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SPACE ELEVATOR: FEASIBILITY AND IMPLICATIONS

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by

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Abstract

A space elevator is a tower extending from Earth's surface to a height above geostationary orbit. This project examines the feasibility of constructing a space elevator using carbon nanotubes and the impacts that such an elevator might have. Attention is also paid to the applications of carbon nanotubes beyond the space elevator. We conclude that with further development and refinement of the carbon nanotube manufacturing process, the space elevator will be feasible with great impacts to social and scientific communities.

Preface

This IQP, analyzing the feasibility and impacts of a space elevator, is part of a larger group of space policy IQPs being conducted during the 2005-2006 academic year. This project expands on previous IQPs which dealt with the space elevator in an introductory manner. Although this IQP covers a technical subject, it is written so that anyone can understand and appreciate this study with little or no background knowledge. While there are many issues surrounding the space elevator, this IQP focuses on specific areas - carbon nanotube technology, its impacts relating to the construction of a space elevator, and the social impacts of the space elevator itself. This project can be used by future IQP teams as a starting point for an in-depth look at other issues surrounding the space elevator concept.

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Table of Contents

List of Figures

Chapter 1: Overview of the Project

The purpose of this project is to explore the feasibility of constructing a space elevator and the scientific, commercial and societal impacts it might have. A space elevator is a giant tower extending from a point on the Earth's equator to a height considerably above geostationary orbit, where it terminates in a counterweight. The idea of such an elevator has a long and interesting history, but only recently did it pass from being a dream into a real scientific possibility. The discovery of carbon nanotubes in 1991 was an event of crucial importance for the space elevator. Carbon nanotubes are the only substance known to be strong enough to build the space elevator with. The purpose of this project is to give a general overview of the space elevator, to explore the feasibility of its construction in the light of advances in carbon nanotube technology, and then to explore the scientific and commercial implications of the elevator when it is finally built.

Although there are many political, international, and technical issues surrounding the space elevator, this project will be focusing on the technical feasibility of using carbon nanotubes as the main component of the space elevator cable. By researching various sources, this project will attempt to determine the outlook of carbon nanotubes for use in the space elevator with respect to their realization of the incredible material properties they're theorized to possess. These properties allow carbon nanotubes to withstand the enormous stresses and tensions that a space elevator cable would experience.

This project will attempt to convey its information in non-technical language for the most part, with technical terms of discussion being included sparingly and only when necessary. The definitions of many of the technical terms used can be found in the glossary. Most technical discussions have been relegated to the appendices and may be skipped without much loss of continuity. A general overview of the space elevator, the origins of its design, and the history of carbon nanotube technology will be presented in order to provide the reader with enough information to fully appreciate and understand the space elevator concept. Numerous charts, tables, graphs and graphics will help convey the findings of this project.

With the rapid growth in the number of Space Policy IQPs at WPI over the past year, we hope that this project will be able to assist current and future IQP students by providing a technical overview and understanding of carbon nanotube technology, and its application to the space elevator.

1.A Literature Review

The idea of an elevator to space is not new. In the book of Genesis, written around 1450 B.C., Moses writes of an early civilization which, in 2100 B.C., tried to construct a tower to heaven. Commonly called the Tower of Babel, this is one of history's first examples of mankind's desire to build to the heavens [31]. The quest for a means to reach the heavens became a topic of scientific interest starting in the nineteenth century when Russian physicist Konstantin Tsiolkovsky, considered by many to be the father of astronautics and rocket dynamics, published the manuscript "Speculations about Earth and Sky and on Vesta". Written in 1895, Tsiolkovsky’s vision of an enormously tall tower extending from earth to space is one of the earliest by a member of the scientific community.

In 1960, Yuri Artsutanov, a Leningrad engineer, published a non-technical account of a space elevator which utilized geostationary orbit. Despite being the first publication to address the space elevator, Artsutanov’s paper was unknown to the West for many years. It wasn’t until 1975 that America got its first glimpse of the space elevator concept. It was at this time that Jerome Pearson, working out of the Air Force Research Laboratory, developed the idea (remarkably, he had no prior knowledge of Artsutanov’s work) and published a technical report in *Acta Astronautica*, the journal of the International Astronautics Association. Soon the idea of an elevator to space had spread globally [31]. In 1979, Arthur C. Clarke wrote the science-fiction novel *Fountains of Paradise*, detailing a space elevator anchored in a fictional country located at the Earth’s equator. Clarke’s technical background allowed him to convey an image of the space elevator which was based in science and yet still accessible to the public who read his book [3]. In 1981, Clarke published *The Space Elevator: ‘Thought Experiment’, or Key to the Universe?* Published in the Great Britain’s Journal *Advances in Earth Oriented Applied Space Technologies*, Clarke detailed how the idea of a space elevator had been independently invented and published by several individuals, and how the work to model and quantify the forces had been successful but also proved the elevator to be impossible until stronger materials were discovered [4].

In 1991, the discovery of carbon nanotubes was made during the research of carbon buckeyballs. Discovered by Sumio Iijima of Meijo University in Nagoya, Japan, the unique structure of carbon nanotubes was instantly recognized as one of the strongest known in the world. Though nanotubes are typically only two nanometers wide – about 10,000 times thinner than a human hair – and at the time around a hundred nanometers long, the material that Clarke and his predecessors had been looking for had been found [20].

In the following years, little progress was made on using carbon nanotubes as the primary material for the space elevator. It took an imaginative, driven researcher at the Los Alamos National Laboratory, Brad Edwards, to recognize the potential of the space elevator and to pursue the idea further. Edwards undertook a two year, $500,000 grant from the NASA Institute for Advanced Concepts (NIAC) to produce a Phase I report on the development of a space elevator program [20].

This Phase I report detailed many of the general concepts and technical aspects of the space elevator. Released in 2001, Edwards' report focused on the technologies which were required for the construction and operation of the space elevator. Starting with the carbon nanotube cable design, Edwards progresses through topics such as the cable climbers, power, construction, and design options. The NIAC Phase I report also includes information on the composition and progress made in the study of nanotubes [8].

Edwards received a second grant for a Phase II analysis of the space elevator. In 2003, Edwards published the book *The Space Elevator: A Revolutionary Earth-to-Space Transportation System* in conjunction with his Phase II report. While the Phase I report detailed technical aspects of the space elevator, the Phase II report focused primarily on the research and the design of the necessary components of the space elevator. The Phase II report was a far greater collaborative effort than the first. It utilized the work of more than 20 institutions and 50 individuals, compared to the virtually solo endeavor of the first [9].

Of particular interest to this IQP is the research done concerning the cable design. Studies on cable dynamics, cable collapse, atmospheric effects, carbon nanotubes, and nanotube composites can all be found in this report. Due to the March 1, 2003 release date of the second report, there is also updated information regarding carbon nanotube development since the publication of the Phase I report.

