The magnetic catapult

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July 2002

Abstract — **We propose a new, highly efficient and conceptually simple, way to accelerate macroscopic objects to high velocities (1-100km/sec). It may be operated in a manner similar to old-style catapults, in which one winches the projectile backwards slowly to store energy in the device, then releases it rapidly during the later forward launch. But unlike old-style catapults, our energy storage is *not* elastic or gravitational, and the energy is not transmitted mechanically; instead energy is stored and transmitted magnetically. Thus any inherent speed limits arise from the speed of light rather than sound. Its analysis is stunningly simple. We give a rough, but hopefully conservative, design for a device of the proposed type capable of hurling a 5-meter-long, 1-meter-diameter cylinder (with added nose cone) weighing 4000kg, at 20 km/sec, 1.9 times Earth escape velocity. We argue that projectiles should be able to survive passage through the atmosphere and still emerge at speeds exceeding escape velocity. The launcher would be (it is estimated) 9 km long, and would consume close to the minimum possible (800 gigaJoules) amount of energy per launch. The cost of construction is estimated to be 2-20 billion dollars and the cost of operation 10-100 million dollars per year. If so, this launcher would largely obsolete all present day space programs.**

A patent is pending.

Keywords — Superconductive magnets, Energy storage, Rockets, Flywheel, Sling, Hypervelocity, Refractory materials, Hypersonic aerothermodynamics, Fixed point theorems, Mountain geography, High-performance switches, Erosion-stable shapes, Space colony critique, Nitrogen gap, Quenching.

Contents

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This paper is long because many details need to be considered. Fortunately it is divided into sections which are readable largely independently. For a quick grasp of the essentials of our new launcher design, just read §2-5.

1 Previous techniques and ideas for reaching high speeds

1.1 *Some general remarks about masses and accelerations*

Mass. Assume your projectile is about the same density as water, and is roughly cylindrical in shape, with a 5:1 length:diameter ratio. Assume it is standing on a high mountain. Then: the column of air above your projectile masses about the same as the projectile itself, if the projectile's mass is 4000 kg.

My point is that the mass 4000 kg is, a priori, something of a **dividing line.** Trying to launch significantly smaller mass projectiles through the atmosphere is silly because one will be, effectively, launching a much larger mass projectile (if one considers all the air the projectile must bore through). Meanwhile, projectiles of significantly larger mass than 4000 kg have the property that air resistance starts to become (as far as dynamics are concerned) neglectible. Actually, to be more realistic, assume the projectile is streamlined so that its drag coefficient $C_D < 1$ (say $C_D \approx 0.2$). Then the dividing line is $\approx$**1000 kg.** In my opinion it is silly to try to launch smaller projectiles than this off Earth. They would have to be launched at speeds far higher than their final intended (post-air-drag) speed, and even if this were done they'd just burn up in the atmosphere.

Acceleration.

Extremely high accelerations are endurable by very tiny payloads, such as bacteria. This is because Newton's law says that $F = ma$ (F=force, m=mass, a=acceleration). Hence for a cubical payload of sidelength r with density ρ, the pressure-stresses p it must endure are $p = r^{-2}F = r\rho a$. So if r is small, p is also. This explains why bacteria have survived being shot (inside rifle bullets) into walls.

It also explains why miniaturized electronics, potted in epoxy, have survived 20,000 gees. Solid state electronics are overall fairly tough, but some parts of them, such as very thin gold wires linking package pins to chips, seem a priori rather delicate. But these delicate components are so small that this is OK, and the density variations in the overall structure (1cm-scale components inside epoxy potting) are on a 1cm size scale, small enough.

Now restrict attention to payloads of macroscopic size (since we've just argued that going below 1000 kg is of no interest for off-Earth launch purposes). In that case, my thoughts are summarized in table G.

Justification of the estimates in table G. Consider a mild-steel cube weighing 1 kg ($\approx$ 5 cm on a side). If this cube is accelerated at 80000 gees by exerting pressure on one of its faces, then the pressure on that face will exceed the tensile strength ($\approx$ 300 MPa) of mild steel. If this were a 1000 kg cube instead of 1 kg, then only 8000 gees would make the face-pressure equal to steel's tensile strength. (Of course, mild steel is about 6 times weaker than strong heat treated steels, and crush strengths tend to be about twice as large as tensile strengths – but on the other hand, mild steel is stronger than most materials, even on a per unit mass basis, so this ought to give at least a rough indication of where we stand.)

A similar computation suggests that 1 kg masses of even the strongest materials (on a per unit mass basis) cannot survive more than about 3-20 million gees. For remarks about accelerations survivable by humans, see footnote 25; remarks about accelerations survived by electronics, mechanical devices, etc are elsewhere in this paper.

All this suggests that if we want to build an off-earth launcher with interesting payloads, accelerations larger than about 30000 gees are not of interest, and accelerations of, say, 3000 gees are of more interest than 30000 because a wider class of less-carefully designed payloads could be accomodated.

gees	allowed contents
0-3	comfortable humans
3-10	uncomfortable humans
10-50	fluid-infiltrated humans?
50-5000	sophisticated electronics & mechanical devices
5000-30000	epoxy-potted electronics, simple mechanical devices
50000-10^6	simple strong homogenous bullets only
$>$ (3-20) $\times 10^6$	none; solid bodies destroyed

Table G: allowable contents for kg^+ projectiles, versus the gee ranges of accelerations they are to be subjected to.

1.2 Rockets

Rockets are an extremely inefficient way to reach high speeds. The "rocket equation" says that to launch a mass-m projectile to speed V, total rocket-fuel mass of *at least* $m\exp(V/V_{exh})$ is required, where V_{exh} is the exhaust velocity of the gases from that kind of rocket fuel. (This bound is achieved only if we assume that the engine, fuel tanks, etc [i.e. all other non-fuel mass] weigh nothing.) Note the *exponential* dependence of the rocket's cost on the desired final speed. (For example, the Saturn V moon rocket, at 2.7×10^6 kg the largest ever used, could only launch 45×10^3 kg to Earth escape velocity. Presumably to reach twice Earth escape velocity, a further factor$\approx$ 50 reduction in final mass, to e.g. 1000 kg, would be necessary, and presumably it would only be possible to push 20 kg to three times escape velocity.) For high speeds this is unacceptable, so rockets are thus effectively limited to speeds of ≈ 5 times their exhaust velocity. Exhaust velocities are limited by available chemical energies E per unit fuel mass m, i.e. $V_{exh} < \sqrt{2E/m}$.

1.3 Guns

Guns cannot reach velocities greater than (roughly) the speed of sound in the hot propellant gases, i.e. less than the exhaust velocity of a rocket using that propellant as its fuel, and therefore are even less acceptable. For example, consider [11] the gun used by the Germans to bombard Paris in World War I, whose range of 116 km was the largest ever achieved. It (including its mounting) weighed about 750 tons. It had a muzzle velocity of 1.7-1.8 km/sec, well below even lunar escape velocity 2.4 km/sec. This gun's barrel eroded noticeably after each shot (with at most 65 shots being possible per barrel – indeed one of the 4 barrels exploded) requiring constant readjustments of its ammunition from 21cm up to 23.5cm calibre[1]. We should also mention the HARP (High altitude research project) gun, supported by the US, designed by Gerald V. Bull [10][11][54][55], and operated in Barbados in about 1965-1975. This was made of two surplus battleship guns welded together and with the rifling bored out to create a 36m-long smoothbore barrel, weighing 180 tons, with 16.5in calibre. Using 1000lb of propellant, and with the aid of discarded wooden sabots and a lubricated and evacuated barrel with bursting membrane, it launched a reduced-diameter 85kg finned projectile to a record 180km altitude in Nov. 1966. (Muzzle velocity$\approx$ 1.9km/sec; efficiency of[2] chemical to projectile-kinetic energy conversion$\approx$ 8%.) The barrel had to be relined every 50 shots. Conventional telemetry electronics potted in epoxy (as well as some simple mechanisms for, e.g. releasing chemical clouds, parachutes) survived the peak acceleration of $\approx$ 20000 gees. Pressures within the gun's barrel were of order 3000atm.

1.4 Rocket-assisted gun-launched projectiles

Rocket assist would have been necessary in Bull's plans for gun-to-orbit launchings[3] – and indeed, the vast majority of the final velocity would have to be provided by the rocket. Because of this, I do not understand why Bull was so attracted to his gun-launch idea as opposed to relying 100% on rockets. The improvement seems small.

In contrast, the launcher of the present paper can eject projectiles from the Earth's atmosphere at beyond escape velocity (or at any lesser speed), with no need for rocket assist. A tiny rocket would then suffice to convert a launch at slightly below escape velocity into an highly elliptical orbit similar to the orbit of the 1962 Telstar communications satellite (apogee 10802km, perigee 972km). The 3 orientation parameters of this highly elliptical orbit could be, by means of tiny rocket adjustments, changed to any values. I admit that to convert such a highly elliptical

[1] In World War II the Germans planned to bombard London with a 25-barrel gun, with range $\approx$ 150 km, located near Calais, called the V3. But this gun was destroyed by the RAF before its completion. The V3 was a smoothbore gun with an arbitrarily long barrel, with additional propellant charges in secondary-branched-off chambers every 8ft along the 127meter-long main tube. It employed finned projectiles with discarded sabots, Smaller-length versions of this gun were used in combat Jan-Feb 1945 to shell Luxembourg, and killed about 10. Similar ideas were to be employed by a giant gun, designed by G.V.Bull, partially constructed by Iraq in 1990 for the probable purposes either of bombarding Israel (500 km away) or of creating an Arab space program for gun launching rockets into orbit. (There is reason to doubt it would have been an effective weapon since it would have only been able to make a few shots per day.) Of course it is possible for guns to exceed the speed of sound in the propellant gases by various multistaging ideas, but it becomes exponentially difficult, so that *effectively* there is a speed limit on the order of the speed of sound.

[2] Shots with larger-mass slower projectiles are more efficient, $\approx$ 40%.

[3] And he wanted to develop such rockets. E.g. he proposed [54] shooting a 3-stage rocket, weighing about 2000lb, from the 16.5-inch gun at about 1250m/sec, for the goal of placing 50lb payloads in orbit (Earth low orbit velocity is 7.9 km/sec). Such plans were prevented by lack of funding. Of course, it is possible to combine other propulsion methods, e.g. electromagnetically augmented conventional guns, 2SLGGs with rocket assist, etc.

orbit into a (usually more desirable) *circular* orbit would require *large* rocket assistance[4]. But because this **orbit-conversion** could be performed in the vacuum of space without any need to do it quickly, it could be carried out with high-energy low-thrust devices such as ion drives, instead of chemical rockets, greatly reducing the need for reaction mass. Also, if the launcher were (at least once a day) oriented to point (at least on some days at some times) at the moon then by "slingshotting"past the moon it would be possible, with only tiny assistance from rockets, to produce directions of ejection from the Earth-moon system arbitrarily selected from within a full 2-parameter continuum set. (For a paper taking this sort of slingshotting idea to its ultimate limit, see my [84].)

1.5 Two stage light gas gun (2SLGG)

The 2SLGG [20] involves the use of explosive-driven pistons to compress and heat hydrogen gas, which in turn is used to drive the projectile. Similarly the "nuclear powered rocket" involves using a nuclear reactor to heat hydrogen gas, which is then expelled. The point is that the speed of sound in hydrogen is greater than in any other gas at the same temperature. Projectile speeds of 1-8 km/sec (20 gram projectile) are achieved by the 2SLGG at Lawrence Livermore National Labs. 2-stage guns are substantially less efficient than a conventional 1-stage gun, and still suffer from the same inherent limitations – merely with a larger speed of sound, limited by the maximum temperature we are allowed to heat the hydrogen to without melting the containment vessel. For this reason, it is commonly believed that no 2SLGG will be able to achieve 12 km/sec. (Also: the nuclear rocket obviously is unacceptable for Earth use for safety reasons.) Also, these guns typically can only make a few shots per day due to the need to clean the gun scrupulously between shots. Such a gun could easily achieve lunar escape velocity, but hydrogen and helium gas are in short supply on the moon[5].

1.6 Low thrust devices

We shall ignore ion rockets, solar sails, etc since they cannot achieve high thrust levels and hence are unusable on the Earth and Moon. They are only useable in space.

1.7 Rotary sling

An intriguing idea is a modernized version of the "sling" used by David versus Goliath[6]. This could consist of a cable attached to a hub at one end and the payload at the other end. It would be spun up to high speed in vacuum before payload release is triggered.

It is theoretically possible to achieve unboundedly arbitrarily high tip speeds with a bounded-strength cable material, but only by making the cable become exponentially thinner at large radii. Specifically, consider a bi-*infinitely* long cable made of material with tensile strength T Pascals and density ρ kg/meter^3, with cross-sectional area $A(\ell) = A_0 \exp(\frac{-\ell^2\omega^2\rho}{2T})$ meters^2 at length ℓ meters along it. (A_0 is the cross sectional area at the hub, where $\ell = 0$.) This could withstand being spun at $(2\pi)^{-1}\omega$ revolutions per second. (This geometry is optimal in the sense that the stress is uniform everywhere. Uniform-stress *flywheels* also have this kind of geometry. These optimal-geometry results deserve to be better known.) The infinite ends of this cable could be mentally "snipped off" at some ℓ and replaced by two detachable payloads, each of mass $M = TA(\ell)/(\ell\omega^2)$.

Notice that the parameter governing achievable tip speed at any given cable-shrinkage ratio is $\sqrt{T/\rho}$. Samples of high strength steel (density 7.8 grams/cm^3) have exhibited tensile strengths of 2 gigaPascals (commonly commercially available steel cable is about 60% as strong as this), and hence have $\sqrt{T/\rho} = 0.50$ km/sec.

Graphite whiskers were (at least until recently) the material with the largest known strength to mass ratio (density 2.25 grams per cm^3, tensile strength sometimes as high as 1.96×10^{10} Pascals). For them $\sqrt{T/\rho} = 2.95$ km/sec. Unfortunately, so far the total world intentional production of whiskers (of all materials combined) has been < 1 kg.

The material with the highest strength to mass ratio, among those that presently can be produced *in bulk*, is "linear polyethylene fiber," with $\rho = 0.97$ gram/cm^3 and $T = 3.0\text{-}4.5 \times 10^9$ Pascals. It has $\sqrt{T/\rho} = (1.76\text{-}2.15)$ km/sec. But unfortunately this material exhibits "creep" under stress and seems to have a fatigue threshhold of zero.

[4] The best way to convert orbits often is to thrust only at apogee, when you get the most angular momentum change for a given amount of energy expended, and at perigee, when you get the largest energy change for a given change in angular momentum. We here are starting with an ultra-elliptical orbit with near-minimal angular momentum, and want to reach a circular orbit having maximum possible angular momentum at its energy. We may proceed by thrusting the spacecraft in its direction of motion when at apogee (increasing its angular momentum by a lot and its energy by a little) and thrusting in the reverse direction at perigee (decreasing its energy, but only decreasing its angular momentum a little) as necessary until the desired angular momentum and energy (i.e., the desired orbit in the same plane) is reached. The latter might be doable, to some extent, by atmospheric braking rather than active thrusting.

[5] In contrast, the launcher described in the present paper might be well suited to lunar use, since it consumes electrical power only – comparatively easy to get on the moon, and needs vacuum and cold temperatures, useful things which also are available on the moon for free. Note: to keep something cold on the moon, proceed as follows. The object should be kept above the moon's surface on top of an insulating post. Place silvered Dewar-like thermal/radiative shields between the object and the moon, and between the object and the sun. (The latter shield should move slowly to track the sun.) However, do not place any shield between the object and the night sky, and indeed attach a black radiator to the object capable of radiating into said sky. The result should be cooling – if the shields are good enough, 2.7°K (the temperature of the "cosmic microwave background") should be approachable.

[6] See the Bible, 1 Samuel 17:40. Slings were used by many armies of the ancient world. They are mentioned many times in the *Anabasis*, a first-person account of a Greek/Persian military campaign in 401-399 BC. Generally they were used to throw standardized round stones. However, Roman army slingers employed ovoid-shaped lead projectiles with about 2:1 length:diameter ratio (1000s have been found by archaeologists) weighing 20-150 grams, and also used stave slings to achieve greater range. The Romans also had special tongs for removing slingstones embedded in people's bodies. According to Greek and Roman writers, slingers could outrange archers and be effective at over 300 meters.

Finally: Yu et al. [94] were able to measure the tensile strengths of 7 carbon "nanotubes" (each about 6 μm long) and found 6 values ranging from 20-39 GPascals and 1 exceptionally strong nanotube with yield stress 63 GPascals. So probably a composite material made largely of aligned nanotubes could be made, perhaps in large quantity, with 10-40 GPascals strength and density 1.5 gram/cc, i.e. with $\sqrt{T/\rho} = 2.58$-5.16 km/sec.

However, even with the best conceivable materials with $\sqrt{T/\rho} = 5$ km/sec, achieving 20 km/sec tip speed would require a hub-to-tip cross-sectional area reduction factor of $e^{16} \approx 2981$, i.e. a cable-diameter reduction factor of $e^4 \approx 55$ (consider a 5.5 meter diameter cable at the hub, thinning to 10 cm diameter at the tip). This would only allow launching small payloads (under 1000 kg) and with very poor efficiency (since the mass of the cable would greatly exceed the mass of the projectile). Furthermore, assuming a more realistic cable material with the (still high) $\sqrt{T/\rho} = 2$ km/sec, the required area reduction factor would be e^{100}, which is completely ridiculous.

In other words, both currently available materials and probably future hypothetically available materials are too weak to build a sling capable of competing with the off-Earth-launcher that will be proposed in the present paper.

1.8 Rotary pellet launcher (RPL)

This sling idea is a rediscovery. It, including the optimal geometry result, had been previously published by G.K.O'Neill ([61], box on page 34), and called by him the "rotary pellet launcher." He envisioned it as being 2-armed and permanently rotating, with the arms being hollow tubes; small pellets (a few grams) would be repeatedly injected near the hub for launching a pellet stream off the moon.

Let me update and correct O'Neill's analysis. The first new realization, not made by O'Neill, is that the RPL actually will achieve launch velocities *exceeding* cable tip speed, because the pellets will be accelerated radially along the tubes before ejection, and thus will be ejected with *tangential* velocity equal to the tip speed, *plus* radial velocity *also* equal[7] (assuming no friction as the pellet slides along the tube, which is an ideal that might be approachable via lubrication) to the tip speed. In other words, the total pellet velocity will be $\sqrt{2}$ times the tip speed, in a direction at a 45° angle to the radius of the circle.

Consider a 10-meter radius linear polyethylene sling with a cable diameter-shrinkage factor of 4, and cable diameter 1cm at the tip, whirling at 75 revolutions/sec in vacuum. It would have tip speed 4.7 km/sec. Then the launch velocity will be 6.7 km/sec. So it seems plausible that (≤ 15)-gram projectiles could be hurled at this speed. This[8] might be considered as competing favorably with the 2SLGG and rail guns at US national labs. Also, by building two adjustable counterrotating slings it might be possible to make the projectiles hit one another[9] thereby achieving twice the impact speed (and with the advantage that the lab frame would be the center of mass frame). The energy efficiency of an RPL might be excellent.

Unfortunately, there is a big problem (also not noticed by O'Neill) with RPLs. The peak acceleration experienced by the RPL projectile is $\sqrt{2}V^2/R$, which in our example is 3140 km/sec^2, i.e. 320,000 gees – too enormous to be of much interest, since only very simple, small, and robust projectiles could survive this. Also, I suspect that friction forces at the enormous contact pressures (≈ 3000 atm) implied by this acceleration, while perhaps not greatly hurting the RPL's performance on any particular launch, would nevertheless be large enough to cause serious damage and limited lifetime of the RPL. (This was ignored by O'Neill.) Quite probably, at most a few hundred pellets could be launched before it became necessary to reline the RPL's barrel, in which case both its energy-efficiency and attractiveness for unattended operation would be drastically reduced.

O'Neill envisioned performing fine aim adjustments via post-launch electrostatic deflection, but he did not provide any analysis of that idea, and I am skeptical of it.

1.9 Rail gun

The electromagnetic rail gun involves accelerating a small projectile (1 cubic-centimeter polystyrene cubes with a copper coating on their rear side have been used) sliding in vacuum between thick parallel copper rails. The copper coated side of the projectile constitutes a small part of an electrical current loop, also containing the two rails. By dumping an enormous current through this loop, the projectile is accelerated along the rails by the Lorentz electromagnetic force. Several methods have been used to provide the current pulse: giant switched capacitor banks, homopolar generators with switched inductive storage devices as back ends, and explosive-driven 1-turn DC "generators." The latter may be thought of as a 2-stage gas gun with the role of the compressed hydrogen gas now played by the compressed magnetic field. Hence there is no speed-of-sound limitation; the corresponding limit is now the speed of light. Of course the projectile's copper coating is immediately vaporized, but continues conducting as plasma. This approach has achieved a speed of 16 km/sec for an 0.1 gram projectile (Sandia National Labs) and 4 km/sec for multi-gram projectiles (capacitor bank plus explosive-drive flux compressor). See [73] for a different railgun design which achieved 5.9 km/sec for a 2-gram "Lexan" (polycarbonate plastic) cube projectile (2-story-high 500MJ homopolar generator with inductive storage device). This paper noted that it was necessary to limit currents to 200 kA to avoid rupturing their projectile, whereas their generator was capable of providing up to 500 kA. This suggests that a stronger projectile (e.g. "Kevlar" or diamond) might have achieved over

[7]Proof: The centrifugal force $m\omega^2 r$ at radius r, leads, upon integration dr, to a potential energy drop from $r = 0$ to $r = R$, of $mV^2/2$ where $V = \omega R$ is the tip speed at $r = R$.

[8]And in this same example, a cable diameter-shrinkage factor of only 2 would suffice to achieve tip speeds of up to 3.3 km/sec, which might be a attractive solution to the problem of launching $\lesssim$ 1kg things off the moon.

[9]This has been achieved with railguns and 2SLGGs.

14 km/sec.

This highlights another big disadvantage of 2SLGGs and railguns: in order to prevent fall-off of gas pressure and temperature, or in the case of railguns, of electric current and magnetic field, it is desirable to keep these guns *short*. However, this forces the peak projectile acceleration to be *large* to the point where only the most robust projectiles can survive. (Also, the acceleration in railguns, RPLs, and guns is *nonuniform*, causing the peak acceleration to be larger than the average acceleration, making matters worse.)[10] Thus, some 2SLGG peak accelerations have been as high as 150,000 gees, and some rail guns have had accelerations of 8.4 *million* gees. As we said (§1.1), this is enough to make both of these devices uninteresting for all but the simplest and strongest projectiles.

In contrast, the magnetic catapult described in the present paper can be made as long as desired, and can be made to produce uniform and moderate acceleration.

The need for high-current electrical contact between the projectile and the rails forces the need for mechanical contact at enormous sliding speeds, leading to frictional energy losses, arcing, and also to problems such as severe damage (leading to eventual destruction) of the rails [6][72]. Such damage appears to scale up badly with projectile size, so that some large railguns have been completely ruined after only a single shot. With long rails (as in a sequential multiple railgun) this would also risk destruction (e.g. by melting) of the projectile. (Similarly, the need for hermetic sealing in conventional guns forces the need for a sliding mechanical contact, leading also to high frictional losses and to wear of the gun barrel, forcing its eventual replacement.) For such reasons it has been claimed [72] that inherent limits will prevent railguns from ever exceeding 6-8 km/sec. They support this claim [72] by noting that in the 25 years of heavily funded research since the initial railgun paper [73], nobody has managed to beat this speed limit except by using railguns which self-destruct after only one shot.

Finally, the rail gun seems inherently inefficient, because the large magnetic field needs to be present throughout the volume between the rails, whereas only the small part of that magnetism (in the much smaller volume constituting the projectile's rear electrical coating) is actually used. Also, much energy is lost through ohmic heating. As a result, the best electrical to kinetic energy conversion efficiencies so far achieved by railguns have only been about 30%.

1.10 Dust grains

Small charged dust grains have been accelerated to speeds of over 100 km/sec by the electrostatic field of a Van de Graaf generator. But this method only works for tiny dust grains (which can achieve a very high charge to mass ratio and survive ultrahigh accelerations) and since their charge to mass ratios have (so far, anyway) not been precisely controllable, the speed is not either.

