Pearson BTEC Level 3 Nationals Extended Diploma

Supervised Window:
10 December 2018 – 14 January 2019

Supervised period: 6 hours | Paper Reference **31629H**

Applied Science

Unit 7: Contemporary Issues in Science

Part A

You do not need any other materials.

Instructions

- **Part A** contains material for the completion of the preparatory work for the set task.
- **Part A** is given to learners during the supervised window before **Part B** is scheduled. Learners are advised to spend no more than 6 hours on **Part A**.
- **Part A** must be given to learners on the specified date so that learners can prepare in the way specified.
- **Part A** is specific to each series and this material must only be issued to learners who have been entered to undertake the task in the relevant series.
- **Part B** materials must be issued to learners on the date specified by Pearson.

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Instructions to Teachers/Tutors

This paper must be read in conjunction with the unit information in the specification and the BTEC Nationals Instructions for Conducting External Assessments (ICEA) document. See the Pearson website for details.

This set task has a preparatory period. **Part A** sets out how learners should prepare for the completion of the **Part B** task under supervised conditions.

Part A is given to learners during the specified window before **Part B** is scheduled. Learners are advised to spend no more than six hours on **Part A**.

Learners should undertake independent research on the case study given in this **Part A** booklet.

Centres must issue this booklet at the appropriate time and advise learners of the timetabled sessions during which they can prepare. It is expected that scheduled lessons or other timetabled slots will be used for the preparation.

Learners should familiarise themselves with the specific concepts and terminology used in the articles.

Learners may prepare summary notes on the articles. Learners may take up to four sides of notes of this type into the supervised assessment (**Part B** booklet).

These notes should only include information about scientific terminology, quantities and concepts used in the articles and a summary of the scientific issue discussed. This will enable learners to interpret, analyse and evaluate the articles in **Part B**. Other content is not permitted.

Part B must be completed under supervision in a single 2 hours and 30 minute session timetabled by Pearson. A supervised rest break is permitted.

The supervised assessment should be completed in the **Part B** task and answer booklet. Teachers/tutors should note that:

- learners should not be given any direct guidance or prepared materials
- learners should not be given any support in writing or editing notes
- all work must be completed independently by the learner
- learner notes will be retained securely by the centre after **Part B** and may be requested by Pearson if there is suspected malpractice.

Refer carefully to the instructions in this taskbook and the BTEC Nationals Instructions for Conducting External Assessments (ICEA) document to ensure that the preparatory period is conducted correctly and that learners have the opportunity to carry out the required activities independently.

Instructions for Learners

Read the set task information carefully.

This is **Part A** of the set task and gives information you need to use to prepare for **Part B** of the set task.

In **Part B** you will be asked to carry out specific activities using the information in this **Part A** booklet and your preparatory notes.

In your preparation for **Part B,** using this **Part A** booklet, you may prepare short notes to refer to when completing the set task. Your notes may be up to four sides of A4 and may be handwritten or word processed. Your notes should only include information about scientific terminology, quantities and concepts used in the articles and a summary of the scientific issue discussed. This will enable you to interpret, analyse and evaluate the articles in **Part B**. Other content is not permitted.

You will complete **Part B** under supervised conditions.

You must work independently throughout the supervised assessment period and must not share your work with other learners.

Your teacher/tutor may give guidance on when you can complete the preparation.

Your teacher/tutor cannot give you feedback during the preparation period.

You must not take your preparatory notes out of the classroom at any time and you must hand the notes in to your teacher/tutor on completion.

Your notes will be made available to you at the beginning of the supervised assessment.

Set Task Brief

You are provided with the following articles:

Article 1: Nanotechnology can launch a new age of space exploration
https://www.theguardian.com/nanotechnology-world/nanotechnology-can-launch-a-new-age-of-space-exploration

Article 2: 60,000 miles up: Space elevator could be built by 2035, says new study
https://www.extremetech.com/extreme/176625-60000-miles-up-geostationary-space-elevator-could-be-built-by-2035-says-new-study

Article 3: Space Elevator Technology and Research

Your notes should only include information about scientific terminology, quantities and concepts used in the articles and a summary of the scientific issue discussed.

You should spend up to a maximum of six hours to complete your preparatory notes. You may take up to four sides of A4 notes into the supervised assessment.

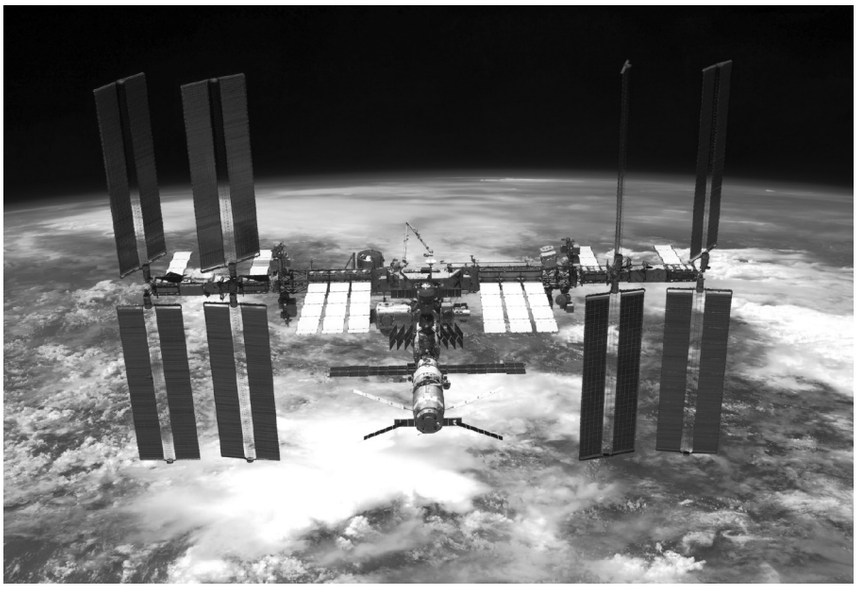
Part A Set Task Information

Article 1

'Nanotechnology can launch a new age of space exploration'

This is an edited version of an article that appeared in 'The Guardian' newspaper in April 2012. The article was written by Stuart Clark.

NASA and the European Space Agency have some ambitious plans. But if manned missions to Mars, super-thin spacesuits and shoebox-sized shuttles become a reality, then nanotechnology will undoubtedly have played a key role.



Existing multi-tonne spacecraft may one day be swapped for shoebox-sized craft weighing just 2kg-5kg as developments in nanotechnology progress. Photograph: NASA/Getty Images North America.

Launching equipment into space is an expensive business: it costs $10,000 (£6,300) to lift every 0.45kg (1lb) of stuff into orbit. Making things smaller and lighter is, therefore, a natural route to reducing the cost of launching a spacecraft. It is no surprise then that the principles of nanotechnology – and the potential to reduce the mass and size of spacecraft and payloads – are focusing the minds of space engineers.

"When nanotechnology is really developed, even countries that don't presently think about space will be able to afford space exploration," says Meyya Meyyappan, Chief Scientist for Exploration Technology at NASA's Centre for Nanotechnology, California.

He envisages swapping the multi-tonne spacecraft of today for shoebox-sized craft weighing just 2kg-5kg, yet matching all the capabilities of today's behemoths.

Taking its first step towards nano-sized instruments, NASA has developed a sensor, which utilises nanotechnology, for the International Space Station (ISS) that is the size of a postage stamp and can detect toxins in the air. It was taken into space briefly in 2009 for tests and, according to Meyyappan, is now ready for deployment. It is likely to be incorporated into NASA's space shuttle replacement vehicle and could be used on a future Mars rover to sample the alien atmosphere.

The sensor could also be modified to sample liquids. At present, astronauts' blood and urine samples have to be returned to ground control in Houston and checked in large-scale laboratories there for diseases, infections and general health. Nano-based sensors on board the ISS could provide instantaneous analyses and diagnoses. If manned Mars missions were ever to become a reality, such capabilities would be vital.

The European Space Agency (ESA) has also been studying the potential of nanotechnology. "There seems to be no limit to the potential application of nanotechnologies for space applications. Almost all technical domains covered by space research and development could benefit from these emerging technologies," says Laurent Marchand, Head of Components Technology at ESA's European Space Research and Technology Centre, Noordwijk, the Netherlands.

Nanoengineering could produce surfaces that regulate spacecraft temperatures more efficiently than the materials used today. It could also generate more efficient solar cells, rendering large panels redundant. This summer, ESA will be hosting its eighth biannual meeting to assess the technological readiness of various micro and nanotechnologies. Topics of discussion will include the possible uses of nanotech, how to test its reliability in space, and the current strategy for the development of such systems for space.

While making smaller components is an obvious way to drive down the mass and power consumption of an otherwise conventional spacecraft, nanotechnology offers much more potential than that.

"Nanotech can completely change the way we do space exploration," says Constantinos Mavroidis, distinguished Professor of Engineering, Northeastern University, Boston, Massachusetts. In 2006, he assembled a team to investigate concepts that could be possible within 50 years. "We wanted to think of what was simply not possible without nanotech," he says.

They hit upon two ideas. The first was a lightweight spacesuit that was more flexible than current garments. It would consist of three layers and be suitable for spending long periods of time exploring the Moon or Mars. Being thinner, however, the potential for damage would be higher, so Mavroidis investigated how to make it repair itself using self-assembling nanounits held inside the suit's layers. The nanounits would be based upon proteins and free to move along the suit layers. In the event of a breach, they would spill out, attaching to one another and building bridges across the damage. They could even carry emergency drugs to immediately treat any wound the astronaut may have suffered.

The team's second idea was a "spider's web" of hairline tubes that could be deployed across large tracts of a planet's surface. Inside the tubes would be an army of nanosensors that could measure the surface temperature and composition. Each web would span a dozen kilometres and be capable of sensing a planetary environment in great detail.

In space itself, nanotechnology-based missions hold great promise. Instead of general purpose spacecraft, hundreds or even thousands of identical microchip-sized spacecraft could be deployed to perform highly specific tasks. Using funding from the European Research Commission, Colin McInnes, Professor of Engineering, University of Strathclyde, Scotland, is currently studying such missions.

At present, ESA uses four nearly identical spacecraft called Cluster to measure the Earth's magnetic field and gauge its response to solar storms. Large numbers of smaller, nanotechnology-based spacecraft, known as "nanosats", could do a more detailed job by "carpeting" a much wider volume of space to provide continual monitoring of magnetic behaviour with high sensitivity.

Such nanosats would be so small that any gravitational attraction to the Earth would easily be overwhelmed by other forces, such as the pressure of sunlight and the minuscule drag of the Earth's highest atmosphere. This means that a nanosat would find it much easier to escape Earth's gravitational pull altogether, opening up new possibilities for propulsion.

Part of McInnes's study is to find the natural pathways in space that such nanosats could settle into. Once identified they could be exploited for future missions, allowing the tiny spacecraft to drift like dandelion fluff through the solar system.

"Nanotech is a new way of thinking about space missions. Once the idea is out there, people will think of all sorts of applications," says McInnes.

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Article 2

'60,000 miles up: Space elevator could be built by 2035, says new study'

This is an edited version of an article that was published on the ExtremeTech website in March 2014. The article was written by Graham Templeton.

Imagine a ribbon roughly one hundred million times as long as it is wide. If it were a metre long, it would be 10 nanometers wide, or just a few times thicker than a DNA double helix. Scaled up to the length of a football field, it would still be less than a micrometre across — smaller than a red blood cell. Would you trust your life to that thread? What about a tether 100,000 kilometers long, one stretching from the surface of the Earth to well past geostationary orbit (GEO, 22,236 miles up), but which was still somehow narrower than your own wingspan?

The idea of climbing such a ribbon with just your body weight sounds precarious enough, but the ribbon predicted by a new report from the International Academy of Astronautics (IAA) will be able to carry up to seven 20-ton payloads at once. It will serve as a tether stretching far beyond geostationary (aka geosynchronous) orbit and held taut by an anchor of roughly two million kilograms. Sending payloads up this backbone could fundamentally change the human relationship with space — every climber sent up the tether could match the space shuttle in capacity, allowing up to a "launch" every couple of days.

The report spends 350 pages laying out a detailed case for this device, called a *space elevator*. The central argument — that we should build a space elevator as soon as possible — is supported by a detailed accounting of the challenges associated with doing so. The possible pay-off is as simple as could be — a space elevator could bring the cost-per-kilogram of launch to geostationary orbit from $20,000 to as little as $500.

