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THE SPACE ELEVATOR: ECONOMICS AND APPLICATIONS

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ABSTRACT

Conceived as a 100,000 km ribbon built of carbon nanotubes, the Space Elevator will have a tremendous impact upon society and industry when launch-to-orbit costs are reduced to around an anticipated $100/kg. This paper will cover the approximate budget estimates for the various components of the Space Elevator (e.g. initial spacecraft, ribbon production, climbers, power beaming facility, anchor platform, and debris tracking system) and compare the economic aspects, potential savings and return on investment from such a construction as it relates to other megaprojects. The paper will then consider some possible applications for the Space Elevator, as well as its use, and show how these might benefit society in the long run. The risks which face some megaprojects, including the Space Elevator, will also be briefly addressed.

INTRODUCTION

The Space Elevator, as currently conceived[1], is a 100.000km ribbon of carbon nanotubes stretching up into space along which climbers will travel to release payloads into orbit at diverse points. The system is comprised of various components: an initial spacecraft, the ribbon, climbers, power beaming facility, anchor platform, and tracking facility.

The Space Elevator is essentially a space project – it will be built to launch into orbit and deep space satellites, telescopes, components for orbital structures and other elements too large or too risky for conventional launch systems. As such, it necessarily has to be compared to the costs of launching and operating spacecraft conventionally, i.e. via rocket and the space shuttle, as well as the costs of building and maintaining objects in space such as space stations and space telescopes.

However, the Space Elevator is also a mega construction project and it thus behoves us to examine the costs of other megaprojects in order to get another perspective and some sense of the degree of value they might bring. Megaprojects are the result of vision – a far-sighted future; they are challenging our design concepts and are being achieved through new technologies and materials and new building and manufacturing techniques.

The aim of this paper is to show that the Space Elevator could be build for a relatively modest price when other construction endeavours (both space and non-space) are considered. The paper will also consider some applications for the Space Elevator as well as some policy implications.

SPACE ELEVATOR COMPONENTS AND BUDGET ESTIMATES

As already adumbrated, the Space Elevator will consist of several main elements: an initial spacecraft, the ribbon, climbers, power beaming facility, anchor platform, and tracking facility. Under continuous revision as more detailed costs are worked out, it is currently anticipated that the Space Elevator could be built for a total of $6.2bn (excluding legal, regulatory and certification charges) – though it should be cautioned that a more realistic number for actual construction could perhaps be twice this. The latest budget estimates[2,3] for the various components are outlined below.

The initial spacecraft would be large, comprising engines to move the spacecraft from LEO to GEO, fuel tanks and fuel delivery system, control and communications package, attitude control system, photovoltaic panels, counterweight mass, payload and ribbon deployment mechanism. Because it would be one of the largest spacecraft ever launched, the idea is to assemble it in plug n' play fashion in LEO rather than try to launch it intact. Since the spacecraft is not complex in terms of electronics and optics, it is believed that it could be built for around $500m. Some form of launch capability will be required to get the initial spacecraft components from Earth to LEO. With the space shuttle being phased out, an expendable launch vehicle, Atlas or Delta possibly, would be selected at a cost of around $250m each. Four such rockets would be required to get the initial spacecraft and its ribbon spools and dispensers to LEO.

Regarding cost estimates for the ribbon, carbon nanotube (CNT) technology is rapidly advancing throughout the world. Individual CNTs metres in length are now being produced, CNTs are entering mass production (many thousands of kilos per month), CNTs are being spun together and CNT composite fibers kilometres in length are now being drawn. This is a dramatic change from a few years ago when CNTs were made in extremely small quantities for initial lab tests. Current estimates suggest that the basic CNT material can be obtained for $100/kg in the coming year. This price is obviously likely to fall as the technology improves and the material becomes available in greater quantities. The present configuration of the Space Elevator requires two 20.000kg ribbons carried to and deployed from space in addition to 230 other ribbon strands added by means of the climbers. Thus some $90m will be needed for the CNT ribbon material plus another $20m for the cross-tie adhesive material. In addition $100m or so will be needed for a dedicated ribbon production facility. Allowing for a 90% contingency the ribbon cable production costs would be some $390m.

Current designs call for 230 climbers to be sent up the initial ribbon to enlarge it. While all will be of the same basic design, each successive climber will have to cope with a ribbon of ever-increasing size, thus the later climbers will be larger than the earlier ones up the ribbon. The climbers are not sophisticated: consisting mainly of photocells for receiving the beamed laser power, DC electric motors, tread-based drive and controls. The budget estimates for the first climbers are in the order of $1.6m each, but this figure is expected to be reduced by as much as two thirds when commercial operations are commenced and there is a regular supply of cargo-carrying climbers. It is estimated that the cost of the 230 climbers including their construction and equipment will amount to $370m.