1.11 Mass driver

G.K. O'Neill's "mass driver" [61][64][65][62][85] consisted of a sequence of coils connected to precharged capacitor banks. A magnetic projectile would approach a coil, be sensed, and then the dormant capacitor would be switched to drive current through the coil, magnetically attracting the projectile. Once the projectile had passed through the coil, that coil would be switched off (or would switch itself off automatically since its capacitor's charge had been used up), and the process would be reiterated at the next coil. This is really just one instantiation of a wide class of devices that often are called "linear electric motors" since they operate on the same principle as familiar rotating electric motors, only geometrically "straightened out" to cause linear motion [7] [70] [18] [42]. O'Neill, with collaborators including H.H.Kolm, built several small working models [64][65][85], each approximately 1 meter long, capable of accelerating multigram masses to speeds of order 35 meter/sec. They used power-SCR (*s*ilicon *c*ontrolled *r*ectifier) solid-state devices for switching. One advantage of O'Neill's system is its simple extensibility – an arbitarily large number of coil/capacitor/sensor drive units, operating almost independently, and independently replaceable, could be placed in a line in vacuum. O'Neill envisioned using such a system for launching material off the moon, or as a reaction engine for space propulsion.

O'Neill also had the idea that the expensive magnetic "buckets" could be "recycled" by the following procedure. After launch, the bucket would eject its payload, which would continue on along a near-parallel path. The bucket would then enter a *de*accelerator essentially the same as the accelerator, but working in reverse (and perhaps even attempting to recover some energy by operation as a generator rather than a motor). O'Neill never built a working model of *this* (ejector plus deaccelerator). I point out that a simpler deaccelerator could just be a metal tube, which would act as an eddy-current brake for any magnet flying along its axis. Any such flying magnet would also be automatically "levitated" away from the walls of the tube and hence would automatically enjoy a certain amount of stability.

1.12 Other linear electric motors (LEMs)

O'Neill's mass driver concept has a considerable resemblance to the EM-catapult concept proposed here. I'll now mention some other previous ideas that resemble it even more closely.

The **brush-commutated helical coilgun** [27] involves a long solenoid. Only the part of this solenoid lying ahead of the projectile (which traverses it axially) contains flowing current – a goal attained by making the projectile, equipped with commutating brushes, be part of the current loop. One such gun built at the Bitter magnet lab at MIT [44] during the 1970s attained an efficiency of 22% at low launch

[10] One could generalize the German V3 repeated-detonation gun idea to railguns by making the projectile slide through a sequence of many railgun segments, which, if feasible, could uniformize their accelerations to some extent.

velocities (60m/sec, 4 kg projectile). However, brushes are unuseable beyond about 2 km/sec.

Glen Robertson [74] invented a **"Meissner effect launcher."** That was a linear electric motor for the purposes of propelling a cryogenic pellet coated with superconductor. Magnetic coils behind the pellet would be repeatedly activated, repeatedly repelling it via the Meissner (superconductor-magnetic "levitation") effect.

The **"quench gun"** apparently was first described by Mongeau in 1991 ([51] p.571). This involves a sequence of coaxial superconducting coils which are "quenched" to above T_c (converting them from superconducting to normal) after the magnetic projectile passes through them. It is quite close to the right (the present paper's!) idea, but doesn't quite get there. The quench gun will be abused in detail at the end of our §6.3. For now, suffice it to say that tremendous heat is released during coil quenching, which leads at best to extremely poor efficiency, and in high energy cases to coil destruction. A later improved version called the "SPEAR coilgun" was built by Bresie et al [9] in 1995. This, instead of using quenching, deactivated coils by using solid-state "passive" switching by an SCR. (The "passive" is because they elegantly contrived the circuit so that the SCR automatically switches itself off at approximately the right moment – the coil itself inductively senses the projectile – without need for any external control.) Unfortunately this too was highly inefficient, achieving only 7% efficiency (although they regarded this as good!). The fundamental reason for that (cf. our §6.1) is that by incorporating an SCR in a current loop, its superconductivity is necessarily broken, wasting energy and necessitating the use of external power supplies for each coil (Bresie et al use capacitor banks). Indeed, once the SCR is in place, it seems pointless to use superconductive coils at all – might as well just use ordinary wire. Without superconductivity it similarly becomes pointless to magnetize the coils well ahead of time – might as well magnetize them only immediately before they are used, via a timed pulsed power source. In this case, the quench/SPEAR gun really just becomes a "conventional" LEM ([37][41][42] being representative of the breed; these achieved efficiencies – kinetic energy divided by energy initially stored in capacitors – of 38, 23.3, and 7%, respectively) with a slightly more elegant than usual off-switching circuit. Also, there are inherent limits on SCR breakdown voltages, imposing a speed limit on their device concept[11]. In contrast, our catapult uses true-superconductive coils, does not need capacitor banks, and should achieve efficiencies near 100%.

1.13 Summary of advantages of present catapult vs. these previous schemes

We've seen that rockets become exponentially unattractive at speeds beyond a few km/sec. Guns have speed limits below 2km/sec and are degraded by use. 2SLGGs, non-destructing rail guns, and rotary sling devices have for most purposes unacceptably high accelerations, suffer damage when they are used, and have speed limits of, respectively, 12 km/sec, 8 km/sec(?), and exponential-unattractiveness beyond about 2 km/sec. Also 2SLGGs and railguns inherently have low efficiencies. So our only remaining competitors in the realm above 12 km/sec muzzle velocities are linear electric motors. As far as I can tell no previous linear electric motor scheme can claim all of the following properties possessed by our catapult:

1. No electrical or mechanical contact is made between the projectile and anything else.
2. We do not use capacitors or any other external energy storage devices; instead the launcher *is* the energy storage device, and energy is stored throughout it at essentially uniform density in the form of magnetic field.
3. We do not even need an external source of electric power; instead the accumulation of stored energy in the device may be accomplished gradually, losslessly, and purely mechanically; this energy will be released rapidly upon launch.
4. There are fundamental topological reasons why essentially 100% of this stored energy will be converted to projectile kinetic energy; there will be essentially zero ohmic and frictional losses and essentially none of the magnetism will be "unused." Also, there are fundamental topological reasons why essentially 100% of the input energy will be stored in the device. As far as I can tell, previous devices cannot match this inherent ultra-efficiency. Incidentally, high efficiency is not only important merely for the sake of saving energy. It is also important because inefficiency leads to tremendous production of waste energy, which can severely damage launchers. (Examples: we've already mentioned the damage suffered by guns, railguns, and RPLs.)
5. The magnetic catapult has manifestly inherently *stable* operation, whereas many schemes involving non-coaxial geometry or magnetic repulsion may operate in an unstable or at least suspicious manner[12]. Of course, instabilities at these velocities could be catastrophic.
6. The magnetic catapult does not require on- or off-switching of large currents and voltages through large inductive loads; while linear electric motors do. (There

[11] Actually, that limit ought to be evadable by instead using *vacuum tubes* for the switches – although that creates a whole other set of problems.

[12] Example #1: Robertson's Meissner effect pellet launcher [74], would, if the superconductor were used, as he suggested, to coat only the rear side of the projectile, be unstable because the projectile would tend to flip over. Even if the entire pellet were coated with superconductor, then for drive coils shaped such that, in some locations, the maximum magnetic field was on-axis, the pellet would tend to move sideways to get off-axis. Example #2: Schemes based on *repulsion* between two magnets are in general unstable because the free magnet tends to flip over so that it is attracted rather than repelled. Example #3: Cowan et al.'s non-coaxial "reconnection gun" [18] seems stability-suspicious. Indeed when a version of this was later constructed [41] it exhibited "intermittent contact" between the projectile and the stationary coils.

actually *is* electrical switching in the magnetic catapult, but the switching only occurs at moments when the current through, and voltage across, the switch are *zero*. This minimizes stress on the switch and maximizes energy-efficiency.)

This leads to wonderful simplicity and optimum compactness and efficiency. For these reasons, at least for use on *Earth*, I believe the EM-catapult should be infinitely *superior* – i.e. I believe O'Neill's or Robertson's systems (not to mention railguns, slings, and 2SLGGs) would have sufficiently poorer performance that it would not be feasible to use them for off-Earth launching at all. (Our off-Earth launcher proposed in §5 is 9km long. Meanwhile a non-optimally-compact launcher might be 30 km long – too long to build.)

But due to its need for cryogenics and expensive "high tech materials," my EM-catapult might be considered *less* attractive than O'Neill's mass driver or Cowan et al's "reconnection gun" [18] for use on the moon. I will not attempt to decide that.

1.14 *Critique and resume re Gerard O'Neill and his space cadets; their friends, opponents, and rich fantasy lives**

Gerard K. O'Neill (1927-1992) had proposed all of his mass driver ideas [64] in the 1970s as a small, but integral, part of a giant program [61][62] of "space colonization." One part of this program [63] was the construction of geosynchronous "solar power satellites," each a huge ($10 \times 5 \times 0.5$km) array of photovoltaic cells, each attached to a 1km-diam dish antenna and 10^5 klystrons for beaming microwave power to 12km-diam "rectenna" arrays on Earth, which would convert it to 5 Gwatts of continuous DC power at 75% efficiency (as a fraction of the power in the microwave beams)[13].

I believe I can summarize the central idea of this program in manner both more concise and more true than was ever stated by its proponents: "Once we create ultra-intelligent self-repairing robots capable of 'living' in space (e.g. on asteroids and the moon), acquiring direct solar power, mining, and manufacturing, and of building complicated machines (such as the one proposed in this paper), and of reproducing exponential numbers of themselves, we humans can just sit here on Earth and do nothing while enormous wealth, resources, industrial goods, and electric-power-on-tap will flow to us automatically without need for degradation of the biosphere. This is since the available amount of solar power and resources out there, even if the robots only grant humankind a small fraction of it, is far vaster than that available to us on Earth."

When stated in this way, this thesis seems impossible to argue with. The problem completely ignored by O'Neill is that nothing even close to this level of robotic competence and Artificial Intelligence is currently available, nor does anybody have much inkling of how to create it in any amount of future time whatever. Put another way: It is currently beyond the capability of the human race to create a machine capable of playing a strong oriental game of "Go," of examining, diagnosing, and repairing a broken tractor, or of following spoken directions such as "go to the school and get my daughter, then clean my bedroom," or of answering written questions such as "which country contains the largest ratio of minable gold to agricultural production?" or "which of the following 10 animals (pictured) is the fastest?". The whole problem is really not one of space technology or physical limitations at all, it is one of artificial intelligence and robotics. *But* the whole focus of O'Neill and his ilk (whom I will call, for short, the "space cadets") – and most of the focus of today's space agencies, which still are concentrating on such misguided missions as a manned "space station" in low Earth orbit and a manned mission to Mars! – was on the former rather than the latter! O'Neill seems to have the attitude that once he's established something is physically possible, the rest is a triviality. E.g., he claims he is intentionally only employing the "technology of the 1970s" in his vast plans, because he wants to be "unrealistically conservative." This claim can only be accepted if we ignore AI as a "technology." This is rather akin to the attitude a super-pure mathematician might have that factoring a million-digit number into primes, is a triviality, since it obviously is algorithmically possible. In both cases, the development costs *of the algorithm* (or of the robotics) are, entirely possibly, beyond any amount of money humankind will ever have. These costs thus may vastly dominate the costs (which are the only ones O'Neill adds up!) of the – therefore comparatively "trivial" – cost of *using* that algorithm.

Indeed, O'Neill essentially envisions duplicating most of the industry (electronic, chemical, mechanical, mining, construction, transportation, etc.) presently on Earth, in an appropriately altered form, in space, as a prerequisite for space colony construction. Furthermore, most of this industry would have to be run by a new form of life (which he needs to create), i.e., self-replicating, ultra-intelligent robots. Now one might expect, a priori, that such a development would cost at least a comparable amount to the cost of all industry on Earth. But O'Neill [61] thinks it will only cost about \$30 billion dollars to build each space colony. (It cost about \$1.5 billion to build the World trade center, workplace for about 20000 office workers, in 1966-1973. O'Neill's \$30 billion space colony is planned to be self-sufficient and house between 10800 and 20 million people.)

Furthermore, even if we accept O'Neill's point of view that all that matters is what is physically possible, many of the prognostications, plans, and breezily stated numerical-physical estimates made by many of the space cadets (and their critics!) seem wrong, and in some cases *very* wrong. I am going to discuss some of these errors in detail because F.J.Dyson, in his preface to the third (posthumous) edition of O'Neill's book *The high frontier*, stated that none of O'Neill's technical claims had yet (after almost 30 years) been refuted. I hope we won't hear that anymore, since I will now refute several of them.

[13] The numbers are taken from [57], and no endorsement of them by either me or O'Neill is implied.

1. O'Neill has the idea that raw materials mined on the moon will be fired off to human "space colonies" / luxury-living resorts located at the L_5 Earth-moon "Lagrange point." There they would be refined and processed into manufactured goods such as more space colonies, solar power stations, oxygen, aluminum, titanium, ultrahigh-purity silicon, etc. How are the (solid and gaseous) waste products of this manufacturing and refining to be disposed of? Why won't the stream of incoming material knock the receiving space colony off course? O'Neill [61] does not address either issue at all[14].

2. O'Neill ([61] p.33 & 34) argues that his space colonies (4600m-diam, 16 km long counterrotating cylinders with windows) would have Earth-like weather inside, thanks to the fact they would be filled with Earth-composition air at about 2/3-atm pressure. Via a pressure-decrease calculation, O'Neill finds that clouds would occur at about 1000m internal radial "altitude."

I believe this calculation is too naive. One reason Earth's atmosphere is colder at altitude is the "greenhouse effect" (transparency of our atmosphere to visible but opacity to IR radiation). The greenhouse effect is thought to warm Earth's surface to 15°C, which is 35°C above what its average temperature would be otherwise. In O'Neill's cylinders, the greenhouse effect will not work that way! Since hot air rises we might expect hotter, lower pressure, air in the center of his cylinders – exactly the *opposite* of what is wanted for clouds to form! Another related reason: consider the energy cascade Sun→Earth→Lower Atmosphere→Upper atmosphere→Outer space, with each stage in the cascade being colder than the previous one. Because O'Neill's "upper" atmosphere is, unlike Earth's, well insulated from space, the energy cascade seems unlikely to work this way, so that O'Neill's "upper" atmosphere will not be colder than the lower atmosphere. But O'Neill is correct that one reason Earth's lower atmophere gets colder (by 6.5°C/km) as one rises is a giant wind-powered "atmospheric refrigerator:" random winds cause parcels of air to rise and sink, and the rising parcels expand and hence cool, whereas the falling parcels are compressed and hence heated (in both cases by 9.8°C/km for dry air). Such a refrigerator will still operate in O'Neill's space colonies. But my guess is that there will be less wind inside O'Neill's colonies than on Earth, so this refrigerator will be less active – perhaps even inactive[15] – while the greenhouse and energy cascade effects will be deactivated, so the net effect may be that clouds may *not* form at internal "altitude" and rain will *not* happen. In the absence of a continual natural distillation-precipitation water-purifying cycle, it seems to me O'Neill has failed in his primary goal of recreating "Earth-like living conditions" in his space colonies.

3. O'Neill ([61] table p.34) gives a table of masses required to build a space colony. Completely absent from this table is the mass of the *nitrogen* required for the Earth-composition air. That is no minor omission, since this N_2 mass would have to be lifted entirely from Earth (since there's essentially none on the moon or asteroids) and, by his calculations lower on the same page, that mass would be approximately equal to the combined mass of everything else in the colony!

Of course, due to fire risk and destruction of the ecological nitrogen cycle, full pressure pure-O_2 would not be acceptable. Replacing N_2 with some other inert gas (e.g. Ar) would merely recreate the same mass problem with a different name. While it probably would be possible for humans to live in a reduced-pressure pure O_2 atmosphere (long term physiological consequences?), certainly that would represent a failure of O'Neill's goal of recreating "Earthlike living conditions" – e.g., the Apollo astronauts discovered that it is impossible to hear a shouting person 10ft away in 0.2atm of pure O_2. Also, the ecology would have to be radically altered since means would have to be found to prevent nitrogen from decaying soil and vegetation from leaking into the air...

This "nitrogen gap" completely destroys O'Neill's cost calculations [61], all of which were predicated on tiny costs for lunar materials (including their refinement, manufacturing, and transport), with *only* Earth→ L_5 lift costs being large. (The correction: multiply O'Neill's final cost estimate by 50.)[16]

4. O'Neill claims his space colonies will pay for themselves via production of aluminum from lunar rock (with production accomplished via cheap solar energy, and with

[14] Perhaps a solution would be to have a second launcher located at L_5, which, by ejecting waste products at high speeds in the right directions, would both prevent itself from being knocked off course, and would get rid of the waste products. This might create a "pollution hazard" of high-speed objects, though.

[15] In the absence of moisture, an air parcel slightly hotter than its surroundings, will, when it rises, cool at a faster rate (9.8°C/km) than the surrounding stationary air (6.5°C/km) and hence will sink. I.e. Earth's atmosphere, when dry, is "stable." *Wet* air, however, when it cools, condenses out water, which reheats that air, so that the net effect is that wet air cools more slowly as it rises – under some conditions by as little as 4°C/km. Since this is less than 6.5°C/km, wet air can be *unstable* – rising warm wet air parcels can *increase* their temperature difference above their surroundings and rise faster (at least, until they run out of water vapor). It is this instability that creates weather, and indirectly, winds (which power the atmospheric "refrigerator," increasing the instability). But if Earth had a temperature gradient < 4°C/km, presumably there would be no such instability, and hence almost no weather and no wind. It seems plausible to me that this "stagnant" stable situation will in fact happen inside an O'Neill colony. Complicating the situation is the fact the Coriolis forces inside O'Neill's cylinders will cause "rising" air to drift "spinward" and "falling" air to drift "antispinward," perhaps creating permanent "trade winds" around the axis, or perhaps creating permanent cylindrical convection cells with axes parallel to the rotation axis. So there are complicated weather possibilities and the bottom line is I do not know what will happen.

[16] It might be better to redesign O'Neill's space stations to *not* be cylinders with windows, but instead be cylindrical shells with 100% opaque strong outer surface (the "floor"), and 100% transparent inner surface (the "ceiling"), with the colonists living between. These could be oriented with axis at an angle to the sun, so that the sun's rays would light only part of the rotating inner surface at any time. This would allow a large reduction in the mass of the space colonies' atmospheres, and a doubling of the useable ground area, and might improve structural integrity. Unfortunately, such a setup might not provide enough radiation protection and could lead to undesirable meteorology. Also, possibly N_2 could be got from carbonaceous chrondite asteroids, which seem to contain about 0.1wt% nitrogen [28]; but of course this is a long way from the composition of O'Neill's space colonies, which are more like 50% nitrogen.

downshipments to Earth aided by atmospheric braking). A quick comparison of the present-day (2002) price ($1.54) of a kg of aluminum, versus the present price ($100,000) of lifting one kg of trade goods to L_5, again underlines the vast extent to which O'Neill is depending on hoped-for future robotics, and the tiny extent to which he is depending on cheap solar power at L_5. (And even if such great robotics does become available – would it not decrease the price of producing aluminum – and of solar power – *on Earth* also?) He also speculates the space colonies will earn money via producing single crystals currently unproducable (due to the deleterious effects of gravity) on Earth. This, of course, is totally at variance with the fact that all crystal-growth attempts in space so far, have been unable to equal the quality of Earth-grown crystals.

5. "Around the year 2000, a fully reusable chemical rocket system could transport payloads to L_5 at a cost of about $100 per pound (in 1972 dollars). A prospective colonist could therefore save enough money (1-2 years salary) to emigrate with his family of three. The near certanty of continued advances in propulsion systems suggests that the actual costs will be lower..." ([61] p.39). In response, I point out that actually, the year-2002 cost of transporting cargo to L_5 is about $100,000 per kg. O'Neill underestimated by 3 orders of magnitude! This again completely destroys his cost calculations. (Correction: multiply cost by 500. If combined with the previous "nitrogen gap" cost correction, this factor is 25000, which would be enough to bring the cost of even a single space colony beyond humanity's reach.)

6. O'Neill simply ignores health problems among space workers caused by low-gee conditions and radiation exposure. Most long term astronauts have been debilitated by the former to the extent that upon landing back on Earth, they are unable to walk.

7. O'Neill is not content with solving the energy crisis; he also wants to save humanity [61]: "[starting in 2050] within less than 30 years Earth's population could be reduced [by emigration to space colonies] from a peak of 16.5×10^9 people to whatever stable value [suggests 1×10^9] is desired." In response, I again point out that the year-2002 cost of transporting a kg to L_5 is $100,000. Unfortunately, far from saving Earth's population, these emigration costs (reckoned both in dollars and in environmental destruction) would in fact destroy humanity and the habitable Earth, be beyond the total amount of money in the world, and indeed it probably would be impossible for people to emigrate quickly enough to cause Earth's population to decrease at all.

8. During his bogus discussion of how his space colonies will solve even a dramatic Earth overpopulation problem, O'Neill relies on a huge number of colony copies, whose total land area far exceeds the surface area of the Earth. Again this ignores the question of where the nitrogen would come from – the total amount of required nitrogen would far exceed the Earth's atmosphere's mass! The prospect of removing the Earth's whole atmosphere for N_2 supplies stands in some contrast to O'Neill's introductory claim [61] that all will be accomplished "without robbing or harming anyone and without polluting anything."

9. O'Neill imagines a self-contained ecology. This stands in contrast to the difficulties experienced in E.Bass's "biosphere" sealed self-contained ecology project in Arizona. Many of the biospherians believe they suffered permanent health damage from semi-starvation (due to crop failures, death of their bees, infestations, and numerous equipment failures) and nitrogen-oxide poisoning due to breakdowns of the nitrogen cycle. (Incidentally O'Neill's space colony plans as stated exclude both UV light from the sun, and lightning – which probably would cause similar problems with the nitrogen cycle, assuming the nitrogen was there at all.) O'Neill claims infestations could easily be avoided by not introducing unwanted life forms, and by evacuating infested colonies and sterilizing them. Perhaps – but this stands in contrast to the presence of unwanted infestations in every previous human colonization effort (including Australia, New Zealand, and Bass's "Biosphere"). Also, I am not aware of any previous useful attempt to evacuate 10800 to 20 million people from their homes, then sterilize same, suggesting that all this may not be quite as easy as O'Neill thinks.

But, in his defense, at least O'Neill usually *tried* to make calculations, however careless and overoptimistic they might have been. Meanwhile, his critics [57] often relied merely on making bald assertions unsupported by any calculation or reasoning whatever. For one example, the National Research Council 1981 "study" [57] analysing the infeasibility of solar power satellites, baldly stated that the only feasible energy conversion technology was silicon single crystal photovoltaic cells. No supporting reasoning was given whatsoever. This completely ignores the fact that even on Earth, in places that are highly arid and at high altitude (i.e. in which direct, unscattered solar radiation predominates) it is commonly thought that mirror arrays focused on a conventional heat engine is the most economical way to proceed (numerous pilot solar power plants of this form have been built). Space, since it is the ultimate limit of these trends, would seem to favor this even more. (O'Neill [63] had recommended precisely this approach. But the NRC study didn't consider this option at all, refused to cite anything by O'Neill, and then complained that radiation damage of their Si solar cells could ruin everything!) The NRC study also stated the efficiency of conversion of energy from a 2.45GHz microwave beam to DC at the Earth rectenna would be 75%, while O'Neill said "over 90%;" neither gave any calculations or explicit citations to support these crucial (and contradicting) claims. The NRC study also decided that Solar Power Satellites should be $10 \times 5 \times 0.5$km in size. Why? Why the 0.5 km thickness, for example? And why 2×1 rectangular shape, not square? No supporting reasoning was given. No calculation, not even a crude one, of the forces on the satellite, was given.