In addition to Edwards' recent accomplishments in his field, he has also been a speaker at numerous space conferences, including the last two Annual International Space Elevator Conferences. Both of these conferences (there have been three in total but transcripts from the first one appear to be nonexistent) featured over 30 speakers presenting on all topics related to the space elevator. These conferences, held in 2003 and 2004, provide the most up-to-date information on carbon nanotube technology and progress made in the design of the space elevator. Presentations were given on the newest carbon nanotube advances, the tapered ribbon cable designs, stress studies, cost analysis, orbital debris, weather impacts, terrorism risks, collapse of the cable, and many other topics. Representing the most promising advances in the space elevator concept, these presentations are very valuable to this IQP for their information on the current state of the space elevator.

Two of the most current sources essential to this IQP are the previous IQPs which inspired the goals of this project. The first of these two, *Forecast of Space Technological Breakthroughs*, consists of a Delphi study on the most promising breakthrough technologies. By polling two main groups – WPI alumni and professional researchers/engineers – this first IQP identified breakthrough technologies that had both strong implications for the future as well as being technically feasible. The space elevator and carbon nanotube technology were two such subjects identified by the study. Though the IQP does not detail the space elevator or carbon nanotubes, it includes alumni and expert opinions regarding the likelihood, significance, and timeframe of the space elevator as well as carbon nanotubes as a breakthrough material.

The second IQP, *Social Implication of Breakthrough Technology*, provides a detailed account of nanotube technology and describes the concept of a space elevator. As its title states, this IQP project is critical for our research because it explains the impacts of a large-scale undertaking like the space elevator on society. Because one of the goals of our project is to define the impacts of the space elevator, this previous IQP serves as an excellent starting point for our research.

1.B Methodology

The focus of this project is on analyzing the concept of the space elevator and the rapidly improving carbon nanotube technology that could be used for its construction. The main question when looking at the space elevator is whether carbon nanotubes make its construction possible. One focus of this project is on carbon nanotubes and whether it is technically feasible to use them in space elevator cable construction. Because carbon nanotubes are so vital to the space elevator, we will study not only the impacts that carbon nanotubes will have on the proposed space elevator, but also their impact on technology in general.

Another focus includes the impacts of the space elevator if it is constructed. The greatest potential of the space elevator is that the cost of transporting materials into space would be drastically reduced. Many commercial applications could utilize the space elevator as a result. The possibility for tourism into space would become a more realistic venture. Other advancements may also result from the realization of a space elevator. For example, space elevators may be placed on other bodies in the solar system, allowing for easier manned exploration of the solar system. The advancement of science in space would be an important aspect of our increased access to space via the space elevator.

Our main goals in this project are to determine whether current studies show that carbon nanotubes are feasible for use in the space elevator and to examine the impacts the material and resulting space elevator would have. The advancements in carbon nanotube technology will be represented in a timeline to depict how quickly such advancements are being made. Our research into these impacts will determine which would be most important to science and society and how long it would take for these impacts to be realized.

Current studies suggest that carbon nanotubes are strong enough to withstand the extreme forces involved in the space elevator. This conclusion was reached by observing the ideal properties of carbon nanotubes and calculating the forces they will be required to withstand. After gathering material data on carbon nanotubes and hypotheses from scientists who have researched the concept, we will have a better understanding of the technical feasibility of the space elevator. Other sources, including past IQPs and further research into carbon nanotubes will reveal how carbon nanotubes could have an impact in other fields. In order to sort these impacts, we will look at the resulting ventures in terms of importance, attainability, and likelihood of occurrence.

We will study and analyze diagrams that explain principles of carbon nanotube technology and its use on the space elevator, such as what the ribbon-like cable would look like. Additional information on the material properties of carbon nanotubes and carbon nanotube advancement in relation to the space elevator will be gathered from existing reference materials and their sources. These sources include the NIAC reports and the Annual Space Elevator Conferences. We will research whether other fields have interest in carbon nanotube technology and what advancements would have an impact on these other fields.

This IQP will examine the impact of constructing a space elevator by researching possibilities that would exist if the space elevator could launch objects into orbit for a fraction of current launch cost. Some of these impacts are commercial ventures that would result while others are scientific advances that could result from the space elevator. We will gather data for this research from projects that have already gained interest since the mention of the space elevator and will also study expert opinions on the amount of time it will take before these impacts are realized.

Chapter 2: Introduction to the Space Elevator

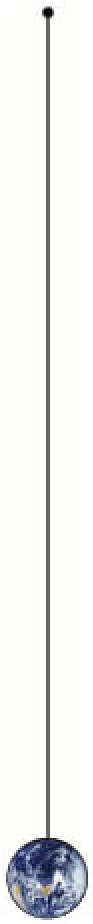

Figure 1: Scale representation of space elevator [8]

In order to understand the space elevator concept, one must be familiar with the physics and mechanics behind its design. There are several variations on the space elevator, from the Low Earth Orbit (LEO)[i] Space elevator to the more familiar surface-to-geostationary orbit (surface-to-GEO) form in which a cable connects the surface of the Earth to an object in geostationary orbit. Although this project will focus on the surface to GEO space elevator, familiarizing oneself with these different versions will allow one to develop a better sense of the future possibilities**.**

In the LEO version, a cable is extended from a midpoint station in relatively low Earth orbit, down to the upper part of the atmosphere, with another cable extending up to a counterbalance in a higher orbit. The bottom end of the lower cable would be at an altitude low enough so that a spacecraft would require 2.5 km/sec less change in velocity than a single-stage-to-orbit (SSTO) vehicle launched directly to LEO. The space plane and LEO space elevator combination would likely be able to carry 10 to 12 times the payload as an equivalent-sized SSTO launch vehicle without the LEO space elevator. The length of the upper cable is chosen so that its endpoint is traveling at slightly less than Earth escape velocity for its altitude. This is done so that a spacecraft headed for higher orbit, the Moon, or beyond, can be placed in the proper orbit with only minimal use of its onboard propellant. It has been estimated that this version of a space

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[i] See Appendix 1 for information regarding Earth orbits

elevator can be constructed with current high-strength materials and space technology [30].

For the surface to GEO space elevator, there is a physical connection from the surface of the Earth to an object in geostationary orbit. This object could be a platform for deploying space assets or a station. The cable connecting this platform to the surface of the Earth will also extend past geostationary orbit in order to balance the enormous tension forces that the cable will experience. Because the platform will be in geostationary orbit, it will appear to an observer on the ground that the space elevator is hovering over a fixed point. This lack of movement will allow for a climber (or multiple climbers) to traverse the cable, bringing large amounts of materials into space at a cost per pound orders of magnitude less than current launch technologies.