The cost estimates for the Space Elevator assume laser power beaming for supplying power to the climbers moving up the ribbon. The beaming system will necessitate high powered lasers and a large deformable mirror as the beaming device. For continuous operation it is deemed necessary to have at least three power beaming systems (including one on the anchor platform) each with one or two lasers. The cost of the lasers is $100m each with another $135m each for the associated adaptive optics (mirrors) and power generation system. Estimates are based on current designs for laser power beaming systems and it is anticipated that the prices will become more economical in the years ahead as technologies improve further and systems can be better integrated and combined. The power beaming system and infrastructure is the most expensive element of the Space Elevator by far; assuming two lasers on three ocean-going platforms, then the budget estimate is $1.5bn.

The anchor platform is one of the most straightforward elements of the Space Elevator – such platforms are available from commercial ventures. If the platform is based on the Sea Launch vessel, then the total cost for this part (excluding the power beaming facility) would be around $120m. The only major modifications to the vessel would be the addition of a ribbon tension system, the climber attachment housing, and the power beaming infrastructure.

One of the reasons the Space Elevator uses a sea-based platform is so that it can be moved out of the way of orbiting objects deemed to pose a risk of impact. This implies that a facility is available that is able to track and monitor the time and trajectory of objects and space debris. Although existing radar and optical tracking facilities exist and others are coming on-stream, it is the current thinking that the Space Elevator should have its own collision avoidance facility to avoid being possibly compromised by political or labour disputes or military exigencies. The budget estimate for the necessary tracking capabilities is $500m.

In addition to these basic elements there are also costs associated with administration, integration and infrastructure, as well as additional facilities (such as living quarters, a landing pad and the like near the anchor platform, plus a supply vessel). If all these components are totalled and a contingency of 30% is factored in, then the budget estimate for the Space Elevator consisting of one ribbon is somewhat over $6bn. However, the cost of a second ribbon would be around $2bn since much of the cost of constructing the first ribbon will not recur. Subsequent ribbons would be even cheaper.

COMPARATIVE COSTS: AEROSPACE

Getting things into perspective is instructive and illuminating. The technical aspects of the Space Elevator (i.e. to develop, launch, construct and become operational) are estimated to cost $6.2bn. How does this figure compare to some other aerospace systems and non-space spending patterns? Some examples are given below from aerospace. No attempt has been made to be comprehensive – just a few figures are given which have been come across in the course of everyday reading.

The forecasts of cumulative expenditures from 2005 through decommissioning the ISS after 2016 total nearly $60bn – an amount that is pretty much the same as the shuttle development programme. NASA's budget plans call for $6.6bn for Project Constellation – the Crew Exploration Vehicle that will take astronauts back to the Moon. The X-30/NASP cost about $7.5bn. The cost of Prometheus is said to be $1.5bn. The last shuttle, Endeavor, completed in May 1991, cost $2.1 billion. The cost of ESA's cometary spacecraft Rosetta was $1bn for the 165kg payload, orbiter and 100kg lander. A few years ago, when NASA asked the US Space Command to track and monitor all space debris down to below 1cm in the ISS altitude band, the Space Command responded with a request for $7bn to upgrade its radars.

Boeing is planning to spend some $7.5bn on development of its new 7E7 airliner. This is not a revolutionary new aircraft, but merely one incorporating incremental improvements in efficiency and safety from the past 40 years of operating the 7 series. Meanwhile, the US Army has just cancelled a two-seater scout helicopter project after over 20 years of development and $8bn in costs with no production aircraft in sight – closeout costs could be another $3bn. The cost for a new Patriot missile system – which is not even reliable - has soared to $7.8 billion, with over $1bn for the software alone, while the total (US) missile defense development cost for 2002 through 2009 is estimated at $62.9 billion.

The average cost of a GEO satellite is about $250m. Delta and Atlas rockets can lift about 22.000kg to LEO. Conventional wisdom has current launch running about $10.000/kg to LEO and $80.000/kg to GEO. The average cost of each shuttle mission over the next few years will be in the order of $1.1bn – this will bring the cost of taking freight to the ISS to $64.000 per kilogram. An Ariane 5G is capable of launching 7000kg into GEO at a cost of some $163m – though, like all launch costs, the sum is subject to market forces and is dependent on the identity of the customer. This works out to $23.285 per kilo. The launch vehicle company SpaceX is expecting to charge $6m for its Falcon 1 launch vehicle which can lift 650kg to LEO (ie $9230 per kilo) and $12 million for the larger Falcon 5 which can lift 4200kg (ie slightly over $2850 per kilo). Whereas Falcon I will be the world's lowest cost per flight to orbit of a production rocket, Falcon V will be the lowest cost per unit mass to orbit so it is claimed.

However, initial estimates for the Space Elevator – which can lift over 5000kg - give a lift cost for the first simplistic system to any desired orbit of $150-$1100/kg depending on financing[1], with the ultimate lift cost being eventually reduced to a mere $10/kg. Compare these launch costs to the price of missiles – essentially small rockets with much smaller payloads. Cruise missiles cost over $1m apiece. The costs for Patriot missiles are variously given as between $2-5m per missile, while a battery can cost $225 million. Hundreds of expensive missiles were fired at a time during the Gulf War at a total cost of several billion dollars.