It is very hard to take any of this seriously in the presence of such vast miscalculations and unrealized crucial omissions. But I do not want, by pointing out these things, to kill the whole area. Keep in mind that it is possible, even for a cultist who makes laughable miscalculations, still to be, in many ways, right. As I have said, the fundamental premise (not stated as such by O'Neill and Dyson, but I claim it really is their premise) that superior AI/robotics would enable vast technological feats, *is* correct. Also, most of O'Neill's calculations aimed at demonstrating certain feats are physically possible, *are* correct. What I hope is that my analysis debunks some of the weird cultlike mythological atmosphere that surrounds O'Neill, the space cadets, and their (in many ways less competent, and certainly less inspired) critics who wrote the NRC study, and refocuses attention this time on the *real* problems. (Experience and cynicism suggest that it won't, though.)[17] The whole area deserves a more serious look than it has gotten during the last 30 years.

1.15 How that relates to the present paper

To return to the topic at hand: it seems evident that a cheap off-Earth launch technology (at least in the absence of super-intelligent and super-competent robots) is going to be a crucial ingredient and enabling technology for any and all of the O'Neill/space cadet plans, or anything like them, including any non-insane future manned Mars missions, a moonbase, a space-based economy, or interstellar [82][83] flight attempts. It is the purpose of this paper to provide that technology. Our goal is to launch mass off Earth at a potentially far greater rate, and for far less money per kg, and more safely and simply, than is presently possible, at speeds exceeding escape velocity. Hence the moon, L_5, and perhaps Mars, the asteroids, or Jupiter could be reached directly.

The ideas proposed here would in fact allow muzzle velocities *far exceeding* Earth escape velocity, *but* such a super-high-speed launcher would be useless for Earth use since the projectiles would vaporize before emerging from our atmosphere. So such super-launchers could only be operated on the moon or in space[18]. Surely our Earth-based launcher would be a prerequisite for the construction of any similar space-based launcher.

2 New approach

2.1 Subproblem: magnetizing a superconducting ring

Before we begin, consider the problem of causing a ring-shaped piece of superconductor to become a superconducting magnet by somehow causing a permanent supercurrent to flow around it. A way to accomplish this is to thread the ring, by another magnet (e.g., a solenoid, either superconducting or not) whose North end is on one side, and whose South end is on the other, of the ring. We then cool the ring below its superconducting transition temperature (or assemble it from disconnected ring-fragments). Finally, we *remove* the magnet from the ring. Its flux no longer traverses the ring, but the total magnetic flux through the ring must remain unchanged (since lines of flux can never penetrate a superconductor and hence the flux threading the ring must remain constant for as long as the ring remains superconducting). Therefore the ring is now magnetized via a permanent supercurrent – success. It costs mechanical energy to remove the magnet from the ring; this energy essentially powers a "generator" which induces the permanent supercurrent round the ring. We could, alternatively, not remove the magnet from the ring, but instead (if it is a solenoid) simply turn its current supply off. This costs no energy, but we end up with only one magnet instead of two, i.e. less magnetic energy total. (Pay less, get less.)

Incidentally, it is important to note that there is no need for the internal removable magnet to have outer diameter exactly the same as the inner diameter of our ring. It could be considerably smaller. If it is a factor $x < 1$ smaller, then it needs to have x^{-2} times the average magnetic field we intend to eventually generate with the ring, i.e. so that the same total magnetic *flux* passes through the internal magnet as the ring. Thus we could ultimately magnetize the ring to generate an average magnetic field of 12 Tesla, by removing a cylindrical internal magnet, with average magnetic field 17 Tesla, threading it, if the internal diameter of the cylinder were 84% of the internal diameter of our ring, since $17 \cdot 0.84^2 \approx 12$.

The above discussion has been slightly oversimplified. Although it is true that magnetic flux cannot penetrate a *type-I* superconductor, it can and does penetrate *type-II* superconductors along an equilateral-triangular "Abrikosov lattice" of "flux vortices." Typical H_{c1} values (at which type-I superconductivity breaks down) are of order 0.1 Tesla, but many important type-II superconductors continue to superconduct while penetrated by a flux lattice, in magnetic fields up to H_{c2} which (at absolute zero) is 10-700 Tesla for commonly used superconductors (see table S). But all this does *not* affect our logic, because it is *still* true that the flux threading a superconducting *ring* must stay constant if the superconductor is type-II with *pinned* flux lattice (because a pinned flux lattice cannot move "sideways," so the ring-threading flux cannot escape). Commercial Nb_3Sn and NbTi materials for use in magnets have been treated so that they exhibit flux-lattice pinning, and it has been shown that proton irradiation (or other treatments, e.g. synthesis in such a manner that oxide or SiC nanoparticles are embedded throughout the MgB_2) of MgB_2 suffice to cause it to have a pinned flux lattice too. Also, melt grown $Y_1Ba_2Cu_3O_{7-\delta}$ material exhibits flux pinning[19] [39] and achieves a critical current density of $17 \mathrm{kA/cm}^2$ at 77°K.

So for most of our purposes it will be perfectly fine to continue to oversimplify and pretend flux cannot penetrate our superconductors. More precisely, any such penetrating flux will remain *constant* since the flux lattice cannot "move

[17] It seems depressing testimony re the unseriousness of work in this area, if (as was claimed by Dyson in his foreword to [62]) in 28 years, all the severe errors in the field's foremost work have remained unnoticed.

[18] For example, the 9 km-long Earth launcher design in §5, extended to be 100 km long, would achieve 67 km/sec instead of 20 km/sec provided it were feasible to decrease the the ring-switch-off times from 50 to 14μsec despite now requiring the switch to withstand 250kV instead of 75.

[19] By enhancing that natural pinning further by Au-ion surface irradiation [52], bulk YBCO was made to have improved critical current densities of $100 \mathrm{kA/cm}^2$ at 45°K and $200 \mathrm{kA/cm}^2$ at 25°K.

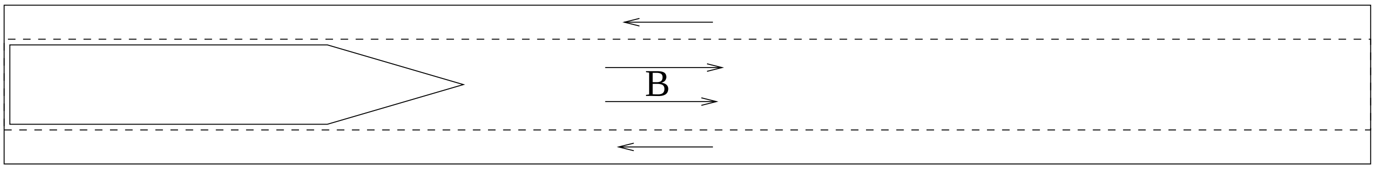

Figure 1: Part of the launcher; magnetic fields $\vec{B}$ indicated.

sideways" in materials featuring "flux pinning."

2.2 *Proposed launcher*

Now we are ready to describe our scheme. The projectile will be a cylindrical shaped permanent magnet, e.g. [5] a piece of superconducting pipe such as we just described. (The payload is placed inside this pipe segment.) The accelerator will consist of a sequence of coaxial stationary rings, each of which is also a supercurrent-loop magnet. The projectile and the rings all generate the same amount of magnetic flux, which could be assured by initially magnetizing all the rings using the method of §2.1, using the *projectile* as the internal magnet which we mechanically remove (e.g. by pulling it backward with a winch). During launch, our projectile will pass through the rings. The projectile is oriented North end forward. The rings are also. Thus the South end of the first ring attracts the North end of the projectile, which accelerates into it. Once the projectile has reached a central position inside that ring, further motion unfortunately would then be *deaccelerated* rather than accelerated by magnetic forces from that ring. At this moment of centrality, note that we are now in the same situation as we were in during the initial magnetization of that ring, i.e. the supercurrent around the ring is now zero. We now *switch off* the superconductivity in the ring, converting it to an insulator. The projectile now may continue on to exit this first ring, *without* experiencing any deacceleration. In fact it no longer "feels" the effect of this first ring at all. (If the ring is not totally converted to insulator, but instead is converted to several superconducting disconnected ring fragments, then the projectile will "feel" a short range repulsive effect, i.e. the usual magnet-superconductor "levitation" force, from those fragments, which will, if anything, only increase its forward velocity.) Meanwhile it is attracted toward, and accelerates into, the second ring. Again we switch off the superconductivity in the second ring at the appropriate moment (of central position and of zero supercurrent) and repeat the process for as many times as there are rings. The projectile exits the last ring at high final speed.

From the point of view of the projectile, it is always positioned at the end of, and is being sucked into, a long solenoid containing a constant magnetic field. That solenoid keeps retreating since its superconductive rings behind the projectile keep being deactivated. Thus the projectile is subjected to an essentially constant acceleration for as long as the rings continue.

The entire accelerator would be enclosed in a pipe with a superconductive inner coating. This outermost pipe would serve several purposes:

1. It is a vacuum vessel (the whole process of acceleration is performed in a vacuum to avoid air resistance).
2. It would serve as a perfect electromagnetic shield, preventing nearby iron objects from being flung into the magnets, and preventing the emission of damaging "electromagnetic pulses."
3. It would serve as a thermal insulator, preventing heat from getting in and raising components above their superconducting transition temperatures.
4. It would (partially) serve to "levitate" the projectile, by the well known phenomenon that magnets are repelled from superconducting surfaces, so that the projectile would never touch any solid object during the launch process. (More about this in §2.4; the rings, and really, the whole geometry, have a levitating effect.)
5. The sequence of rings may be thought of as a long solenoid, containing a magnetic field. That field must come back the other way on the outside of this solenoid to close the loop, and this back-returning magnetic field will be channeled (since superconductors are impermeable to magnetic fields) to lie in the annular region between the inner solenoid and the outer pipe. This channeling compresses the backwards magnetic field, usefully increasing its energy. Indeed if the radius of the outer pipe is made $\sqrt{2}$ times the radius of the solenoid, then the backwards field strength outside the solenoid will be exactly the same as the forwards field strength on the inside of the solenoid, representing a doubling of stored magnetic energy.

The projectile, upon exiting the launcher, would burst a membrane at the end of the tube (needed to maintain vacuum). The membrane should then be replaced by a sliding cover as soon as possible to prevent much air from howling into the pipe. In fact, it would be best if the final segment of the pipe were an "airlock," i.e. containing *two* doors one at each end. The first door is shut behind the onrushing projectile, then the second door (to the outside world) is opened (this could be a bursting membrane), and then outside air can only contaminate the airlock and not the main body of the launcher. (Such air would need to be pumped out again before the next launch, and it would also heat things unnecessarily, and create frost deposits inside the launcher, all of which would just waste energy and cause trouble.) Of course it is only necessary that the inner airlock door be shut not long after the outer door is opened –

since the inrushing air will only attain speeds of the order of the speed of sound, it will take a while before it reaches the inner door. That delay is a "grace period" during which the inner door should be shut.

2.3 Remarks on ring spacing

We assume the rings are spaced sufficiently closely (perhaps $\leq L/10$ apart, if the projectile's magnetic length is L) so that the effective acceleration of the projectile will seem non-jerky. ("Jerk" is the time derivative of "acceleration.") There are several reasons to desire this.

1. By avoiding jerk, the projectile is subjected to a *constant* acceleration, so that the peak acceleration is equal to the average acceleration and hence is minimum possible, minimizing the gee forces the projectile must endure.
2. This also avoids the possibility of exciting mechanical resonances within the projectile, which could (at the wrong frequency for the wrong projectile or payload) cause damage.
3. Spacing the rings closely avoids magnetic field nonuniformities in time and space, avoiding the need for higher than usual peak magnetic fields, avoiding causing larger-than-critical supercurrents or magnetic fields.
4. In this continuum-solenoid limit, the projectile experiences a constant magnetic environment as it traverses the launcher. That (in the event the payload contains conductive or ferromagnetic components) prevents any losses to induced eddy-currents or hysteresis within the payload[20].

2.4 Remarks on "levitation" and stability

Our proposed magnetic field is near uniform in strength everywhere. Since the energy density of a magnetic field is proportional to its square, any *non*uniformity or asymmetry in the field (but preserving the total integrated flux) would represent *increased* field energy. In particular if the projectile were off-center in the tube, that would be energetically disfavored. If this disfavortism is large enough to outpull gravity, the projectile will automatically "levitate" to lie in a near-central position in the tube. Since the design we shall sketch in §5 involves 2250-gee magnetically-induced projectile acceleration (and other designs in table D involve even larger accelerations), it seems plausible that levitation forces comparable to a mere few gees (which would suffice) should be easy to achieve. Also, due to the $\vec{B} \cdot \vec{d}$ dipole-field interaction energy – a similar but simpler reason – it is disfavored for the projectile to turn to point at any other angle other than directly forward. These effects should automatically self-stabilize the launcher. And as experimental confirmation, we note that O'Neill's small working "mass drivers" exhibited these behaviors.

Incidentally, for the same reason, the solenoid will automatically self-center itself within the outer tube (when magnetized) causing there to be less need for structural support, than one might have imagined. Lorentz-force "magnetic pressure" will squeeze that solenoid from all directions (axially, and radially inward from the outside, and radially outward from the inside) causing its material to be under high compression when operating – which will act beneficially to avoid cracking. The outer tube, however, will be pressurized purely from the inside outwards, and hence would require outer (e.g. steel) reinforcement. If that outer reinforcement has smaller Young's modulus than the superconductor, then that superconductor will be under beneficial purely compressive stress also.

3 Advantages of the proposed scheme

No capacitor banks are needed. No toxic and dangerous chemicals (e.g. rocket fuels, hydrogen) are needed. No explosives are needed. All the stored energy is in the magnetic fields of superconducting magnets, which is a very cheap and permanent way to store energy, and the accumulation of that energy may be done gradually and essentially losslessly during a comparatively long prelaunch winch-back period; no high power energy transfer is ever required. Throughout this winch-back, forces can be precisely measured, and that information, combined with the (known) mass of the projectile, will allow precise understanding of (and control of) the launch velocity. Note the energy storage device is the launch device, so no *external* energy storage is needed. That minimizes expenses and maximizes simplicity. There is no sliding friction and no sliding parts and no sliding electrical contacts, preventing damage. There are no ohmic losses since we only employ superconductors and insulators, and we only switch circuits when there is zero current in, and zero voltage across, them. (That avoids ohmic losses during the switch transition, i.e. during the only time when we have somethign other than a perfect insulator or perfect conductor. Note: any normal metal, e.g. steel structural parts, should either be coated with superconductor, or laminated and silicized as in transformer steels, to reduce its effective conductivity, otherwise the projectile's magnetic field, as it flies by, would induce eddy currents in these metal parts, leading to ohmic losses. I would recommend fiberglass rather than steel structural parts.) Our design is "optimal" in the sense that the entire launcher tube is initially filled with a magnetic field of

[20] Incidentally, it is possible somebody would want to launch payloads which should not be cooled to cryogenic temperatures. The projectiles could be designed to allow quick insertion of a warm payload into a cryogenic projectile – since the launcher traversal time is of order 1 second, we need have only enough thermal insulation to keep the thermal relaxation time considerably longer than seconds, for this to work – no problem.

Another payload-protection idea would be to add to the projectile (a magnetized superconducting cylinder) two type-II superconductive *endcaps*, cooled below T_c in the presence of the magnetizing field of that (already cooled and magnetized) cylinder. These endcaps would then be penetrated by a pinned flux lattice. The payload inside the cylinder-with-caps would then experience *constant* magnetic field no matter what happened outside, because it lies inside a perfect superconductive "Faraday cage" shield.

launch method	speed limit km/sec	stable dynamics ?	typical effic %	need quick release energy store (capac.)?	friction losses & wear?	ohmic losses ?	typical acceln (gees)
dust grain electrostatic accel	> 100	yes	$\ll 1$	no	no	no	10^7-10^8
rockets	exp, 3	yes	exp, 50	no	no	no	0-100
guns	2	yes	8-40	yes	yes	no	5000-20000
2-stage light-gas gun (2SLGG)	12	yes	< 10	yes	yes	no	40000-150000
rotary sling	exp, 2	yes	small	no	no	no	200000
Rotary Pellet Launcher (RPL)	exp, 3	yes	high	no	yes	no	300000
rail gun	8?	yes	5-30	yes	yes	no	10^5-10^7
brush commutated LEMs	2	yes	22	somewhat	yes	yes	100-1000
coilgun & reconnection gun LEMs	100?	maybe	7-38	yes	no	yes	0-15000
quench gun LEM	low	yes	0-7	no	no	yes	< 5000
Robertson's Meissner LEM	100?	no	30?	yes	no	yes	0-5000
Magnetic Catapult	100?	yes	95-100?	no	no	no	0-7500

Table A: Comparison of launch technologies. "exp" indicates no speed limit per se, but exponentially increasing obstacles to high speeds (and/or exponentially declining efficiency) beyond the speed indicated. "Speed limits" arise from theoretical analyses (which are consistent with the experimental evidence to the extent the latter exists). Efficiency numbers are experimental values, except those with "?," which are guesses. (Warning: in literature in the early 1980s, one often encounters optimistic claims of $> 90\%$ efficiencies being presumably attainable, but these claims have remained unsupported by experimental evidence during the ensuing 20^+ years of heavily funded railgun and coilgun research.) LEM=Linear Electric Motor. Analysis in present paper indicates high performance quench guns seem impossible with presently available materials except BSCCO-2212. Other advantages of magnetic catapult include: no toxic/flammable chemicals needed; tiny electrical energy consumption.

roughly uniform strength everywhere, maximizing the total stored energy while minimizing physical size, and essentially all of the energy stored in that field is converted to projectile kinetic energy. There are no air-drag losses since we operate in vacuum. Thus the efficiency should be very near 100% – in fact, this would probably be the most efficient ultralarge machine yet constructed[21]. For the same reason, only tiny amounts of waste heat would be generated, avoiding special methods for safe disposal of huge heat pulses. The acceleration experienced by our projectile is essentially constant, allowing minimization of the maximum 'gee' stress on it (unlike the nonuniform accelerations arising in most of the previously discussed competing launcher technologies). The design is automatically inherently stable.

Incidentally, another, not very obvious, advantage is that the projectile itself need not be very magnetic and hence need only contain a small amount of comparatively cheap superconductor. It perhaps might even be made of conventional room-temperature permanent magnets. Suppose the flux through the solenoid-of-rings is Φ. Each ring, as we magnetize it during winch-back, passes flux $(1-f)\Phi + P$ where P is the flux generated by the projectile, and f, $0 < f < 1$, is the fraction of solenoid flux that leaks out of the solenoid between its last active ring, and the present (new, as yet inactive) ring. So asymptotically for a long solenoid we have $\Phi = (1-f)\Phi + P$ with solution $\Phi = P/f$. Because f can be made small by spacing the rings closely, we can still get a large magnetic flux Φ in the solenoid (after an initial flux-buildup in a short initial part of the solenoid) even with the projectile generating a comparatively small magnetic flux P. In the Earth-launcher design of §5 we imagine a magnetic field in the solenoid of 12 Tesla, and a ring spacing (1m diameter rings) of 1 ring per 3cm. It seems plausible $f \approx 1/10$, in which case the projectile would only need to generate a magnetic flux $\Phi/10$. If the projectile's diameter were 80% of the ring diameter, it would need to generate an average magnetic field of only about $12/(10 \cdot 0.8^2) = 1.9$ Tesla.

4 Design Equations

Let the projectile be a cylinder of length L, mass M, and outer-radius$< R$. The rings have inner radius r and contain constant axial magnetic field B inside. The coaxial outer superconducting tube has radius $R = \sqrt{2}r$ so that the returning magnetic field (outside the rings, but inside the outer tube) also is constant with the same strength B. The "magnetic pressure" (or energy density) of[22] this field B is $p_{mag} = B^2/(2\mu_0)$. The ring current I needed in each ring to support the magnetic field B inside our solenoid, obeys $\mu_0 n I = B$, where n is the number of rings per unit length. Let V be the final velocity we wish the projectile to reach. Let E_{mag} be the magnetic energy stored in the interior of the launcher, per unit length. We have $E_{mag} = \pi r^2 B^2/\mu_0$, where we have included a factor of 2 to account for the back-returning magnetic field outside the solenoid but inside the outer pipe. Let the launcher be L_{tot} long; then the total energy transferred to the projectile is $E_{mag}L_{tot}$. The final projectile speed V thus obeys $MV^2 = 2E_{mag}L_{tot}$. The projectile will experience constant energy gain E_{mag} per unit length, and thus will experience roughly constant acceleration $a = E_{mag}/M$, which would correspond to an average

[21] Cf. §9.2 for remarks about previous experiences with high-efficiency superconducting machines.

[22] $\mu_0 = 4\pi \times 10^{-7}$Henry/meter denotes the magnetic permeability of free space.

pressure on its rear face of $p = Ma/(\pi r^2) = 2p_{mag}$. The total traversal time of the projectile through the launcher will be $\tau_{trav} = 2L_{tot}/V$. If each ring-magnet must be "switched off" in a time equivalent to 1/5 of the time it takes for the projectile to pass through it, then the minimum switch-off time must obey $\tau_{sw} \leq 0.2L/V$.

The ring current I needed in each ring to support a $B = 12$ Tesla field inside our solenoid, obeys $\mu_0 nI = B$, where n is the number of rings per unit launcher length. The fraction f, $0 < f < 1$, of the solenoid's magnetic flux that leaks out between the last active solenoid ring and the next (inactive) solenoid ring, should be about $f \approx 2/(nR)$, enabling the projectile to generate only $f\Phi$ flux, i.e. below the full Φ.

If the magnetic flux, emanating from the projectile, threading our ring, is designed to decrease (this decrease commencing after a certain grace period after switch-off) from $f\Phi = \pi r^2 fB$ to 0 at a roughly constant rate in a total time of $0.5L/V$, then the maximum EMF the switch must withstand is $\mathcal{E} \approx 2\Phi fV/L = 2\pi Vr^2 fB/L$.

5 Rough Earth-launcher design – numbers

(See table D.) We envision a cylindrical projectile of *magnetic* length $L \geq 5$ meters (actual length, including the non-magnetic nosecone, would be larger), radius$< R = 0.5$ meters, and mass $M = 4000$ kg. (For a cylindrical projectile, this would correspond to a projectile density slightly larger than water[23].) The design goal launch velocity is $V = 20$ km/sec. (Compare Earth escape velocity 11.19 km/sec; solar system escape velocity starting from Earth surface and using the Earth's own velocity to help is 23.4km/sec.)

Let us imagine the superconducting rings are 3.2m-long rods, in cross-section 2×2cm square with rounded corners, bent into a circular ring with inner diameter 1m. They can be made either of (1) American Superconductor's YBCO-based RABiTS^{TM} tape material (soon planned to be commercially available), or more simply of (2) melt-textured cast polycrystalline YBCO [39][52], both at liquid-neon temperatures, or of (3) Nb_3Sn or Nb_3Al at liquid-helium temperatures. The rings are encased in 5mm thick fiberglass-reinforced plastic for purposes of inter-ring electrical insulation and surface protection, but most importantly, the fiberglass enhances their strength. There will be additional outer fiberglass support structure to hold the rings in place[24]. With these materials, conventional switches based on moving contacts apart should be used (§6.2). Of these materials, choices 2 and 3 seem the most likely to work most easily; the ring-pieces may be fabricated as rigid castings, with the precision switch-contact planes later machined and polished. Another choice of ring material is (4) BSCCO-2212 at liquid-helium temperatures; with this choice, thermal switching (§6.3) seems best.

Unfortunately well-developed present-day bulk materials have insufficiently large critical currents and magnetic fields for use at $(\ell)N_2$ temperatures, forcing us to liquid neon temperatures. However, $(Tl_{0.5}Pb_{0.5})(Sr_{0.8}Ba_{0.2})_2Ca_2Cu_3O_y$ (T_c = 117-119°K) [31] may be the hero material that allows operation at liquid nitrogen temperatures.

The inner radius of the outer pipe is chosen to be 72cm so that the volume of the region outside the solenoid but inside the outer pipe, exactly equals the volume inside the solenoid.

