Moon for a lunar base, which will use its own surface-based Launch Loop for shipping ore from the surface to the smelters and foundries being built at L-5. Those materials will be launched back down to NBC-1, and used for building more antennas; the extra momentum of these cargos will compensate for lost momentum from Earth shipments. When that happens, NBC will sell their ion engines to U.S. Steel, who is planning a mining expedition to the asteroids. You are wondering if you will follow them out.

There is a slight jolt as the Can is lowered onto the ribbon and slowly released by the crane. The ribbon in front of the Can is heated to dim incandescence; perhaps that is only your imagination, but the force starting to push you back into your seat is not. The end of west station passes by, and it feels like you are on your back with someone on top of you; strange but not painful.

In six minutes the acceleration will end, followed by four hours of free fall. Thousands have taken this path before you, billions more will follow; but you still feel, and rightly so, like a pioneer. ■

ABOUT THE AUTHOR

Keith Lofstrom was born September 5, 1953, and received an MSEE from U. C. Berkeley in 1975. He works as an integrated circuit design engineer at Tektronix in Beaverton, Oregon. He is a member of L-5, AAS, AIAA, BIS, NSI, and SSI. He believes governments are for gravity wells. He plans to be permanently living and working in space before the year 2000.

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● There has been opposition to every innovation in the history of man, with the possible exception of the sword.

Benjamin Dana