COMPARATIVE COSTS: MEGAPROJECTS

Due to its size and scale – 100.000km in length - the Space Elevator can be considered as a megaproject on a par with other major engineering constructions such as bridges, towers and railway tracks. But the amount involved to build the Space Elevator is not at all out of proportion when other megaprojects (and some that are not so mega) are considered.

Buildings and pipelines

There is a constant urge to build the world's largest structures. No sooner is one project finished than another is on the drawing boards. Italy aims to beat Japan's record for suspension-bridge length, Dubai plans to surpass Taiwan's world's tallest building, and Japan is working on another that will dwarf these.

Located in a region known for its hurricanes and earthquakes, the Taipei 101 tower is currently the world's tallest building. Developed by the Taiwan Financial Center Corp., the 101 story building is 508m high – 56m higher than the previous record holder, the twin Petronas Towers in Kuala Lumpur. The building consists of brace core and movement frames to withstand earthquakes. To control the Taipei tower's lateral acceleration due to wind, an 800.000kg spherical tuned mass damper suspended from cables on the 88th floor has been installed. The cost of the Taipei 101 tower is $700m, with each of the express, pressurized elevators to move between the 101 stories costing $2m.

Not to be outdone, Dubai is planning a massive residential and hotel tower estimated to cost between $1-2bn. The building will be some 610m high and, like the Taipei 101 tower, will have to withstand some severe wind speeds causing vortex shedding and shaking. The small footprint of the building necessitates a single 11.000 voltage power line and the elevators will ascend (though not descend) at 1100m per minute.

In southeast Australia, EnviroMission is building a 914m high solar tower soaring out from a glass roof at its 7km wide base to convert sun-heated air into electricity. The 200 megawatt tower, costing as much as $1bn to build, will generate enough electricity to supply 200.000 homes by 2006. The solar chimney, which will contribute towards renewable energy as well as a reduction in greenhouse gases, will require high intensity obstacle lights to warn aircraft in the area.

On a smaller scale in terms of size, but not in cost, last year General Motors opened a new Vehicle Engineering Center as part of a $1bn renovation and construction project. And the new AOL Time Warner Center in Manhattan, which will contain luxury condominiums and a hotel in its 55 stories, is a $2.2bn building project.

In Japan, Shimizu Corporation is creating not just a megaproject, but a megacity which will try to solve the problems of overcrowding and pollution. The Mega-City-Pyramid TRY 2004 will be 2004m tall with a base of 2800m on each side. The gigantic tubular structure will house offices, shops, hotels, apartments – some 1 million people living and working within its confines. Each building within the structure will have its own energy resources – including wind and solar and waste recycling. Concentrated sunlight will be transmitted throughout the buildings by means of optical fibres. Carbon and glass fibre materials will be employed for lightness and durability. A linear induction system will enable the transportation of people and goods on a continuous vertical circulatory system. The construction will take seven years. Oh, and the cost? 88 trillion yen – that's around $800bn!

Not content with the world's tallest building, Dubai is also constructing the world's largest man-made offshore islands at a cost of $3.5bn. One of the two islands, 5km offshore, was completed at the end of 2003 after two years work and the second is underway. Each 8km long island will sport villas, hotels, marinas, and shopping complexes and everything will be connected by high-speed monorail. And if that isn't enough, Dubai is planning an even bigger project – an archipelago of 250 islands laid out to mimic the Earth's landmass.

Another huge made-made project is the proposed Third Delta Conveyance Channel in Louisiana which will initially be a 9-12m deep, 107m wide, 160km long channel off the Mississippi River that will transport 566 cubic metres of water per second through the delta into the Gulf of Mexico. Over the next 20-60 years, the channel is supposed to erode until it is 305m wide, 15-18m deep and flowing at 5663 cubic metres per second. The cost of this project to rebuilt the marshes around Louisiana's barrier islands by sedimentary deposition is estimated to be $2-3bn.

In Canada, a group of oil companies (Shell, Esso, ComocoPhillips, ExxonMobil, Imperial Oil) are planning to build a 1220km long gas pipeline through the Mackenzie Valley to connect Canada's North West Territories onshore gas fields with North American markets. Work on the pipeline should start in 2006/7 and gas is expected to start flowing in 2010. Initial estimates for the Mackenzie Gas Project gave a price tag of around $4.5bn – but this is expected to increase significantly once work gets underway.

One other megaproject is worth mentioning – the 10.000 year radioactive nuclear waste storage facility at Yucca Mountain, Nevada. If it is allowed to go ahead, the first stage of the project will commence in 2010 with the building of 100km of access and emplacement tunnels 305m underground to house stainless steel waste casks. A robotic system of gantries, cranes and railcars will transport the radioactive waste packages to their final destinations. Studies alone on the geology and hydrology of Yucca Mountain have accounted for $5bn and the current estimate for this mega engineering project is getting on for $60bn.

Bridges and tunnels

Like tall building, bridges and tunnels also cost significant money to build. The world's longest suspension bridge – the Akashi bridge in Japan which cost around $4bn - is almost 4km in length and has a main span of 1.9km, but a bridge to finally connect Sicily to mainland Italy will have a single 3.2km long span – nearly double the length. Over the centuries, a wooden bridge was proposed in Roman times, then a tunnel was considered and rejected. The bridge will be of a light, strong design and comprise 305m high towers on Sicily and the mainland. Not yet underway, the bridge is anticipated to cost $5bn.