Not only is a geostationary orbit intrinsically useful for satellites, but it's far enough up the planet's gravity well to be able to use it in cheap, Earth-assisted launches. A mission to Mars might begin by pushing off near the top of the tether and using small rockets to move into a predictably unstable fall — one, two, three loops around the Earth and off we go with enough pep to cut huge fractions off the fuel budget. Setting up a base on the Moon or Mars would be relatively trivial, with a space elevator in place.

Those are not small advantages, and are worth significant investment from the private sector. Governments and corporations spend billions installing infrastructure in space — an elevator could easily pay for itself, and demand investment from anyone with an interest in ensuring cheap access to it down the line. A space elevator is relevant to scientists, telecoms, and militaries alike — and with Moon- and asteroid-based mining becoming less hare-brained by the minute, Earth's notorious resource sector could get on board as well. It will certainly be expensive, probably the biggest mega-project of all time, but since a space elevator can offer a solid value proposition to everyone from Google to DARPA to Exxon, funding might end up being the least of its problems.

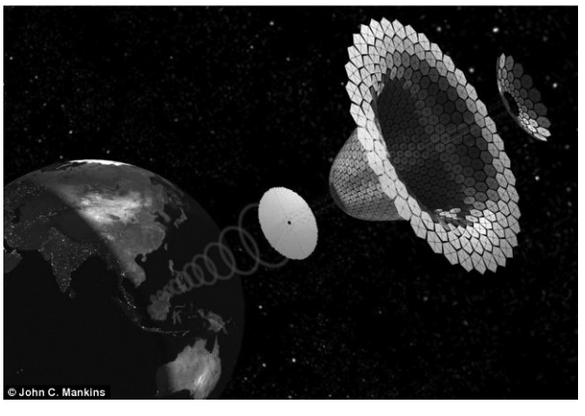
This report lays out a number of technological impediments to a space elevator, but by far the most important is the tether itself; materials science has still to invent a substance that could provide the strength, flexibility, and density needed for a space elevator. Existing technologies will be little help; tethers from the EU and Japan are beginning to push the 100-kilometre mark, but that's still a long way off orbital altitude, and the materials for existing tethers will not allow much additional length.

Projecting current research in carbon nanotubes and similar technologies, the IAA estimates that a pilot project could plausibly deliver packages to an altitude of 1000 kilometers (621 miles) as soon as 2025. With continued research and the help of a successful LEO (low Earth orbit; anywhere between an altitude of 100 and 1200 miles) elevator, they predict a 100,000-kilometre (62,137-mile) successor will stretch well past geosynchronous orbit just a decade after that.

When you get right down to it, how do you build a space elevator?

The proposed design really couldn't be simpler: a sea platform (or super-ship) anchors the tether to the Earth, while a counterweight (also called an "apex anchor") sits at the other end, keeping the system taut through centripetal force. Though many have dreamed of asteroid-capture missions to wrangle a space rock into being our anchor, the IAA points out that such a mission would likely require a space elevator to be possible in the first place.

Instead, the report argues that a nascent space elevator should be anchored first with a big ball of garbage — retired satellites, space debris, and the cast-off machinery used to build the elevator's own earliest stages. Interestingly, a tether stretching 150,000 kilometres or more would have enough weight of its own to sidestep the need for a counterweight altogether. All tethers, no matter the length, will have to be made in a curved shape so no single edge-on micro-collision could sever the ribbon entirely — though at just a metre wide, a collision wouldn't have to be very "macro" to cover the entire silhouette.



Climbers might well deploy huge solar arrays like this to power the climb past about 40 kilometres in altitude. © SPS-ALPHA Image and concept courtesy John C. Mankins

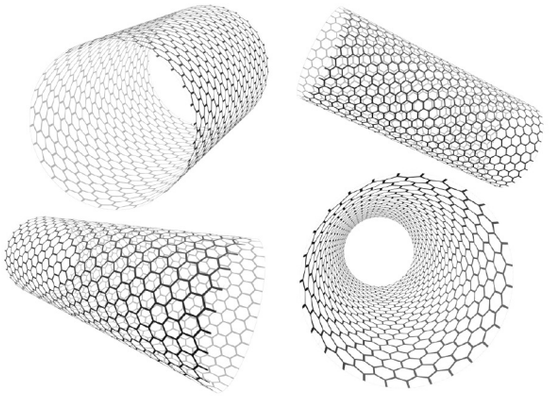
To keep weight down for the climbers (the elevator cars, if you will), this report imagines them as metal skeletons strung with meshes of carbon nanotubes — how would you like to ascend to space in a huge future-hammock? Each car would use a two-stage power structure to ascend, likely beginning with power from focused lasers fired from the ground, or with power sent down from a dedicated box satellite. Past 40 kilometres altitude, though, the climber's own solar array should be able to keep it moving with light unfiltered by Earth's atmosphere. IAA hopes for a seven-day climb from the base to GEO — slow, but still superior (and *far cheaper*) to the rockets that lead to months-long delays in launches today.

And more importantly, can we get the international cooperation to build such a mega contraption?

In terms of placement, IAA is unequivocal: a space elevator would be too precious a resource to be built within the territory of any particular nation-state — they reference the Suez Canal as an example of the problems in giving a self-interested nation control over global infrastructure. Though every government would certainly love a space elevator of its very own, cost considerations will likely make that impossible in the near-term. Purely by virtue of its physical size, a space elevator will stretch through multiple conflicting legal zones, from the high seas to the "territorial sky" to the "international sky" to outer space itself. Each of these presents its own unique legal and political challenges. The US could very well find itself lobbying China for help in building a tether that will help in the surveillance of Chinese territory — this will not be an easy project to plan.

Attacks by terrorists or enemies in war are also a major concern — though politically neutral, the eventual location of the Marine Stage One base station will immediately become one of the most aggressively defended no-fly zones in the world. It will be watched from beneath by underwater security, at altitude by radar sweeps and fighter patrols, and in space by nearby satellites. Notice that while this would be a stateless project, it would require a state's assets to maintain — likely via the UN or some new autonomous body tasked exclusively with elevator defense.

A team works on the YES2 tether, which is more than 30 kilometres long and just half a millimetre wide. © ESA - A. Le Floc'h



Though there are several possible tether materials, carbon nanotubes are the most likely candidate. © metamorworks/Shuttlestock

Arthur C. Clarke once famously said that we will build a space elevator 10 years after they stop laughing — and they've stopped laughing. He said that in 2003, and while his timeline may have been off, his sentiment surely wasn't. The concept of a space elevator is taken seriously at NASA these days, as it eyes both shrinking budgets and growing public expectations. Space is quickly becoming a bottleneck in the timeline of human technological advancement.

From mega-telescopes and surveillance nets to space mining operations and global high-speed internet coverage, most of our biggest upcoming projects will require better access to space than we could ever derive from tanks of combustible liquids. It's simultaneously a boring infrastructure project and a wide-eyed dream machine, a mega-project that illustrates how further progress in space will necessarily require global cooperation. In the eyes of this report, that cooperation could end up being the greatest challenge of all.

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Article 3

Extract from 'Space Elevator Technology and Research'

This is an edited version of an article that was published in volume 69 of the Journal of the British Interplanetary Society in June/July2016. The article was written by John Knapman, International Space Elevator Consortium.

The feasibility study on space elevators published by the IAA presented the state of the art in many areas, including characteristics of the tether climbers, how to deal with Earth's atmosphere, avoiding space debris, tether dynamics and the feasibility condition that gives a minimum acceptable tether strength. Since then, progress has been made on areas including the reduction of tether climbers' power requirements, dealing with the atmosphere and design of the Earth station. There remains a shortfall in material strength, but there is a new proposal – the multi-stage elevator – to enable the use of weaker materials than previously envisaged. At the same time, there have been some advances in methods of making stronger materials. Further areas of proposed research are in simulation of the tether's movement in its environment, including radiation, design of tether climbers, and stronger materials.

Keywords: Tether climber, materials, power, debris, atmosphere, simulator

1. INTRODUCTION

Building a space elevator will become feasible when either a strong enough material becomes available or another method is found for utilising existing materials. Meanwhile, there has been significant progress on a number of other relevant areas, much of it described in the feasibility study published by the International Academy of Astronautics [1]. This is referred to below as "the IAA study". It builds on the work of Edwards and Westling, Pearson and others [2, 3]. The following major topics are included:

1. Tether climber characteristics
   (a) Power source
   (b) Payload capacity
2. Dealing with Earth's turbulent atmosphere
   (a) Protecting tether climbers
   (b) Effects of wind and ice on the tether
   (c) High Stage One
3. Avoiding space debris
   (a) Tracked and untracked debris
4. The feasibility condition for minimum acceptable tether strength
5. Dynamics of the tether

Since that publication, more work has been done on the following:

1. Minimising the power requirements for tether climbers
2. Dealing with the Earth's atmosphere
3. Design of the Earth station
4. Building a tower or ladder based on the technology of High Stage One
   (a) Enabling space elevator construction with weaker materials
5. Progress in making stronger materials

A programme of research has been drawn up on several topics, including the following proposals:

1. An improved simulator for dynamics and electrodynamics
   (a) Linking to a model of the radiation environment in which the tether has to operate
2. Design of the tether climbers
   (a) Lightweight electric motors of the required power able to operate in a vacuum
   (b) A suitable gripping mechanism between the tether and each tether climber
3. Tether materials

2. STATE OF THE ART IN THE IAA STUDY

The IAA study showed several areas of progress and increased knowledge that bring the world closer to seeing the realization of the first space elevator.

2.1 Tether Climber Characteristics

For the first few years of operation, tether climbers will be unmanned and all operations will either be autonomous or will be controlled remotely. Each tether climber is composed of the following major components:

- Structure (with cargo bays)
- Energy management (source, distribution, storage)
- Motors
- Tether interface equipment
- Drive apparatus (wheels)
- Communications payloads and antennas
- Environmental controls (heat, cold, vacuum, radiation, etc.)
- Attitude control (star sensors, GPS sensors, thrusters, spinning devices, controllers, magnetic torque rods)
- Support equipment (robotic arm to load or offload cargo, housekeeping, etc.)

The tether climbers will be designed to operate above 40 km altitude with some type of external protection below that altitude for winds, lightning, rain, etc.

2.1.1 Power Source

Edwards proposed that power should be transmitted from the ground to the climbers by lasers. However, recent progress in thin-film photovoltaics makes the alternative of using solar power quite feasible. The solar power industry has made astonishing progress because of the widespread commercial interest in finding sources of power that are alternatives to fossil fuel.

2.1.2 Payload Capacity

The proposed design of a tether climber calls for a payload capacity of 14 tonnes (14,000 kg) to be lifted by a climber of 6 tonnes (6000 kg). The mass has been calculated with the assumption that the main structural material will be similar to that used for the tether.

2.1.3 Drive Mechanism

The climber elevates by friction wheels that grip the tether. Lightweight electric motors drive the wheels. Some successful experiments have been performed with a similar design using available materials. An acceptable coefficient of friction of the tether material is an important requirement in addition to its strength.

2.2 Dealing with Earth's Turbulent Atmosphere

Rocket launches can be scheduled for good weather, but the space elevator should provide a regular daily service. Tether climbers need to depart at regular times so that the load on the tether is within constraints. If a launch is delayed by three hours, for example, the next day's launch must be delayed by at least the same amount. When using solar cells for power, the hours of daylight are an additional constraint.

As a tether climber passes through the atmosphere, it is subject to the hazards of wind and ice. The solar panels will need to be stowed and protected. The receivers for laser power will be smaller but will still need protection.

The tether itself is also subject to atmospheric phenomena, and it has to endure all weathers. It is reasonable to cancel the launch of a climber in extreme weather, but the tether is a permanent part of the infrastructure. A tether design specific to the atmosphere is needed, much narrower than the 1 metre width that is appropriate for avoiding space debris and meteors. Edwards and Westling propose a width of 20 cm in the atmosphere, but a much narrower shape would be better to minimise wind impact [4].

Figure 1, table 1 and table 2 have been removed from the edited version.

2.2.1 Protecting Tether Climbers

A container could protect a climber's fragile solar panels from wind, ice and electric storms. It could be lifted by the tether climber's own mechanism, or it could have a separate climbing mechanism. An advantage of a separate mechanism would be to give greater flexibility in the tether design. A drawback is that a separate climbing mechanism for the box in the atmosphere would add extra weight to the tether.