The magnetic field inside the launcher-solenoid is $B = 12$ Tesla. The magnetic "pressure" corresponding to a $B = 12$ Tesla field is $p_{mag} = 57$ megaPascals, i.e. about 570 atmospheres, comparable to the pressures experienced in 6km-deep ocean. Actually the solenoid will experience this pressure pushing it inward from the outside as well as outward from the inside, thus experiencing a beneficial (since it prevents cracks) squeezing effect but approximately *zero* net force. The outer tube will experience 570 atmospheres of outward-directed pressure (which should be countered by placing it inside another tube with good tensile strength). The launcher, therefore, would have to be built robustly. But since 21 Tesla Nb_3Sn-based magnets are commercially available, a 23 Tesla Nb_3Al-based magnet has been constructed, and high-T_c materials have been used to construct 30 Tesla magnets, this clearly is achieveable. Note that 12 Tesla is well below H_{c2} for our materials at these temperatures.

The ring current I needed in each ring to support a $B =$ 12 Tesla field inside our solenoid, obeys $\mu_0 nI = B$, where n is the number of rings per meter of launcher length, i.e. for us $n = 33.33$. Hence $I = 287$kAmperes. This corresponds (assuming the ring's almost-square cross section has cross sectional area 3.5cm^2) to a current *density* of 82kA/cm^2, which (see table S) looks safely below the critical current-density capacity of our materials.

The outer tube could be made either of melt-textured cast polycrystalline YBCO at liquid-neon temperatures, or Nb_3Sn or Nb_3Al at liquid-helium temperatures, with the former probably being very preferred. It would be surrounded by a steel jacket to protect and strengthen it. (Possibly this could be fabricated by plasma-spraying YBCO onto the interior surface of a steel tube. YBCO melts at about 1000°C and iron and steel melt at about 1535°C and 1370°C. I would recommend austenitic stainless steels, e.g. AISI 304LN or 316LN, since they have increased toughness and strength at cryogenic temperatures, unlike most steels which become brittle. Recently even better cryo-strong steels incorporating Ni, Mn, and/or N have been developed; see recent issues of *Cryogenic Engineering*.) An inner heat-shield could be placed between the outer tube and solenoid, especially if it is desired to operate the latter at lower temperatures than the former. Also one or two outer heat shields must surround the outer tube, which

[23] 4000 kg is more mass than almost all unmanned spaceprobes so far, including the Viking Mars landers, Galileo Jupiter orbiter, Landsats, Soviet Moon shots and Venera Venus explorers. NASA's Cassini Saturn orbiter, billed as the "third heaviest spacecraft ever," is an exception, with launch mass 5650kg. The two heaviest were the failed Soviet Phobos Mars crafts at 6220kg, both of which were successfully launched in 1988 by Proton-K rockets.

[24] I'm arbitrarily choosing "fiberglass" (by which I always mean "fiberglass-reinforced plastic") as a commonly available dielectric structural material which still has good properties at cryogenic temperatures [93].

parameter	symbol	Launcher	"Toy"	intermediate
projectile mag. length	L	5 meter	5 cm	50 cm
ring inner radius	r	0.5 meter	0.5 cm	5 cm
projectile mass	M	4000 kg	4 gram	4 kg
magnetic field	B	12 Tesla	3.2 Tesla	8 Tesla
goal velocity	V	20 km/sec	320 meter/sec	3 km/sec
projectile energy	$\frac{MV^2}{2} = E_{mag}L_{tot}$	800 GJoule	205 Joule	18 MJoule
magnetic pressure	$p_{mag} = \frac{B^2}{2\mu_0}$	57 MPascal	4.1 MPascal	25 MPascal
mag. energy per len	$E_{mag} = \frac{\pi}{\mu_0} r^2 B^2$	9×10^7 Newton	640 Newton	4×10^5 Newton
total launcher length	L_{tot}	8.9 km	32 cm	45 meter
const. acceleration	$a = E_{mag}/M$	22.5 km/sec^2	160 km/sec^2	100 km/sec^2
equiv. pressure	$Ma/(\pi r^2)$	114 MPa	8 MPa	51 MPa
traversal time	$\tau_{trav} = 2L_{tot}/V$	0.9 second	2 millisec	30 millisec
max switch-off time	$\tau_{sw} \leq 0.2L/V$	50 μsec	31 μsec	33 μsec
solenoid magnetic flux	$\Phi = \pi r^2 B$	9.4 Weber	0.25 milliWeber	63 milliWeber
rings per unit length	n	33/meter		
flux-leak fraction	$f \approx 2/(nR) < 1$	0.12		
switch EMF	$\mathcal{E} \approx 2f\Phi V/L$	9.1 kVolt	$3.2f$ Volt	$754f$ Volt
ring current	$I = B/(\mu_0 n)$	287kAmp		

Table D: design sketches for Earth-Launcher and scaled-down versions. (Note that final velocity is proportional to magnetic field times the square root of launcher length. Hence a moon launcher could be a truncated version of the Earth launcher only 200 meters long, if its goal velocity were only $V = 3$km/sec.)

in turn would be enclosed in an outermost vacuum vessel. Since vacuum is inadequate for structural support, some supporting members would have to be provided – preferably made of a material with a good combination of thermal insulation and strength. CO_2-foamed plastics tend to be excellent insulators at cryogenic temperatures because the CO_2 freezes out, leaving the foam's bubbles filled with vacuum. Evacuated silica "aerogels" may be superior to these, especially when "doped" with tiny carbon particles which increase their strength while at the same time reducing radiative heat transfer. "Multilayer" insulation is weaker, but $\approx 20\times$ better as an insulator, whereas solid nylon is stronger [93], but $\approx 20\times$ worse as an insulator.

The constant acceleration: $a = 2.25 \times 10^4$ meter/sec^2 = 2250 gees. Needless to say, no human could withstand such an acceleration. The catapult is intended only for nonliving cargo[25]. On the other hand, complex electronics packages such as the radar proximity fuses in WWII antiaircraft shells and the laser-guidance and inertial navigation system in the US's "Copperhead" 155mm artillery shell (introduced in 1980), necessarily tolerated accelerations of at least about 10000 and 3000 gees, respectively. (We have already mentioned the epoxy-potted telemetry electronics in the HARP projectiles withstanding 20000 gees; epoxy potting was not

[25] As Arthur C. Clarke had already pointed out in the first paper about electromagnetic launchers [17], a launcher permitting acceleration ≤ 10 gees (commonly regarded as maximum acceptable for humans) would have to be 600 km (i.e. impracticibly) long. To that I add: Even if building a launcher that long were feasible, consider the fact that the drag deacceleration on the 4000 kg projectile proposed here is, as soon at it emerges into the atmosphere, 200-1000 gees. This could be reduced by making the projectile more massive. But for a projectile containing humans packed at the densities common in today's airliners to experience ≤ 10 gees of drag, it would need to be at least 500m, and perhaps many km, long. This too seems infeasible. This indicates there is no hope for lofting humans into space by any method other than rockets, and therefore Earth-to-space travel will always be very *expensive*, polluting, and resource-consuming (and this includes the possibility of nuclear-powered rockets) and will never be a feasible way to, e.g., solve Earth overpopulation (as had been wrongly claimed [61]). E.g. consider the fact that the ATLAS launcher used to launch the 1360kg Mercury capsule, containing the first US astronaut to orbit Earth (confined in a volume approximately the size of a coffin) weighed 118,000 kg and cost \$3 million in 1960-dollars; such prices later increased, so that in 1995 an individual could purchase a short return trip to the Russian Mir space station for about \$10 million.

But: is 10 gees really the human limit? Humans lying on acceleration couches can sometimes withstand 9 gees for a few minutes without losing consciousness and while sustaining only minor injuries. But if fully immersed in water they withstand 14 gees. ([66], see chapters 4 and 6. Experience $\approx n$ gees for yourself by jumping into water from n meters up, contriving to hit in the maximally ungraceful, high-drag, spreadeagle position possible.) Perhaps by immersion in liquid *including* replacing all internal gas by liquid, humans could withstand 50 gees. If so, our 2250-gee 9km-long launcher in §5 could be replaced by a 50-gee *405km-long* launcher. With a *40m-long* projectile half-filled with water, the drag-forces during atmospheric traversal would also be about 50 gees. The period of high acceleration (including deacceleration during atmosphere traversal at the small rise-angle necessitated by the long launcher) would then be about 50 seconds. The prospect of being force-filled with liquid, then immersed for a full minute while experiencing 50 gees acceleration in two different directions, then force-emptied of liquid, while exceedingly unattractive, is perhaps possible. (Anyway, you'd probably necessarily be unconscious. The human brain, 1.4kg and soft, is about 4% denser than the surrounding cerebrospinal fluid [24], so at 50 gees, it would be as though a 2.8kg weight were sitting on your brain. But that could be dramatically reduced by temporary replacement of cerebrospinal fluid by a 4% denser fluid, e.g. containing 36% D_2O. Your bones are about 7% of your total body mass [75] and have 2-3 times the density (1 gram/cc) of water and flesh. The bouyancy effects after filling your lungs with water, etc. would reduce the effective density of bones to 1-2, with further reduction seeming impossible, so that, at 50 gees in water, your skeleton would feel like a weight equivalent to 3-7 times your bodyweight.) If so, it might indeed be possible to loft humans off Earth for a low price. This would give "economy class travel" a whole new meaning.

used in the Copperhead.) As an equivalent pressure on the rear of our projectile, this is 1100 atmospheres, which is considerably below what is experienced in big guns and (with care) is well within strengths of materials limitations.

The switch-off time of $\tau_{sw} \le 50\mu$sec and the switch EMF $\mathcal{E} \approx 75f$ kVolts both seem within reach. Actually, because the flux leak fraction $f \approx 0.12$ (see the end of §3) the switch EMF needs only to be about $75f = 9.1$kVolts, and the projectile needs only to generate flux $f\Phi$, both of which are very gratifying reductions.

The launcher is 9km long. The traversal time of the projectile through the launcher is $\tau_{trav} = 0.9$ seconds.

Of course, by initially only winching the projectile backwards a small fraction of the full length of the launcher, smaller muzzle velocities than usual would be obtained. I would recommend that as a method of testing the launcher before constructing 100% of it!

If the altitude of the outward end of the launcher is 6km above sea level (5.5km is above approximately 1/2 the atmosphere; 8.4 km is above approximately 2/3 of it; Mount Everest is 8.85km above sea level) then our projectile, if launched near-vertically and equipped with attitude stabilization (either active, via spin, or via shaping of the projectile for natural aerodynamic stability) and ablative nose cone (more re that in §7) should be able to force its way through the atmosphere and still exceed escape velocity, because the total mass of air in the path of this (very hypersonic) projectile is approximately the same as its own mass, and its drag coefficient C_D should be [19][34] considerably less than 1.

If the 9km-long launcher started 3 km below and ended 6 km above sea level, then the angle of the launch trajectory could be vertical. But it might be more realistic to make the launch angle be more like 30°, 45° or 60° to the horizontal, though, requiring passage through 2, 1.41 and 1.15 times more air, respectively, but making construction simpler.

There is a conflict here between the desire for dense and slender projectiles, which are able to punch their way through the atmosphere, and wide and light projectiles, which are able to contain more magnetic energy per unit length and per unit mass and hence can be accelerated to higher launch speeds despite using a shorter launcher. By using a rotund superconducting "carrier" during launch, but which is discarded immediately afterwards, with a much slenderer projectile continuing onwards, one could seek the benefits from both sides of this conflict – but I have not used this idea.

6 Switches seem the performance-limiting factor

At first, it might seem that there is almost no limit on catapult performance – arbitrarily high nonrelativistic speeds are achievable by simply using more rings and winching back the projectile further. That is in *principle* largely true[26].

But in practice I believe there will be an important *technological* limitation on all this set by the performance of the electrical switches. Admirably, stress on the switches is minimized by only performing switching when the circuit being switched is carrying *zero* current and there is zero voltage across the switch[27]. But unfortunately, when the projectile is moving at high speed, its magnetic field goes from threading our circuit (i.e. the ring we are trying to switch off) to evading it, in a small amount of time, i.e. there is a high rate-of-change of the flux Φ threading our ring. By Faraday's law that induces a high EMF $\mathcal{E} = -\dot{\Phi}$ around that ring, which must not be enough to break down the insulation on our switch. So we need a way to switch superconducting circuits off very rapidly (1-100μsec), with very precise timing, such that, once in the "off" state, our switch is capable of withstanding high voltages.

6.1 *Discussion of different possible kinds of switches*

The best design of such a switch is subtle.

6.2 *Mechanical switch*

An old-fashioned mechanical switch is perhaps the best, and certainly the most straightforward, switching method.

6.2.1 *The wrong way to build a switch: separate two pieces a long distance*

Imagine our superconducting ring is cut into two portions; we move them apart at a speed of 100 meters/second, e.g. achieved by a sudden, precisely timed impact of a solid body traveling at a speed of this order. Note 100m/sec is far smaller than the speeds of sound (3-6 km/sec) in our solids. Also note 100 m/sec=0.1mm/μsec.

In principle at least, these switch-opening speeds and breakdown-field threshholds should more than suffice for the design sketched in §5, even if (ℓ)He – the worst insulator mentioned in table I – is used. In that design we have 50μsec to switch off the switch, which at this 100 m/sec

[26] There are a few non-idealities which eventually would have an effect: superconductors actually do resist the flow of *alternating* current, but at the nonrelativistic projectile speeds we are considering, the effective frequencies should be low enough that this effect should be negligible; also magnets made of type-II superconductors are not truly permanent due to thermal excitations unpinning their flux lattices, but again these losses seem negligible, e.g. well under a part per million per day in commercial magnets. At high enough speeds the EMFs induced by the rapidly moving projectile's magnetic field will be large enough to cause dielectric breakdown in nearby materials, but that should not be a problem at nonrelativistic speeds. Before that point is reached, there will be dielectric and paramagnetic energy losses, but such effects should be, relatively speaking, small.

[27] To see the importance of that, consider the following. In any switch whose contacts are separated at finite speed to turn off a fixed voltage V, the region between the contacts will experience unboundedly large electric field (V/d when the contacts are distance d apart, which goes to ∞ as $d \to 0$). Therefore, dielectric breakdown, and arcing, will occur every switch-off, for some amount of time, for *any* kind of switch, inevitably both damaging the switch and wasting energy. In the presence of inductive loads or capacitive charge storage, such damage can be severe. However, if the switch-off only occurs when $V = 0$, then it is possible, by moving the contacts apart at a sufficiently high speed in comparison with the rate of increase in V, to prevent any dielectric breakdown. Damage and energy loss can thus be entirely avoided.

stuff	dielectric strength
rubber	16-40
paraffin	15-50
ebonite	30-110
glass	30-150
sapphire	100-200
BN(graphite-like)	200
SF_6 gas(5 atm, room temp.)	30
dry insulating oils	150
$(\ell)N_2$	20-60
(ℓ)He	10
vacuum	10-90

Table I: Dielectric strengths of insulating solids, gases, and liquids in kV/mm. "Vacuum" assumes smooth polished electrode surfaces.

speed would yield a contact separation of 5mm. After that time, the EMF across the switch is predicted to rise to up to 75kVolt (if $f = 1$; actually with $f \approx 0.12$, we only get $75f \approx 9.1$kVolts). The dielectric breakdown threshhold of a 5mm gap is 50-1000kV, depending on which of the insulators in table I is used – and $50 \times 2 > 75$ (keeping in mind we are introducing *two* gaps into the ring) so that even (ℓ)He suffices.

The *problem* with this whole idea is as follows. We are demanding that the moveable portion of our ring achieve an average speed of 100 meters/second, starting from 0, over a timespan of 50μseconds. That implies an acceleration of at least 200,000 gees, which (assuming the ring material masses 13 grams per cm^2 of outward-surface area) corresponds to a pressure of 250 megaPascals (2500 atmospheres). This pressure is nearly as high as the tensile strength of mild steel (cf. §1.1), so considering that all available high-performing superconductor materials are brittle and weak, they would undoubtably be shattered![28]

6.2.2 Better way to build a switch: separate many pieces a short distance

Imagine that each ring is cut into a large number of pieces, each roughly trapezoid shaped, using a zigzag cut. For example, the launcher design of §5 involves a ring 3.2 meters in circumference and 2cm thick. To be precise, imagine it as cut into 80 trapezoids, 40 inward-facing and 40 outward-facing, each 2cm long measured on the shortest side and 6cm long measured on the longest side, and with the zigzag sides at about a 45° angle to the longest sides, and with the 45° cut faces polished to optical flatness. These trapezoid ring-fragments are encased in a fiberglass support structure. Imagine the outward-facing trapezoids are thus rigidly held in place. When the ring is conducting a large supercurrent, fulfilling its mission of magnetizing the solenoid-interior to 12 Tesla, the 2-sided total magnetic pressure, due to Lorentz forces, of 570 atmospheres will squeeze the inward-facing trapezoids into firm contact with the outward-facing ones, ensuring a good electrical connection. However, at the moment when we want to switch off the ring, remember that the supercurrent has automatically already dropped to 0, and hence the Lorentz forces and magnetic pressure also are 0. Elegantly, the pressure that keeps the switch "on" automatically removes itself precisely when we want it to! Now, to turn the switch "off," exert an inward pressure of 150 atmospheres on the (small outward) faces of the inward-facing trapezoids[29]. This pressure will cause them, in 50μseconds, to move inward a distance of 146μm. The total length of all 80 of the 45°-slanted gaps thus created will be 0.9cm, more than sufficing to withstand the 75kV EMF. The switch is now "off!"

How do we exert 40 such 150-atmosphere pressures simultaneously with precise timing? The simplest way is to use some mechanism which *always* is pressing every one of the trapezoids inward with 150-atmosphere pressure. This mechanism could be elastic, hydraulic, or based on the Meissner (superconductor-magnetic repulsion) effect[30]. Then – with no need for any external agency to intervene to control anything – the switches will automatically switch themselves off, beginning at the moment when the ring current has decreased to the point[31] at which the magnetic squeeze pressure has fallen to 150 (instead of the full 570) atmospheres. This "no-brains" method will sacrifice $150/570 \approx 26\%$ of the stored magnetic energy to switching losses, so it is suboptimal. There are other, albeit more complicated, ways to proceed, in an effort for more efficiency. First, a similar "no brains" method could be devised (by using a more complicated geometry involving some sliding contact) such that *motion* would begin once the magnetic pressure had decreased to 150 atm, but electrical *contact* would not be lost until later. Second, we could wait until the ring current has decreased to almost *precisely* zero, then detonate a thin layer of explosive on the outward face of the appropriate trapezoids. One could instead use piezoelectric or hydraulic transducers to perform the motion, or one could pulse a shielded electromagnet to use the Meissner effect to repel the superconducting trapezoids. In principle, the fractional energy losses incurred during switching (if assumed equal to the summed maximum kinetic energies of the moving ring fragments, divided by the ultimate kinetic energy of the projectile) need only to be 0.000042 fractionally for the launcher of §5. Even if this is multiplied by a 1000:1 refrigeration inefficiency factor at (ℓ)He temperatures, such switching losses still would only lead to 4% inefficiency[32].

[28] With $f \approx 0.12$ as in §5, and hence with a maximum EMF of only about 10kVolts not 75, we really could get away with a switch-gap about 8 times narrower and hence switch contact speeds and accelerations could be 8 times smaller. Still, even this would cause considerable risk of shattering.

[29] Actually only 75 atm is required if one uses the average cross sectional area of the trapezoids when reckoning pressure=force/area. However, the average width of our trapezoid is twice that of its small face.

[30] It may be useful to remark that Teflon and Parylene are materials whose flexibility/elasticity properties are largely unaffected at cryogenic temperatures [93].

[31] Of course, during the initial magnetization of each ring, we would have to pull these trapezoids into position manually.

[32] And really the situation is substantially better than this in every way for the same reason as in footnote 28.

6.2.3 *Experiments with superconducting contacts*

Will mechanical contacts between bulk YBCO (or conventional metal) superconductors, even at hundreds of atmospheres of squeezing pressure, conduct *super*current? The good news is that experimentally, the answer is "yes."

The bad news is that the switches that have been created by experimenters so far, exhibit much smaller critical current densities than the bulk superconductors. If this situation cannot be improved, mechanical supercurrent switching will never be usable in high power applications.

The have only been two experimental studies of superconducting contact switches that I know of. One was on NbTi alloy at 4.2°K, and the second was on YBCO oriented single crystals at 77°K.

The NbTi experiments [59][60][88] were compatible with the theory that, by driving two NbTi contacts together, the kinetic energy of impact causes tiny microwelds which then conduct supercurrent with the same properties as the bulk material – but with greatly reduced cross-sectional area and hence greatly reduced critical current. Repeated on-off cycles caused a "training effect" so that the switch conducted 8-10× larger supercurrent on the 40th on-off cycle than on the first; but further training ceased to cause improvement. Higher static squeezing pressures increased the supercurrent capability of the switch, but only up to a pressure of about 30 atmospheres, beyond which improvement ceased. "Mirror finish" (1μm surface roughness) polished NbTi contacts performed better than rough ones. No effort was made to try to polish the contacts even more finely, which is perhaps a pity, because I would expect the Ginzburg-Landau "coherence length" of the superconductor to be the length scale that matters here, and that is 30-40nm for NbTi. They achieved 200Amp/cm^2 current densities with planar contacts, which is only 0.2% of NbTi's bulk critical current density of 100kAmp/cm^2. They also experimented with convex-concave contacts having 209% of the surface area (per normal area) as their plane contacts (due to slant). It appears that these slanted contacts were far more successful than the plane contacts. They were unable to measure their critical currents because they were beyond their power-supply's capabilities, but extrapolation of training data suggests 2000Amp/cm^2. Note, this was well beyond 209% of 200Amp/cm^2, which they suspect is because slanting causes greater conversion of impact kinetic energy to microwelds. Even so, 2000Amp/cm^2 is only 2% of NbTi's bulk critical current density of 100kAmp/cm^2.

The YBCO experiments [91] were with YBCO infused with phenol-formaldehyde resin for extra strength. Only plane contacts, polished smooth (it was not stated how smooth), were tried. Again greater supercurrent was found with greater squeezing pressure, up to about 75 atmospheres, at which point improvement ceased. No evidence was presented for microwelding. Training happened. Two crystal directions yield supercurrent switches, the third doesn't. They achieved 21Amp/cm^2 current densities (13.5 Amps across an 8×8mm square contact area). Again this is only a small fraction of the current densities which have been achieved in bulk YBCO at 77°K. (Different kinds of YBCO have widely differing critical current densities from 1-100kAmp/cm^2.)

It is unknown what effects other materials, temperatures, surface treatments, choices of environmental gases or liquids (or vacuum), superflat polishing, etc, will have on superconducting switch performance.

If critical current density across switch contacts can be improved to 25% of critical current density in bulk material, then high power supercurrent switches will be become achieveable with characteristics just as good as uninterrupted bulk material, because of these ideas:

1. In our switches, the direction of current flow need not be perpendicular to the switch contact plane. In fact I had envisioned 45-degree angle. The advantage of angle is that one can have a high current density in the bulk, while enduring a lower current density across the switch plane (if measured normal to that plane). The angle of 45° buys us a factor of 1.414 in this way; going to higher tilts, say 70° off-normal, would buy us a factor of $1/\sin(20°) \approx 2.92$. (This would also have the benefit, in the launcher of §5, of increasing switch contact pressure.)

2. One could go further by corrugating the switch contact surfaces (same corrugations both sides) increasing their surface area more. (This area-increase would decrease the squeezing pressure – but we have plenty of room on that parameter since we are well above 75 atm.) By combining both corrugation and tilt, we could readily get naive switch contact areas 4 times larger than the cross sectional area of our ring.

6.2.4 *Destroy a loop*

A solid ring could be switched off by intentionally fracturing it. Fracture occurs at speeds comparable to the speeds of sound in solids, which is fully sufficient for our purposes. This is really just a variation of the above mechanical-contact-switching idea, but the "contact" is now a weld. Of course, after fracture, each ring would then have to be welded back together to allow another launch. Rings could be designed pre-notched to allow controllable fracturing.

Unfortunately, our above analysis deprecating using a single contact plane and encouraging chopping our ring into many fragments – also argues for making multiple fractures, and hence multiple re-welds, per ring. With only two ring fragments, weld energies might be small enough to still allow high efficiency, but that seems unlikely with many fragments. Is all this feasible? Perhaps. Much depends on the particular superconductor material, its "weldability," and the development of automated welding machinery.