The Japanese and Italian bridges are big, but a bridge spanning the Straits of Gibraltar and linking Spain and Morocco would be the longest and tallest bridge ever built. With a deck of fibreglass, the bridge would have a length of 14km with spans of an unprecedented 5km long and towers over 900m tall – half as high again as the world's tallest building. The cost of this deep water construction project is estimated to be $15bn.

Construction costs for the Great Belt Link between the East part of Denmark and the West of Denmark attached to continental Europe were in the order of $6bn for the tunnel and bridges between Zealand and Funen in Denmark and $3bn for the coast to coast Øresund Bridge between Denmark and Sweden. The landworks which comprise the Øresund motorway and railway to the airport cost a further $1bn.

The Tokyo Bay Aqualine, built between 1989 and 1997 at a cost of $11.3bn consists of a 4.4km bridge and a 10km tunnel that connects Kawasaki City in Kanagawa Prefecture with Kisarazu City in Chiba Prefecture. The bridge and the tunnel meet on the artificial Kisarazu Island "Umihotaru" and allow commuters to cross the bay in about 15 minutes instead of taking a 50km detour around the bay.

In California, the construction of a new Bay Bridge extending from Yerba Buena Island to the East Bay toll plaza has been underway for nearly three years. The original 14km long bridge from Oakland to San Francisco (completed in 1936 at a cost of $78m) was damaged during an earthquake in 1989 and a replacement eastern span was required. After some considerable delays, this 3.5km long, twin deck East Span, so far on schedule, is expected to be completed by 2007 and has an estimated price tag of $3.5bn.

One of the most complex and controversial engineering projects in modern history has been the Big Dig in Boston – a three km or so underground road which will connect the city with the harbour and replace an overhead highway. Started in 1987, the megaproject was completed at year's end 2003 at a cost of $14.6bn after an original estimate of $2.6bn.

Another mega construction project has been the Channel Tunnel – an underground rail link between England and France. The possibility of a tunnel linking the two countries had been on the cards for over 200 hundred years and digging actually started several times, but it was not until 1987 that the project finally got underway. It was completed in 1994 at a cost of approximately $13bn. In another costly project, the British government has also just allocated $2.9bn for widening parts of the congested M25 motorway which encircles London.

High speed trains

Magnetically levitated trains (maglevs) float along a guideway on an electromagnetic cushion at incredible speeds. Although expensive when compared to conventional rail or even other modes of transportation (one kilometre of track costs at least $5m to build excluding the cost of the giant electricity substations required), the cost of maglev trains are only a few million dollars per vehicles compared to $200m for the average Boeing 747. Maglev trains offer higher speeds than conventional ones, but consume three-to-five times less energy per passenger kilometre than a jet aircraft for the same performance, thus contributing to a reduced pollution environment. The system is said to be cleaner, cheaper to run and require less maintenance than passenger aircraft. In addition, maglevs are more reliable and safer and less affected by bad weather and traffic congestion.

Several countries, including the USA, China, Germany and Japan are examining projects which feature maglevs – though they seem to work best for countries (eg the USA and China) without an already existing efficient high speed rail network. A short maglev line is already operating in Shanghai between the airport and city centre with trains reaching top speeds of 430kph and whisking people the 30km between the two locations in a mere seven minutes. The cost was about $1.2bn and China is evaluating whether to build more maglev routes to provide the high-speed rail network it doesn't currently have. A 1200km maglev connection between Shanghai and Beijing is estimated to cost some $24bn, while the cost of the Californian maglev project is estimated to be more than $7bn for the 150km long system. Approximately a quarter of this cost is for the system elements: vehicles, communications, propulsion and operation control. The cost of the monorail guideway is about $3bn.

A maglev rail system for the Baltimore/Washington corridor is also under study. This 63km long project will link downtown Baltimore and Baltimore-Washington International Airport with Washington, D.C. Possible future connections include Philadelphia, New York and Boston to the north, and Richmond, Raleigh and Charlotte to the south. The preliminary cost estimate for the project is $3.7bn which includes technology components, guideway infrastructure, stations, operation and maintenance facilities, right of way, and engineering construction management and training. The total estimates include a 10-30% contingency factor.

An even more ambitions maglev project is the vacuum tube train from New York to London. As currently envisioned, a neutrally buoyant tunnel with the air pumped out, submerged 45-90m beneath the

Atlantic Ocean and anchored to the seabed would allow a maglev reaching speeds of up to 6500kph to cross in an hour. Since above-ground sections would be cheaper to built than underwater, the proposed route would pass through northeastern Canada and touch land in Greenland and Iceland before reaching the British coast. Even so, the project is estimated at $25-50m per kilometre or between $88-175bn for the New York-London link.

Canada also recently announced a $3bn high-speed rail system in the Quebec-Windsor corridor. The train would run on diesel and use existing tracks, but the amount is considered unrealistically low compared to previous estimates. For instance, in 1993 the estimated cost for a 200kph electrically-driven train was $9.5bn or $17bn in today's prices taking into account interest and inflation.