Power for the box protection could be supplied from a cable connected to the surface. Carbon nanotubes can be made to act as conductors, semi-conductors and insulators. Hence they can form a very light power cable for the box protection up to the required altitude of at least 40 km. At this point, the box releases the tether climber to continue under its own solar power, while the box returns to the surface.

2.2.2 Effects of Wind and Ice on the Tether

Strong winds are sometimes experienced in the upper atmosphere. The significant factor for the space elevator is the wind pressure.

2.2.3 High Stage One

High Stage One absorbs the forces due to the atmosphere without affecting the tether. The relatively delicate movements needed to deflect the tether when avoiding space debris are carried out above most of the atmosphere, rather than being swamped by strong forces lower down. The delicate solar panels can be deployed at high altitude, where the tether climbers commence their ascent under their own power, avoiding the need to lift their deployment mechanism. The atmospheric buffeting of the climber itself is also absorbed by High Stage One.

High Stage One is useful whether employing solar power or laser power transmitters. Lasers can be positioned at an intermediate altitude, say 20 km, where the beam dispersion due to the atmosphere is much less than at sea level. At that altitude, they are still separated from the tether by a horizontal distance of 30 km or so.

Figure 2 has been removed from the edited version.

High Stage One is an adaptation of the Lofstrom Loop [5]. That was designed for direct launch of vehicles to orbit. Using this technology, it is possible to support a platform weighing several thousand tonnes, if necessary, at an altitude as high as 100 km. The proposed height for the platform is between 40 and 50 km. 50 km is the boundary between the stratosphere and the mesosphere. The tether is anchored to the platform, which is the place where we transfer payload to the tether climbers before they commence their ascent. [Chapter 5 in ref. 1] A separate system transfers payloads and equipment between the platform and the surface. It operates like a mountain railway or funicular, using the tubes as a track.

In the original Lofstrom Loop, each rotor was envisaged as a continuous, flexible loop travelling inside an evacuated tube. However, in High Stage One a rotor consists of a stream of bolts, each of which is a short, rigid structure up to a metre in length.

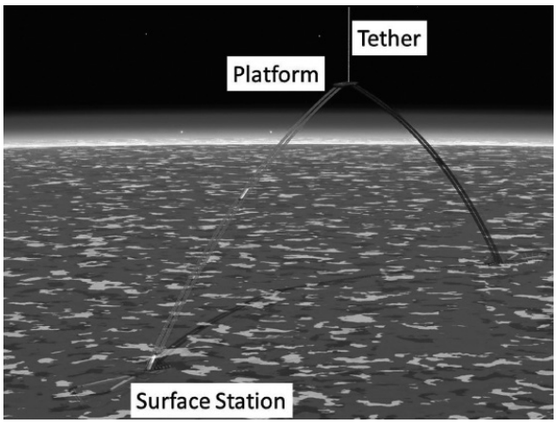

Figure 3

High Stage One 1

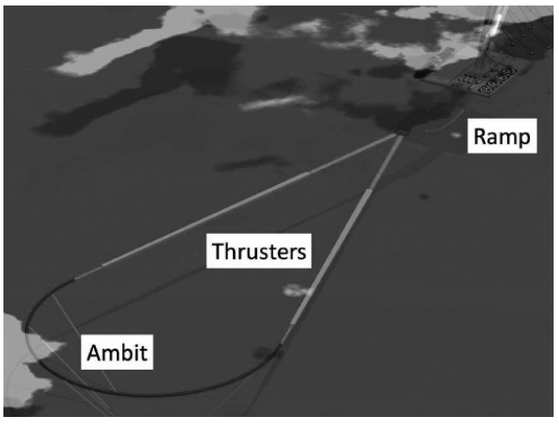

Figure 4

Detail of Surface Station 1

The different parts are illustrated in Figures 3 and 4. At the surface station, the thrusters accelerate the bolts, which then pass up the ramp at 1.6 km/s to reach the platform at a height of 40 km.

Magnetic levitation is a proven technology used in railways in China and Japan, and also used in certain machines such as pumps with magnetic bearings. It is used here to minimise friction. Each bolt has permanent magnets on each side that are attracted to permanent magnets in the track. Electronic controls operate electromagnets in each bolt to ensure that it remains central, and thus balanced, between the two sides.

2.3 Avoiding Space Debris

The space-elevator tether faces a small risk from a few natural meteoroids, but the vast majority of debris is due to the remnants of previous spacecraft, particularly those that have suffered collision or explosion. It is essential that the tether be able to deal with collisions without critical failure. Repair in place is required via specialised repair climbers as soon as possible after the impact.

2.3.1 Tracked and Untracked Debris

Items of debris larger than 10 cm are tracked and can be avoided. A climber's ascent can be delayed, and the tether can be moved by action at or near the Earth's surface. However, the tether must be able to sustain impacts with smaller objects without breaking. For this reason, it is shaped as a ribbon 1 metre wide and curled into a half cylinder so that what remains after a collision is still strong enough to support its own weight and the weight of climbers below the point of collision.

2.4 The Feasibility Condition for Minimum Acceptable Tether Strength

The feasibility condition states that the space elevator must be able to lift enough material to replace that lost due to damage and wear. [Chapter 3 in ref. 1] In addition, during construction it must be able to lift its own weight in a reasonable time. This is because the construction process requires a thin tether to be launched to geosynchronous altitude (GEO) by rocket and then used to lift more material until the full tether mass is ready for operations. The key measure is the time it takes to double the tether's mass. If the complete tether mass is 6400 tonnes and we launch 100 tonnes by rocket, we need six doublings to complete construction. If the doubling time is 18 months, construction takes nine years.

2.5 Dynamics of the Tether

Pearson's original paper showed that the tether dynamics are laterally stable, but he did not calculate the precise effects of such forces as tether elasticity and tides caused by the Moon and Sun. To avoid space debris, it will be necessary to set up travelling lateral waves timed to coincide with the expected impact.

3. RECENT DEVELOPMENTS

Since the IAA study was published, more work has been done and is summarised in this part of the paper.

3.1 Minimising the Power Requirements for Tether Climbers

In the interests of completing the IAA study in a reasonable time, some simplifying assumptions were made. It turns out that considerable savings can be made in the power consumption of tether climbers in conjunction with some adjustments in the tether's cross section and capacity. In turn, this leads to a motor design that is much smaller and easier to achieve, as well as a smaller requirement for the solar panels.

The IAA study assumes that tether climbers ascend at a constant speed of 60 m/s, about 216 km/hr. Power is supplied by solar panels, rather than terrestrial lasers, because of safety and technical considerations. [Chapter 4 in ref. 1] Only 6 tonnes mass is allowed for the climber mechanism, including the solar panels, to lift a 20-tonne climber, which includes a 14-tonne payload. Near the tether base, the power required to achieve this speed is 11.8 MW – quite a challenge for lightweight solar panels, and stretching the capacity of electric motors substantially beyond their present capabilities for this size of vehicle.

As the climber ascends, its effective weight diminishes because of the reduced gravity, reaching zero at GEO, where it attains orbital velocity. Consequently, the power required higher up the tether is much reduced. For example, at 2600 km altitude, the weight is half that at the surface, and so the power required is only 5.9 MW. At 6100 km, the power needed is 3 MW. Consequently, the climbers are weighed down and made more complex by power units that are only needed for less than one sixth of the distance to be travelled.

Shelef has pointed out that it is also possible for climbers to ascend at constant power [6]. This has the great advantage that much smaller motors and power supplies are needed. The drawback is that climbers have to travel more slowly up the lowest parts of the tether. This causes an extra load on the tether, because the climbers are bunched closer together at the lower elevations, where their weight is greater. In the IAA study, it is shown that the tether climbers reach an altitude of 4070 km in the first day at a constant

60 m/s (allowing for a wait of 5.4 hours during the night). At this altitude, a 20-tonne climber weighs a little over 7 tonnes, and the power consumption is down to 4.3 MW.

On the other hand, at a constant 4 MW, a climber starts at only 21 m/s; it reaches 32 m/s at the end of the first day and attains an altitude of only 1580 km, where its weight is 12.7 tonnes. However, it can make up for this slow progress later on and still reach GEO within seven days, even if we limit the speed to 83 m/s (300 km/hr). Figure 5 shows both arrangements with the weights of the tether climbers at various altitudes. We assume that the climber commences its ascent from High Stage One at 40 km altitude. [Chapter 5 in ref.1] There is already a small weight saving, so that a 20-tonne climber weighs 19.7 tonnes, as shown.

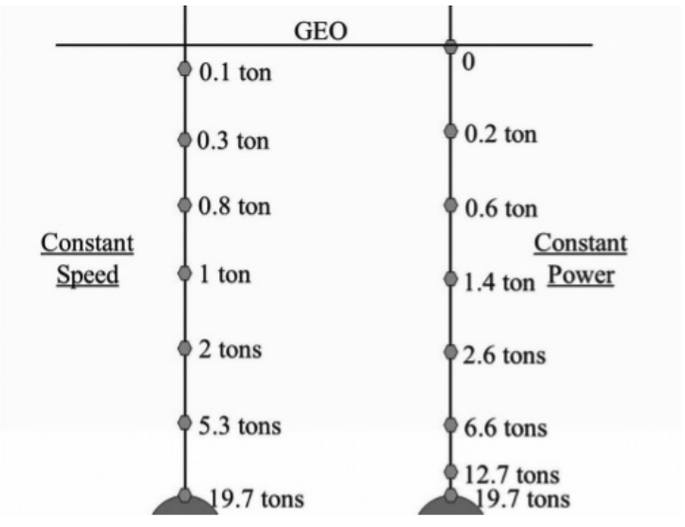

Figure 5

Disposition of tether climbers under constant speed (left) or constant power with speed limit (right)

3.2 Dealing with the Earth's Atmosphere

Three concepts have been proposed for dealing with the atmosphere: Box Protection, Spring Forward and High Stage One.

3.2.1 Spring Forward

When the time is close for launching a tether climber, the concept is to pull the tether down so as to utilise the natural elasticity of the tether material. Assuming the climber uses solar power above the atmosphere, launch preparations would begin a couple of hours before dawn.

The tether above the atmosphere is a metre wide but only 9 to 70 microns thick, depending on altitude. The tether must remain attached to the Earth's surface in order to launch a climber and also to ensure that the climber receives the benefit of the Earth's rotation. However, within the atmosphere the tether will be subject to atmospheric effects, principally wind and ice.

We call the part of the tether that is always in the atmosphere the auxiliary tether. The rest of the tether is the main tether. The main tether only has to be in the atmosphere while it is being pulled down and released. The tether climbers' drive mechanism is designed for the main tether, which is thin and a metre wide. When using Spring Forward, the climbers do not have to climb the auxiliary tether.

When preparing for a climber launch at the Marine Node, machinery pulls in the auxiliary tether to draw down the main tether, which becomes exposed to wind and ice risks until it is restored to its normal altitude. This is the time of greatest hazard, since the winds in the stratosphere are often very strong. The auxiliary tether has to take the full tension of the main tether, which must be sufficient to support the weight of the climber, plus the additional force needed to stretch the tether. When the Marine Node releases the tether, this stretching force provides lift to accelerate the climber.

The effect of lateral forces on a tether is to move it sideways until its tension increases sufficiently to overcome the forces, according to Newton's third law: action and reaction are equal and opposite.

These forces dwarf the delicate movements required for Spring Forward. They also swamp the moderate 5-tonne forces needed to deflect the tether when manoeuvring to avoid space debris. These considerations seriously call into question the viability of Spring Forward.

3.2.2 Box Protection

Box Protection was first devised as a way of protecting the delicate solar panels proposed for powering tether climbers. The solar panels must be very light in weight so as to fit into the mass budget. 4 MW is required to power a climber of 20 tonnes using the constant power method. This power must be delivered from panels weighing less than 2 tonnes. The present state of the art is about a factor of three short of that needed, and it is reasonable to project that level of improvement over the next few years, given the enormous worldwide investment in R&D on this topic.

The space elevator's unique mode of operation also requires a strong enough structure to support the solar panels under full gravity when they are deployed just above the atmosphere. This contrasts with the normal usage in space, where a spacecraft reaches microgravity before it deploys them. This means that the supports on the tether climber must be quite strong, but even so, the wind forces would still be too great without protection.