Transportation from the Earth to geostationary orbit would be by means of the space elevator’s cable, which would be comprised of carbon nanotubes. An initial strand, far weaker than the final cable, will be put in place first to allow climbers to continually add to the cable, in a similar way that large suspension bridge cables are constructed. That being said, the final cable would still be very thin, but also wide, similar in shape to a ribbon. These dimensions would make it safer and easier to repair than a cylindrical, or alternatively shaped cable.

The space elevator cable's thickness (as opposed to width) will vary depending on altitude. The cable width remains very narrow, on the order of a few centimeters, and relatively thin for the lower parts of the atmosphere, in order to minimize any disturbances or oscillations caused by high velocity winds. Once the lower atmosphere has been passed, the cable widens in order to increase safety and ease of repair in the region of Earth orbit with the most amount of space debris. The cable will also have a curved shape to decrease the chance of a catastrophic failure from space debris impact.

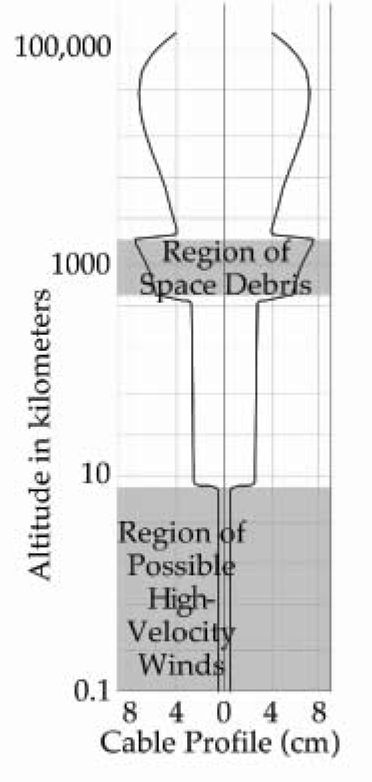

Figure 2: Width profile of space elevator cable [8]

During the 2004-2005 academic year, an IQP team created a forecast of space technological breakthroughs. In this study, the team contacted alumni and experts and inquired their perspectives on possible space technological breakthroughs. The alumni and experts were asked to offer their opinion on the likelihood, significance, and possible timeline of each breakthrough. Among these breakthroughs was the space elevator.

From the surveys performed, the space elevator was ranked as highly unlikely by both groups. They ranked the likelihood as 2.3 and 2.4 out of 6 respectively, meaning that they rated the likelihood of the space elevator as between “improbable” and “unlikely”. Alumni commented that the space elevator seemed too impractical to be likely. They were also very concerned with the outcome if the space elevator failed, such as if the space elevator wrapped itself around the earth. However, many of the concerns that left the alumni hesitant about the space elevator were studied in the NIAC reports. The reports detail a number of worst-case scenarios for the space elevator – all less destructive in terms of physical damage and lives lost than traditional rocket or shuttle programs. Much of the experts’ concern was with regard to the amount of money it would take to construct the elevator, but as one expert pointed out, the concept of the space elevator is starting to get more attention and also more funding [19].

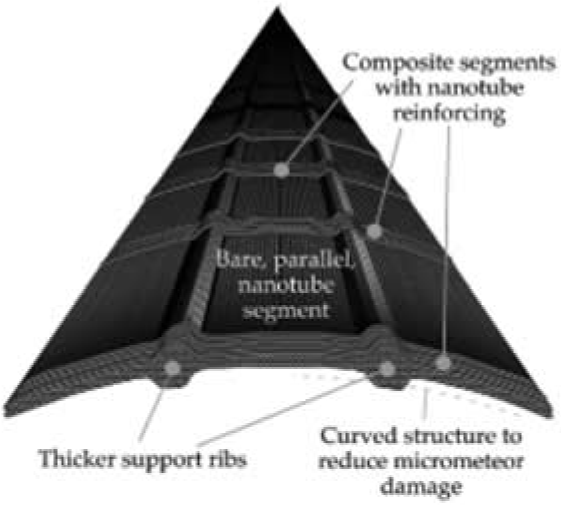

Figure 3: View of curved space elevator cable shape [8]

Although both groups agreed that the space elevator was a far fetched design, they ranked the space elevator as very significant if it could be constructed. They ranked its significance as 4.3 and 4.5 out of 6, meaning that they placed the space elevator between “moderate significance” and “major significance”.

In terms of the timeframe in which the space elevator could be constructed, the alumni and experts both rated it as very distant. They believe that the space elevator will not be built within the next 30 years, giving it a timeframe of 2035-2050 [19].

Liftport, Inc., a privately held corporation, is more optimistic than the survey results that were obtained from the past IPQ team studying the feasibility of advanced space concepts. Recognized as one of the leaders in space elevator technology, Liftport is dedicated to constructing the space elevator and has been researching the components that would make it possible since 2003. They have recently opened their own carbon nanotube factory, with hopes that their further research will help to make the space elevator a reality. Liftport plans to have a completed space elevator built and ready to lift objects into space by April 12, 2018. They hope that with future improvements in carbon nanotechnology they will be able to accomplish their goals [1].

Chapter 3: Introduction to Carbon Nanotubes

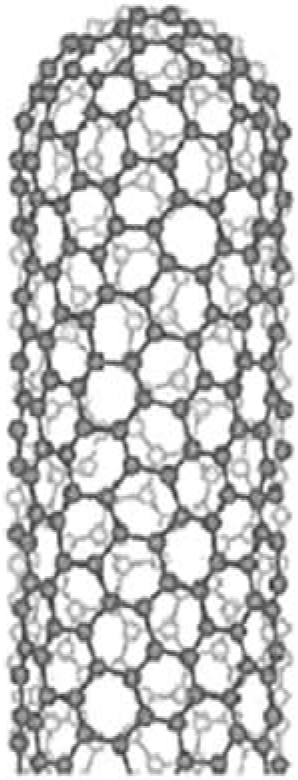

Figure 4: Structure of carbon nanotube. Each circle represents an atom of carbon, and the lines connecting each atom represent the bonding between those atoms [44].

Due to the sheer size of the space elevator, enormous forces will be exerted on the structure. Once the physical forces and their variance throughout the space elevator have been determined, focus can be shifted to the nature of the space elevator cable's primary material: carbon nanotubes (CNTs). The structure of a CNT is essentially a sheet of carbon atoms – one layer of graphite – rolled into a cylinder and capped by half a buckyball at either end. Figure 3 provides an illustration of the structure of a carbon nanotube. Although carbon nanotubes were discovered as recently as 1991, significant developments have been made in this short amount of time.[ii]

Carbon nanotubes can be single-walled – comprised of a single cylindrical structure, or multi-walled – with progressively smaller cylindrical structures nested within one another. The first nanotubes discovered were of the multi-walled variety. These invariably contain at least two graphite layers, and generally have inner diameters of around 4nm [14]. In 1993, the synthesis of single-walled carbon nanotubes was reported. This proved to be an important breakthrough, as single-walled carbon nanotubes are comprised of structures which approximate those of "ideal" nanotubes [14].