A downtown extension to its monorail will provide Las Vegas with a 21st century public transit system by 2008 which will reduce traffic congestion and air pollution. The privately funded $650m Las Vegas Monorail connects eight major Las Vegas resorts. $20m has been secured for a second phase which connect downtown Las Vegas and the airport.

The 120km high speed rail link between the Channel Tunnel in Folkestone and Central London is the first major new railway built in the UK in over a century and will provide quick and easy access to Paris and Brussels by tilting trains capable of reaching 300kph. About one quarter of the route will be through tunnels and over 150 bridges will be required. The cost of the rail link, started in 1998, partly opened in mid-2003 and due to be completed in 2007, will be in the order of $9.4bn. The eventual cost of modernizing Britain's train tracks between London and Glasgow is expected to be $18.3bn by the time the network is completed in 2008 – modernizing the entire rail network for high speed trains would cost around $50bn.

And although not so high speed, a $1bn dollar 1400km rail link has just been completed between Alice Springs and Darwin by workers who had to endure temperatures ranging from freezing to 50°C in inhospitable terrain.

ADDED VALUE OR WASTE OF MONEY?

There is no doubt that many space projects, as well as building bridges, tunnels, and maglev systems are costly and many people, not least the public, consider such megaprojects a huge waste of money. Space exploration, for instance, is estimated to cost Americans $50 per annum, compared to $15 in Europe. But a lot has to do with the perceived value of the projects, what the benefits are and to whom, and whether the costs can be recovered in a reasonable amount of time. What good does it do to have a half a billion dollar launch vehicle (the space shuttle) carrying spacecraft worth just a few million dollars into orbit? What is the tangible value of the costly ISS? Will the experiments performed in space, or the experience gained in helping astronauts survive there, result in health and medical products that will improve our daily lives? These are questions that are asked regularly. In some instances, there have already been space spin-offs which are benefitting segments of society[4].

Some mega building projects bring immediate and tangible results and benefits to users and therefore may, eventually, justify the cost. In the case of tall towers and buildings, for some there will be accommodation and housing – and the fact of growing upwards rather than expanding outwards will bring environmental benefits because of the reduced footprint. For many – including the general public - the value will be in greater convenience. Bridges allow rapid transport of goods and people between points at a saving of cost and time. The Tokyo Bay Aqualine saves motorists a 50km detour. The Øresund bridge obviates the need to fly or take a car ferry between Copenhagen and Malmö. Similarly the Straits of Gibraltar bridge will immediately open African markets to European goods and vice-versa in an unprecedented manner – the time-saving over sea transportation will be astounding. The Channel Tunnel has opened up the border between Britain and the Continent – permitting quicker freight and passenger transfers. However, despite the fact that the Channel Tunnel was expected to put ferry boats out of business, they still command 50% of the market. Furthermore, budget airlines have also flourished because planes are still perceived by the general public to be faster, even though trains through the tunnel actually provide a quicker city centre to city centre link between London and Paris.

Better road and rail links also improve the flow of traffic – the widening of the M25 around London and the Boston Big Dig should do this, so should establishing high-speed rail links as people movers. Maglev trains will help meet growing travel demands, reducing the need for additional highways, rail capacity and airport expansion. In the Baltimore-Washington corridor as well as along the Eastern Seaboard, maglev is projected to divert about 20% of air travel to the maglev mode. It is believed it will divert 27,000 vehicles per day from the highway system in 2010, and reduce daily vehicle kilometres travelled in the corridor in the year 2020 by over 800,000 vehicle kilometres every day. Furthermore, maglev does not produce local air quality impacts associated with gasoline engines, diesel locomotives or jet engines.

There are other ways in which communities may benefit. Maglevs are fast people movers and it is suggested that a high speed maglev connection could draw the Baltimore and Washington metropolitan regions closer together by reducing travel times between the two cities to less than 20 minutes. This could foster economic growth, particularly in downtown Baltimore. Maglev could also greatly increase the market share for the Baltimore-Washington International airport in the Washington region by reducing the travel time from downtown Washington. The same applies to other maglev systems connecting cities and airports such as Shanghai where the travel time is reduced a mere seven minutes.

Like any major construction project, be it aerospace or construction, significant job opportunities in regard to both construction and operation can manifest themselves. The Channel Tunnel created building infrastructures, shops, petrol stations on each side of the tunnel with all the attendant economic and employment benefits for the regions. The Mackenzie Gas Project aims to have the involvement, participation and ownership of the indigenous communities and will provide work, cheap gas, and heating for homes as well as creating benefits for aboriginal and other northern and Canadian people. Such benefits include education and training, improved skills, employment and business opportunities. Indirect benefits include the expansion of service, transportation and other industries to support the Project, as well as natural gas exploration and development by oil and gas companies. Governments will also benefit by collecting royalty payments and taxes. The Alice Springs to Darwin rail link exceeded its agreement to use a 15% indigenous workforce and, furthermore, land around the track was rehabilitated using native soils in order to meet environmental concerns.