The estimated surface area of solar panels required is 66,000 m^2, and the wind force on them in the stratosphere could be as high as 66 MN, equivalent to a force of 6700 tonnes. It is therefore quite clear that the panels must be stowed inside a protector with a relatively small surface area. The same applies in Spring Forward as in Box Protection.

The proposed shape and size of a climber is a cylinder 20 metres in diameter by 15 metres high. [Chapter 4 in ref. 1] To this we add an estimate of another 5 metres in height to hold the deployable solar panels. This presents an effective surface area to the wind of 400 m^2, giving a maximum force in the stratosphere of 400 kN. However, whereas the tether must withstand freak or exceptional conditions, it is reasonable to assume that the operators would cancel a scheduled launch if the wind is more than double the average speed. That brings the maximum expected wind pressure down to 250 Pa, giving a maximum force on a climber of 100 kN, equivalent to 10 tonnes, which the tether has to absorb.

The tether climber is acting rather like a sail. So large is the force on it that we would probably want to consider making the tether climber smaller to avoid the effects, as otherwise it will triple the overall load that would have to be carried by the whole space-elevator tether all the way to the Apex Anchor.

To reduce the effects of winds on the tether, it needs to be narrower in the atmosphere than the one metre width it has in space. A width of 4 cm is suggested, wide enough for an adequate grip; the thickness must be about 250 microns. Even so, it will still experience wind forces that cause a load as great as 700 kN or 71 tonnes on top of the wind forces on the climber.

Box Protection is simpler than Spring Forward or High Stage One, but it does involve increasing the load on the tether by a factor of up to four. This factor can be reduced somewhat by making the tether climber smaller so that it acts less like a sail when it is climbing through the atmosphere, but this would constrain the payload space available to customers. High Stage One takes care of all these forces without loading the tether.

3.3 Design of the Earth Station

One vision of the Marine Node is shown in Figure 6. This concept is appropriate if High Stage One is not used.

The Marine Node provides a location for the tether terminus that can enable safe and routine operations. Its primary purpose is the mating and de-mating of satellites and climbers. This would include stabilising the tether, moving the tether, loading and unloading of cargo, and local operations support. It is where the climbers are prepared and then sent on their way safely. This fundamental support of the two-way transportation of goods connects the space elevator to the rest of the world and the rest of the world to the space elevator. The Marine Node will tie together all of the aspects of the terrestrial component to include safety, security, inspection of cargo, loading of cargo to climber, loading climbers on the space elevator tether, offloading climbers, and support to teams in the area.

The Marine Node is a city on multiple floating platforms in the eastern Pacific Ocean. The main element of the Marine Node, the Floating Operations Platform (FOP), will be the size of an aircraft carrier or larger. Secondary elements are now envisaged outlying from the FOP to give the tether terminus a strong base leg for tether anchoring stability. The Marine Node will have living quarters, kitchens and laundries, as well as recreational and medical facilities. It has room for helicopter landings, local support water craft, and the loading/unloading from larger ocean-going vessels.

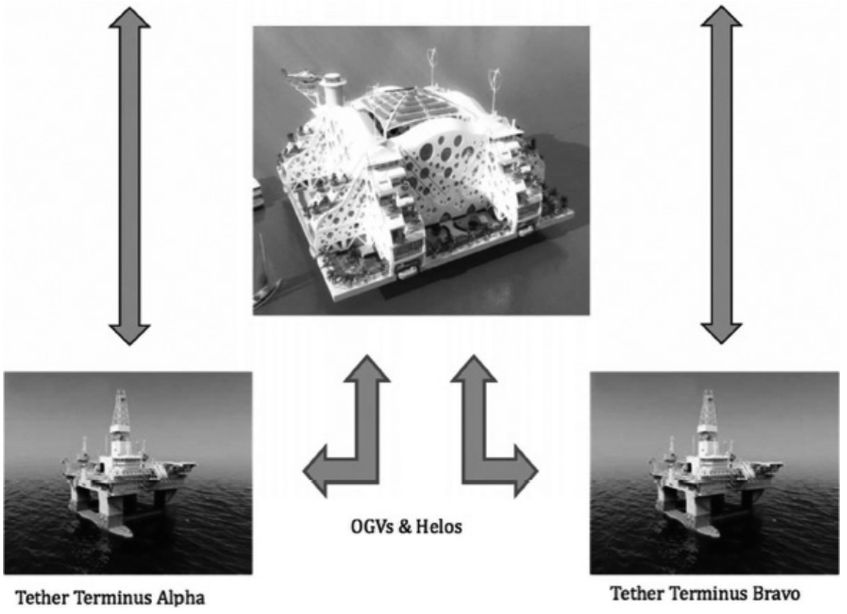

Figure 6

Marine node concept

3.4 A Multi-Stage Space Elevator

High Stage One uses the momentum of magnetically levitated bolts travelling inside evacuated tubes to support a structure at high altitude. A major limiting factor in the altitude that can be reached is the problem of space debris. For a structure to reach above the atmosphere, a solution to that problem is needed. That solution is to dispense with the evacuated tubes above the atmosphere, since there is already a vacuum. Then a collision with space debris will lead to the loss of a few bolts among the thousands in use, which will be of no consequence.

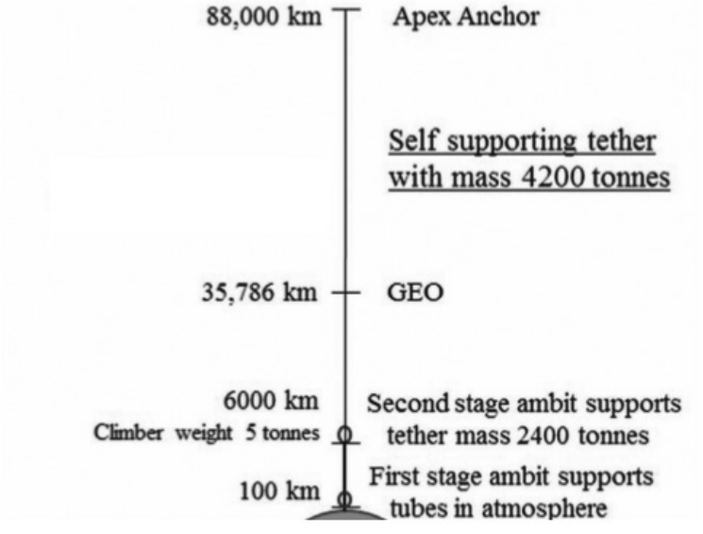

Figure 7

Bolts rise to 6000 km altitude to support the weight of a tether.

That opens up the possibility of using a vertical arrangement as in Figure 7 [8]. The structure at 6000 km is an ambit – the second stage ambit; there is another ambit at 100 km – the first stage – to support the evacuated tubes needed in the atmosphere; and there is a much larger ambit at the Earth's surface [7]. The force generated by turning the ascending bolts through 180°, so that they descend, is enough to support the weight of a tether that reaches down to Earth, together with the tether climbers. Another tether reaches from there up past GEO to the Apex Anchor at about 88,000 km. The combined mass of these two tethers is 6600 tonnes, similar to that needed for the architecture in the IAA study. However, the strength needed is less than one third.

More complicated arrangements with more stages permit an even weaker material to be used. For example, a three-stage architecture will work with a material strength of only one fifth of that needed for the more conventional architecture. Five stages are sufficient to permit the use of Zylon, which is already available commercially.

3.5 Progress in Making Stronger Materials

CNT films have recently been reported with a strength of 9.6 GPa and a density of 1.85×10^3 kg/m^3. After the safety margin, this gives a usable strength, sufficient for a four-stage architecture [9].

4. RESEARCH PROGRAMME

A programme of research has been drawn up on several topics, including the following.

4.1 An Improved Simulator for Dynamics and Electrodynamics

To avoid space debris, it will be necessary to set up lateral travelling waves in the tether timed to coincide with the expected impact. There will also be movements caused by wind. The tether's elasticity will lead to longitudinal waves as climbers ascend.

Various pieces of work have been done on the dynamics of the tether, but there is a need for much greater consistency. A comprehensive simulation tool is needed that is consistent with recent configurations (100,000 km length) but with enough latitude that engineers, scientists and strategists can examine variations and effects of several kinds of disturbance, including the following:

1. Propagation along the tether of both lateral and longitudinal movement
2. Effect of massive or fixed nodes (Apex Anchor, GEO, Earth's surface)
3. Effect of the moving tether climbers, including launching them to orbit or to interplanetary space – at least 10 below GEO and some above
   (a) Both ascending and descending climbers
   (b) Propagation of acceleration from the Earth's rotation
4. Disturbance due to impact of meteors or small pieces of debris (<10 cm), short of severance
5. Further work on severance scenarios at various altitudes
6. Tides, lunar and solar
7. Effect of external forces, including atmospheric winds and solar pressure in space
8. Effect of (hypothetical) thrusters to help manage tether movement
9. Positioning or moving the Marine Node off the equator
10. Long-term stability and station keeping
11. Elasticity of tether and the dynamics related to stretching
12. Special Case: deployment of bare tether from GEO, both up and down

The electrodynamics of the tether are coupled strongly to its motion and stability. Electromagnetic properties and their interaction with the space environment must therefore be well understood in order to predict things like climber motion, endpoint motion and the possibility of power generation and transmission. It will also be necessary to understand the effects of electrical discharges in the vicinity of strand breaks, given that substantial charges may build up along the length of the tether. Work has already been done on many of the following topics, but others have not yet been addressed:

1. Electromagnetic properties of the tether: resistivity, capacitance as a function of tether geometry, material, temperature, radiation environment
2. Electromagnetic environment of the tether: magnetosphere, electric fields, storms
3. Coupling of tether motion with electrodynamics, gravity, angular momentum
4. Electromagnetic and dynamic effects of tether damage: breaks, material degradation
5. Exploiting tether electrodynamics: power transmission

4.1.1 A Model of the Radiation Environment in which the Tether has to Operate

The tether and climbers will pass through Earth's radiation belts and the solar wind beyond the magnetopause. They will as a result be exposed to large fluxes of charged particles that pose a radiation hazard to humans, electronics and materials. In order to estimate this hazard in terms of dose to passengers, cargo and equipment, it is essential to have a comprehensive model of the radiation field throughout the range of tether and climber motions. Detailed simulations of the effects of penetrating radiation on various materials will be required in order to understand increased cancer and morbidity rates in humans, single event effects (SEE) in electronics and material degradation in the tether and climbers. Simulations of passive and active shielding arrangements for the climbers and of radiation hardening schemes for sensitive electronics must be done, and the results factored into climber and tether design. The particle flux near the tether will also affect the electrodynamic forces it sees, thus coupling closely to its motion via the charging mechanism. The following topics should therefore be addressed:

1. Charged particle flux along the tether as a function of distance and time: electrons, protons, ions
2. Effect on humans (dose, cancer risk, etc.)
3. Effect on electronics (single event effects, etc.)
4. Induced activation of tether and climber materials
5. Climber shielding
6. Coupling of charged particle flux to tether electrodynamics

The proposal is mostly based on updating and expanding the paper by Jorgensen and Patamia [10].

4.2 Design of the Tether Climbers

The overall objective is to keep the mass as low as possible. Several high-priority research areas are listed here:

1. The layout of the power source, which itself depends on the choice between transmitting laser power from the Earth and utilising solar power
2. Heat management, as all excess heat must be radiated away into space
3. Traction between climber and tether, which depends critically on the surface friction of the tether
4. Electric motors that are light enough yet capable of delivering the required power and operating in a vacuum

4.3 Tether Materials

Tether material is arguably the single most important issue in the realisation of the space elevator. Although numerous groups worldwide have carried out research on the manufacture of materials with strength suitable for the tether, no macroscopic sample with suitable specifications has ever been manufactured. Indeed there are a number of materials suitable for the tether, ranging from polymers to CNTs, but strengths vaguely close to the required values have been observed only in microscopic samples with sizes substantially smaller than 1mm.