[ii] See Appendix 2 for a timeline of carbon nanotube breakthroughs

An important property of CNTs with regard to the space elevator is its tensile strength. Although not accurately measured because of the small scale and precision of existing instruments, an analysis of the bond angles and bond characteristics gives rise to its theoretical yield strength of 300 GPa. This is two orders of magnitude greater than steel or Kevlar (3.0 GPa and 3.7 GPa, respectively) [9]. Carbon nanotubes also have a low density – 1300 kg/m^3 compared to 1440 kg/m^3 of Kevlar and 7900 kg/m^3 of steel.

For use in the space elevator, the carbon nanotube ribbon would have to be tapered – the width of the end closest to Earth being much narrower than the width at geostationary orbit (GEO). The reason for this taper is due to the force which the space elevator cable will be subjected to. An analysis of the forces on the cable, carried out in Appendix 7, shows that the tension in it rises exponentially as one rises from the Earth's surface towards geostationary orbit and then drops exponentially thereafter. If one wishes to maintain a constant stress (tension per unit area) in the cable, its cross sectional area must increase exponentially from Earth's surface to GEO and then decrease exponentially thereafter. The ratio of the cross sectional area of the cable at GEO to its area at Earth's surface is known as the taper factor. From the remarks in Appendix 7, we see that the taper factor depends exponentially on the ratio of the tensile strength of the cable to its density[iii]. A cable with a reasonable taper factor requires a very strong material that also has a relatively low density. Both steel and Kevlar, which are among the strongest conventional construction materials, would call for unreasonably large taper factors (1.7 x 10^33 and 2.6 x 10^8 respectively) for a cable ascending from Earth to GEO. This fact shows that constructing a space elevator using these materials is

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[iii] See Appendix 5 for additional details on how a tapered shape benefits the space elevator, and why a low taper ratio is crucial in building the space elevator.

unrealistic. The discovery of carbon nanotubes afforded us with a material that is orders of magnitude stronger than steel and Kevlar. The material is also less dense, making it possible to contemplate cables with a much smaller taper factor of 1.5, thus making the construction of the space elevator realistic [8].

It is important to clarify how carbon nanotubes will be used in the construction of the space elevator. The technology has not reached a level of sophistication to make a single CNT which could span the distance from the earth's surface to GEO and beyond. Current technology can only produce nanotubes up to four centimeters [45]. However, CNTs of unlimited length are not required for the creation of a space elevator. Two other options currently exist, relying on the use of polymers to create a CNT composite.

The first method, using CNT fibers, relies on Van der Waal's forces to hold nanotubes together similar to the way a hemp rope achieves its strength. A polymer facilitates the interaction of the nanotubes and increases the strength. This method is promising because incredibly long fibers of up to 100 meters have already been made, and the process is relatively simple. However, CNT fibers are weak, inconsistent bundles of individual CNTs, and unusable now for the space elevator at the current values of their material properties.

The second type of composite consisting of CNTs and a polymer utilizes stronger covalent forces. Though the surfaces of the nanotubes must first be functionalized so that the polymer can bond properly, the result is a composite that is very strong and consistent. This technology is critical for the space elevator as it can utilize high-purity CNTs of very small lengths compared to the space elevator's overall length. Though scientists haven't been able to produce CNTs long enough or strong enough for the space elevator, the latest research suggests that the length barrier may soon be overcome. Newly developed laboratory growth techniques can, in theory, be used to grow SWNT to any length desired. Once the remaining strength barrier has been overcome, the use of longer and amply strong CNTs in a polymer composite will be the most likely technique for the space elevator's construction.

Like any other large-scale construction, the space elevator cable will need a certain factor of safety built into its design before it can be considered feasible. By comparing the space elevator cable to other large cables used in terrestrial construction projects, we can approximate a factor of safety which will be needed for the Elevator cable. The National Cooperative Highway Research Program, in a 1998 appraisal of various suspension bridges, concluded that the main suspension cables of these bridges had factors of safety varying from 2.0 to 4.0 [26].

If we assume that a factor of safety of 2.0 is the minimum required for the space elevator to be considered a feasible project, we can make predictions for the amount of material, taper ratio, and strength of materials needed for the elevator cable. These predictions again show that carbon nanotubes are the only material which can realistically be used for the space elevator cable construction.[iv]

[iv] Appendix 5 details these calculations, and provides graphs of material strength versus taper ratio, as well as material density and weight versus strength, assuming a factor of safety of 2

Chapter 4: Implications of the Space Elevator and Carbon Nanotubes

The construction of the space elevator will have a multitude of impacts on space issues as well as impacts on terrestrial issues via the space elevator's driving technology – carbon nanotubes. All of these impacts will bring about significant changes in many aspects of society, from economics and tourism to technology and science. Appendix 4 gives an overview of these impacts, along with the importance and approximate timeline in which each impact could be realized once the space elevator has been completed. A numerical ranking is assigned to each impact which rates how important each of these impacts might be. This chapter gives a more detailed discussion of some of the impacts in each of the different categories.

1.A Space Elevator

When completed, a space elevator will allow for the gradual lifting of extremely heavy payloads to Low Earth Orbit and beyond. Currently, the most powerful rocket is the Boeing Delta IV Heavy. This rocket has the ability to launch up to 28,124 lbs to geostationary orbit [6]. A completed space elevator will be able to ferry an equal load to and beyond geostationary orbit. Due to the slow speed at which climbers will traverse the elevator, vibrations and high g-forces will be nonexistent. With regard to cost, current estimates predict that the cost per pound to transfer material to orbit will be reduced from $10,000 per pound to around $100 per pound [33].

Essentially, the space elevator will eliminate the need for heavy lift rockets. While this seems far fetched, current NASA officials and Aldridge Commission[v] members have been quoted as saying that although a space elevator does not fall into their short-term goals, they would support the concept after their immediate needs have been met [11].