In addition, such megaprojects foster new research and development into new technologies and materials (including subsequent spin-offs) as well as additional transportation and industrial applications. This will be the case of the Space Elevator. There has been an interest in beaming power to aircraft for over thirty years and NASA has recently completed trials in which a model aircraft maintained flight through a ground-based laser beam which was converted to electricity by photovoltaic cells on the aircraft to turn the propeller. An aircraft could remain flying without batteries or onboard fuel as long as the laser energy source was uninterrupted. The concept has potential commercial value to the remote sensing and telecommunications industries and the technological advances being developed in laser power beaming for the Space Elevator will be able to be employed in many other applications.

The private sector alone cannot usually finance and build these massive infrastructure megaprojects because risks are too great and the return is too small. They need to be either joint public-private partnership ventures, such as the Øresund Bridge, or funded entirely by the State. The construction of the Great Belt Link in Denmark and the Øresund Bridge between Denmark and Sweden was funded by loans in the Danish and international capital markets and these loans are guaranteed by the Danish and Swedish governments. The entire construction costs (some $10bn), including interest, will eventually be paid by the users of the road and rail links including tolls from the motorists and fees from the railroad operators. The debt for the Øresund bridge is thus expected to be repaid in 2035 – 35 years after the opening of the bridge, although the debt for the landworks will be repaid within a time frame of almost 60 years. Other bridges and tunnels will also be funded by tolls. A variety of tolls will also help finance Boston's Big Dig and it has been intimated that it will take up to 50 years to pay back the project costs. For the Californian maglev system, it is projected that revenues from passenger fares, parking fees, freight and the like will be some $60bn over the next 40 or so years. And despite the huge costs of building the Channel Tunnel, revenue emanating from its use, although lower than projected and anticipated, is still greater than its operating costs.

In a similar manner, revenues can be earned by the Space Elevator to pay off public or private loans, by the transportation of goods (e.g. space outpost structural elements, satellites, stores, passengers) to various departure points along the ribbon. Such revenues could be generated early on and the expense of building a Space Elevator could become akin to building a motorway or rail network. Taking into account the cost recovery durations of for example 35 years for the Øresund bridge and even 20-30 years for a typical house mortgage, then there is no reason why the costs of building the Space Elevator should be not be recovered over a similar period. But it could pay for itself in far less time. If the Space Elevator costs $6bn and is paid back over 30 years – that works out to something like half a million dollars per day having to be recovered. If launch (operating) costs are eventually reduced to the projected level of $10/kg and a charge was made of $110/kg then the operators would get this $0.5m with the first elevator just lifting 5000kg/day. At a charge level of $1000/kg the elevator could be run at rates of current launches and make $5m/day. With second-generation climbers capable of transporting 20.000kg, a $1000/kg charge would bring in $20m per day with just one climber. Contrast this to the space shuttle which henceforth is expected to do only four launches per year. Even conventional launchers such as Ariane, Delta, Atlas or Proton are carried out only a few times per year.

It has been argued that reusability (in the form of a space shuttle) is the death-knell of low cost access to space. On the other hand, it might make sense to have reusability if the cost of that convenience outweighs the costs and inconvenience of expendability – as it does with megaproject bridges, tunnels and trains, and as it would do with a Space Elevator. The profit of the Space Elevator will lie not so much in the cheap cost of placing objects and manufacturing facilities into space, but more in bringing the results down again. So what could the Space Elevator be used for which would outweigh its costs of construction and give a perceived benefit and value to its customers and the public at large?

JACK'S BEANSTALK AND OTHER APPLICATIONS

The Space Elevator will be capable of placing into various orbits, including LEO and GEO and beyond, large payloads such as very long optical booms, huge radio dishes, complex planetary probes, and manned modules including hotels and penal colonies. It will be particularly suited to oversized, awkwardly-shaped and/or fragile structures and components since there will be no restrictions on size (up to a point, of course), nor will the payloads be subject to launch forces. This in turn implies that spacecraft can be constructed more cheaply since delicate components will not need to be protected against vibration to the same degree. Examples of payloads and applications include telescopes, interplanetary spacecraft and probes, Moon and Mars access, space tourism, power beaming, asteroid mining, telecommunications, weather stations, and asteroid detection to mention but a few. And no doubt the military will also be interested for its own activities.

One major use envisioned at the outset is that of launching solar energy platforms which will collect the limitless energy of the sun and beam it down to Earth for a constant source of clean, renewable power. This would have enormous implications for the environment and sustainable development by cutting fossil fuel consumption and thus eliminating harmful greenhouse gases. It would also avoid the necessity of constructing tall solar towers which, of necessity, have huge ground footprints. The solar tower under development in Australia, for instance, will have a collector nearly 6km in diameter and require over 50 square kilometers for the construction.