A considerable amount of work needs to be done on the subject, including:

1. Experimental investigation of materials that exhibit strengths suitable for the tether
   (a) CNT bundles
   (b) Aligned polymers
   (c) Crystalline materials
2. Investigation of catalysts and/or processes capable of manufacturing samples of the above at least 1 cm long
3. Technologies capable of increasing the size of bundles above 1mm
4. Scaling of the process to lengths in excess of 1 metre
5. Development of technologies to weave bundles in yarns maintaining their high strength
6. Scaling of the process to lengths in excess of 1 km
7. Developing a continuous manufacturing technique suitable for yarns greater than 100 km long
8. Study of material and yarn performance under stress
9. Study of degradation mechanisms

5. CONCLUSION

The key issue remains the strength of the tether materials. Long lengths of high strength are required. It is also worth exploring alternative technologies that can be used to augment or support a tether made with existing materials or materials of intermediate strength that may soon become available. In this author's opinion, a viable solution would render the construction and operation of several space elevators so attractive that solutions would be found to the other problems in relatively short order.

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Pearson BTEC Level 3 Nationals Extended Diploma

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Monday 14 January 2019

Time: 2 hours 30 minutes | Paper Reference **31629H**

Applied Science

Unit 7: Contemporary Issues in Science

Part B

You will need:
Up to four sides of A4 notes from Part A

Total Marks

Instructions

- Use **black** ink or ball-point pen.
- **Fill in the boxes** at the top of this page with your name, centre number and learner registration number.
- Answer **all** questions.
- Answer the questions in the spaces provided
  – *there may be more space than you need.*
- **Part A** will need to have been used in preparation for completion of **Part B**.
- **Part B** must be undertaken in a single session of 2 hours and 30 minutes in the assessment session timetabled by Pearson.
- **Part B** materials must be issued to learners for the specified session.
- **Part B** is specific to each series and this material must only be issued to learners who have been entered to undertake the task in the relevant series.
- **Part B** should be kept securely until the start of the 2 hours and 30 minute supervised assessment.

Information

- The total mark for this paper is 50.
- The marks for **each** question are shown in brackets
  – *use this as a guide as to how much time to spend on each question.*
- The three articles are at the back of **Part B**.

Advice

- Read each question carefully before you start to answer it.
- Try to answer every question.
- Check your answers if you have time at the end.

Turn over ▶

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Pearson

Instructions to Teachers/Tutors

This paper must be read in conjunction with the unit information in the specification and the BTEC Nationals Instructions for Conducting External Assessments (ICEA) document. See the Pearson website for details.

Part B set task is undertaken under supervision in a single session of 2 hours and 30 minutes in the timetabled session. Centres may schedule a supervised rest break during the session.

Part B set task requires learners to apply understanding gained through familiarisation with the articles. Learners should bring in notes as defined in **Part A**.

Learners must complete the set task using this task and answer booklet.

Maintaining security

- Only permitted materials for the set task can be brought into the supervised environment.
- During any permitted break and at the end of the session materials must be kept securely and no items removed from the supervised environment.
- Learner notes related to **Part A** must be checked to ensure length and contents meet limitations.
- Learner notes from **Part A** will be retained securely by the centre after **Part B** and may be requested by Pearson if there is suspected malpractice.

After the session the teacher/tutor and/or invigilator will confirm that all learner work was completed independently as part of the authentication submitted to Pearson.

Outcomes for submission

This task and answer booklet should be submitted to Pearson.

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Instructions for Learners

Read the set task information carefully.

Complete all your work in this taskbook in the spaces provided**.**

This session is of 2 hours 30 minutes (during the day). Your teacher/invigilator will tell you if there is a supervised break. Plan your time carefully.

You have prepared for the set task given in this **Part B** booklet. Use your notes prepared during **Part A** if relevant. Attempt all the questions in **Part B**.

Your notes must be your own work and will be retained by your centre until results are issued.

You will complete this set task under supervision and your work will be kept securely during any breaks taken.

You must work independently throughout the supervised assessment period and must not share your work with other learners.

Outcomes for submission

You will need to submit the following document on completion of the supervised assessment period:

- a completed **Part B** taskbook.

Set Task

Answer ALL questions in the spaces provided.

1 Discuss the implications of the scientific issues identified in the articles.

(12)

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(Total for Question 1 = 12 marks)

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2 Identify the different organisations/individuals mentioned in the articles and suggest how they may have an influence on the scientific issues.

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3 Discuss whether Article 3 has made valid judgements.

In your answer you should consider:

- how the article has interpreted and analysed the scientific information to support the conclusions/judgements being made
- the validity and reliability of data
- references to other sources of information.

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(Total for Question 3 = 12 marks)

4 Suggest potential areas for further development and/or research of the scientific issues from the three articles.

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(Total for Question 4 = 5 marks)

5 You are a research assistant for the UK Space Agency.

You have been asked to write a report on the advantages and disadvantages of participating in an international project to build a space elevator.

Your report will be sent to a UK House of Commons committee, who are not scientists.

The report will be used by the committee to decide whether the UK takes part in the international project.

Use information from the three articles provided for this task.

When writing your report, you should consider:

- who is likely to read the report
- what you would like the reader to learn from the report.

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(Total for Question 5 = 15 marks)

TOTAL FOR PAPER = 50 MARKS

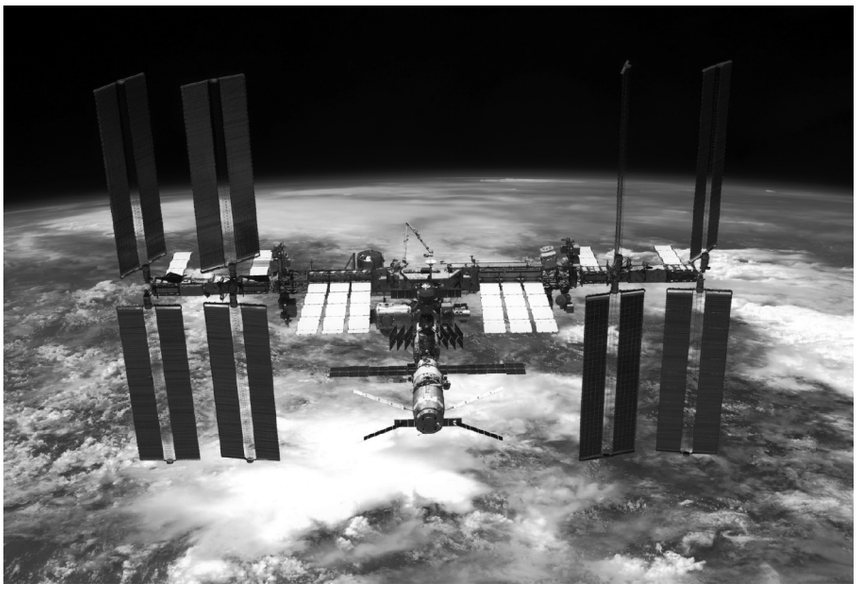
Set Task Information

Article 1

'Nanotechnology can launch a new age of space exploration'

This is an edited version of an article that appeared in 'The Guardian' newspaper in April 2012. The article was written by Stuart Clark.

NASA and the European Space Agency have some ambitious plans. But if manned missions to Mars, super-thin spacesuits and shoebox-sized shuttles become a reality, then nanotechnology will undoubtedly have played a key role.



Existing multi-tonne spacecraft may one day be swapped for shoebox-sized craft weighing just 2kg-5kg as developments in nanotechnology progress. Photograph: NASA/Getty Images North America.

Launching equipment into space is an expensive business: it costs $10,000 (£6,300) to lift every 0.45kg (1lb) of stuff into orbit. Making things smaller and lighter is, therefore, a natural route to reducing the cost of launching a spacecraft. It is no surprise then that the principles of nanotechnology – and the potential to reduce the mass and size of spacecraft and payloads – are focusing the minds of space engineers.

"When nanotechnology is really developed, even countries that don't presently think about space will be able to afford space exploration," says Meyya Meyyappan, Chief Scientist for Exploration Technology at NASA's Centre for Nanotechnology, California.

He envisages swapping the multi-tonne spacecraft of today for shoebox-sized craft weighing just 2kg-5kg, yet matching all the capabilities of today's behemoths.

Taking its first step towards nano-sized instruments, NASA has developed a sensor, which utilises nanotechnology, for the International Space Station (ISS) that is the size of a postage stamp and can detect toxins in the air. It was taken into space briefly in 2009 for tests and, according to Meyyappan, is now ready for deployment. It is likely to be incorporated into NASA's space shuttle replacement vehicle and could be used on a future Mars rover to sample the alien atmosphere.

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The sensor could also be modified to sample liquids. At present, astronauts' blood and urine samples have to be returned to ground control in Houston and checked in large-scale laboratories there for diseases, infections and general health. Nano-based sensors on board the ISS could provide instantaneous analyses and diagnoses. If manned Mars missions were ever to become a reality, such capabilities would be vital.

The European Space Agency (ESA) has also been studying the potential of nanotechnology. "There seems to be no limit to the potential application of nanotechnologies for space applications. Almost all technical domains covered by space research and development could benefit from these emerging technologies," says Laurent Marchand, Head of Components Technology at ESA's European Space Research and Technology Centre, Noordwijk, the Netherlands.

Nanoengineering could produce surfaces that regulate spacecraft temperatures more efficiently than the materials used today. It could also generate more efficient solar cells, rendering large panels redundant. This summer, ESA will be hosting its eighth biannual meeting to assess the technological readiness of various micro and nanotechnologies. Topics of discussion will include the possible uses of nanotech, how to test its reliability in space, and the current strategy for the development of such systems for space.

While making smaller components is an obvious way to drive down the mass and power consumption of an otherwise conventional spacecraft, nanotechnology offers much more potential than that.

"Nanotech can completely change the way we do space exploration," says Constantinos Mavroidis, distinguished Professor of Engineering, Northeastern University, Boston, Massachusetts. In 2006, he assembled a team to investigate concepts that could be possible within 50 years. "We wanted to think of what was simply not possible without nanotech," he says.

They hit upon two ideas. The first was a lightweight spacesuit that was more flexible than current garments. It would consist of three layers and be suitable for spending long periods of time exploring the Moon or Mars. Being thinner, however, the potential for damage would be higher, so Mavroidis investigated how to make it repair itself using self-assembling nanounits held inside the suit's layers. The nanounits would be based upon proteins and free to move along the suit layers. In the event of a breach, they would spill out, attaching to one another and building bridges across the damage. They could even carry emergency drugs to immediately treat any wound the astronaut may have suffered.

The team's second idea was a "spider's web" of hairline tubes that could be deployed across large tracts of a planet's surface. Inside the tubes would be an army of nanosensors that could measure the surface temperature and composition. Each web would span a dozen kilometres and be capable of sensing a planetary environment in great detail.

In space itself, nanotechnology-based missions hold great promise. Instead of general purpose spacecraft, hundreds or even thousands of identical microchip-sized spacecraft could be deployed to perform highly specific tasks. Using funding from the European Research Commission, Colin McInnes, Professor of Engineering, University of Strathclyde, Scotland, is currently studying such missions.

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At present, ESA uses four nearly identical spacecraft called Cluster to measure the Earth's magnetic field and gauge its response to solar storms. Large numbers of smaller, nanotechnology-based spacecraft, known as "nanosats", could do a more detailed job by "carpeting" a much wider volume of space to provide continual monitoring of magnetic behaviour with high sensitivity.

Such nanosats would be so small that any gravitational attraction to the Earth would easily be overwhelmed by other forces, such as the pressure of sunlight and the minuscule drag of the Earth's highest atmosphere. This means that a nanosat would find it much easier to escape Earth's gravitational pull altogether, opening up new possibilities for propulsion.

Part of McInnes's study is to find the natural pathways in space that such nanosats could settle into. Once identified they could be exploited for future missions, allowing the tiny spacecraft to drift like dandelion fluff through the solar system.

"Nanotech is a new way of thinking about space missions. Once the idea is out there, people will think of all sorts of applications," says McInnes.

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Article 2

'60,000 miles up: Space elevator could be built by 2035, say new study'

This is an edited version of an article that was published on the ExtremeTech website in March 2014. The article was written by Graham Templeton.

Imagine a ribbon roughly one hundred million times as long as it is wide. If it were a metre long, it would be 10 nanometers wide, or just a few times thicker than a DNA double helix. Scaled up to the length of a football field, it would still be less than a micrometre across — smaller than a red blood cell. Would you trust your life to that thread? What about a tether 100,000 kilometers long, one stretching from the surface of the Earth to well past geostationary orbit (GEO, 22,236 miles up), but which was still somehow narrower than your own wingspan?