1.A.1 Space Travel

Moon exploration could be impacted significantly from the use of a completed space elevator. Currently, there is much excitement regarding future moon missions, mainly due to the presence of Helium-3 on the moon. At the present and anticipated usage rates of energy in the world, the reserves of oil and natural gas will be exhausted by the mid-21st century, with coal reserves lasting up to 50 years more [37]. However, there is 10 times more ^{3}He fusion energy on the Moon than in all these Earthly reserves. The potential use of D-^{3}He fusion for energy generation requires a ready supply of ^{3}He, and there is a distinct rarity of this fuel on Earth. However, compared to the Earth, the Moon is a virtual "oasis with springs of solar-wind helium." Conservative estimates of the helium contents of the regolith on a Moon-wide basis are 3.7 ppb (6.7 mg/m^3) of ^{3}He for the highland areas and 7.8 ppb (14 mg/m^3) for the maria. At current energy consumption rates and a 50% mining recovery rate, there is sufficient ^{3}He in the upper 3 meters of only the maria of the Moon to supply the entire energy needs of the Earth for over a thousand years [37]. The potential for greatly enhanced supplies of ^{3}He at the lunar poles may

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[v] The Aldridge Commission is a group which advocates the private sector's involvement in space.

make the utilization of this energy-generation process even more attractive [37]. In addition, unlike typical nuclear fission reactions, a ^{3}He-^{3}He fusion reaction (although it will require a level of technology much more sophisticated than that needed to produce a D-^{3}He reaction) will produce no neutrons, as well as producing no greenhouse gas emissions or acid gas emissions during operation [18]. The amount of research into Helium-3 energy sources has increased dramatically as well. To fully illustrate the significance of Helium-3, former NASA astronaut Harrison Schmitt stated in a 2003 testimonial that “the energy equivalent value of Helium-3 delivered to operating fusion power plants on Earth would be about $4 billion per ton relative to today’s coal [32].”

A completed space elevator would also open up the possibility of constructing a space elevator on the Moon or Mars. Because of a less intense gravitational pull by these bodies, these space elevators could be constructed out of less exotic materials than those derived from carbon nanotechnology, thus decreasing their cost dramatically [32]. These space elevators could capture materials launched toward the Moon or Mars by the Earth-orbiting space elevator, and could gently ferry them down to the surface of the Moon or Mars, at a minimal cost in propellant. This means that a greater capacity of a spacecraft's volume can be dedicated to cargo instead of fuel required to power a propulsion system to adjust the speed of the spacecraft for landing. In addition, recent discoveries such as the possibility of water on Saturn’s moon Enceladus [36] are causing a shift in focus to the ability to explore space beyond the inner planets. Not only will a completed space elevator allow for cheaper missions throughout the solar system, it will allow for more complex missions, attributed directly to its lifting capacity.

One of the many probable impacts in the space elevator's future would be the development of space tourism. Zogby International performed a survey which indicated that 7% of affluent people would pay $20 million for 2-week orbital flight and 19% would pay $100,000 for 15-minute sub-orbital flight [9]. If the cost of taking a ride into space was reduced by 50-90%, the interest in space tourism may be even greater. A study performed in Japan in 1993 indicated that 80% of people under the age of 40 would like to visit space once in their lifetime. In addition, 70% of those people would be willing to spend three months' salary for such a trip [35]. The study by Collins concludes that if a ticket to LEO and back to earth could be offered between $10,000 and $20,000, there would be interest to the order of 100 million people that would want to make the trip. With this kind of demand, 1 million passengers per year paying an average of $10,000 per ticket would create an industry of $10 billion per year [35]. Future tourists able to take an elevator ride into space would face costs in this price range, and even less. Creating vacation facilities in orbit would allow them to stay for extended periods of time [8]. This amazing chance to take a vacation into space would create a new space tourism industry and could also boost public perception of space initiatives, making the public more interested in the possibilities that space travel holds.

Space travel has the potential to become a booming industry. However, it would not be feasible in the first fifteen years after the completion of the space elevator. It would take a few decades before the elevator could be used for vacation facilities [8]. After this time, the possibilities for space vacations facilitated by the space elevator could begin with day-long ventures into LEO but could expand into long-term "hotels" for prolonged time in space for tourists [9].

1.A.2 Scientific Implications

Space observation and exploration can be increased significantly through the use of a space elevator. Again, due to the increased lifting ability of the space elevator compared to traditional rockets, larger, more complex payloads of scientific instruments can be transported to and beyond geostationary orbit. The ability to ferry large loads means that complex weather satellites can be placed in geostationary orbit [7]. Constellations of weather satellites could therefore be used for global weather pattern and climate research. Once the space elevator is completed, implementation of such a constellation could happen relatively quickly. We see this if we take the development of the GPS constellation as an example. From 1980 to 2000, the number of GPS satellites in the GPS constellation rose from a single experimental satellite to 28 functioning satellites [7]. The cost and limited availability of rockets to launch these satellites into orbit contributed to this 20 year span. With a new generation of global climate observing weather satellites, the problem of waiting for an appropriate launch time would be eliminated. The completed space elevator could ferry a large constellation of complex satellites into orbit with a minimal time delay after the initial research and development of the satellite technology. Constellations of weather satellites could therefore be used for global weather pattern and climate research.

The fields of astronomy and cosmology could also be greatly enhanced through the use of a space elevator. Being able to lift 26,000 lbs, the space elevator could lift larger telescopes into space than ever possible. Currently, the Delta IV Heavy rocket is the most powerful launch system available, being able to lift 29,000 lbs to geostationary orbit [6]. With the absence of the Space Shuttle as a means of transporting cargo, the Delta IV Heavy would only be able to lift a telescope the size of the Hubble Space Telescope, at a weight of 24,500 lbs. Unlike the Space Shuttle or the Delta IV Heavy, a completed space elevator would be able to lift multiple sections of a large space-based telescope to geostationary orbit. Using conventional launch systems, launching multiple sections of a space-based telescope would result in considerable launch costs. By using the principle of interferometry, multiple smaller telescopes could replace the more traditional single, larger telescopes of the past, while providing much greater viewing resolution. There exists also the possibility of placing radio telescopes in orbits around different Solar System bodies, such as the Moon, where for periods of time the radio telescopes would be able to observe without the massive interference produced by Earth radio communications.

Radiation exposure remains a very important research area, with specific interest in Van Allen Belt radiation. Located in Medium Earth Orbit (MEO), this region poses great danger to humans traveling through it. The Van Allen Belts are torus-shaped regions where high energy protons and electrons are trapped in the Earth's magnetic field. The number of particles encountered (flux) depends on the energy of the particles; in general, the flux of high-energy particles is less, and the flux of low-energy particles is more. Very low energy particles cannot penetrate the skin of a spacecraft, or even the skin of an astronaut.

The National Space Sciences Data Center at NASA's Goddard Spaceflight Center gives a summary which indicates that electrons with energies over 1 MeV have a flux above a million per square centimeter per second from 1-6 earth radii (about 6,300 - 38,000 km). Protons over 10 MeV have a flux above one hundred thousand per square centimeter per second from about 1.5-2.5 Earth radii (9,500 km - 16,000 km). At the speed Apollo spacecraft traveled at, astronauts were exposed to Van Allen Belt radiation for about 1.5 hours. This is the time it took for the spacecraft to pass beyond 38,000 km. During this time, astronauts received a dose of 1 - 2 rem (20 mSv) [10].