6.3 *Thermal switching strategy*

Another idea for off-switching, which has the advantage of not requiring any moving parts, is: we could suddenly dump **heat** into some portion of our superconducting ring, raising it above its transition temperature T_c (this is assuming we are using a superconductor whose non-superconducting state has high resistivity). This might be accomplished by ohmic flash-heating of a fine network of resistive wires embedded in the superconductor, or perhaps by chemical heating via detonation of a fine network of embedded gelignite filaments, or perhaps via radiation. These ideas might work, but they seem to require a high rate of power transfer from, e.g. a large capacitor bank to power the heater, and/or the use of chemical explosives. We had wished to avoid those things. But still, if these total heating-energies were much smaller than the energies of the supercurrents energizing the launcher, this might nevertheless be acceptable. The key questions are: **(1)** what off-state switch resistance $R_{\rm off}$ is required, and **(2)** what resistance will be achieved by this method? The answer to the first question is that if $n\mathcal{E}^2/R_{\rm off}$, where $\mathcal{E}$ is the EMF in the ring (that the switch is supposed to withstand) and n is the the number of rings thought to be withstanding large EMFs at any one time, is negligibly smaller than the rate P of power input to the projectile, then energy losses caused by the finiteness of $R_{\rm off}$ will be negligible in comparison to the energies being used, so that the overall efficiency will still be near 100%. In our design of §5, the rate of power input to the projectile is $P = 900$ gigaWatts, and $\mathcal{E} = 75$kV. Therefore to make $\mathcal{E}^2/R_{\rm off} < 0.0001P$ it suffices[33] if $R_{\rm off} \geq 64\Omega$.

To answer the second question, consider the normal-state resistivities of the YBCO and BSCCO ceramic superconductors given in table S. Concentrate on BSCCO-2212, which has very favorably [45] atypical (and remarkably high) resistivity behavior, peaking at 17-40 Ωcm at about 90°K, but then actually dramatically *dropping* to about 4-7Ωcm at 250°K. (Most other high-T_c materials have much smaller resistivity, and what there is increases, roughly linearly, with temperature.) This tells us that if we could heat up a 3.5-cm long region of the 1m-diameter superconducting ring (assuming a BSCCO-2212 ring with cross sectional area 3.5cm^2 as in the Earth-launcher design in §5) to 300°K, we would cause its resistance to be 4-7Ω. Actually, it is only necessary for us to heat it to a small increment above T_c, because the EMF in the ring would take over at that point to heat the resistive chunk of the ring further (causing the size of the non-superconductive chunk, and its temperature, both to increase) until the resistance rose enough to stop said heating. If the entire ring (circumference 3.2m) were heated in this manner to 300°K, its resistance would be 360-630Ω, and hence it would then dissipate (at an applied EMF of 75kV as in §5) 10-16 megaWatts for about 200μsec, for a total dissipation of ≤ 3.2 kJoules of heat (which would in fact only have been sufficient to heat the ring by a few °K). On the other hand if only a 1cm-long chunk of the ring were heated to 90°K, then its resistance would be 5-12Ω, leading to a dissipation of 94-225 kJ, enough to heat that small chunk of the ring to over 1000°K. BSCCO-2212's resistance decrease is highly beneficial because it means that hot spots will be heated less, and cold spots (provided they are above T_c) will be heated more, by any given current density, tending to equilibrate temperatures and damp out such instabilities.

The energy costs, even when one figures in refrigeration inefficiencies at $(\ell)N_2$, (ℓ)Ne, or even (ℓ)He temperatures, to recool these rings would well below the energy cost of the launch itself, hence fully acceptable.

But if our rings were instead made of melt-textured polycrystalline YBCO or BSCCO-2223 (far less favorable materials for this purpose due to their > 1000 times smaller resistivity) they unfortunately probably would unavoidably be heated to > 700°K.

Moral. This calculation suggests that this heat-based switching technique could be adequate for BSCCO-2212 rings. Its feasibility depends entirely on the warm-resistivity of this ring material being remarkably large. Unfortunately, presently available BSCCO-2212 material does not have large enough critical currents at high temperatures and magnetic fields, and hence could not be used in the launcher design of §5 above liquid helium temperatures. But at these temperatures, BSCCO-2212 might be fully acceptable (e.g. it has been used to build a 30-Tesla magnet). Triggering the quench could require suddenly heating at least a small portion of each ring to $T_c \approx 90$°K, far above the ambient 4.2°K. On the other hand "natural" heating due to magnetic hysteresis effects (if carefully controlled, cf. §9.6) might be fully adequate to cause a quench with no need for any intentional heating at all.

Meanwhile, the normal-state resistivity of all other commonly touted superconductive materials – especially metals – are not large enough[34] to make thermal switching feasible. The ohmic heat generation and consequent inefficiency would be enormous. Only a tiny fraction of the stored magnetic energy would be converted to projectile kinetic energy, while most would suddenly be converted to an enormous amount of heat – enough, for the launcher design of §5, to destroy the launcher!

Incidentally, this analysis is (for everything besides BSCCO-2212) a devastating indictment of so-called "quench guns" [51][9], a previous idea very closely related to the magnetic catapult, depending on the use of "quenching" to deactivate the portion of the superconducting solenoid lying behind the projectile. For a superconductor material with high enough normal-state resistivity, quench guns become a special case of the magnetic catapult; otherwise they are far worse. The problem is that thermal quenching, while it deactivates *super*conductivity, does *not* deactivate ordinary conductivity, in which case the entire propulsive mechanism will not work. The quench gunners had not realized the fact that efficiencies of 100% would be attained with ideal switching, and had not seen our elegant "winch back" approach to initially storing the magnetic energy without need of any external electrical power supply, and had not

[33] Actually, for the same reason as in footnote 28, things are substantially better than this: really $\mathcal{E} \approx 10$kVolt so $R_{\rm off} \geq 1\Omega$ should suffice. In the text we are being very conservative and considering switching rings well isolated from all other rings, i.e. the large ring-spacing limit where $f \approx 1$. In reality close-spaced rings can allow $f \ll 1$ and hence the use of projectiles generating small magnetic flux and hence causing small EMFs; see the end of §3.

[34] Of course, no effort has been made by materials scientists to *increase* the normal state resistivity of YBCO and its ilk. If this could be achieved, the thermal-switching technique could also become adequate for YBCO; but [58] suggests that any such resistivity increase unfortunately will be accompanied by a critical-current decrease, suggesting thermal-switching will *never* be acceptable for YBCO-like materials.

seen the fact that comapratively nonmagnetic projectiles could be used; these are the central ideas behind the magnetic catapult.

6.4 Less attractive-looking off-switching ideas

We've already discussed the pointlessness of using **semiconductor devices** or **vacuum tubes** as switches in §1.12.

Superconducting transistor-like devices exist [23][67] which (by cascading them) presumably could achieve enormous current gains. However, either their off-state resistances are low or they depend on thin insulator films incapable of withstanding high voltages.

One could initiate a superconductor-to-normal transition **magnetically** instead of thermally. (Actually, that can happen automatically, see below under "helpful effect.")

"Josephson junction" devices are capable of switching supercurrents very quickly (subnanosecond) but, since they are based on very thin insulator layers (thin enough to permit quantum tunneling) they again are useless for withstanding high voltages.

A **depressurization approach** (or strain-based approach) could be based on the fact that some materials superconduct only when under pressure. (A famous, although not useful for our purposes, example [79], is Lithium, which does not superconduct at any temperature at ambient pressure, but under 48 GPascals of pressure, superconducts with the remarkably high critical temperature of $T_c = 20$ Kelvin – higher than that of any other known pure element. Other elements that superconduct only under high pressure include O, Si, Se, Te, Be, Sb, Bi, Ba, Li, Ce, Fe. Indeed, the world record material $Hg_{0.8}Tl_{0.2}Ba_2Ca_2Cu_3O_{8.33}$ with $T_c = 138$ Kelvin has 25-30 degrees higher T_c under 300,000 atmospheres of pressure – provided one is willing to make the most generous possible interpretation of the "onset" of superconductivity as temperature is decreased. By suddenly releasing the pressure, one could rapidly switch off superconductivity in such a material. However, only materials for which the critical pressure is 1000 times smaller, e.g. $\lesssim$ 200 atmospheres, would be practically useful for our purpose here, and I know of none.

A **helpful effect** is: just as the rear end of the projectile is *leaving* a ring, is when that ring will experience maximum externally applied magnetic field (which will point in a radially inward direction, see figure 2). (When the projectile is *entering* a ring, that ring will experience minimum externally applied field because the field from the projectile will tend to cancel, rather than augment, the field from the rest of the rings in front of it. See figure 2.) That could be used to shut off that ring's superconductivity "automatically," just at the moment when it is experiencing the most EMF, by exceeding the critical magnetic field H_c. Although this shutoff would only be temporary, it comes at the most-needed time for the purpose of helping our switches do their jobs.

6.5 Summary

We seen that the requirement to off-switch coils rapidly, with switches that can withstand EMFs that quickly rise to high values, seems to be the limiting factor on catapult velocities.

Naive mechanical switches won't work as well as mechanical switches based on moving many ring segments apart by a small distance. These switches have many desirable attributes, such as high contact-squeezing pressure happening automatically when we want "on," and zero squeezing pressure happening automatically when we want "off." Unfortunately experiments so far indicate that such switches conduct 2 orders of magnitude less supercurrent than bulk superconductor (per unit area) – even if squeezed hard – which rules them out unless this can be improved.

Thermal "quench" based off-switching was shown to be very poor-performing with all presently available superconductor materials besides BSCCO-2212, because only BSCCO-2212 has high enough normal-state resistivity. Unfortunately, presently available BSCCO-2212 would need to be used at liquid helium temperatures. With BSCCO-2212, this strategy has many desirable attributes such as no moving parts, thermal self-stabilization, and possible "automatic" off-switching due to hysteretic self-heating (§9.6) and the presence of high magnetic fields just when switch-off is wanted.

7 Will Earth-launcher projectiles vaporize?

A severe, and possibly fatal, flaw in the whole Earth launcher idea is the fact that the projectile will be subjected to extremely high atmospheric frictional heating as soon as it emerges from the launcher's protective vacuum. Will it melt? (Of course, this would not be an issue if the launcher were on the moon.) This section will give analysis and design ideas to explain why I believe we can build projectiles that will survive their transit through the atmosphere. Both the engineering of such projectiles, and their analysis, are highly nontrivial.

7.1 Naive first impression

When I initially thought of this, I knew that the Apollo moon missions had returned unscathed from atmospheric reentry despite initial velocities ≈ 13 km/sec, and despite the less advanced state of materials technology during the 1970s. The Apollo capsules had mass (5545 kg) comparable to our projectiles, but considerably larger cross-sectional area, smaller density, and more fragile and temperature-sensitive contents. This all made me think heating was not going to be an insuperable obstacle.

But that initial impression is very misleading. Apollo could choose to enter Earth's atmosphere at an almost-horizontal angle, thus experiencing most of its deacceleration, and most of its heating, in the thin upper atmosphere, over a very long distance (1000s of km) and a long time (many minutes). We in contrast will be ejected at a near

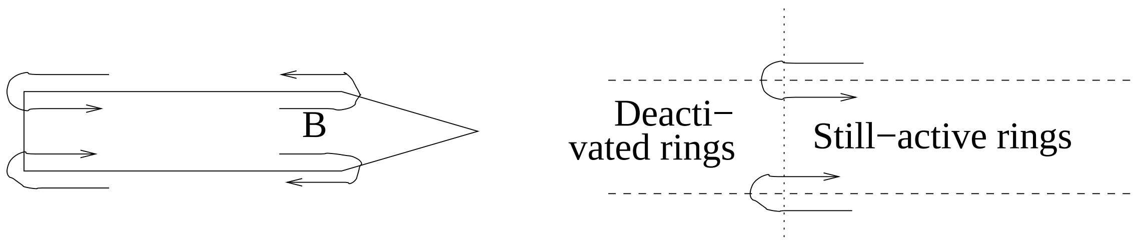

Figure 2: Details of some magnetic fields.

vertical angle directly into thick atmosphere, and at considerably higher speed than escape velocity (and note that the heat energy input is roughly proportional to the *square*, and the heat power input to the *cube*, of the velocity) and will experience all heating over a timespan of only *seconds*. So clearly our task is, despite appearances, far more difficult than Apollo's.

7.2 Materials

Table R collects useful data about palusibly useful heat-shield materials.

Carbon (graphite) has the highest melting point (actually, it sublimes directly to vapor) for any single element (about 4000 ± 100 Kelvin). A mixture of Hafnium carbide (HfC) and Tantalum Carbide (TaC) has the highest melting point known, about 4300 Kelvin.

The heat energy required to heat then vaporize a gram of room temperature graphite is about 67 kJoules. Note that this slightly *exceeds* the kinetic energy (62.6 kJoules) of a gram moving at[35] Earth escape velocity (11.19 km/sec). All of the substances in table R have heats of sublimation (at low temperature) between 300 and 920 kJoule per mole of atoms. (The 920 is for TaC, and the 300 is for Al metal.) Hence, the materials with the greatest heats of sublimation *per gram*, rather than per *atom*, are the strongly bonded substances made entirely of *light* atoms, namely Be (35 kJ/gram), B 52, C (graphite or diamond) 59, BN (graphite-like or diamond-like) 36, and BeO 29. (All these figures are at least about twice as large as for any substances, e.g. MgO, TiC, involving elements from later rows of the periodic table. They do not include the heat, usually 0.6-6 kJ per gram, required to raise the solid's temperature to its boiling point, and hence for our purposes are underestimates.) In fact *hydrogen* (the lightest element) has the highest bond energies per unit mass and hence is desirable to incorporate; this can be achieved by using 3D-network plastics.

7.3 Counterintuitive comments about these materials properties

The **melting temperatures** of these materials are *not* particularly important for us, because even the highest among them will be far exceeded. There is no question that our projectiles will be eroded; the only question is by how much. (Melting temperatures *would* be important if one were interested in designing projectiles that are intended to remain unscathed, but that is not possible at our speeds.) More important is the heat of fusion (or of vaporization, or of chemical decomposition) of these materials, starting from a low temperature state, since it is this that governs the amount of (that type of) erosion that can be caused by a given energy input. It is best to use materials which **sublime** directly from solid to vapor (e.g. graphite, BeO) or materials which chemically decompose (e.g. 3D network plastics, boron nitride) since heats of sublimation and decomposition tend to be much greater than heats of melting[36]. An illustrative example of all this is "Teflon," the polymerized form of $F_2C{=}CF_2$, which unpolymerizes at the comparatively low temperature of 324-550°C. It has nevertheless been suggested as (and used as) an ablative material because its heat of decomposition is 2.2 kJ/gram. (For materials which sublime or decompose rather than melt, I gave in table R the appropriate temperature and heat of sublimation or decomposition.)

Second, even the most **thermally conductive** among these materials are actually fairly good insulators, as far as we are concerned, so that their thermal conductivity is also largely irrelevant. For example, suppose the outer skin of our projectile were 4000° Kelvin and the material 1cm beneath the skin were cold. Then the total heat flux into the projectile (even assuming an ultrahigh thermal conductivity of 250 watts/meter/°K, comparable to good metals) would be at most about 96 megawatts per square meter. Meanwhile, the energy required to vaporize that 1cm-thick layer of graphite would be about 1400 megajoules per square meter. So with a duration of heating of only a few seconds, the heat must stay on the outer layer, so that the surface will erode from the outside in by progressive boil-off of the outermost surface. *After* this severe atmospheric heating ends, it then will be important to protect the payload from the now-cooling high temperature outer skin. This could be accomplished using a subskin layer of good insulation, such as the porous silica material used for space-shuttle tiles, which is about 1000 times less heat-conductive than bulk materials. All that is important is that this insulation be good enough (which it is) to make the heat flux inward be far

[35] In contrast, the energy released by exploding a gram of TNT is only about 4.2 kJoules.

[36] It is conceiveable that, at our enormous rates of heat input, it may not matter if our material melts, because the liquid may vaporize before it has time to flow off the solid, so that, effectively, the solid vaporizes directly. But I do not think this question may be settled purely mentally, by means of simple theoretical estimates. I.e., I *do not know* whether this will happen.

stuff	Melts* °K	Spec.Heat J/g/°K	H_{fus} kJ/g	Expn.Coef ppm/°K	Thrml cnd W/m/°K	Densty g/cm^3	Emissvty (0-1)	Therml shock	Color
Al†	936	.90	.39	23.5	237	2.7	0.05		silv
Fe†	1811	.25	.25	12.1	80.4	7.8	0.2		silv
Nb‡(9.25°K)	2750	.27	.30	7.2	53.7	8.57	.15-.22		silv
Ti†	1930	.52	.32	10	22	4.5			silv
Mo†	2895	.25	.38	5.0	138	10.2	.08-.37		silv
W†	3670	.13	.19	4	173	19.3	.1-.5	E	silv
Nb_3Al‡(18.3°K)	1900								silv
B	2450	1.03	3.6	8.3	27	2.35			black
MgO	3080	.87-1.2	1.9	8	14-36	3.6	.4-.5	PF	white
ThO_2	3600	.32	.29	9.5	3-10	9.9		P	white
BeO(toxic)	2850	1.02-1.12	2.85	8-13	6-300	3.0	.3-.5	E	white
Al_2O_3	2330	.41-1.26	.85-.9	5-13	9-35	4.0	.3-.5	FG	white
ZrO_2	3000	.61-.84	.71	2-8	1.5	5.5	.4-.5	FG	white
SiO_2(vitreous)	2000	.67-1.17	1-1.6	.5-.6	1.6-2.5	2.3	.4-.7	E	white
$Al_6Si_2O_{13}$(mullite)	2100	.8-1.3	?	5	3-6	2.6-3.3	.4-.5	FG	white
C(pyr.graphite)†	4000s	.71-1.64	59.5	0.5-6	3-400	2.2	0.8	E	black
BN(pyr.gr-like)	3100d	.8-2.0	36-57	.1-36	1-60	2.2	0.5	E	white
C(diamond)	4000s	0-2.0	58	1-5	500-5000	3.5		E?	white
BN(cubic)	3200d	.6?	35-56	1.2	740	3.48		E?	gold
AlN	2800d	.74	21	5	20-200	3.3		G	white
Si_3N_4	2170d	.7	14	3	15-40	3.44		GE	gry-blk
TiN‡(5.5°K)	3220d		12.2	9	19	5.4		E	gold-yel
NbN‡(17.3°K)	2500d			10	4	8.5			gray
HfC†	4000?	.2		6-7		12.4			gray
TaC†	4200			8	32	14.4	0.5		gold
WC‡(10°K)	3050	.20		5-7	63	15.7			gray
ZrC†	3700			7	21	6.7	0.4		gray
NbC‡(11.1°K)	3900	.34		7	13	7.6	0.6		lavdr/gry
TiC†	3400	.15-.21		7	21-30	4.93			gray
SiC†	2500d	.75-1.2	23?	4-6	60-200	3.2	.93	E	black
TiB_2†	3200	.66		8	25-125	4.5			gray
ZrB_2†	3500			6	23-25	6.1			
MgB_2‡(39°K)	1070								silv
epoxy	d	1.26	4.6-16.3	7-8	??	1.3			

Table R: Interesting refractory (and not so refractory) materials and their properties. Data extracted from numerous literature sources. The thermal data (judging by the large disagreements between different literature sources!) often contains errors of 10% or more. Although heats of fusion for the carbides are not known, their partial heats of evaporation for evaporation of carbon atoms are known to all be about 900 kJ per mole of carbon atoms. Key to comments: s=sublimates directly from solid to vapor (heat of sublimation given instead of fusion); d=decomposes chemically instead of melting (heat of decomposition given instead of fusion). The "effective heats of ablation" under hot-air-flow conditions are not necessarily the same as the heats of fusion, decomposition, or evaporation. For example measurements of erosion in air plasma torches suggest the effective heat of ablation of graphite is about 35 kJ/gram (below its heat of vaporization), of MgO is 19-35 kJ/gram (well above its heat of fusion, and comparable to its heat of sublimation 15 kJ/gram; this is compatible with the fact that "vigorous vaporization" of MgO prevented solar furnace experimenters from measuring its melting point; [33] 1967, p.240) and of vitreous SiO_2 is 1-1.6 kJ/gram (about same as its heat of fusion). Under "epoxy," table gives representative effective heat of ablation for various thermoset plastic materials, in some cases with filling by graphitic or inorganic fibers. †=electrically conductive, ‡=also of note as a superconductor (T_c given), otherwise insulator. (SiC's resistivity can vary from 1 to 10^6 Ωcm depending on dopants etc.) Thermal shock resistance is given on a subjective scale E,G,F,P (Excellent, Good, Fair, Poor).

smaller than radiation losses to space, and that it survive the highest temperatures it is exposed to.

"Thermal shock" (rapid thermal expansion of the outer skin of the projectile relative to subsurface material, causing fragmentation) should be extremely important. Most nonmetal (and many metal) materials fracture when exposed to maximally high temperature gradients. It could actually be best to use materials with *high* thermal conductivity, since they experience smaller temperature gradients and hence are less thermally shockable. Also desirable to increase thermal shock resistance: higher strengths, lower thermal expansion coefficients, and lower Young's moduli ["softer"] materials.

The most thermal-shock resistant nonmetal materials seem to be pyrolytic graphite, pyrolytic boron nitride BN, and glassy fused silica SiO_2. (Si_3N_4, BeO, TiN, and SiC also are touted as shock resistant.) The former two materials are deposited on a surface from a gas, and are very anisotropic; they have very small thermal expansion (-3 to $+3$ ppm per °C) and high thermal conductivity in the in-plane (tangent to the surface) directions[37]. Pyrolytic BN plates are undamaged after quenching from 2000°C into icewater. Similarly, because fused quartz has tiny thermal expansion (0.55 ppm per °C from 0-1600°C), thin plates are undamaged after quenching from 1500°C into icewater. Because quenching places the surface under tension, whereas our projectile will experience the opposite (heating our surface places it under compressive, and the bulk under tensile, stress), easier-to-withstand, situation, I believe our projectile skins, if constructed of these materials, will survive thermal shocking.

Strength of our material should *not* be very important per se, because typical pressures ($\leq$ 500 atm) should be withstandable, with care, even by fairly weak bulk materials.

Electrical conductivity at low temperatures is undesirable for a nosecone material (unless, perhaps, it is type-II *super*conductivity) because eddy currents, induced by the high-speed projectile moving in magnetic fields within the launcher, could cause ohmic heating and inefficiency. Thus, almost certainly metals are not wanted, and probably graphite and many of the carbides and borides (at least, in bulk form) also are unwanted.

I believe that the **chemical resistance** of our material to high temperature air *also* should be largely irrelevant for our purposes (and again would only matter if one were interested in designing projectiles intended to remain unscathed). E.g. it should be largely irrelevant that graphite burns in air, whereas MgO is inert. This is because I suspect that such chemical reactions will be a comparatively small heat-energy source, as far as the projectile is concerned, under our conditions. For experimental support for the unimportance of resistance to chemical attack at high heating rates (the "sublimation regime" of [80] p.59) see [8], where oxidation was reckoned to be a comparatively small fraction of the heat budget even at heating rates considerably smaller than those we expect; and experiments ([13] p.545; [4]) which found similar erosion rates in air versus Argon in extreme heating via either plasma-torches or radiation. The subsonic situation behind the shock wave is a molecular traffic jam which retards air from reaching the surface of the projectile. Our Earth-launcher design in §5 involves a projectile with roughly the same mass as the column of air in front of it. Since air is 20% oxygen, this amount of available oxygen would theoretically be adequate to oxidize about 20% of the projectile, if every oxygen molecule combined with projectile material. However, in practice, most of the air is shunted aside and only a tiny fraction of it ever comes in contact with the projectile surface. (Oxidation reactions happening in the *gas* should be largely irrelevant from the point of view of the *projectile*, since that heat will be left behind.)

Indeed, both chemical reactions and convective and conductive heat transfer to the projectile will happen, in the ultimate limit of high projectile speeds, at comparatively low rates. I predict that in this limit, the dominant source of heating of the projectile will be *radiation* from the ultrahot gas shock in front of the projectile, since radiation is not affected by any "molecular traffic jam" and since its intensity grows (naively) proportionally to the 4th power of the gas-shock temperature, i.e. proportionally to the 8th power of the projectile velocity.