The idea of climbing such a ribbon with just your body weight sounds precarious enough, but the ribbon predicted by a new report from the International Academy of Astronautics (IAA) will be able to carry up to seven 20-ton payloads at once. It will serve as a tether stretching far beyond geostationary (aka geosynchronous) orbit and held taut by an anchor of roughly two million kilograms. Sending payloads up this backbone could fundamentally change the human relationship with space — every climber sent up the tether could match the space shuttle in capacity, allowing up to a "launch" every couple of days.

The report spends 350 pages laying out a detailed case for this device, called a *space elevator*. The central argument — that we should build a space elevator as soon as possible — is supported by a detailed accounting of the challenges associated with doing so. The possible pay-off is as simple as could be — a space elevator could bring the cost-per-kilogram of launch to geostationary orbit from $20,000 to as little as $500.

Not only is a geostationary orbit intrinsically useful for satellites, but it's far enough up the planet's gravity well to be able to use it in cheap, Earth-assisted launches. A mission to Mars might begin by pushing off near the top of the tether and using small rockets to move into a predictably unstable fall — one, two, three loops around the Earth and off we go with enough pep to cut huge fractions off the fuel budget. Setting up a base on the Moon or Mars would be relatively trivial, with a space elevator in place.

Those are not small advantages, and are worth significant investment from the private sector. Governments and corporations spend billions installing infrastructure in space — an elevator could easily pay for itself, and demand investment from anyone with an interest in ensuring cheap access to it down the line. A space elevator is relevant to scientists, telecoms, and militaries alike — and with Moon- and asteroid-based mining becoming less hare-brained by the minute, Earth's notorious resource sector could get on board as well. It will certainly be expensive, probably the biggest mega-project of all time, but since a space elevator can offer a solid value proposition to everyone from Google to DARPA to Exxon, funding might end up being the least of its problems.

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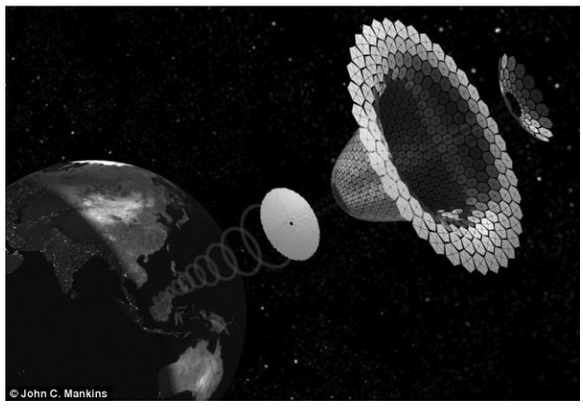
This report lays out a number of technological impediments to a space elevator, but by far the most important is the tether itself; materials science has still to invent a substance that could provide the strength, flexibility, and density needed for a space elevator. Existing technologies will be little help; tethers from the EU and Japan are beginning to push the 100-kilometre mark, but that's still a long way off orbital altitude, and the materials for existing tethers will not allow much additional length.

Projecting current research in carbon nanotubes and similar technologies, the IAA estimates that a pilot project could plausibly deliver packages to an altitude of 1000 kilometers (621 miles) as soon as 2025. With continued research and the help of a successful LEO (low Earth orbit; anywhere between an altitude of 100 and 1200 miles) elevator, they predict a 100,000-kilometre (62,137-mile) successor will stretch well past geosynchronous orbit just a decade after that.

When you get right down to it, how do you build a space elevator?

The proposed design really couldn't be simpler: a sea platform (or super-ship) anchors the tether to the Earth, while a counterweight (also called an "apex anchor") sits at the other end, keeping the system taut through centripetal force. Though many have dreamed of asteroid-capture missions to wrangle a space rock into being our anchor, the IAA points out that such a mission would likely require a space elevator to be possible in the first place.

Instead, the report argues that a nascent space elevator should be anchored first with a big ball of garbage — retired satellites, space debris, and the cast-off machinery used to build the elevator's own earliest stages. Interestingly, a tether stretching 150,000 kilometres or more would have enough weight of its own to sidestep the need for a counterweight altogether. All tethers, no matter the length, will have to be made in a curved shape so no single edge-on micro-collision could sever the ribbon entirely — though at just a metre wide, a collision wouldn't have to be very "macro" to cover the entire silhouette.



Climbers might well deploy huge solar arrays like this to power the climb past about 40 kilometres in altitude. © SPS-ALPHA Image and concept courtesy John C. Mankins

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To keep weight down for the climbers (the elevator cars, if you will), this report imagines them as metal skeletons strung with meshes of carbon nanotubes — how would you like to ascend to space in a huge future-hammock? Each car would use a two-stage power structure to ascend, likely beginning with power from focused lasers fired from the ground, or with power sent down from a dedicated box satellite. Past 40 kilometres altitude, though, the climber's own solar array should be able to keep it moving with light unfiltered by Earth's atmosphere. IAA hopes for a seven-day climb from the base to GEO — slow, but still superior (and *far cheaper*) to the rockets that lead to months-long delays in launches today.

And more importantly, can we get the international cooperation to build such a mega contraption?

In terms of placement, IAA is unequivocal: a space elevator would be too precious a resource to be built within the territory of any particular nation-state — they reference the Suez Canal as an example of the problems in giving a self-interested nation control over global infrastructure. Though every government would certainly love a space elevator of its very own, cost considerations will likely make that impossible in the near-term. Purely by virtue of its physical size, a space elevator will stretch through multiple conflicting legal zones, from the high seas to the "territorial sky" to the "international sky" to outer space itself. Each of these presents its own unique legal and political challenges. The US could very well find itself lobbying China for help in building a tether that will help in the surveillance of Chinese territory — this will not be an easy project to plan.

Attacks by terrorists or enemies in war are also a major concern — though politically neutral, the eventual location of the Marine Stage One base station will immediately become one of the most aggressively defended no-fly zones in the world. It will be watched from beneath by underwater security, at altitude by radar sweeps and fighter patrols, and in space by nearby satellites. Notice that while this would be a stateless project, it would require a state's assets to maintain — likely via the UN or some new autonomous body tasked exclusively with elevator defense.

A team works on the YES2 tether, which is more than 30 kilometres long and just half a millimetre wide. © ESA - A. Le Floc'h

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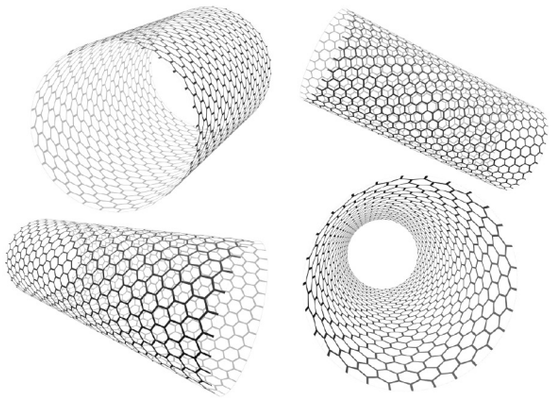

Though there are several possible tether materials, carbon nanotubes are the most likely candidate. © metamorworks/Shuttlestock

Arthur C. Clarke once famously said that we will build a space elevator 10 years after they stop laughing — and they've stopped laughing. He said that in 2003, and while his timeline may have been off, his sentiment surely wasn't. The concept of a space elevator is taken seriously at NASA these days, as it eyes both shrinking budgets and growing public expectations. Space is quickly becoming a bottleneck in the timeline of human technological advancement.

From mega-telescopes and surveillance nets to space mining operations and global high-speed internet coverage, most of our biggest upcoming projects will require better access to space than we could ever derive from tanks of combustible liquids. It's simultaneously a boring infrastructure project and a wide-eyed dream machine, a mega-project that illustrates how further progress in space will necessarily require global cooperation. In the eyes of this report, that cooperation could end up being the greatest challenge of all.

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Article 3

Extract from 'Space Elevator Technology and Research'

This is an edited version of an article that was published in volume 69 of the Journal of the British Interplanetary Society in June/July 2016. The article was written by John Knapman, International Space Elevator Consortium.

The feasibility study on space elevators published by the IAA presented the state of the art in many areas, including characteristics of the tether climbers, how to deal with Earth's atmosphere, avoiding space debris, tether dynamics and the feasibility condition that gives a minimum acceptable tether strength. Since then, progress has been made on areas including the reduction of tether climbers' power requirements, dealing with the atmosphere and design of the Earth station. There remains a shortfall in material strength, but there is a new proposal – the multi-stage elevator – to enable the use of weaker materials than previously envisaged. At the same time, there have been some advances in methods of making stronger materials. Further areas of proposed research are in simulation of the tether's movement in its environment, including radiation, design of tether climbers, and stronger materials.

Keywords: Tether climber, materials, power, debris, atmosphere, simulator

1. INTRODUCTION

Building a space elevator will become feasible when either a strong enough material becomes available or another method is found for utilising existing materials. Meanwhile, there has been significant progress on a number of other relevant areas, much of it described in the feasibility study published by the International Academy of Astronautics [1]. This is referred to below as "the IAA study". It builds on the work of Edwards and Westling, Pearson and others [2, 3]. The following major topics are included:

1. Tether climber characteristics
   (a) Power source
   (b) Payload capacity
2. Dealing with Earth's turbulent atmosphere
   (a) Protecting tether climbers
   (b) Effects of wind and ice on the tether
   (c) High Stage One
3. Avoiding space debris
   (a) Tracked and untracked debris
4. The feasibility condition for minimum acceptable tether strength
5. Dynamics of the tether

Since that publication, more work has been done on the following:

1. Minimising the power requirements for tether climbers
2. Dealing with the Earth's atmosphere
3. Design of the Earth station
4. Building a tower or ladder based on the technology of High Stage One
   (a) Enabling space elevator construction with weaker materials
5. Progress in making stronger materials

A programme of research has been drawn up on several topics, including the following proposals:

1. An improved simulator for dynamics and electrodynamics
   (a) Linking to a model of the radiation environment in which the tether has to operate
2. Design of the tether climbers
   (a) Lightweight electric motors of the required power able to operate in a vacuum
   (b) A suitable gripping mechanism between the tether and each tether climber
3. Tether materials

2. STATE OF THE ART IN THE IAA STUDY

The IAA study showed several areas of progress and increased knowledge that bring the world closer to seeing the realization of the first space elevator.

2.1 Tether Climber Characteristics

For the first few years of operation, tether climbers will be unmanned and all operations will either be autonomous or will be controlled remotely. Each tether climber is composed of the following major components:

- Structure (with cargo bays)
- Energy management (source, distribution, storage)
- Motors
- Tether interface equipment
- Drive apparatus (wheels)
- Communications payloads and antennas
- Environmental controls (heat, cold, vacuum, radiation, etc.)
- Attitude control (star sensors, GPS sensors, thrusters, spinning devices, controllers, magnetic torque rods)
- Support equipment (robotic arm to load or offload cargo, housekeeping, etc.)

The tether climbers will be designed to operate above 40 km altitude with some type of external protection below that altitude for winds, lightning, rain, etc.

2.1.1 Power Source

Edwards proposed that power should be transmitted from the ground to the climbers by lasers. However, recent progress in thin-film photovoltaics makes the alternative of using solar power quite feasible. The solar power industry has made astonishing progress because of the widespread commercial interest in finding sources of power that are alternatives to fossil fuel.

2.1.2 Payload Capacity

The proposed design of a tether climber calls for a payload capacity of 14 tonnes (14,000 kg) to be lifted by a climber of 6 tonnes (6000 kg). The mass has been calculated with the assumption that the main structural material will be similar to that used for the tether.

2.1.3 Drive Mechanism

The climber elevates, by friction, wheels that grip the tether. Lightweight electric motors drive the wheels. Some successful experiments have been performed with a similar design using available materials. An acceptable coefficient of friction of the tether material is an important requirement in addition to its strength.

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2.2 Dealing with Earth's Turbulent Atmosphere

Rocket launches can be scheduled for good weather, but the space elevator should provide a regular daily service. Tether climbers need to depart at regular times so that the load on the tether is within constraints. If a launch is delayed by three hours, for example, the next day's launch must be delayed by at least the same amount. When using solar cells for power, the hours of daylight are an additional constraint.

As a tether climber passes through the atmosphere, it is subject to the hazards of wind and ice. The solar panels will need to be stowed and protected. The receivers for laser power will be smaller but will still need protection.