Currently, human exposure to Van Allen Belt radiation is limited to the Apollo missions and certain Gemini missions. During the Apollo missions, mission planners deliberately plotted courses to take the Apollo astronauts through the Van Allen Belts in the quickest manner possible, thus hoping to reduce the amount of radiation exposure they received. Unfortunately, due to the slow speed of a space elevator transfer through Medium Earth Orbit, any human passengers on a space elevator climber would be exposed to a much greater level of radiation than experienced by the Apollo astronauts, a level which is dangerously unacceptable. A completed space elevator would allow for a much easier method of testing new radiation shielding technologies; this will be essential if humans are ever to travel beyond LEO on the space elevator.

Currently, little is known even regarding the implications of space radiation on the human body. On May 9, 2005, Dr. John Dicello of the John Hopkins University School of Medicine, in a NASA statement, explained the current issues with regard to space radiation which need to be solved.

> "Some astronauts, veterans of long space missions, have "significant chromosome aberrations" in their blood cells. These aberrations may be "associated with the development of cancer," says Dicello, but they do not, by themselves, cause cancer. For that to happen, cells with aberrations must undergo a series of further mutations. According to the National Cancer Institute, "the number of cell divisions that occur during this

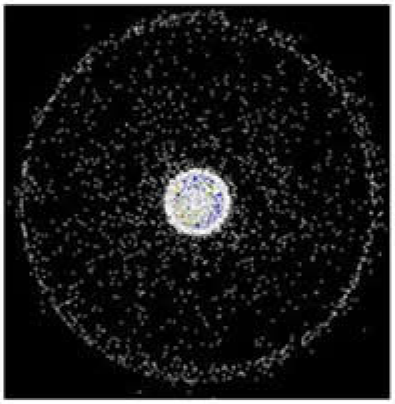
> process can be astronomically large--human tumors often become apparent only after they have grown to a size of 10 to 100 billion cells." Years, even decades, might pass between the onset of the problem, the exposure to radiation, and the appearance of a tumor. Because of the delay, it's very difficult to determine exactly when or why a cancer starts [25]."

Clearly, humans cannot traverse into high radiation areas of Earth orbit above LEO for extended periods of time without further research being conducted on this problem. A completed space elevator could greatly enhance this research, by allowing dedicated research platforms to be placed at different altitudes, with varying levels of radiation exposure, in order to gather data and possibly test new prevention measures.

The NIAC reports also list potential scientific uses of the space elevator. One very promising use would be an inexpensive means of large-scale manufacturing in microgravity. This manufacturing could not take place directly on the space elevator, as microgravity conditions would not exist for anything attached to it. However, a manufacturing module could be lofted into Low Earth Orbit and then detached, allowing for micro gravity construction. Near perfect crystals could be manufactured in this situation. These near perfect crystals have benefits in everything from medicine to microelectronics [8]. Benefits from microgravity protein growth experiments have already been seen. Many of the crystallization experiments conducted on the Space Shuttle have yielded crystals that furthered structural biology projects. For example, microgravity crystallization experiments have been conducted with recombinant human insulin. These studies have yielded X-ray diffraction data that helped scientists to determine higher-resolution structures of insulin formations. This structural information is valuable for ongoing research toward more effective treatment of diabetes. Other very successful microgravity crystallization experiments have provided enhanced X-ray diffraction data on a protein involved in the human immune system. These studies have contributed to the search for drugs to decrease inflammation problems associated with open-heart surgery [34].

Another important issue in building a space elevator is the space debris that may come in contact with it once it is built. There are two types of space debris: natural and artificial. Natural space debris occurs from asteroids and comets that may have passed near earth's orbit. Debris from these bodies sometimes breaks off and enters into Earth's orbit. Artificial debris consists of fragments from space missions and satellites that are now in orbit around the earth. These fragments occur from satellite breakup, mission deployment and operation, and non-functional spacecraft. There are currently many fragments of both types of debris around the earth. Approximately 100,000 of these fragments are larger than 1 cm and up to 30 cm in diameter. 11,000 fragments are greater than 10 cm in diameter. In addition to this, there are many millions of tiny fragments that are smaller than 1 cm in diameter [15].

a) View of debris in LEO



b) View of debris out to GEO

Figure 5: These images depict a white dot for each fragment of space debris currently being tracked by the Orbital Debris Program Office at NASA Johnson Space Center. [15]

Most of this debris is located within 2000 km of the earth's surface. Debris amount varies with the altitude but there are significant concentrations at 800 km, 1000km, and 1500km.[vi] This debris may be traveling 10-15 km/sec. At this speed, fragments greater than 1 millimeter in diameter are capable of causing damage to a spacecraft or the space elevator [15].

Much of the space elevator cable design is meant to protect the space elevator from damage; however, the space elevator may provide the impetus to eliminate potentially dangerous debris from orbit. The construction of the cable will also make it easier to catch this debris and send it towards the earth where it will burn up in the atmosphere [8]. The space elevator would also make it easier to recover and repair malfunctioning satellites so there would be less need to deliver new satellites into space each time one needed a repair, reducing the amount of additional space debris [8]. Removing and preventing additional debris will not only benefit the space elevator, but also the satellites currently in orbit that are in danger of being damaged. If the debris is removed, the satellites will be safe from this damage. This would lead to fewer interruptions in communication networks. Economically, this means reduced operating costs for companies with satellites [8]. The importance of removing space debris was communicated in a recent study published by *Science* magazine. In the study, NASA scientists claimed that the space debris currently in orbit will be a much greater threat in the near future and can be a problem for space ventures such as commercial and research flights [22]. Nicholas Johnson, NASA's orbital debris program manager, suggests there is currently no solution to remove debris from space. However, with a space elevator, a solution to this problem could be reached. Once the space elevator is completed, it would be only a short time before a debris removal system could be initiated.

[vi] See Appendix 3 for data regarding the special density of space debris at various altitudes.

1.A.3 Commercial Implications

The space elevator also has great implications in the commercial field. For example, the commercial satellite industry is one that will benefit greatly from a completed space elevator. The current cost for launching a satellite into geostationary orbit can reach as much as $400 million. The space elevator can provide a 50%-99% reduction in cost for delivering satellites into space and will benefit companies by allowing them to place more satellites into orbit. The space elevator's ability to send satellites into Earth orbit would begin as soon as the first cable was completed. The cost associated with launching these satellites into space would be the cost of the climber to transport the payload [8]. According to research performed on the NIAC II report, the operating cost will be $100 per pound to any Earth orbit [9]. This cost reduction not only makes it cheaper for companies that currently deploy satellites, but smaller companies will also be able to afford placing satellites in orbit, causing a boom in the satellite industry.