Unfortunately it is difficult[38] for me to tell purely mentally, at the Earth launcher parameter values in §5 whether convective or radiative heating will dominate.

If radiation dominates, then, what may matter a good deal more than chemical reactivity is the **optical reflectivity** of our material, which governs how much of this radiation the projectile will absorb. Shiny white projectiles should be superior to dull black ones. I have quoted "blackbody emissivity" figures to help judge this (larger emissivity$\Rightarrow$darker), but I warn the reader that these figures may be deceptive since they were usually measured at temperatures lower, and wavelengths longer, than those we shall be interested in. (The emissivity of tungsten increases from 0.1 at 7μm, to 0.45 at 250nm wavelength. Graphite is commonly reckoned to have an emissivity of 0.77 if its surface is polished but 0.90 if it is dulled [13]; but it is also temperature dependent: one measurer found an emissivity of 0.4 at 1000°K, increasing to 0.5 at 3500°K and to nearly

[37] Out-of plane thermal conductivity is 20 or more times smaller than in-plane, and out-of-plane thermal expansion is 35 ppm/°C.

[38] There are numerous complicating factors such as: whether we have turbulent or laminar hypersonic flow (turbulent flow causes much greater heating), the presence of ionization and dissociation of the air, ablation affecting the flow, the fact that no airflow experiments have ever been done at these speeds except for observations of meteorites, different opacity lengths of different wavelength photons in different gases, the possibility of gases absorbing energy via chemical changes and ionization and then releasing it *later* after a *delay*, the effect of ablated gases on all this, etc. Extensive theoretical and empirical analysis summarized by H.J.Allen [2] suggests that 20 km/sec is approximately the speed at which the transition from convective to radiative heating dominance occurs; that radiative heating grows like the 15.5th power of the projectile velocity between 8 and 13.7 km/sec, but above 13.7km/sec grows only as the 5th power; and that radiative heating is proportional to the 1.8th power of the air density so that it is relatively more important than convective heating at lower altitudes.

1 at 4000°K.)

7.4 *Provisional choices of my favorite materials*

Boron Nitride (BN) strikes me as a particularly promising material. It (I am speaking here of the lower-density, softer, graphite-like form) is commercially available from, e.g., GE advanced ceramics, may be coated (by chemical vapor decomposition) onto most materials favorably anisotropically (BN is also available as isotropic polycrystalline hot pressed material, but that is less resistant to thermal shock), is nontoxic, and is readily machined into numerous shapes. It decomposes at about 3100 Kelvin, has a high specific heat and heat of decomposition, is white, and is fairly resistant to oxidation (stable in air up to 800°C). It has excellent thermal shock resistance (plates may be heated to 2000°C and plunged into cold water with no damage). It has anisotropic thermal expansivity (1.5ppm/°K in the in-plane directions versus 35 in the out-of-plane direction) and thermal conductivity (20 times smaller out-of-plane than in-plane). It is an excellent electrical insulator. BN actually becomes stronger at higher temperatures (peaks at 2200°C; such hot strength is actually a common phenomenon in refractory carbide and nitride materials). Similar properties (but poorer oxidation resistance, and it is black, and it is an electrical conductor) are possessed by graphite.

Beryllium and BeO are probably bad choices because they are toxic.

Thermoset plastic materials reinforced by carbon or SiO_2 fibers (similar to the composite material used in the Apollo heat shields) also seem promising.

It also is perhaps worth noting that polycrystalline diamond coatings (C) can nowadays be deposited on many things from gas mixtures stimulated by microwaves. Diamond has extremely high strength, decomposition temperature, and thermal conductivity. (The secret is that hydrogen in the gas mix reacts with graphite faster than it reacts with diamond, preventing the deposition of graphite despite the fact it is thermodynamically favored.) Unfortunately the resulting diamonds are presently very expensive: $500/gram.

BNC compounds such as BC_2N may be superior to either BN or C alone [22][86] in the sense that they can have greater thermal and chemical stability [96][22], higher strength, lower thermal expansion, and higher thermal conductivity (and as a consequence of these, better thermal shock resistance). For example they are stable in 1400-1500°C air, which is better than either BN, graphite, or diamond. However, unlike these latter three substances, BNC compounds are not presently commercially available.

I also mention that the alloy $(NbN)_{0.75}(TiC)_{0.25}$ is both a superconductor ($T_c \approx 18$K) *and* a highly refractory material – although its thermal shock resistance is probably too poor for use as outer skin.

7.5 *Thermo-aerodynamical analysis and optimal geometry*

Initial crude model: inelastic collision with air. Suppose (for simplicity, and also since it is approximately true for the 4000 kg projectile of §5) that the column of air in front of our projectile masses exactly the same as the projectile itself. If every atom of that air collided with our projectile inelastically (i.e. after the collision it has exactly the same speed as the projectile; this crude model corresponds to drag coefficient $C_D = 1$) and all of the kinetic energy lost during such collisions were converted to heat, and all of that heat were used to heat our projectile, and assuming our projectile were made of 100% graphite, then the maximum possible initial projectile speed (to avoid 100% vaporization) would be 14.1 km/sec, leading[39] to a final projectile speed of 8.5 km/sec. (The 14.1km/sec speed was chosen so that the difference between the projectile's initial and final kinetic energies is equal to its heat of vaporization starting from a low temperature state.) Since 8.5km/sec is approximately the same as low-Earth-orbital speed, this makes the situation seem hopeless!

Improvements. Fortunately the situation is better than this crude model, for three reasons. **1.** Drag coefficients considerably below 1 are typical of pointed projectile shapes [19][34], e.g. $C_D = 0.1$ would reduce the instantaneous heat input by a factor of 10, while also increasing our final (slowed) velocity.

2. Most of the heat will be carried away by the air stream instead of heating the projectile. W.Hankey's reentry book [30] estimates that the fraction of heat actually deposited in the projectile will be approximately equal to the "Stanton number" St, and this in turn, by a combination of "Reynolds' analogy" and (uncited) "empirical relations developed over the last century" is approximately given, in turbulent flow, by

$$\mathrm{St} \approx \frac{0.0296}{\mathrm{Re}^{0.2}} \tag{1}$$

where Re is the "Reynolds number," $\mathrm{Re} = \rho L U/\mu$.(Note that the faster we fly, the larger fraction of the heat is carried off by the air.) The Reynolds number was always a little imprecisely defined (what should one use as the "characteristic length" L?) and here it is still more difficult to estimate it because it is unclear what the viscosity μ of air will be at the expected very high temperatures – but fortunately the final result is quite insensitive even to large errors because $x^{0.2}$ is a function of x that is very insensitive to large error factors in x. For us, with an $L = 5$ meter long projectile traveling at speeds of $U =$ 10-20 km/sec in very hot air of density $\rho \leq 0.6$ kg/meter^3, I estimate $\mathrm{St} \approx 1.5 \times 10^{-5}$-$1.5 \times 10^{-4}$. I.e., if Hankey's crude estimate is to be trusted, the heat input is reduced, versus the crude model, by a factor of at least 6000.

3. Allen [2] estimates that "fending off" of the airstream by ablated gases should reduce the heat input to the pro-

[39] This and the below calculations are based on the following formula: $V_{\text{final}} = V_{\text{init}} \exp(-C_D M_{\text{air}}/[2M_{\text{proj}}])$. Derivation: since drag force F obeys $F = -C_D \rho A V^2/2$ where A is the cross sectional area, by Newton's law $F = M\dot{V}$ we have $dV = -C_D \rho A V^2/(2M)dt = -C_D \rho V A/(2M)ds$ where s is distance traveled, since $ds = V dt$. Integrating using $\int \rho A ds = M_{\text{air}}$, we have $\ln(V_{\text{final}}/V_{\text{init}}) = -C_D M_{\text{air}}/(2M)$. Incidentally, note the drag-force$\propto V^2$ law is a strict upper bound asymptotically at high speeds, and $C_D \leq 2$ as $V \to \infty$ for all shapes.

jectile by a factor of roughly $1 + kV^2/\zeta$ where $k = 0.1$ for turbulent and 0.3 for laminar flow, V is the projectile velocity, and ζ is the energy required to vaporize a unit mass of the ablated material. In our case, this reduction factor is 1.6-6 depending on the ablator material and whether flow is turbulent, so we shall (to be conservative) use 1.6.

Combining these three improvements to get a net heat reduction factor of $6000 \times 1.6/C_D = 9600/C_D$, we *now* estimate that with $C_D = 0.1$ and an initial projectile speed of 20 km/sec, its final speed will be 19.0 km/sec, and it suffices (for the projectile to dissipate its heat) if a fraction of at most 1.6×10^{-6} of the projectile's mass is graphite, provided all of the heat is used to vaporize that graphite, with the rest of the projectile remaining unharmed.

With $C_D = 0.3$ (corresponding to a less-pointed shape) [34] and an initial projectile speed of 20 km/sec, the final speed will be 17.2 km/sec, and it suffices if a fraction 1.4×10^{-5} of the projectile's mass is vaporizable graphite.

Finally, with $C_D = 0.6$ (a rather blunt shape) and an initial projectile speed of 20 km/sec, the final speed will be 14.8 km/sec, and it suffices if a fraction 5.2×10^{-5} of the projectile's mass is vaporizable graphite.

These estimates make the problem look *trivial!* But unfortunately, the situation is worse than that, for two reasons.

1. At high speeds I doubt the validity of Hankey's estimate that led to the factor$\geq$ 6000 heat reduction. That is because clearly, asymptotically in the limit of high projectile speeds and air densities (and I believe we *may* be, at least at the hot spots, in this limit), the bulk of the heat flowing from the hot gas shock [glowing in the UV at temperatures of order (2-20) $\times 10^4$ Kelvin] in front of the projectile to the projectile will arrive by *radiative* transfer and *not* by convection [15][2], as Hankey had assumed. We perhaps could make the projectile's front surface be 60% reflective, in which case about 80% of the heat would be dissipated into the air with only 20% heating the projectile. This factor of 5, while good, is 1200 times worse than Hankey's factor of ≥ 6000 we've been using. Furthermore, quite probably even 60% reflectivity will be impossible to achieve in the UV below about 120nm wavelength, in which case the situation would be even worse[40].

As I said, it is difficult to tell purely mentally how important radiative effects will be. To be safe, let us redo all the above estimates with Hankey's factor ≥ 6000 replaced by a factor of only 5. We have:

With $C_D = 0.1$, the required mass fraction of vaporizable graphite is 0.0019; with $C_D = 0.3$, 0.017; and with $C_D = 0.6$, 0.062. I have not heard of any previous design of any projectile which attempts anywhere near the latter fraction (6%) of sacrifice – i.e. we are here entering a new design regime.

In reality, I suspect the truth will be intermediate between Hankey's factor of 6000 (too optimistic) and my factor of 5 (too pessimistic). Allen's extensive analysis [2] suggests that the true factor of available kinetic energy decrement divided by heat energy actually absorbed by the projectile (for a 30° half-angle cone traveling in air at speeds of 0-24 km/sec) should be 200-330, causing the required mass fraction of vaporizable graphite to be, at most, somewhere between 0.00092 and 0.0072.

2. In practice it is unlikely to be possible to distribute the incoming heat *uniformly* within some sacrificial layer of graphite, while sparing the rest of our projectile. There will be hot spots. (In particular, the leading point of the nose will be the hottest spot.) If the hot spots erode quickly and then (due to the consequent shape change causing the aerothermodynamics to become worse) become even hotter spots, the result could be a runaway nonuniformity, e.g. resulting in cutting the projectile in half. I'll now explain new strategies which I believe will be able to tame this threat and allow a very high percentage of sacrificial ablation without failure, and indeed, if necessary, in an actively-controlled manner.

I believe the **best foreshape** will be roughly of the power-law form $r \propto z^{0.7}$ (where r is the radius z behind the nose) [2][49]. This shape approximately minimizes drag [49][19], with drag about 40% of that of a cone with the same base and height. Unfortunately the nose of this shape is expected to flatten due to a higher rate of erosion (due to higher gas temperatures, smaller shock standoff distance, and decreased thermal conduction into the subskin). So I envision this forenose region as being the rounded front end of an **extrudable rod**, made of extremely refractory stuff, which will be continually pushed out of the front of the projectile to compensate for that erosion. The purpose of this forenose is to create a protective buffer zone of compressed subsonic air in front of the projectile. In front of this buffer zone will be a gas shock, and most of the heat generation will be at this shock discontinuity, not at the projectile's surface itself. I have not seen this "extruding rod" design idea in the previous literature. The idea is that by extrusion, we may preserve the foreshape of the projectile *despite* the inherently greater erosion rate at the nose tip, allowing that nosetip to exert its protective effect on the rest of the projectile. Now if the remaining front surface of the projectile erodes at a nonuniform rate, that could be compensated for by either making the protective front layer be of nonuniform thickness, or again by means of shape-preserving extrusion-tactics (e.g. perhaps using several coaxial extrudable tubes, each extruded at different rates). The extrusions of rod or tubes could even be controlled by an active feedback loop, with thickness sensing done by sonic, thermal, or capacitance-sensing techniques.

Another idea is to construct the heat shield layers of thin overlapping **shingles** or backward-combed **hairs**. The point of this geometry would be that a large amount of thermal expansion of the hot ends of the shingles/hairs could

[40] It has often been (wrongly) claimed in much of the literature that black surfaces are best, to permit more radiative cooling of the projectile. That is actually only true for those parts of the projectile which emit more radiation than they receive, i.e. which are not particularly relevant since they experience low heat load. This black-is-best thinking is only correct if one is interested in designing projectiles intended to remain unscathed and intended for environments in which the radiative heat input is negligible. Actually, in our high speed limit, we prefer all the key parts of the projectile to be *white*.

be tolerated, without leading to stress-induced "thermal shock" fracture.

Magic erosion-preserved shape? The following (new) **theorem**, may be of aerothermal interest. Under the following unproven assumptions about the nature of the foreshape and its erosion:
(1) the projectile foreshape $z(r)$ is axisymmetric, convex, monotone decreasing, and with bounded slope everywhere on $[0, R)$;
(2) erosion rate is a continuous functional (in some suitable metric, such as the L_2 metric) of $z(r)$;
(3) erosion preserves property 1;
we may conclude that there exists a particular foreshape which is preserved (except for the decrease of $z(r)$ by an overall additive constant) by erosion.

Proof: The class of foreshapes obeying property 1 is a compact convex set within the function space $L_2[0, R)$. Therefore J.P.Schauder's fixed point theorem from topology [81] shows that there must exist a fixed point of the erosion map. Q.E.D.

The idea of making the nose be *convex* is that any locally increased rate of erosion will decrease the convex curvature of the foresurface, thereby decreasing its local surface-to-volume ratio, and thereby (hopefully) increasing its rate of conductive cooling and decreasing its rate of radiative heat input and hence of erosion. In other words, this convex curvature will conjecturally cause the erosion process on our magic erosion-preserved shape to be inherently *stable* and self-uniformizing – surface patches more convex than the magic shape will tend to fallten out, and patches flatter than the magic shape will tend to erode less and hence start to bulge outward – i.e. the magixc shape will not only have a fixed point, but in fact a stable (attractive) fixed point.

Due to the launch velocity of 20 km/sec, the entire heat load will be thrust upon us in a timespan – the atmospheric traversal time – of order 1 second. Hence (as we said before) there will not be enough time for heat to conduct inwards from the surface of our projectile. Thus high heat input power is very beneficial – it means that the skin of our projectile will continually boil off, while the interior remains relatively cool, so we need not fear that, e.g., some internal part will explode and thus fragment off a chunk of projectile, thus "wasting" it for the purpose of evaporative cooling.

7.6 Other remarks

Recently NASA, as part of its "SHARP" (*s*lender *h*ypervelocity *a*erothermodynamic *r*esearch) *p*rogram, developed "ultra high temperature ceramic" (UTC) structural materials, based on ZrB_2/SiC, HfB_2/SiC and ZrB_2/SiC/C, capable of withstanding 3400 Kelvin temperatures continuously in highly dissociated hot air, and featuring high thermal shock resistance, low thermal expansion coefficients, and good machinability and formability. These were successfully tested in 3 conical reentry vehicles. Supposedly these would permit continuous flight of such cones at 8 km altitude with speed 2.7 km/sec – but at higher speeds or lower altitudes, ablation would occur. We are interested in 5-7 times faster speeds! This again makes it obvious that part of our projectile will have to be sacrificed (ablated away) in order for the rest to survive.

Of course, throughout the above, we have arbitrarily chosen graphite merely for the purpose of making concrete numerical calculations. In fact graphite might not be the optimum choice due to the facts that is electrically conductive, is black in color, and oxidizes in hot air. (However, bulk room temperature graphite cannot be ignited.) The UTC materials, diamond, BN, BNC compounds, thermoset plastic composites, and/or other refractories (MgO, fused SiO_2) might be superior, and presumably using them instead of graphite would not greatly change the calculation. For example, tests show [8] that a composite of bakelite (phenol-formaldehyde 3D network polymer) and linen erodes, in an air plasma torch providing 31 MW/meter^2 of heat flux, at 2cm/minute, which is about 1.9 times faster than graphite. Considering graphite is 1.5 times denser, this is comparable on a per-unit-mass basis. (And both erode much more slowly than stainless steel.)

7.7 Big "boom?"

The "boom" (energy transferred to the air) created by one of our launches may be of order 300 gigaJoules. This figure is equivalent to exploding about 70 tons of TNT. A better analogy, since the energy would be dissipated along a line segment many km long, rather than at a point, would be that this is equivalent to about 30 top-1-percentile lightning bolts combined into one. Based on past experience[41] with blasts of this order in mountain areas, such a boom could be audible 130km away. Therefore, it would not be acceptable to build the launcher in a populated area. But it should be acceptable to put it in some unpopulated location such as Canada's Mount Logan.

7.8 Summary

I've proposed new design ideas: low-drag projectile shapes, "shingle" and/or "hairy" construction to increase effective thermal shock resistance, extrudable rods or tubes possibly controlled via an active feedback loop, and erosion-stable foreshapes.

If (by means of these approaches or in spite of their absence) foreshape erosion is kept *uniform*, and if catastrophic thermal shock fracture is avoided, then present physical and mathematical understanding of hypersonic aerothermodynamics (which agrees with experiment to the extent that experiments so far have been feasible) suggests that the projectile will survie and only a few percent, or less, of the projectile-mass needs to be ablatively sacrificed in order to dump the heat – this even for a projectile of our rough proposed size (4000 kg) passing through the whole atmosphere in a timespan of a few seconds (initial speed 20-25 km/sec). This is because most of the heat is carried off by the air stream and not deposited on the projectile; and

[41] E.g., during construction of the Jungfraujoch rail tunnel in the Swiss Alps, 30 tons of dynamite accidently exploded in a blast heard 100km away. The 1945 Alamagordo atomic bomb test (15-20 kilotons) was audible over 70km away.

also because, at heating rates this powerful, the heat does not have time to conduct into the projectile, and hence the outer skin surface will boil off from the outside in in an orderly manner, with the inner material remaining solid and comparatively cool; and also because chemical effects (air oxidation) will not have time to occur since not enough air molecules will be able to make contact with the surface due to a molecular "traffic jam." (Oxidation reactions occurring in the gas rather than at the surface will be largely irrelevant since that heat will be left behind in the projectile's wake.) This conclusion also is supported by Allen's analysis [2].

The heat shield should be made of a refractory material, extremely resistant to thermal shock, with high heat of ablation per gram, layered above a high temperature insulator such as porous SiO_2. It appears that it will not be important for the material to be highly resistant to air-oxidation, so we shall not be forced to use oxides such as SiO_2 and MgO. It is unclear

1. whether radiative heating will be more important than convective heating (in which case white material would be much preferred over black),
2. whether it will matter if the material melts instead of subliming (or chemically decomposing) directly from solid to vapor.

BN, fused SiO_2, and reinforced 3D network polymers have been identified as especially promising commercially available materials, and compounds of B,N, and C, not yet commercially available, may have even better properties. The "boom" produced by a launch should be acceptable in unpopulated areas.

8 The numbers for a small-scale toy prototype

Unfortunately it is a lot easier to design a large high-speed launcher than a small high-speed launcher; the concept does not scale down well. The reason is that small launchers would require very fast switching times. However, designing *low*-speed small launchers is not difficult.

We envision a cylindrical projectile of length $L = 5$ cm, radius< $R = 0.5$ cm (both have been scaled down by a factor of 100 versus the full-size Earth-launcher of §5), and mass $M = 4$ grams. The design goal launch velocity is $V = 320$ m/sec. (About sonic speed in air.)

The magnetic field inside the projectile, and inside the launcher-solenoid: $B = 3.2$ Tesla. $p_{\text{mag}} = 41$ atm.

$MV^2/2 = 200$ Joules. $E_{mag} = 625$ Joules/meter. $L_{tot} = 32$ cm. $a = 1.6 \times 10^5$ meter/sec^2 = 16000 gees. $\tau_{sw} \leq 31\mu$sec. $\Phi = 2.5 \times 10^{-4}$ Weber. $\mathcal{E} = 10$ volts. $\tau_{trav} = 2$ milliseconds.

The only difficult parts to fabricate would again be the precision-timed switches. But of course, matters are simplified with this small an EMF (only 10 volts), since there are not going to be any worries about switch arc-over. This switch could also be built of BSCCO-2212 thermal-strategy switches (§6.3) or indeed even of YBCO thermal-strategy switches if low efficiency were acceptable. The scaling has been chosen in such a way that the switch-timing requirements are slightly more demanding in this scaled down launcher than for the full size one, enabling a developer to concentrate on this, the most difficult part of the design.

element	boils	melts	H_{evap}	cost
Helium	4.2	–	2.59	3.25
Hydrogen	20.3	14.0	31.6	0.59
Neon	27.2	24.6	104	200
Nitrogen	77.3	63.2	160	0.12
Oxygen	90.2	54.4	243	0.50

Table C: Properties of liquid cryogens: boiling points and freezing points (Kelvin), heat of evaporation (kJ per liter), and approximate cost (in 2002 dollars) per liter. *Gaseous* helium may be preferable to expensive or hazardous liquid cryogens. (Oxygen and Hydrogen are fire hazards.) Cryogen mixtures can freeze lower than pure substances. For example a eutectic mixture of 24% oxygen and 66% nitrogen freezes at only 50.1°K. Propane (C_3H_8) is the lowest-melting hydrocarbon (84°K; boils 232°K) but mixing it with 10-12% ethane makes it freeze at only about 80°K.

9 Superconductivity, thermal analysis, and refrigeration costs

Things will be much better if the main body of the launcher – or at least the outermost pipe – is only required to be cooled to liquid nitrogen or liquid neon rather than liquid helium temperatures because of the use of "high-T_c" superconducting materials for the rings or the pipe-coating. (See table C. Of course the projectile itself could be cooled to 4 Kelvin at comparatively negligible cost, because it is so small in comparison with the launcher.) If room-temperature superconductors ever appear, the situation would become optimal. High-T_c materials seem well suited for the outer pipe since no flexible wires (only a rigid, solid, passive coating) are needed. In fact, *no* flexible wires, *only* rigid parts, seem required anywhere, and *no* electrical connections between our superconducting components (or between them and anything else) are required. All this is favorable for high-T_c materials, which are brittle and difficult to work by any methods besides sintering powders. The trickiest parts to fabricate would be the rings, since they are required to have *interruptable* superconductivity.

9.1 Discussion of superconductors

We remark that among the more "conventional" (i.e., metallic) superconductors, Magnesium diboride MgB_2 [68] has $T_c = 39$ Kelvin (well above liquid neon). Meanwhile Niobium-Titanium NbTi, Niobium-Tin Nb_3Sn (which have both been heavily commercialized) Nb_3Al, and Nb_3Ge have $T_c = 9$, 18, 18.3, and 23.2 Kelvin respectively (all well below liquid neon). Wires, films, and sintered powders of MgB_2 have been made, but unfortunately [46][14] this material exhibits a large dropoff of critical current with magnetic field, which causes it to be much less useful in most high-field engineering applications, than one might have thought. But [68] various treatments which dirty or disorder the MgB_2, such as irradiation with fast neutrons, incorporation of SiC or Y_2O_3 nanoparticles, or Ti-doping, can raise $H_{c2}(0°K)$ from 16T to 30T and increase critical current densities by a factor of 5, although decreasing T_c. A new and promising process called TRUQ has recently been developed by T.Takeuchi et al. at Tsukuba Magnet Labs in Japan to make Nb_3Al conductors (in particular, Takeuchi used his Nb_3Al wires to wind the first 22.5 Tesla magnet made of metallic superconductors), and our data on Nb_3Al has been taken from their preprints [89].