The tether itself is also subject to atmospheric phenomena, and it has to endure all weathers. It is reasonable to cancel the launch of a climber in extreme weather, but the tether is a permanent part of the infrastructure. A tether design specific to the atmosphere is needed, much narrower than the 1 metre width that is appropriate for avoiding space debris and meteors. Edwards and Westling propose a width of 20 cm in the atmosphere, but a much narrower shape would be better to minimise wind impact [4].

Figure 1, table 1 and table 2 have been removed from the edited version.

2.2.1 Protecting Tether Climbers

A container could protect a climber's fragile solar panels from wind, ice and electric storms. It could be lifted by the tether climber's own mechanism, or it could have a separate climbing mechanism. An advantage of a separate mechanism would be to give greater flexibility in the tether design. A drawback is that a separate climbing mechanism for the box in the atmosphere would add extra weight to the tether.

Power for the box protection could be supplied from a cable connected to the surface. Carbon nanotubes can be made to act as conductors, semi-conductors and insulators. Hence they can form a very light power cable for the box protection up to the required altitude of at least 40 km. At this point, the box releases the tether climber to continue under its own solar power, while the box returns to the surface.

2.2.2 Effects of Wind and Ice on the Tether

Strong winds are sometimes experienced in the upper atmosphere. The significant factor for the space elevator is the wind pressure.

2.2.3 High Stage One

High Stage One absorbs the forces due to the atmosphere without affecting the tether. The relatively delicate movements needed to deflect the tether when avoiding space debris are carried out above most of the atmosphere, rather than being swamped by strong forces lower down. The delicate solar panels can be deployed at high altitude, where the tether climbers commence their ascent under their own power, avoiding the need to lift their deployment mechanism. The atmospheric buffeting of the climber itself is also absorbed by High Stage One.

High Stage One is useful whether employing solar power or laser power transmitters. Lasers can be positioned at an intermediate altitude, say 20 km, where the beam dispersion due to the atmosphere is much less than at sea level. At that altitude, they are still separated from the tether by a horizontal distance of 30 km or so.

Figure 2 has been removed from the edited version.

High Stage One is an adaptation of the Lofstrom Loop [5]. That was designed for direct launch of vehicles to orbit. Using this technology, it is possible to support a platform weighing several thousand tonnes, if necessary, at an altitude as high as 100 km. The proposed height for the platform is between 40 and 50 km. 50 km is the boundary between the stratosphere and the mesosphere. The tether is anchored to the platform, which is the place where we transfer payload to the tether climbers before they commence their ascent. [Chapter 5 in ref. 1] A separate system transfers payloads and equipment between the platform and the surface. It operates like a mountain railway or funicular, using the tubes as a track.

In the original Lofstrom Loop, each rotor was envisaged as a continuous, flexible loop travelling inside an evacuated tube. However, in High Stage One a rotor consists of a stream of bolts, each of which is a short, rigid structure up to a metre in length.

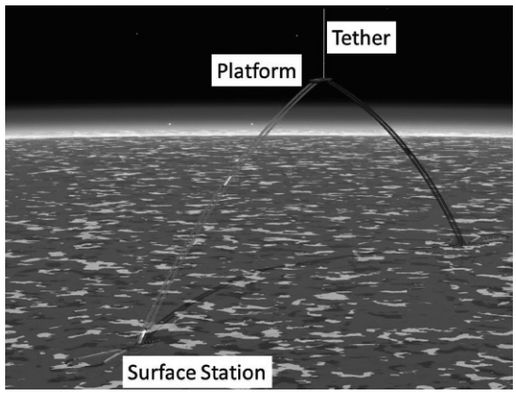

Figure 3

High Stage One 1

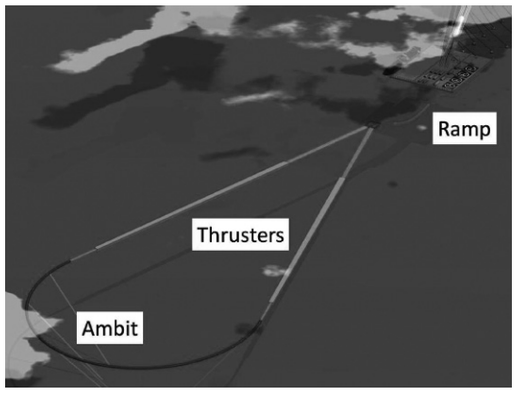

Figure 4

Detail of Surface Station 1

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The different parts are illustrated in Figures 3 and 4. At the surface station, the thrusters accelerate the bolts, which then pass up the ramp at 1.6 km/s to reach the platform at a height of 40 km.

Magnetic levitation is a proven technology used in railways in China and Japan, and also used in certain machines such as pumps with magnetic bearings. It is used here to minimise friction. Each bolt has permanent magnets on each side that are attracted to permanent magnets in the track. Electronic controls operate electromagnets in each bolt to ensure that it remains central, and thus balanced, between the two sides.

2.3 Avoiding Space Debris

The space-elevator tether faces a small risk from a few natural meteoroids, but the vast majority of debris is due to the remnants of previous spacecraft, particularly those that have suffered collision or explosion. It is essential that the tether be able to deal with collisions without critical failure. Repair in place is required via specialised repair climbers as soon as possible after the impact.

2.3.1 Tracked and Untracked Debris

Items of debris larger than 10 cm are tracked and can be avoided. A climber's ascent can be delayed, and the tether can be moved by action at or near the Earth's surface. However, the tether must be able to sustain impacts with smaller objects without breaking. For this reason, it is shaped as a ribbon 1 metre wide and curled into a half cylinder so that what remains after a collision is still strong enough to support its own weight and the weight of climbers below the point of collision.

2.4 The Feasibility Condition for Minimum Acceptable Tether Strength

The feasibility condition states that the space elevator must be able to lift enough material to replace that lost due to damage and wear. [Chapter 3 in ref. 1] In addition, during construction it must be able to lift its own weight in a reasonable time. This is because the construction process requires a thin tether to be launched to geosynchronous altitude (GEO) by rocket and then used to lift more material until the full tether mass is ready for operations. The key measure is the time it takes to double the tether's mass. If the complete tether mass is 6400 tonnes and we launch 100 tonnes by rocket, we need six doublings to complete construction. If the doubling time is 18 months, construction takes nine years.

2.5 Dynamics of the Tether

Pearson's original paper showed that the tether dynamics are laterally stable, but he did not calculate the precise effects of such forces as tether elasticity and tides caused by the Moon and Sun. To avoid space debris, it will be necessary to set up travelling lateral waves timed to coincide with the expected impact.

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3. RECENT DEVELOPMENTS

Since the IAA study was published, more work has been done and is summarised in this part of the paper.

3.1 Minimising the Power Requirements for Tether Climbers

In the interests of completing the IAA study in a reasonable time, some simplifying assumptions were made. It turns out that considerable savings can be made in the power consumption of tether climbers in conjunction with some adjustments in the tether's cross section and capacity. In turn, this leads to a motor design that is much smaller and easier to achieve, as well as a smaller requirement for the solar panels.

The IAA study assumes that tether climbers ascend at a constant speed of 60 m/s, about 216 km/hr. Power is supplied by solar panels, rather than terrestrial lasers, because of safety and technical considerations. [Chapter 4 in ref. 1] Only 6 tonnes mass is allowed for the climber mechanism, including the solar panels, to lift a 20-tonne climber, which includes a 14-tonne payload. Near the tether base, the power required to achieve this speed is 11.8 MW – quite a challenge for lightweight solar panels, and stretching the capacity of electric motors substantially beyond their present capabilities for this size of vehicle.

As the climber ascends, its effective weight diminishes because of the reduced gravity, reaching zero at GEO, where it attains orbital velocity. Consequently, the power required higher up the tether is much reduced. For example, at 2600 km altitude, the weight is half that at the surface, and so the power required is only 5.9 MW. At 6100 km, the power needed is 3 MW. Consequently, the climbers are weighed down and made more complex by power units that are only needed for less than one sixth of the distance to be travelled.

Shelef has pointed out that it is also possible for climbers to ascend at constant power [6]. This has the great advantage that much smaller motors and power supplies are needed. The drawback is that climbers have to travel more slowly up the lowest parts of the tether. This causes an extra load on the tether, because the climbers are bunched closer together at the lower elevations, where their weight is greater. In the IAA study, it is shown that the tether climbers reach an altitude of 4070 km in the first day at a constant 60 m/s (allowing for a wait of 5.4 hours during the night). At this altitude, a 20-tonne climber weighs a little over 7 tonnes, and the power consumption is down to 4.3 MW.

On the other hand, at a constant 4 MW, a climber starts at only 21 m/s; it reaches 32 m/s at the end of the first day and attains an altitude of only 1580 km, where its weight is 12.7 tonnes. However, it can make up for this slow progress later on and still reach GEO within seven days, even if we limit the speed to 83 m/s (300 km/hr). Figure 5 shows both arrangements with the weights of the tether climbers at various altitudes. We assume that the climber commences its ascent from High Stage One at 40 km altitude. [Chapter 5 in ref.1] There is already a small weight saving, so that a 20-tonne climber weighs 19.7 tonnes, as shown.

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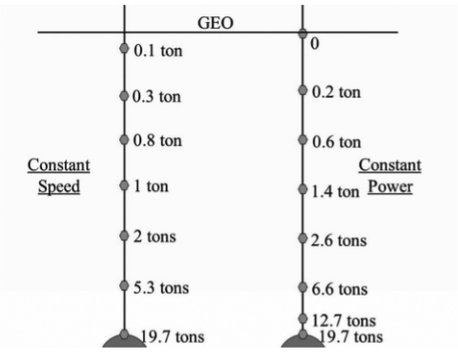

Fig. 5 Disposition of tether climbers under constant speed (left) or constant power with speed limit (right).

Figure 5

Disposition of tether climbers under constant speed (left) or constant power with speed limit (right)

3.2 Dealing with the Earth's Atmosphere

Three concepts have been proposed for dealing with the atmosphere: Box Protection, Spring Forward and High Stage One.

3.2.1 Spring Forward

When the time is close for launching a tether climber, the concept is to pull the tether down so as to utilise the natural elasticity of the tether material. Assuming the climber uses solar power above the atmosphere, launch preparations would begin a couple of hours before dawn.

The tether above the atmosphere is a metre wide but only 9 to 70 microns thick, depending on altitude. The tether must remain attached to the Earth's surface in order to launch a climber and also to ensure that the climber receives the benefit of the Earth's rotation. However, within the atmosphere the tether will be subject to atmospheric effects, principally wind and ice.

We call the part of the tether that is always in the atmosphere the auxiliary tether. The rest of the tether is the main tether. The main tether only has to be in the atmosphere while it is being pulled down and released. The tether climbers' drive mechanism is designed for the main tether, which is thin and a metre wide. When using Spring Forward, the climbers do not have to climb the auxiliary tether.

When preparing for a climber launch at the Marine Node, machinery pulls in the auxiliary tether to draw down the main tether, which becomes exposed to wind and ice risks until it is restored to its normal altitude. This is the time of greatest hazard, since the winds in the stratosphere are often very strong. The auxiliary tether has to take the full tension of the main tether, which must be sufficient to support the weight of the climber, plus the additional force needed to stretch the tether. When the Marine Node releases the tether, this stretching force provides lift to accelerate the climber.

The effect of lateral forces on a tether is to move it sideways until its tension increases sufficiently to overcome the forces, according to Newton's third law: action and reaction are equal and opposite.

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These forces dwarf the delicate movements required for Spring Forward. They also swamp the moderate 5-tonne forces needed to deflect the tether when manoeuvring to avoid space debris. These considerations seriously call into question the viability of Spring Forward.

3.2.2 Box Protection

Box Protection was first devised as a way of protecting the delicate solar panels proposed for powering tether climbers. The solar panels must be very light in weight so as to fit into the mass budget. 4 MW is required to power a climber of 20 tonnes using the constant power method. This power must be delivered from panels weighing less than 2 tonnes. The present state of the art is about a factor of three short of that needed, and it is reasonable to project that level of improvement over the next few years, given the enormous worldwide investment in R&D on this topic.

The space elevator's unique mode of operation also requires a strong enough structure to support the solar panels under full gravity when they are deployed just above the atmosphere. This contrasts with the normal usage in space, where a spacecraft reaches microgravity before it deploys them. This means that the supports on the tether climber must be quite strong, but even so, the wind forces would still be too great without protection.