This impact would also allow developing countries to afford satellite communication systems [8]. Many countries cannot benefit from advancements in information technology due to their lack of a proper infrastructure to facilitate these developments. This is often referred to as the "Digital Divide [17]." Improved information technology in these countries would have a large impact on their economies. Instead of spending billions of dollars on a complex communications infrastructure, a developing country would need to spend a fraction of that cost in order to send satellites into orbit. The G8 countries have committed to promoting the use of Information and Communications Technologies (ICTs) in these developing countries to alleviate problems such as poverty, lack of education, and inappropriate health services [42]. Information systems in developing countries are often inadequate and make it difficult and costly to distribute and acquire information. This leads to problems such as inefficiencies and distortions in the economy. If the information systems in the countries could be improved, their economies could be improved as well.

Global communication systems would also be improved due to inexpensive global television and telephone systems. There would no longer need to be long distance calls and it would be much easier to broadcast television all over the world [8].

These are some of the advances that would result from the space elevator's ability to deliver satellites into orbit for a fraction of current cost. Easy access to launching satellites can play a major role in improving the economy of developing countries. The growth of the satellite industry is another benefit that results from the ability to launch satellites for lower cost. The impacts of cheaper satellite launch make it one of the most important commercial impacts the space elevator can provide.

The energy industry would also benefit from the space elevator. With the space elevator, it is possible to erect solar arrays in space that could collect solar power. An otherwise impossible operation because of size and weight constraints, solar arrays become feasible if the space elevator is built. The power generated could then be beamed back down to earth for consumption. A 1994 article by Glaser describes the concept of a Solar Power Satellite (SPS):

> “Solar cell arrays would convert solar energy directly into electricity and feed it to microwave generators forming part of a planar, phased-array transmitting antenna. The antenna would direct a microwave beam of very low power density precisely to one or more receiving antennas, at desired locations on Earth. At the receiving antennas, the microwave energy would be safely and efficiently reconverted into electricity and then transmitted to users [13].”

Current data shows that if the cost of transporting these arrays to GEO can be reduced to less than $500 per pound, then the capital investment would be low enough for solar arrays to provide power at competitive rates to fossil fuels [9]. Since it is projected that it may be less than $100 per pound (and perhaps even $10 per pound) after the space elevator is built, it seems that this is a reliable source of energy for the future.

The NIAC Phase II Report outlines that this is a major market that would be developed once the space elevator is operational. With assessment of societal and environmental issues regarding solar arrays and the technology perfected [13], the solar array market could begin to take effect as soon as the space elevator is complete [9]. The current energy crisis reveals the importance of solar satellites as an impact the space elevator can provide. If a space elevator were constructed and able to provide the world with a much cheaper and cleaner energy source, it would have a great impact.

1.B Carbon Nanotubes

Besides the direct impacts that the construction of a space elevator may have on society and the science, there are many additional impacts that the development of carbon nanotubes, the driving technology of the space elevator, will have.

Carbon nanotubes were discovered fifteen years ago. Despite their incredible promise in material science, little time was devoted to their study. Our research shows major interest forming in CNT research beginning in 1998 with the creation of parallel CNTs of increasing purity. Starting in 2000, material testing of individual CNTs, both single-walled and multi-walled, was being performed. Further emphasis was put on large-scale production of CNTs, rather than the idealization of their structure.

Coincidentally, Brad Edwards received Phase I funding from NIAC for his space elevator design, with the work period beginning May 1, 2000. With increasing media coverage, the space elevator concept began to spread. By 2003, Brad Edwards claimed in his overview of his Phase II report that the space elevator could be operational in 15 years at a cost of 10 billion dollars. He also claimed that CNTs would be at the proper state of development for use in the elevator in just two years. Our research suggests that the goal for CNTs has not yet been met, ultimately delaying Edwards's proposed timeframe of the elevator. In an effort to speed up CNT development, Edwards started his own company to research and produce CNTs for the space elevator and for industries looking to take advantage of the new material. Other companies soon followed, and there are now over 17 companies specializing in CNT production [28]. Judging by the overwhelming increase of the CNT industry as a result of the initial groundbreaking CNT research and introduction of the modern space elevator concept, it is our conclusion that the development of the space elevator has close ties to and will make a significant impact on the CNT industry.

This resulting carbon nanotechnology can be considered a disruptive technology because of its ability to better-satisfy and displace current technologies used in industry.

Similar to the way computers eliminated the typewriter or the zipper hurt the button industry, CNTs are thought to become the disruptive technology for the plastics industry, as well as others, because of their incredible material properties [28]. As discussed shortly hereafter, CNTs may even eliminate the 40 billion dollar hard drive industry.

Perhaps the most important property of carbon nanotubes besides their strength is their ability to have properties of either semiconductors or metals. The cause of this is closely related to the amount of twist (chirality) in the cylindrical structure of CNTs. Depending on the chirality of CNTs, they behave either as semiconductors or metals [5].

As metals, CNTs have a variety of applications which have strong commercial implications. The first of these is in the field of nanoelectronics, an emerging field of electronics which involves the use of single atoms or molecules as components of nano-scale electronic devices. To this end, CNTs have the capability to function as true nanowires, allowing a single-walled CNT (called SWNT) to be used as a current-carrying device. The atoms of most other metals, when arranged end-to-end to make a nanowire, undergo a rearrangement of atomic positions to become more stable. The result is that the wire becomes semi conducting. The structure of SWNT, however, make it more favorable for the electrons to remain unstable than to expend energy rearranging, and thus it remains conducting [5].

Additionally, individual CNTs have been shown in preliminary experiments to act as transistors at room temperature. This remarkable attribute gives CNTs great potential as the solution to the scaling problem associated with current data processing technology which is predicted to reach its limits within the current decade [41]. CNTs of different chirality have been seen to bond end-to-end in unique configurations resembling a bent tube (called a heterojunction). Researchers predict that CNT heterojunction molecules are capable of forming nano-scale diodes for use in nanoelectronic devices [5].

The final CNT use in nanotechnology is in the tip of scanning probe microscopes (SPM). Their inert structure as well as their ability to be easily defined makes them ideal for this task [27]. In addition, CNTs are robust enough not to permanently deform if they are accidentally plunged into a surface [5]. As virtually the only small, strong substance capable of all of the tasks previously mentioned, CNTs are indispensable for the future of nanotechnology.

Semiconducting CNTs also play a critical role in the future of consumer electronics. When paired up with metallic CNTs in criss-crossed sheets, electromechanical devices are formed which are capable of functioning as non-volatile (to retain data even when power to the device is turned off) memory storage devices for computers. One company, Nantero, is the first to date which has developed memory storage devices using this technique, and has achieved capacities of up to 10 GB in 2003. Though this technology exists at a stage of infancy right now, the potential for this new technology – dubbed NRAM by Nantero – to replace the existing $40 billion magnetic hard drive industry by offering smaller-scale, nonvolatile data storage is serious [41].