Current costs put the capital investment needed for a space solar power system well in the tens of billions of dollars. Such systems would be able to supply power at approximately $0.2/kW-hr which is still above conventional power production rates of competitive terrestrial options such as fission plants and wind turbines. The major hurdle has been the launch costs required to place 20 million kilo systems at geosynchronous altitude. Conventional rocket systems can place 5000kg in geosynchronous for roughly $200m (Atlas V or Delta IV). This would place the total launch costs at $800bn. However, recent work suggests that these costs would drop with the Space Elevator. Total launch costs would be around $30bn and allow for roughly 0.1/kW-hr power production[5]. This is competitive with terrestrial-based power supplies. More R&D work is needed to bring the technology to maturity for such a programme but countries such as Japan have stated a commitment to construct a space solar power system by 2040.

In a period when the days of the ISS seem numbered, the Space Elevator could step in to fulfill the promise of providing facilities to test and develop new drugs and materials in microgravity. Specialist automated labs could be placed at various locations adjoining the ribbon to create and manufacture components for the pharmaceutical and electronics industries. Other labs could house space gardens to grow plants and crops – not only to develop improved varieties for terrestrial use, but also to provide food for people living and working in space.

One tremendous problem that the Space Elevator could easily solve is the disposal of nuclear waste which is accumulating at three million kilos per year in the United States alone. Over 43million kg of nuclear waste are already in temporary storage. The same picture is to be found in other nuclear nations. There have been several ideas for getting rid of spent fuel – including letting it melt its way down through the Antarctic ice cap until it reached bedrock and dumping it at sea. These options are banned under international treaty. Another option, being looked at in the US, is burying it under a mountain forever. Even though safeguards will be put in place, there is still the worry, as with all nuclear power stations, that there will be inevitable environmental contamination. Yet another possibility is blasting nuclear waste off towards the sun. The fear here is that if the rocket carrying the nuclear waste exploded on take-off then that would be an unacceptable disaster – spreading radioactive fall-out over a wide area. But, nuclear waste containers could be easily and safely transported up the Space Elevator to a suitable point and then launched from there towards the sun with an absolute minimum risk to life and the environment on Earth.

The idea of a Space Elevator was first mooted in 1895 by a Russian scientist who was inspired by the construction of the Eiffel Tower, although the concept may have originated much earlier in the old children's story of Jack and the Beanstalk. When it is in place, the Space Elevator could be used for another, more scientific, purpose – it could be used as a giant sticky flypaper to trap cosmic dust all along its length. Cosmic dust – comprising particles from distant stars, from nearby planets, from deserts, forest fires and coral reefs on Earth – is there in abundance and much can be gleaned from the relatively few grains that can be captured by current methods. Having dust traps all along a length of 100.000 km would enable a fascinating picture to be built up of the transport and content of dust through the various layers of the atmosphere and space.

RISKS AND DANGERS

The Space Elevator, like the International Space Station and other megaproject structures, will inevitably be subject to several inherent dangers. But steps will be taken to reduce these as much as possible and it is instructive to note some of the risks and dangers that some other expensive megastructures face and which have not precluded their being built. These risks include financial as well as structural and environmental challenges.

For a number of reasons (including cheaper and improved cross-channel ferry services, the emergence of budget airlines, and the fact that passengers in the tunnel cannot see the sea or the famed White Cliffs of Dover), despite the frequency of trains and short journey times compared to cross-Channel car ferries and budget airlines, passenger numbers and freight throughput for the Channel Tunnel have not lived up to expectations and the Eurotunnel operators currently have a debt of around $9bn.

The Straits of Gibraltar bridge will be in one of the busiest shipping lanes in the world – thus there may be a danger of collisions. (In this respect, one only has to remember the recent capsizing of a vessel transporting luxury cars in the English channel. The vessel lay on its side with its bright red hull just about level with the water – despite being visible, surrounded by buoys, and with repeated ship bulletins warning of the hazard, no less than three other vessels ran into the semi-submerged wreck.) Wind speeds are expected to be at least 80mph at the tops of the suspension towers (actually significantly less than at the Taiwan and Dubai towers) and Sahara dust storms will also prevail, not to mention swirling ocean currents. However, the Space Elevator, located off the coast of Ecuador, will be tucked out of the way of air and sea traffic lanes in a region that has been specially chosen for its lack of storms, bad weather and heavy seas.

The Channel Tunnel is a 50km long tunnel under the sea, wide enough for two trains in separate shafts as well as a service and access shaft. Drilling and boring problems notwithstanding, the finished tunnel is subject to several hazards which have to be guarded against as much as possible. These hazards include natural disasters such as an earthquake which could cause the tunnel to collapse or water to seep in, or a tsunami wave which could swamp the tunnel. As with Alpine and other subterranean tunnels, pollution and air freshness is a problem, as is fire. There have already been major fires in Alpine tunnels as well as the Channel Tunnel leading to both loss of life and lengthy inconvenient closure of the routes through them.

The Taipei 101 tower, considered to be a $58bn asset, was built to withstand the severe forces of natural disasters such as earthquakes, hurricanes, and typhoons, as well as fire and also potential terrorist attacks. Like tall buildings, bridges have innovative structures designed to damp oscillations during dynamic loading in a major earthquake.