See table S. Among the "high-T_c" ceramic materials, two of the most popular at present are $(Pb,Bi)_2Sr_2Ca_2Cu_3O_{10+\delta}$ ("BSCCO-2223," $T_c = 110$ Kelvin; usually about 10-16% of the bismuth is replaced by lead) and $Y_1Ba_2Cu_3O_{7-\delta}$ ("YBCO;" $T_c = 93$ Kelvin). The former is now commercially available as flexible wire and/or tape, and the latter will soon be. The highest T_c material I know of is $Hg_{0.8}Tl_{0.2}Ba_2Ca_2Cu_3O_{8.33}$ with $T_c = 138$ Kelvin [21] but it is not commercially available.

The high-T_c ceramic materials usually have much lower critical currents than one might have expected if they had been conventional metal, or inter-metallic, superconductors. [The $Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$ ("BSCCO-2212") material, the "weak sister" of BSCCO-2223 (in the sense of having lower T_c) has exceptionally high critical currents at liquid helium temperatures.] This is largely thought to be because they are polycrystalline; each crystal grain is a highly anisotropic material made of 2D layers; and grain boundaries between grains with highly misaligned crystal orientations are superconducting "weak links." (MgB_2, although intermetallic and "conventional," also has 2D-layered highly anisotropic crystal structure.) This picture is also supported by the fact that by post-diffusing Ca into the grain boundaries (see *Physics Today* 53,10 page 21) critical currents in bulk polycrystalline YBCO may be enhanced by a factor of 6-10. Therefore, to improve the current-transport properties of the high-T_c ceramic materials, people have resorted to

1. Aligned thin films. For example, American Superconductor soon plans to go into commercial production of RABiTS^{TM} tape, based on depositing 1-2μm-thick YBCO on an axially aligned substrate material. The resulting YBCO films, though polycrystalline, exhibit a high degree of angular alignment among the crystal grains, resulting in far higher critical current densities than for bulk polycrystalline YBCO. RABiTS^{TM} YBCO has critical current density 1700kA/cm^2 in the YBCO layer, reduced to about 500kA/cm^2 if the non-superconducting layers are reckoned as part of the thickness too, at 77°K. The similar YBCO tapes studied in [43] were 1 μm thick YBCO film deposited on an axially aligned backing. At 60°K, these tapes conducted 300 kA/cm^2 even in an in-plane (of the tape) magnetic field of 18 Tesla – and 90 kA/cm^2 at 70°K. This performance at 60°K, and indeed even at 70°K (if these films could be layered to create an effective bulk material) would be more than sufficient for our Earth-launcher design in §5. However, in these same experiments [43], if the magnetic field were instead oriented *perpendicular* to the plane of the tape, the critical current density at 70°K dropped to only 10 kA/cm^2 even at only 6 Tesla. This shows the high degree of anisotropy of the materials properties – and would force any launcher design based on such a material to be done carefully!

One of the most impressive achievements of this sort was [31], where 1-2μm thick films of $(Tl_{0.5}Pb_{0.5})(Sr_{0.8}Ba_{0.2})_2Ca_2Cu_3O_y$ (T_c = 117-119°K) were grown on aligned substrates to create tapes. These exhibited critical currents of 1200 kA/cm^2 at 77°K (in self field), 400 kA/cm^2 at 77°K and 6 Tesla (in-plane magnetic field), but only 100 kA/cm^2 at 77°K and 1 Tesla (*perpendicular* to plane magnetic field), dropping to 0 at 5 Tesla. This material (again if the films could be layered to create an effective "bulk" material) might be adequate to build a somewhat derated Earth-launcher (having only a 9 Tesla field) capable of operation at 77°K.

2. Melt "texturing." This refers to casting polycrystalline material from the melt, but then either cooling that melt in a strong magnetic field, or using certain "swept zone" remelting and directional solidification techniques, designed to encourage the crystal grains in the polycrystal to be comparatively well aligned, angularly. The preferred direction is controllable (and can vary spatially, if desired). For example, melt-textured YBCO (subjected to later neutron irradiation to enhance flux-vortex pinning) is found [26] to support a"trapped field" of 13.3 Tesla at 33°K (structural suport provided by outer steel tube). An even more impressive achievement was trapping 17.2 Tesla at 29°K in YBCO (post-infused with low-melting metal alloy to enhance strength and thermal conductivity, and with support from carbon-fiber/plastic exoskeleton) [90]. Indeed, [90] "it is evident that... much higher fields [than 17.24 Tesla] could be trapped" at 29°K. Indeed their plot makes it look as though 30T could be trapped. It is these results which serve to justify my claim that the 12 Tesla Earth-launcher design of §5 should work, using irradiated melt-textured YBCO, at liquid neon temperatures.

3. It is sometimes also possible to grow single crystals, but this is presently impossible for sizes larger than 1cm, and large crystals probably will never be of commercial importance.

9.2 Sampling of superconductive engineering feats

Unfortunately [47] BSCCO above 40°K exhibits large dropoff of critical current with magnetic fields, rendering it also useless for most high-field engineering applications, except at very low (liquid helium or thereabouts) temperatures, where 30 Tesla has been achieved with BSCCO-2212 material. There is more optimism about the possibility of making high-field magnets with YBCO

In 1997, a 103 horsepower superconducting motor was demonstrated at the Naval Research Laboratory using liquid nitrogen cooling and high-T_c $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ windings. The same motor produced 230 hp with liquid neon and 320 hp with liquid helium. Rockwell Corp.

substance	T_c	H_{c2}	dens	$\rho(T_c)$	$\rho(300°K)$	J_c
Nb	9.25	0.27	8.6		15	?
NbN	17.3	?	8.5			?
$(NbN)_{0.75}(TiC)_{0.25}$	18	20?	6.2			?
NbTi	9	14.5	6.5			≈ 100
Nb_3Al	18.3	29(4.2°K)				$> 10^4$, 116(17T), 26(23T)
Nb_3Sn	18.1	24.5	8.0			$\approx 10^4$, > 200(15T), > 100(10T)
$Nb_{12}Al_3Ge$	20.7	43.5				?
Nb_3Ge	23.2	38				?
MgB_2	39.4	16, 9(20°K)	2.7	0.4	9.6	1000(1T), 100(10T)
YBCO	93	100-670?, > 1(77°K)	6.4	5	380-4500	100(45°K), 200(25°K), 100(77°K, 1.3T)
NdBCO	96	> 10(50°K)	6.9	?	?	600(77°K), 76(77°K, 6T)
BSCCO-2223	108	465, 50(77°K)	5.4	1500-4500	1700-7000	> 10(10T, 4.2°K), 13.5(commrcl tape, 77°K), > 100(tape, 4.2°K)
BSCCO-2212	90?		4.4	17-40 $\times 10^6$	4-7 $\times 10^6$	100(10T, 4.2°K); 10(26T, 4.2°K)
Hg-223	138	50-600?				10-20(77°K)

Table S: Properties of superconductors (all type-II): critical temperature T_c (Kelvin, in zero applied field) and critical magnetic field H_{c2} (Tesla, at absolute zero), density (gram/cc), resistivities of the non-superconducting state at T_c and 300°K (in $\mu\Omega$cm), and critical currents J_c in kA/cm^2 (given in self-fields or low fields at (ℓ)He temperatures unless otherwise stated.) YBCO is an abbreviation for $Y_1Ba_2Cu_3O_{7-\delta}$ (melt-textured polycrystal) [39][52]. ($Nd_{1+x}Ba_{2-x}Cu_3O_{6+\delta}$ is similar but cheaper and may have superior properties; various other rare earths, e.g. Sm, Eu, Gd, Nd, may be mixed in...) BSCCO-2223 abbreviates $(Pb,Bi)_2Sr_2Ca_2Cu_3O_{10+\delta}$ (usually about 10-16% of the Bi is replaced by Pb). BSCCO-2212 abbreviates $Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$. Hg-223 abbreviates $Hg_{0.8}Tl_{0.2}Ba_2Ca_2Cu_3O_{8.33}$. Many high-$T_c$ ceramic polycrystals have small critical currents, due to grain boundaries; but *single crystals* or *films* of these materials can have larger critical currents. BSCCO and MgB_2 have exceptionally poor critical currents at high magnetic fields. For example [46] BSCCO at 77°K cannot conduct supercurrent beyond about 0.2 Tesla, despite the fact H_{c2} is, at that temperature, 50 Tesla! Also, it has been difficult to treat BSCCO to cause "flux vortex pinning" at above $\approx$ 40°K, also a severe disadvantage (neutron-irradiation of U-doped BSCCO, fissioning the U's to produce heavy-ion track defects, finally worked). For these reasons BSCCO is probably unsuitable, and MgB_2 is a lot less desirable than it might at first appear, for high-performance launchers or for high-field magnets. Nb_3Al produced by the new TRUQ process, on the other hand, shows excellent J_c's in high magnetic fields.

has now tested an experimental 1000-hp electric motor with $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$ windings cooled to 30 Kelvin by gaseous helium. It has reached 97% efficiency and is hoped to reach 98.5%.

Liquid nitrogen cooled high power HTS transmission lines are now beginning to be used in commercial applications. A pilot project underway at Detroit Edison's Frisbee substation involves replacing cables made of 10^4 kg of copper carrying 2400A at 24 kV (100 MW of AC power), by threading an HTS cable (based on 145 kg of BSCCO superconductor tapes enclosed in a flexible liquid-nitrogen cryostat enclosed in dielectric) through existing ducts.

9.3 Refrigerants and their costs

The initial cost of filling a tube 10 km long and with cross-sectional area 0.5 meter^2 with 5 million liters of liquid nitrogen would be about 600,000 dollars at \$0.12 per liter (current bulk market prices). This would be increased to about \$1000 million if liquid neon (and about \$16 million if liquid helium) were used instead.

To reduce costs, it is therefore important to keep the launcher length short, and to insulate it well. Similar cryogen and thermal insulation problems have been encountered in the design of superconducting particle accelerators, cf. §12.7.

9.4 Thermal insulation, cooling costs

The heat flow between two silvered surfaces separated by a layer of vacuum, one cold, and the other at room temperature, is[42] about $0.05\sigma_{SB}(300\text{Kelvin})^4 = 23$ Watt/meter^2 assuming 90% reflective silvering (10% emissivity). With an outer radius of 1.43 meters, our tube (if insulated this way) would need 103.5 kW of cooling per km of tube-length, i.e. < 1 MW total for the 9-km-long launcher of §5. It is commonly reckoned[43] that 1 Watt of cooling at 77 Kelvin requires 10-12 Watts of power at room temperature (due to refrigeration inefficiencies), which would bring this up to 10-12 MW. This would be quite acceptable – and could be reduced by about a factor of n by using n layers of Dewaring. *But* 1 watt of cooling at 4.2 Kelvin is commonly reckoned to require 300-1000 watts of power at room temperature, which would bring 1MW of cooling power up to 0.3-1 GW, an imposingly large figure.

A typical commercial 200-liter laboratory Dewar empirically loses all of its liquid nitrogen in about 150 days. The loss-time for liquid helium Dewars typically is half that. (Based on the heats of vaporization one would expect helium to evaporate over 61 times more quickly than nitrogen, not 2 times. So evidently they insulate helium Dewars better, e.g. use an additional intermediate-temperature Dewar layer.) Presumably better insulation will be possible for the launcher (since, due to its larger diameter, it has a smaller surface-to-volume ratio, and since its ends are far away), suggesting loss of cooling will take a year. (Empirically, larger Dewars have longer loss-times.) That would add up to a refrigeration bill of about \$600,000 per year with liquid nitrogen, or \$1000 million with liquid neon, and about \$20 million with liquid helium. This estimate is in the same ballpark as the more theoretically based estimate above.

In principle there is no limit to how thick insulation could be made, so that in principle continuing cooling costs could be (after a large *initial* cooldown cost) made *negligible* – just keep it cold and evacuated forever. (It is an open question, though, how good the insulation could *actually* feasibly be made. Also, such benefits could only be gained if any repairs, etc. were conducted by robots operating under cryogenic vacuum conditions.)

9.5 Shrinkage?

When one cools something this big to cryogenic temperatures, there could be considerable problems with shrinkage, possible cracking, and possible problems with brittleness under the large mechanical stresses arising during launches[44]. All these have to be considered and eliminated by design and pre-testing. However, even larger cryogenically cooled structures (particle accelerators employing ℓHe-cooled superconducting magnets, cf. §12.7) have been built, so evidently this obstacle is not insuperable.

9.6 Danger of quench

In discussions with C.J.Martoff after most of this paper had been written, it unfortunately became apparent that the following phenomenon [50][38] could be a very serious performance-limiting factor.

During projectile flyby of a superconducting ring (and also during winchback), the magnetic environment near that ring changes drastically, possibly from as much as ± 12 Tesla to near zero.

Fortunately, for the reasons mentioned at the end of §3, it should be possible to use a much less magnetic projectile with closely spaced rings than would be required in the "$f \approx 1$" limit of well-seperated solenoid rings. The Earth-launcher design of §5 involves $f \approx 0.12$. In that case the additive change would be far less drastic – only of order 2 Tesla.

Such a drastic change necessarily will cause the flux vortices that penetrate the superconductor material, to rearrange themselves. (One may see that it is impossible for them to remain completely pinned because if they did so, then critical current densities would be exceeded in parts of the superconductor.) Such rearrangements will allow ohmic-like energy losses. Such losses will cause heating. In the flyby case, this heating will occur very quickly. *Such heating could be enough to trigger a disastrous quench.*

Indeed, a close look at the 17-Tesla trapped field paper [90] reveals some very interesting information. They started with a YBCO cylinder (2.65cm in diameter, with a 1mm

[42] $\sigma_{SB} \approx 5.670400 \times 10^{-8}$Watt/meter^2/°K^4 denotes the Stefan-Boltzmann radiation constant.

[43] Providing a watt of cooling at a (low) temperature T_L, would require, even with an ideal Carnot refrigerator, $(T_H/T_L) - 1$ watts at the (higher) environmental temperature T_H. Real refrigerators are worse.

[44] The Saturn V moon rocket stood about 100m high, but shrunk by 25 cm when filled with cryogen liquid fuels.

diameter hole drilled on its axis, and with embedded magnetic and temperature sensors) in a uniform 17.90 Tesla external field at 29°K. Their YBCO's strength, thermal conductivity, and heat capacity had been enhanced by infiltration of a low-melting metal alloy ($Bi_{0.5}Pb_{0.27}Sn_{0.13}Cd_{0.1}$; melts 70°C) into microcracks and voids in the YBCO, and by use of a carbon-fiber wrapping. They then gradually ramped down the external field to zero (1 hour rampdown time). [With an earlier (weaker and less thermally conductive) cylinder of YBCO and a faster rampdown, they had experienced a disastrous sudden quench from 17T down to low trapped field, which suddenly raised the temperature of their sample from 29 to 70°K. Examination of that quenched sample afterwards revealed a large crack which may have been caused by, or caused, the quench.] After rampdown, there was a 17.24 Tesla field trapped in the center of their YBCO, and a nonuniform field profile within their YBCO decreasing from 17.24T at the center to 0 at the rim. This change in field profile tells us that flux vortices rearranged themselves during the rampdown. The $17.90 \to 17.24$ decrease (3.6%) tells us that some energy was lost via flux vortex creep. After their rampdown was over, field measurements continued for another 20 minutes, during which only a tiny amount of further loss (less than 1 pixel wide on their graph) occurred. This tells us that very little flux vortex creep happens in YBCO at 29°K on 20 minute time scales under static conditions, even at high field gradients (and in irradiated YBCO, presumably there would be even less vortex creep). But at higher temperatures, flux creep losses can be much larger, e.g. one experimenter [1] saw a 20% loss of stored magnetic energy in a YBCO single crystal "permanent" magnet during 1 hour at 85°K (versus $T_c = 91°$K for that crystal; flux "lattice melting" occurs [40] in YBCO at 85-88°K).

Flux vortex motion is difficult to model [3] at the microscopic level. But fortunately, the energy losses associated with flux-vortex rearrangements in "hard" superconductors (i.e. with pinned vortex lattice) may be modeled [50] *macroscopically* in a way similar to the modeling of hysteresis losses in permanent magnets. Specifically, there is a plot of magnetization versus applied magnetic field, and the total energy loss experienced during some alteration of the applied magnetic field is the area within the appropriate portion of this curve. Thus, a trivial upper bound on the energy release due to vortex rearrangements will be the total magnetic energy stored within all those flux vortices! More realistically, probably only about 1/8 (e.g. $\approx 1/2$ quadrant) of the full hysteresis curve will be traversed during launcher operation – and indeed far less than that, e.g. only $\approx 1/30$, if we are using the "$f \ll 1$ trick" at the end of §3 to make the magnetic environment change be small – in which case this upper bound should be multiplied by $\approx 1/2$ (or 0.1 with $f \ll 1$). The energy density in a 12-Tesla magnetic field is 57 Joules per cc. (Actually the magnetic field profile within launcher YBCO is only ±12T at its *surface* and decreases in the interior, hence the average, as opposed to peak, magnetic energy density within our YBCO is only about 19 Joules/cc.) 57 Joules of heat would be enough to heat a cc of 27°K YBCO by about 70°K, which certainly could be enough to trigger a quench.

Our troubles are increased by the fact that heat capacities are usually much smaller at low temperatures. The vibrational component of heat capacity, according to Debye's theory, is ultimately proportional to T^3. Thus YBCO has a heat capacity of about 1.57 Joules/cc/Kelvin at 120°K, but only 0.90 Joules/cc/Kelvin at 72°K, and probably (?) only about 0.05 Joules/cc/Kelvin at 27°K. (Compare room temperature water, with a heat capacity of 4.2 joules/cc/kelvin.)

Hence if we more optimistically were to use the average rather than the peak magnetic energy density, and were to multiply by 1/2, we would only involve 1/6 of the heating energy; *but* this would produce a temperature rise of a lot more than 1/6 of 70°K – in fact, probably about 45°K – due to YBCO's smaller heat capacity at low temperatures. With the f
$l1$ trick used, perhaps heating to 45°K would occur. Again this would quite likely be enough to trigger a quench.

It helps that current density *decreases* during projectile flyby – thus even if our rings are heated during the flyby they could still hope to avoid exceeding their (hot, hence reduced) critical current limits.

To protect against such a quench, I recommend the same kind of measures adopted by [90], namely, using a finely intermixed "composite" material made of both YBCO *and* an electrically and magnetically inert companion material, with this inert material selected for high heat capacity, mechanical strength, and thermal conductivity (in descending order of importance[45]). Electrical conductivity could be a bad property for the companion material to have, since it would be vulnerable to eddy-current heating by fast-changing magnetic fields; *but* if the companion material were only in the form of small particles, electrical conductivity would be no problem. The $Bi_{0.5}Pb_{0.27}Sn_{0.13}Cd_{0.1}$ alloy used by [90], since it was made of metals with low Debye temperatures (Bi≈ 119°K; Pb≈ 90°K; Sn≈ 200°K; Cd≈ 209°K), probably had a heat capacity of about 0.3 joules/cc/Kelvin at 27°K.

A better material might be TiO_2. This material is commercially available in large quantities as submicron powder (for use as white pigment). Because TiO_2 melts at 2128°K, versus 1270°K for YBCO (and 1166°K for BSCCO-2212) and because it has approximately the same thermal expansion coefficient as YBCO, it seems plausible TiO_2 powder could be mixed with the YBCO melt to create a slurry, yielding, upon solidification, a composite material. Because TiO_2 has [77] an exceptionally high heat capacity of 1 joule/cc/kelvin at 24°K, any such composite would be far more quench-resistant than plain YBCO.

[45] Even the best thermal conductors will not be able to redistribute heat over a 1cm length scale on a submillisecond time scale. Therefore, one should instead concentrate on finely subdividing the composite material, at, say, a 500nm length scale (since even a moderate thermal conductivity suffices for heat redistribution on that length scale on our time scales) and making one of the components of the composite have high heat capacity. Because the Ginzburg-Landau coherence length ("size of a Cooper pair") for YBCO is only about 2nm, any 500nm-scale subdivision should not hurt superconductivity.

Solid CO (CO boils at 81.7°K and freezes at 61.8°K) presumably could be infiltrated into the microcracks in YBCO at least as easily as that Bi-alloy, and also has an exceptionally high heat capacity [77] of 0.84 joule/cc/Kelvin at 25°K. Solid N_2 or oxygen-nitrogen mixtures should behave similarly. These would also have the advantage of undergoing a phase change (melting) – which could prevent exceeding that melting temperature.

Yet another possible approach might be to use thin YBCO films (such as "RABiTS^{TM}") bonded to interlayered thicker nonsuperconductive material.

All this unfortunately would force a slight redesign of the launcher in §5; since the YBCO-*composite* rings would now have to be radially about 3 times thicker to accomodate the volume of the inert companion material. By making a thin surface layer of this 2:1 composite be pure-YBCO, any switch-contact planes could enjoy full superconductivity and hence the switches would gain a helpful enhancement of critical current, relative to the bulk, by a factor of 3. (Cf. the discussion of switch critical current worries at the end of §6.2.2.)

With a 2:1 inert:superconductor ratio, quenches presumably would be prevented because the available heat from magnetic hysteresis effects would be inadequate to raise the temperature enough to cause a quench, at least in the decreasing-current situations present in the launcher. *After* projectile flyby, if a ring had not been "switched off," current would again begin to increase, but at that point a quench would actually be *desirable*. This highlights an amusing conflict: we want to make our superconductor more quench-resistant, but, if we plan to use the thermal switching strategy (§6.3), we *want* a quench. This leads to the intruiging possibility of tuning the quench-resistance properties so that quenching would occur automatically at precisely the right time to cause ring switch-off, with no need for any active control.

The total energy loss due to vortex rearrangement effects would be (as a fraction of launch energy) upper bounded by the ratio of the magnetic energy within the YBCO, to the total stored magnetic energy, which in our Earth launcher design (§5) is about 1/70 (and as we've noted, this probably should be reduced by a factor of 2 to get 1/140 since hysteresis will not convert all of the magnetic energy to heat, and there would be further reduction if we were using the $f \ll 1$ trick mentioned at the end of §3 as we plan to in §5 e.g. by a further factor of 4-5) as the estimated inefficiency due to these hysteresis losses. Unfortunately this figure would ultimately be magnified by refrigeration inefficiency factors of, e.g., 50:1, which in this case would yield 8% inefficiency.

10 Is this a fearsome weapon? Comparatively speaking, no.

The launcher could be used to launch bombs into near-orbital trajectories, from which they could (by means of small attached rockets) be maneuvered to land nearly anywhere on Earth.

However, let me now make counterarguments suggesting that, fortunately, it actually is not a good weapon (at least, comparatively speaking). It seems plausible to me that the launcher will be unable to launch more than about 1 or 2 times per day. At 9 km long and with delicate thermal insulation, cryogens, vacuum, and high powered magnets, it would be an easy target for an enemy to deactivate. On both these counts, today's rocket-bombs in multiple hardened silos seem, therefore, a comparatively *more* fearsome weapon, for those countries that can build them[46]. Furthermore, the launcher would be very expensive and would best be built at a location near both an especially high mountain and a low-altitude place in which deep tunnels could be drilled, and in which there is a convenient near-constant slope extending for many miles. Such locations are rare and certainly could not be kept secret. This all suggests that only one launcher would be built, by an international consortium, in a location probably not regarded by most (or all) participating countries as particularly militarily desirable.