The estimated surface area of solar panels required is 66,000 m^2, and the wind force on them in the stratosphere could be as high as 66 MN, equivalent to a force of 6700 tonnes. It is therefore quite clear that the panels must be stowed inside a protector with a relatively small surface area. The same applies in Spring Forward as in Box Protection.

The proposed shape and size of a climber is a cylinder 20 metres in diameter by 15 metres high. [Chapter 4 in ref. 1] To this we add an estimate of another 5 metres in height to hold the deployable solar panels. This presents an effective surface area to the wind of 400 m^2, giving a maximum force in the stratosphere of 400 kN. However, whereas the tether must withstand freak or exceptional conditions, it is reasonable to assume that the operators would cancel a scheduled launch if the wind is more than double the average speed. That brings the maximum expected wind pressure down to 250 Pa, giving a maximum force on a climber of 100 kN, equivalent to 10 tonnes, which the tether has to absorb.

The tether climber is acting rather like a sail. So large is the force on it that we would probably want to consider making the tether climber smaller to avoid the effects, as otherwise it will triple the overall load that would have to be carried by the whole space-elevator tether all the way to the Apex Anchor.

To reduce the effects of winds on the tether, it needs to be narrower in the atmosphere than the one metre width it has in space. A width of 4 cm is suggested, wide enough for an adequate grip; the thickness must be about 250 microns. Even so, it will still experience wind forces that cause a load as great as 700 kN or 71 tonnes on top of the wind forces on the climber.

Box Protection is simpler than Spring Forward or High Stage One, but it does involve increasing the load on the tether by a factor of up to four. This factor can be reduced somewhat by making the tether climber smaller so that it acts less like a sail when it is climbing through the atmosphere, but this would constrain the payload space available to customers. High Stage One takes care of all these forces without loading the tether.

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3.3 Design of the Earth Station

One vision of the Marine Node is shown in Figure 6. This concept is appropriate if High Stage One is not used.

The Marine Node provides a location for the tether terminus that can enable safe and routine operations. Its primary purpose is the mating and de-mating of satellites and climbers. This would include stabilising the tether, moving the tether, loading and unloading of cargo, and local operations support. It is where the climbers are prepared and then sent on their way safely. This fundamental support of the two-way transportation of goods connects the space elevator to the rest of the world and the rest of the world to the space elevator. The Marine Node will tie together all of the aspects of the terrestrial component to include safety, security, inspection of cargo, loading of cargo to climber, loading climbers on the space elevator tether, offloading climbers, and support to teams in the area.

The Marine Node is a city on multiple floating platforms in the eastern Pacific Ocean. The main element of the Marine Node, the Floating Operations Platform (FOP), will be the size of an aircraft carrier or larger. Secondary elements are now envisaged outlying from the FOP to give the tether terminus a strong base leg for tether anchoring stability. The Marine Node will have living quarters, kitchens and laundries, as well as recreational and medical facilities. It has room for helicopter landings, local support water craft, and the loading/unloading from larger ocean-going vessels.

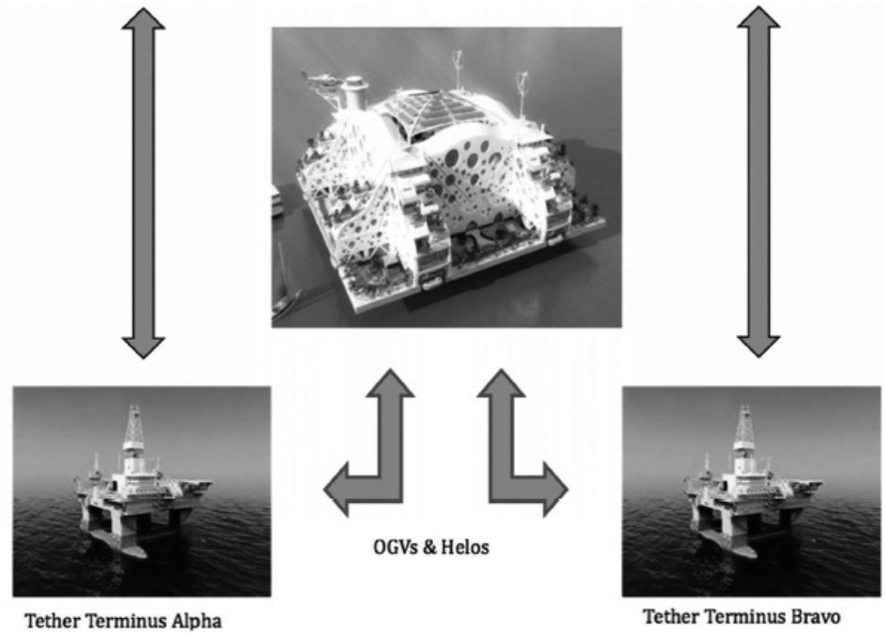

Figure 6

Marine Node concept

3.4 A Multi-Stage Space Elevator

High Stage One uses the momentum of magnetically levitated bolts travelling inside evacuated tubes to support a structure at high altitude. A major limiting factor in the altitude that can be reached is the problem of space debris. For a structure to reach above the atmosphere, a solution to that problem is needed. That solution is to dispense with the evacuated tubes above the atmosphere, since there is already a vacuum. Then a collision with space debris will lead to the loss of a few bolts among the thousands in use, which will be of no consequence.

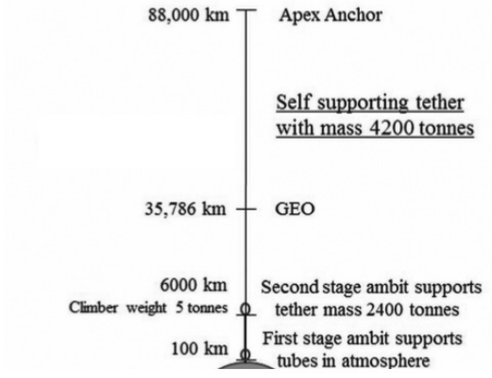

Figure 7

Bolts rise to 6000km altitude to support the weight of a tether.

That opens up the possibility of using a vertical arrangement as in Figure 7 [8]. The structure at 6000 km is an ambit – the second stage ambit; there is another ambit at 100 km – the first stage – to support the evacuated tubes needed in the atmosphere; and there is a much larger ambit at the Earth's surface. The force generated by turning the ascending bolts through 180°, so that they descend, is enough to support the weight of a tether that reaches down to Earth, together with the tether climbers. Another tether reaches from there up past GEO to the Apex Anchor at about 88,000 km. The combined mass of these two tethers is 6600 tonnes, similar to that needed for the architecture in the IAA study. However, the strength needed is less than one third.

More complicated arrangements with more stages permit an even weaker material to be used. For example, a three-stage architecture will work with a material strength of only one fifth of that needed for the more conventional architecture. Five stages are sufficient to permit the use of Zylon, which is already available commercially.

3.5 Progress in Making Stronger Materials

CNT films have recently been reported with a strength of 9.6 GPa and a density of 1.85×10^3 kg/m^3. After the safety margin, this gives a usable strength, sufficient for a four-stage architecture [9].

4. RESEARCH PROGRAMME

A programme of research has been drawn up on several topics, including the following.

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4.1 An Improved Simulator for Dynamics and Electrodynamics

To avoid space debris, it will be necessary to set up lateral travelling waves in the tether timed to coincide with the expected impact. There will also be movements caused by wind. The tether's elasticity will lead to longitudinal waves as climbers ascend.

Various pieces of work have been done on the dynamics of the tether, but there is a need for much greater consistency. A comprehensive simulation tool is needed that is consistent with recent configurations (100,000 km length) but with enough latitude that engineers, scientists and strategists can examine variations and effects of several kinds of disturbance, including the following:

1. Propagation along the tether of both lateral and longitudinal movement
2. Effect of massive or fixed nodes (Apex Anchor, GEO, Earth's surface)
3. Effect of the moving tether climbers, including launching them to orbit or to interplanetary space – at least 10 below GEO and some above
   (a) Both ascending and descending climbers
   (b) Propagation of acceleration from the Earth's rotation
4. Disturbance due to impact of meteors or small pieces of debris (<10 cm), short of severance
5. Further work on severance scenarios at various altitudes
6. Tides, lunar and solar
7. Effect of external forces, including atmospheric winds and solar pressure in space
8. Effect of (hypothetical) thrusters to help manage tether movement
9. Positioning or moving the Marine Node off the equator
10. Long-term stability and station keeping
11. Elasticity of tether and the dynamics related to stretching
12. Special Case: deployment of bare tether from GEO, both up and down

The electrodynamics of the tether are coupled strongly to its motion and stability. Electromagnetic properties and their interaction with the space environment must therefore be well understood in order to predict things like climber motion, endpoint motion and the possibility of power generation and transmission. It will also be necessary to understand the effects of electrical discharges in the vicinity of strand breaks, given that substantial charges may build up along the length of the tether. Work has already been done on many of the following topics, but others have not yet been addressed:

1. Electromagnetic properties of the tether: resistivity, capacitance as a function of tether geometry, material, temperature, radiation environment
2. Electromagnetic environment of the tether: magnetosphere, electric fields, storms
3. Coupling of tether motion with electrodynamics, gravity, angular momentum
4. Electromagnetic and dynamic effects of tether damage: breaks, material degradation
5. Exploiting tether electrodynamics: power transmission

4.1.1 A Model of the Radiation Environment in which the Tether has to Operate

The tether and climbers will pass through Earth's radiation belts and the solar wind beyond the magnetopause. They will as a result be exposed to large fluxes of charged particles that pose a radiation hazard to humans, electronics and materials. In order to estimate this hazard in terms of dose to passengers, cargo and equipment, it is essential to have a comprehensive model of the radiation field throughout the range of tether and climber motions. Detailed simulations of the effects of penetrating radiation on various materials will be required in order to understand increased cancer and morbidity rates in humans, single event effects (SEE) in electronics and material degradation in the

tether and climbers. Simulations of passive and active shielding arrangements for the climbers and of radiation hardening schemes for sensitive electronics must be done, and the results factored into climber and tether design. The particle flux near the tether will also affect the electrodynamic forces it sees, thus coupling closely to its motion via the charging mechanism. The following topics should therefore be addressed:

1. Charged particle flux along the tether as a function of distance and time: electrons, protons, ions
2. Effect on humans (dose, cancer risk, etc.)
3. Effect on electronics (single event effects, etc.)
4. Induced activation of tether and climber materials
5. Climber shielding
6. Coupling of charged particle flux to tether electrodynamics

The proposal is mostly based on updating and expanding the paper by Jorgensen and Patamia [10].

4.2 Design of the Tether Climbers

The overall objective is to keep the mass as low as possible. Several high-priority research areas are listed here:

1. The layout of the power source, which itself depends on the choice between transmitting laser power from the Earth and utilising solar power
2. Heat management, as all excess heat must be radiated away into space
3. Traction between climber and tether, which depends critically on the surface friction of the tether
4. Electric motors that are light enough yet capable of delivering the required power and operating in a vacuum

4.3 Tether Materials

Tether material is arguably the single most important issue in the realisation of the space elevator. Although numerous groups worldwide have carried out research on the manufacture of materials with strength suitable for the tether, no macroscopic sample with suitable specifications has ever been manufactured. Indeed there are a number of materials suitable for the tether, ranging from polymers to CNTs, but strengths vaguely close to the required values have been observed only in microscopic samples with sizes substantially smaller than 1mm.

A considerable amount of work needs to be done on the subject, including:

1. Experimental investigation of materials that exhibit strengths suitable for the tether
   (a) CNT bundles
   (b) Aligned polymers
   (c) Crystalline materials
2. Investigation of catalysts and/or processes capable of manufacturing samples of the above at least 1 cm long
3. Technologies capable of increasing the size of bundles above 1mm
4. Scaling of the process to lengths in excess of 1 metre
5. Development of technologies to weave bundles in yarns maintaining their high strength
6. Scaling of the process to lengths in excess of 1 km

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7. Developing a continuous manufacturing technique suitable for yarns greater than 100 km long
8. Study of material and yarn performance under stress
9. Study of degradation mechanisms

5. CONCLUSION

The key issue remains the strength of the tether materials. Long lengths of high strength are required. It is also worth exploring alternative technologies that can be used to augment or support a tether made with existing materials or materials of intermediate strength that may soon become available. In this author's opinion, a viable solution would render the construction and operation of several space elevators so attractive that solutions would be found to the other problems in relatively short order.

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