Anchoring the tunnel for the proposed vacuum tube train between New York and London to the sea floor will avoid the high pressures of the deep ocean. The Straits of Messina bridge in Italy will present unique engineering challenges – the area has over 100 active seismic faults – including four directly through the strait itself – powerful winds and ocean currents (the Scylla and Charibdis of ancient mythology). The land-based towers eliminate the problem of building support bases in the turbulent waters and the bridge will be capable of flexing by nearly 10m during an earthquake. However, strong winds will still pose a problem. Because it will have a floating anchor, the Space Elevator will not be subject to the major geotechnical issues that bridges, tunnels and buildings are.

While the chances of being hit by a meteorite or asteroid are fairly slim, space stations and spacecraft are prone to impact from the estimated 110,000 pieces of 1cm and larger space debris and other junk which float around in LEO and above. The Space Elevator, passing through LEO and GEO and beyond, will also be subject to such debris, but unlike spacecraft, it will not be pressurized nor made of metals and materials capable of offering protection against a strike. On the contrary, its loose, knitted structure should essentially be able to cope with the occasional hit without breaking. Moreover, the mobility of the sea-based anchor platform means that, given sufficient warning, the ribbon could be towed out of the way of an approaching space object just as an oil rig is towed out of the way of an approaching iceberg.

Should the Space Elevator suffer an accidental break, then most of it would stay up in space or burn up on the way. The ribbon itself – weighing just some 7.5kg/km – would just float down like a feather, doing no damage. Other elements such as climbers and their payloads would break up in the fall, again doing little structural damage and placing less dirt and debris and chemicals into the atmosphere and environment than a typical forest fire or volcano. In any event, since the anchor platform for the Space Elevator is at sea, then even these risks will be minimized.

Regarding terrorist attacks, unlike towers, bridges and tunnels, the thin profile of the ribbon would offer little tempting target and the relatively isolated position of the anchor station means it would be difficult to reach with stealth especially with a restricted flying zone around it.

One risk the Space Elevator might face is that of cost overruns. Because some elements (e.g. carbon nanotubes and power beaming) are still evolving and costs are not yet known precisely, then there could be some price hikes. The Boston Big Dig steadily escalated from $2.5bn to $14.6bn to become America's largest megaproject. According to a Danish study[6], cost overruns have been found in 90% of megaprojects in 20 countries – particularly those involving transportation systems. Rail projects have the worst cost overruns with an average of 45%, followed by tunnels and bridges, and then roads. Contrary to expectations, however, technical hitches were not the cause for the overruns, instead motivations for cost-benefit deceptions are economic gain and/or political leverage – possibly corruption or the urge to attract investment to a particular region. Thus it can be assumed that, if the current budget estimates are on the right track – or even if the component costs double, then since the Space Elevator largely constructs itself, then cost overruns should, in principle, be negligible. However, since there are people involved, the cost could likely increase before the Space Elevator is operational.

One of the biggest risks, of course, as with any megaproject, will be financial. As alluded to earlier, the private sector cannot by itself normally finance the costs of building huge megaprojects because the risks of failure are simply too great and the return is generally too small. Often the government is called upon bail out companies whose projects have not turned out to be so successful.

CONCLUSION

Megaprojects need to be either joint public-private partnership ventures or government ventures and they also need multiple partners. The Øresund bridge linked two countries – Denmark and Sweden, both of whom cooperated and contributed to the project. The Gibraltar bridge is to link Spain and Morocco and not only were these two countries involved in the feasibility study, but so was Unesco in conjunction with the UN Economic Commissions for Africa and Europe. The Channel Tunnel links England the France both of which invested significant sums for the construction. The vacuum train under the Atlantic will need cooperation from several countries. Even, the Baltimore-Washington maglev link will involve cooperation between different cities.

There are companies and agencies in a number of countries that have expressed interest in the Space Elevator – even in participating in the project. The countries include Australia, China and Japan as well as several European ones. As we have seen, the cost of the Space Elevator is not excessive compared to other projects and it is conceivable that several countries or an international consortium could pursue the Space Elevator. It is also possible that a private entity (risks notwithstanding) could provide the financing – several large investment firms have stated interest in construction of the Space Elevator as a private endeavor. However, from a political standpoint there is a case to be made that the Space Elevator should be an international effort like the International Space Station with the inevitable rules for use and access.

The political motivation for a collaborative effort comes from the potential destabilizing nature of the Space Elevator. The Space Elevator clearly has military applications, but more critically it would give a strong economic advantage for the controlling entity. Information flowing through satellites, future energy from space, planets full of real estate and associated minerals, and basic military advantage could all potentially be controlled by the entity that controls access to space through the Space Elevator. An international collaboration could result in multiple ribbons at various locations around the globe, since subsequent ribbons would be significantly cheaper, thus allowing general access to space and consequently eliminating any instabilities a single system might cause.

Whilst there may be few ordinary citizens who might profit from Space Elevator applications unlike space agencies, commercial companies and the scientific community, it is highly likely that the general public will ultimately benefit from it through cheap solar power and a greener environment, enhanced satellite navigation and communication services, reduced risk from nuclear waste, and even through improved health, education and social services made possible because of the savings made by governments in accessing space.

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