11 Suitable mountains

11.1 Mountain desiderata and table

Table M lists various interesting candidate mountains. Mountain desiderata:

- We want a high mountain (over 4000 meters) so that the projectile will be retarded by the smallest possible amount of atmosphere.
- We also want a large total vertical rise above its surroundings, so that we may bore the shortest possible tunnel down into those surroundings to get a given total launcher length. I have gathered data on "vertical rises" of mountains from written descriptions of mountains [35][56], but these are unfortunately subjective. If one has a certain launch angle θ in mind, a wholy objective notion Δ of the "rise" of a mountain would then be: the maximum altitude difference between two points on the mountain, both of which lie on a line at angle θ to the horizontal. Δ values could be ascertained from topographic maps [48] of the area near each mountain. However, in most cases I have not done so.
- Unfortunately for us, steep mountains with large Δ tend to be visually spectacular and hence are often preserved in national parks.
- It is best if the mountain is located near the Earth's equator, and is shaped in such way that the launcher can go up its west slope. This is so that we may take advantage of the

[46] Furthermore, any country wishing to carry out a surprise attack with nuclear bombs would of course have a much easier time of it by simply smuggling those bombs to their targets by low-tech means, hiding them, then setting them off by remote control. (Indeed the attacker, in this case, might well be able to remain incognito, and the bombing could occur at a much later date than the smuggling. Personally I find it difficult to believe that such hidden smuggled bombs have not *already* been implanted by various nuclear-armed powers in numerous strategic locations.) Therefore, the emphasis by certain politicians and defense contractors on rockets and especially on super-expensive "star wars" hypothetical anti-rocket defenses is ridiculous and could be compared unfavorably to France's pre-WWII emphasis on the "Maginot line."

Earth's 0.46 km/sec rotational speed. Roughly speaking, I suspect being on the equator with west-to-east launching, should be worth approximately the same as 400-1600 meters of extra altitude (depending on the drag coefficient). (On the other hand, *east-to-west* launching on the equator is like *losing* altitude.)

• If the west side of the mountain is *coastal*, that could be a construction advantage since it would allow the "tunnel" actually to go under the sea (less digging required). But that perhaps really is a disadvantage (less structural support, need to seal out the water).

• If the mountain is well *isolated* from human settlements, that could be an advantage – since huge sonic booms would be more acceptable. But on the other hand, extreme isolation makes it more expensive to build.

• Most especially high mountains (especially Denali, Logan, and the Himalayas) are covered with *ice*. This might be a disadvantage since we would have to tunnel through rock all the way and probably would not be able simply to place the launcher on top of the ground, due to hazardous properties of the ice. On the other hand, probably a large amount of digging and tunneling would be required regardless because probably no mountain's surface contains a long, exactly straight, line leading up to its summit. In the event of largely subsurface construction, iciness would be largely irrelevant. (It may be of interest that some of the Andes rising out of the Atacama desert get so little precipitation that they have almost no ice.)

• The probability and seriousness of *volcanic activity* would have to be carefully evaluated. For example, Chimborazo has never erupted in historical time. But recently, liquid water has been found within 25 meters of its summit, so there must be a geologic heat source not far underneath.

Neate [56] lists all the world's $\geq$ 7000-meter peaks (all of which are in the Himalayas). Many descriptions of mountains are in mountain books including [56][35]

11.2 Comments on individual mountains; refutation of some geographical myths

It is often stated that Mauna Kea or Mauna Loa is the mountain with the world's largest vertical rise (provided the *subsea* part is considered also).

But really, this statement is only a half-truth. All such claims depend upon how far away horizontally one is willing to go while still considering it part of the "same" mountain! Going 55km west from Mauna Loa suffices to reach 4.2km-deep ocean. Going 50km NE from **Mauna Kea** reaches 5.3km-deep ocean, for a total rise of 9.5km. Unfortunately this 9.5km rise is useless for our purposes because it is at such a shallow angle (10.8° above horizontal). If one is willing to accept smaller angles one can get larger rises than in Hawaii. On the middle of the East side of Mindanao (Phillipines) there is a 2810m-high mountain, and going 120km West from there lands you in a 9144m-deep point of the Phillipines subocean trench, for a total rise of 11.95km. Klyuchevskaya Sopka (4750m) on the Kamchatka peninsula seems about 200km from a 7500m-deep point where the Kuril and Aleutian subocean trenches join, for 12.25km of rise. Some **Peruvian Andes** are over 6km high and within 350km of 6km-deep points in the Peru-Chile subocean trench – so if 350km horizontal displacement is considered acceptable, then a total rise of 12-13km is possible there. But *all* of these huge rises are, on average, at too small an angle to be useful for us.

In general, *volcanos* (bottom part of table M) have comparatively shallow rise angles. Thus Fako (Cameroon mountain) rises out of the sea, but it is a volcano and hence that rise is too shallow (10°). Cotopaxi rises at an exceptionally steep angle (for a volcano) of 30° on 3 sides, 27° on the fourth.

Nanga Parbat and Mont Blanc both have the advantage of being on the west ends of their mountain chains. Nanga Parbat, Ama Dablan, Ushba, Matterhorn, Jirishanca, and K2 all are particularly renouned for having long *steep* slopes (40° to 90°).

Aficionados of Alaska's Mount **McKinley** and Canada's Mount **Logan** often claim (contradicting each other – exaggerations are unfortunately common in descriptions of mountains) that their mountains have the greatest vertical rises above their surroundings. However, *both* of these claims are quite false. Examination of high resolution topographic maps [48] shows that the lowest spot within 9km of Mt. McKinley's 20320 ft summit is on Peter's Glacier about 9km North (and slightly West) of it (and only about 5 km North of the subsidiary 19470 ft summit) with altitude 6000 ft, for a total rise of 14320 ft= 4.36 km (respectively 13470 ft= 4.11 km). Going 5 km SSE from Mount Logan's 19850 ft summit reaches a point with altitude 7500 ft, for a 12350 ft= 3.76 km rise, with perhaps 13000 ft being possible by more optimization. The nearby Mt. **Saint Elias** (18008 ft): go South 8 km to reach a point with altitude 3000 ft, for a rise of 15000 ft= 4.57 km, or South only 5 km to reach 5000 ft altitude, for a rise of 13000 ft= 3.96 km.

But even if all three of those mountains were regarded as rising from *sea level*, their rises still are all topped by at least three Himalayas: **Nanga Parbat** rises a huge 22-23 thousand feet from the Indus River valley to its West and North about 20 km away; it also features an infamously huge and steep "South wall" 4500-4600m high. (Nanga Parbat is pictured on the cover of *The Himalayas* by Nigel Nicolson & Time-Life books, 1975.) **Annapurna** and **Dhaulagiri** (both > 8000m peaks) are 38 km apart and between them flows the Kali Gandaki river in a gorge at altitudes 1160-2010m. Annapurna is about 19km East of a point in the gorge with altitude about 1600m between Ghasa and Tatopani, for a rise of 6490m. Dhaulagiri is about 12.5km West of Larjung (alt. 2560m), located in the gorge, for a rise of about 5610m. Due to their great altitude, large Δ, reasonably low latitude, isolated (but not too isolated) locations, and the possibility (for Nanga Parbat and Annapurna?) of a long west-to-east ascent, Nanga Parbat, and Dhaulagiri or Annapurna, seem to be the top candidates as launcher locations.

name	summit	rise	latitude	longitude	comments
Nanga Parbat (N.Pakistan)	8126	6850	35.2N	75.6E	I,F
Annapurna (mid-Nepal)	8091	6500	28.6N	84.0E	I,F
Dhaulagiri (mid-Nepal)	8167	5600	28.7N	83.5E	I,F
Denali=Mt.McKinley (Alaska)	6194	4200	63.1N	151.0W	FF,II
Mount Logan (Yukon, Canada)	5959	3760	60.6N	140.4W	WC, FF, II
Mt Saint Elias (Yukon)	5489	3960	60.3N	140.9W	WC, FF, II
Ama Dablam	6856	2300?	27.9N	86.9E	I
Mont Blanc (France)	4807	4000	45.9N	6.9E	F, II
K2 (China/Pakistan)	8611	3660	35.9N	76.5E	FF, II
Everest (Nepal)	8850	3960	28.0N	86.9E	FF, II
Jirishanca (Peru)	6126	2000?	10.3S	76.4W	F, II
Kinabalu (Borneo)	4094	2500	6.1N	116.5E	WC
Ushba (Caucasus, Georgia)	4710	3350	43.1N	42.7E	FF, I
Weisshorn (Switzerland)	4505	2780	46.1N	7.7E	F
Matterhorn (Switzerland)	4478	2740	46.0N	7.7E	
Chimborazo (Ecuador)	6267	3350	1.4S	78.8W	WC, F, I, EV
Cotopaxi (Ecuador)	6000	3000	0.7S	78.4W	AV, I
Kilimanjaro (Tanzania)	5895	4700	3.1S	37.5E	F, EV
Ararat (Turkey)	5137	4420	39.7N	44.3E	F, EV
Mauna Kea (Hawaii)	4205	9000	20.7N	156.2W	DV, C
Mount Rainier (Washington)	4392	big	46.9N	121.8W	F, DV, WC, I
Mount Shasta (Calif., US)	4317		41.4N	122.2W	F, DV, WC, I
Mauna Loa (Hawaii)	4170	9000	19.5N	155.6W	AV, WC
Fako (Cameroon)	4095		4.2N	9.2E	AV, WC
Vol. Tajumulco (Guatemala)	4220		15.0N	91.9W	AV, C
Klyuchevskaya Sopka	4750		56.1N	160.6E	AV, C

Table M: Some interesting mountains. Key to comments: F=far from human settlements. FF=very far. I=covered in ice. II=very large amounts ice. WC=west side is near seacoast. C=near seacoast. DV=dormant volcano. EV=extinct volcano. AV=active volcano. “Rises above surroundings” unfortunately are ill-defined and sometimes anecdotal, see text for discussion. Only the rises of the mountains in the top 6 lines of the table are based on actual examination of topographic maps by me personally.

12 Construction and operating costs

I estimate that the launcher could be built for a cost of at most $20 billion, but at least $2 billion (in 2002 dollars), and operated for about $10-100 million per year. The purpose of this section is to justify these estimates, especially the $2-20 billion construction cost, and to compare these costs with those of today's rocket-based space programs.

12.1 High mountains – a problem?

Of course, nobody has ever built anything very large on an 8000m mountain before, and such mountains are very hazardous due to avalanches, risk of falling, frostbite, storms, "snow blindness" from solar radiation, and low oxygen levels at those altitudes. Thus during the years 1922-2001, 171 people died on Mount Everest, versus 1496 people who summitted. (The deaths:summits ratio was 29:28 during 1922-1972, but it improved to 47:882 in 1994-2001.) Another indication of difficulty is that, in 1760, a large monetary prize was offered to the first to climb Mont Blanc, but it took 26 years before it was collected; and during the 1920s and 1930s at least 7 expeditions tried to climb Mount Everest, but all failed, with the first success coming in 1953. However, this does not worry me greatly because no large scale industrial effort has been made (for lack of any reason to try) to do anything on such high peaks. When such an effort *is* made, I have no doubt that matters will improve dramatically. For example, before 1900 nobody had ever survived diving to 150m beneath the sea, visiting the South pole, or ascending to 8000m above sea level, but nowadays these feats are routine. I forsee no great difficulty in protecting against either the solar radiation, the thin air, the storms, the risk of falling, or the avalanches. I expect much of the launcher will be subsurface and built in modular sections. Additional structures might need to be built to try to divert avalanches and glaciers over, around, or under any sections of it that lie aboveground.

12.2 Some relevant high altitude construction projects

China in 2001 began building the world's **highest railway**, stretching 1100km from Golmud city in Qinghai to Tibet's capital Lhasa. It is planned to cost $3.3 billion (i.e. $3000 per meter) with 80% of the track being laid on ground over 4000m in altitude, about 50% of it frozen, with the highest track at 5072m (265m higher than the highest Alp, Mont Blanc). It has been found that laborers on this project need to be in excellent physical condition but still can only work 6 hours per day above 3000m; also diesel locomotives can only run at about 50-60% of full power at such altitudes. About 1km of track seems to be being laid per day.

The Swiss Jungfrau tourist cog railway (1.02m gauge) was constructed during 1896-1912 and funded from tourist revenues. It reaches 3478m altitude at its final stop, the Jungfraujoch hotel (on a col between the Jungfrau and Mönch summits, 4158m and 4099m respectively). This contains a restaurant, an "ice palace" carved into the interior of a glacier, and an observation post reachable via a 111m-high elevator.

The first section of this rail line is in the open air, but beyond Eigergletscher it runs through a 7.8km-long tunnel (10 ft. high and 10 ft. wide), piercing the rock of the Eiger, Mönch, and Jungfrau alps (including windows looking out of the infamous North face of the Eiger). This rail line has slopes as high as 0.7. The original plans called for extending it 610m beyond the Jungfraujoch, leaving the Jungfrau's summit to be attained by an elevator 74m high, but this final extension was never constructed. The total cost of construction was about 14.9 million Swiss Francs, i.e. about $10 million at today's exchange rate, i.e. less than $1000 per meter. Note that the North face of the Eiger was first climbed in 1938 (after many climber fatalities during the 1930s) – long after the railway was built![47]

There is a silver mine atop the snow capped 5624m peak Chorolque near Potosi Bolivia, claimed to be the highest mine in the world (and which once was one of the richest).

La Paz, the capital of Bolivia (pop. 1 million, founded 1548) is 3636m altitude (airport at 4082m). Lhasa, the capital of Tibet, is comparable. Travelers usually take several days to adjust to the altitude.

12.3 Deep shafts

The world's currently deepest single drop mineshaft is in the South Deep gold mine located in Westonaria, Gauteng Province, South Africa. It sinks 2991 meters below the collar and took almost 7 years of sinking; this entire mine's construction cost was about $\$5 \times 10^8$. The nearby "Western Deep mine" contains some tunnels 3.5km below the surface. The South mine is currently being deepened to 4.1km, and the Western Ultra Deep Levels are planned to go down to 5km in the next few years[48]. All this suggests that the deepest we will be able to dig our tunnel is 5km, so the total vertical rise of the launcher tube will be at most 5km plus the vertical rise of its mountain. Commercially available tunneling machines can dig (and have dug) tunnels up to 10m in diameter 15m per day through solid rock, including nonhorizontal tunnels with slope 0.68.

12.4 Launch Energy

The cost of the energy (800 GJoules) required for a launch would be very small compared to current launch costs. (This energy is equivalent to running a large truck's 300 kw engine for 1 month.) In other words, energy costs, compared to conventional space programs, would be tiny: order 1000 times smaller.

12.5 Vacuum

The energy required to evacuate the launcher volume of 1.4×10^4 cubic meters against atmospheric pressure is about

[47] The Eiger and Mönch were first climbed by easier routes in 1858 and 1857 respectively. Another cog railway, built in 1891, goes to the 4300m summit of Pikes Peak in Colorado.

[48] The deepest known natural caves are ≥ 1.6km deep. Lake Baikal is 1637m deep.

1.4 gigaJoules. This is tiny in comparison to launch kinetic energy. A vacuum of 10^{-3} Torr (achieveable with conventional rotary pumps) is adequate to assure that the total energy lost to air friction, even if multiplied by a 1000:1 refrigeration inefficiency factor, is still well below 1% of the projectile's kinetic energy.

12.6 Refrigeration

These energy reckonings have ignored the (potentially large) refrigeration (energy and monetary) costs. We have estimated in §9.3 that these would be of order 10MW and $600,000 per year if liquid nitrogen is used (but more like $16 million per year with liquid neon). First, this still tiny compared to the costs of conventional space programs (see below). Second, with 10 MW continuous refrigerator power, the energy-cost of refrigeration would be smaller than the launch kinetic energies (800 GJ/launch) if at least 1 launch were made every 22 hours.

12.7 Crude estimate of construction costs

The cost of building the launcher (9 km of mechanically strong, precisely placed, superconducting magnets, a vacuum tube, a gas-liquifaction plant) would be about $\$2 \times 10^{10}$. This estimate is based on the fact that the notorious "superconducting supercollider" project[49] had a "final" budget of $8.25 billion in 1991 – but was then canceled by the US congress after more cost overruns. This was a large synchrotron for producing two counterrotating 20TeV proton beams, occupying a tunnel 87 km in circumference. It was to employ 10^4 superconducting magnets, most of them 7m-long, 6.6 Tesla, and (ℓ)He-cooled. (Although the beam tube was only a few inches in diameter, the magnets were enormous, probably because of a desire for highly uniform or accurately shaped magnetic fields.) Of course, the SSC used high electrical power and ultrahigh vacuum. The beam tube was to be contained within two concentric Dewar-thermal shields (the outer one to get down to $(\ell)N_2$, the inner one to get down to (ℓ)He temperatures; these temperatures were to be maintained by cryogen pipes) inside an outermost vacuum shell (at room temperature) about 2m in diameter.

Our tunnel is shorter, our magnets need not be especially precise, our outer vacuum shells are smaller, and our vacuum need not be especially high, suggesting our launcher would be cheaper than the SSC. But on the other hand the launcher would have to be built very robustly and it would need to be located on a high mountain, suggesting it would be more expensive. So: to play it safe let me "guess high;" the result is $20 billion. Note, for a 10km-long launcher, this corresponds to $2 million per meter.

12.8 More detailed look

The cost of sinking the world's deepest mineshaft was $0.17 million per meter (including all costs for all the other equipment and shafts and everything else in that mine). The cost of constructing the world's longest undersea rail tunnel (Japan's Seikan Tunnel joining Hokkaido to Aomori Prefecture on the northern edge of Honshu, opened March 1988 after 6 years construction, 240m deep, 54km long, 10m diam) was $0.13 million/meter (including rails, extra ventilation shafts; final cost greatly exceeded initial cost estimates). Of course, these shafts and tunnels were of much larger diameter than ours.

Costs of large ℓN_2 Dewar flasks (multiple cubic meters capacity) are presently about $20000, so it seems safe to estimate the cost of Dewar-insulating the entire launcher (assuming mass production of Dewar segments) as $0.02 million per meter.

BSCCO high-T_c superconducting tapes based on powder-silver technology capable of carrying 1 kAmp at ℓN_2 temperatures are available from American Superconductor Co. for $300 per meter, which they expect will fall to $50 per meter in 2004. Of course we have *far* less severe materials processing requirements since we do not require flexible wires, but even if we *were* to make the superconducting rings out of this stuff (which we won't), they would cost (if 33 rings per meter, each ring carrying 85 kA round its 3.2m circumference) at most $3 million per launcher-meter, for a total cost (for 9km long launcher) of $27 billion – over budget, but at the predicted 2004 price this would be only $4.5 billion. I will predict that this price of $0.5 million per launcher-meter should be more than adequate for the costs of all the superconducting components.

A different way to estimate superconductor costs is to consider the fact that 99.9%-pure Yttrium metal costs about $2200/kg, 99.9%-pure Neodymium metal about $1100/kg, and pure Barium costs $550/kg. Assuming pessimistically that pure metals were used as the feedstock in synthesizing YBCO or NdBCO, we find that the cost of the required 5 million Kg of YBCO, or 6 million Kg of NdBCO (the costs of processing, and of the other atomic elements, should be by comparison negligible, e.g. copper costs below $3 per kg) would each be about $3 billion, i.e. about $330,000 per launcher-meter. (Actually, there is the potential to save a lot of money versus these estimates by using a natural mixture of [unpurified] rare earths [76] instead of, e.g. pure Yttrium.)

The Lake Ponchartrain Causeway (world's longest bridge, two parallel spans 80ft apart, each 40 km long, made of steel and prestressed concrete) cost $60 million to build in 1956 and 1969 ($30 million and 2 years construction time per span), which is $1500 per meter. The Chesapeake bay bridge (two parallel spans, each 6.6 km long, carrying 2

[49] Lest the reader disbelieve SSC cost estimates (since the SSC was never completed), I point the following facts about the RHIC (Relativistic Heavy Ion Collider) operating at Brookhaven National Labs since June 2000. It was built in a 6m-high tunnel 4km long and 4m below ground. Threaded within this tunnel are two parallel 2m-diam metal vacuum tubes, each containing thermal insulation, the ultrahigh-vacuum ion-beam tube, cryogen coolant pipes, thermal shielding, etc.; also there are 1740 superconducting beam-bending magnets, wound with in total 2600 km of NbTi wire, cooled with (ℓ)He, each 4m long. These magnets are positioned to $\pm 500\mu$m accuracy. After several years of operation, no magnet has failed. The whole RHIC cost about $600 million, i.e. about $\$155,000$ per linear meter. At that price, our 9km-long Earth launcher would cost only $1.4 billion.

lanes and 3 lanes of automobile traffic respectively, amounting to 24 million vehicles per year total; steel and concrete trusses as well as spans suspended by cables from towers) cost \$161 million to build (\$44 million in 1952 after less than 3 years construction; then \$117 million in 1973 for the second span) which is \$24400 per meter of length. It seems safe to assume that these costs will dominate the structural-support costs of the launcher.

So far, all of these costs (Dewaring, tunneling, structural support, and superconductor) have only added up to \$0.8 million per meter at most (using very conservative estimates!), i.e. \$7.2 billion for a 9 km long launcher, leaving us \$12.8 billion to cover all other costs while still remaining inside the \$20 billion total budget.

12.9 *Comparison with cost & safety of today's rocket-based space programs*

According to NASA, it costs an average of \$470 million to launch the space shuttle. (Development costs were about \$45 billion in 1975; costs for space shuttle ground facilities are about \$3 billion annually even with no launches.) The shuttle can carry 29,500 kg into low Earth orbit. Today, typical fees to launch payloads into low Earth orbit are \$10000-20000 per kg, and into geosynchronous orbit, \$66000/kg. During the years 1982-2003, there were 118 shuttle launches (the last being the notorious Columbia explosion). Manned space travel historically had a risk of death of about 5%, e.g. one of the 17 Apollo launches, as did the 25th shuttle launch, killed their occupants. More recently reliability seems to have improved, since there were then 92 shuttle flights in a row with no fatalities until the Columbia disaster at shuttle launch #118. Meanwhile unmanned launches have historically failed at about a 7-20% rate, e.g. the Titan 3E launcher used to launch the USA's "Voyager" spaceprobes and "Viking" Mars landers failed once in its 7 launches; the Soviet Molniya 8K78M launcher, used to launch its Venera Venus landers, failed 19 times in 288 launches. It has been estimated that the USA's moon-landing program cost \$100 billion in 1994 dollars, spent mainly between 1962 and 1973.

I doubt it will be possible to decrease the failure level of rockets to $1/N$ until at least $2N$ launches of that system have happened, and I also suspect that large rockets will always be dangerous and unreliable. Meanwhile the catapult will be able to do N test shots, for large N, much more cheaply and quickly than rockets. Also, I expect the catapult will have good inherent reliability and safety due to its avoidance of dangerous fuels, capacitor banks, sliding friction, and high-current switches, its underground location, robust construction, automatically stable operation, easy status monitoring, and basing of operation on superconducting magnets and nonmoving parts – and the parts which do move need to move only small distances (and if they fail to move, that does not lead to a catastrophic failure). For example, none of the 1740 RHIC (see footnote 49) superconducting magnets have ever failed in 3 years of operation despite performing an enormous number (certainly at least thousands, perhaps millions) of fast current ramp-up and ramp-down operations.

Large liquid-fueled rockets also have the disadvantage that they are extremely vulnerable to anybody who wants to destroy them (an ordinary hunting rifle should suffice; a 0.50-calibre sniper rifle or small surface-to-air missile would presumably be even more destructive).

12.10 *Final verdict*

All this suggests that our launcher could be constructed in 6 years, would cost between 2 and 20 \$billion, and would pay for itself in less than 10 years. The improvement in performance, reliability, vulnerability to terrorists, and the lowering of costs, versus conventional space programs, would be dramatic.

The key technological uncertainties concern the performance of superconducting switches ([91], §6.2.2, §6.3); the impact of "dynamic heating effects," caused by, e.g., flux vortex motion, on superconductor components (§9.6) – possibly leading to disastrous quenches; and the best ways to protect projectiles during atmospheric transit (§7).

13 Acknowledgement

I thank C.J.Martoff (Temple Univ. Physics dept.) for helping me realize the severity of possible quench problems (§9.6); Freeman J. Dyson for helping educate me, e.g. about meteorology; and Eric R. Lee (Stanford, SLAC) for help with human acceleration endurance facts in footnote 25. Martoff suggested my crazy fluid immersion scheme there for humans in hi-gees may have first been invented by sci-fi writer Joe Haldeman [29].

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