CNTs have also been used to replace metallic field emitting elements in display devices such as cathode ray tube display units and vacuum tube lamps [27]. CNT field emitters are revolutionary in the filed of display devices because they operate at room temperature and do not require strong vacuums [5]. When used in vacuum tube lamps, this combination gives them efficiencies up to ten times that of traditional bulbs, as well as twice the brightness and a longer lifespan. The Samsung Advanced Institute of

Technology, in Suwon, Korea, has developed a system which uses SWNT to emit electrons at a phosphorous layer, resulting in an operational screen [41]. Implications of CNT field emitters are therefore improved display definition and longevity, as well as a decrease in the required thickness of displays. Looking even further into the future, CNTs may hold the key to making ultra-thin, flexible display devices.

Macroscopically, CNTs also have some implications in the defense and consumer communications industries. Currently, CNT yarns are being developed which have high tensile strengths as well as electrical conducting properties. Because CNT yarns have the capability to be stronger than Kevlar, garments that both protect soldiers from projectiles as well as electronically sense wounds are possible to construct. Additionally, communications and tracking antennas can be built into these military garments as well as civilian garments to give the clothing of the future added technological function [2].

The final impact of CNTs which will be summarized is their impact on health. The studies that have been done on the health effects of CNTs are few and often conflicting. Many of these tests do confirm in one way or another that CNTs, like most fine particles, do cause respiratory ailments as well as skin problems. The first of these studies focused on exposing skin cell cultures to SWNT. After 18 hours, oxidative stress, cellular toxicity, and other measurable indicators of health conclusively demonstrated that CNTs posed a health threat when skin was exposed to them [30]. Another study, this time examining the effects of SWNT on the pulmonary (lung) system of mice, revealed that SWNT were indeed harmful if inhaled. Interestingly, results showed that many of the health ailments, like granulomas (spherical inflammations in the lungs caused by severe irritation), appeared to be transient – in many cases they regressed over time instead of becoming more serious. The levels of SWNT that the mice and skin cultures were exposed to far exceeded the amounts current workers come in contact with, and so for the time being, the cautionary measures workers take to mitigate CNT contact have been deemed sufficient [43].

Overall, CNT technology has the potential to, and in some cases has already begun to, impact a wide spectrum of established industries that produce consumer goods like computers, display devices, lighting elements, memory, textiles, personal safety devices, and communications. CNT technology also influences the nation’s large defense industries as well as small niche companies like LiftPort. It is important to realize that the impact of the space elevator goes far beyond the prospects of cheaper payload transport and deeper space travel. The companies that will make the CNTs for the space elevator thrive in the present because of the revenues generated by the need for CNTs in many other industries. If the idea of a space elevator had never been taken seriously, it is quite possible that the integration of CNT technology into industry would have been slowed. This is not to say that the space elevator has caused the technology to be dispersed into other industries, for there are many companies which operate without concern for the space elevator and even predate its modern conception. However, it can be argued that the space elevator has made an impact on some of the world’s industries through its enabling, carbon nanotube technology.

Conclusion

In our approach to analyzing the feasibility of the space elevator, our team focused on the carbon nanotube technology necessary to construct the elevator’s cable. By focusing on this technology, which serves as the current “weakest link” of all the technologies required to build the space elevator, we have been able to analyze the feasibility of the elevator. In addition to technical feasibility, our group investigated the impact a completed space elevator would have on space industries, as well as the impact of the continually developing carbon nanotube technology on a number of terrestrial industries.

In recent years, the market for elevator technology has increased to the point where several companies have formed with the intention of developing the space elevator as a commercial project. In addition to Brad Edwards’s company Carbon Designs, Inc., another organization called LiftPort has been actively testing its own elevator and climber prototypes. Formed in 2003, LiftPort has developed several generations of robotic climbers, numerous high altitude tethers, and has opened a carbon nanotube factory to further its objective of building a complete space infrastructure focused around the space elevator [1].

On February 13, 2006, LiftPort announced that it had completed preliminary tests of its high altitude platforms and robotic lifters. In these tests, a stationary platform was launched via balloons one mile into the air, while robotic lifters successfully climbed up and down a ribbon attached to the platform [29]. These lifters climbed 1500 feet along the ribbon, demonstrating to the world that a preliminary working prototype of the space elevator had been a success.

In terms of technical feasibility, the construction of an Earth space elevator hinges on the development and refinement of carbon nanotechnology. If this field reaches a state where high quality nanotube composites can be manufactured in large quantities, it will be feasible to build the space elevator. However, since carbon nanotubes constitute such a recent field of research, their progress is in a state of flux. Unreliable methods of measuring carbon nanotube properties make it difficult to gauge their progress and predict their future. That being said, continued refinements in the manufacturing process of carbon nanotubes, along with an increase in the production level of carbon nanotubes, will hopefully yield the grade of carbon nanotubes necessary and prove the feasibility of the space elevator.

These required refinements and production levels are relatively close to becoming reality. Recent advancements in the field of carbon nanotube manufacturing have opened the door for significant improvements in their material properties. As shown in the carbon nanotube timeline, these advancements have allowed for inner-tube bonding between single-walled carbon nanotubes. This type of bonding can increase the strength of carbon nanotube composites because of the stronger link between individual nanotubes. In 2004, *Nature* published a paper detailing the growth of a 4cm long SWNT, and stated that the then-current techniques could theoretically be used to grow SWNT of unlimited lengths [45]. Between these two most recent advances, the technology required for the space elevator’s construction is closer than ever, and LiftPort’s goal of a completed space elevator by 2018 may be possible. If the elevator is completed, it will open the door to the numerous impacts discussed in this report.

Analyzing the feasibility of the space elevator is a large task which involves many disciplines. In addition to the feasibility of using carbon nanotubes as the primary material for the space elevator cable, as discussed in this report, there are numerous other areas which can be analyzed. These areas include the politics and economics associated with the construction of the space elevator. There are other social issues which can be researched, including public opinion of the space elevator. Though our team did not view these issues as immediately relevant to the feasibility of a space elevator, they will certainly become more important as the issues we investigated become resolved. It is therefore important that these tasks be pursued by future IQP teams, using this report as a platform to expand upon.

Appendices

Appendix 1: Table of Orbits

Type of Orbit	Altitude	Occupied By:
Low Earth Orbit (LEO) [23]	200km – 1200km	Space Station, Space Shuttle Missions, majority of artificial satellites, majority of space debris.
Medium Earth Orbit (MEO) [24]	1200km – 35790km	GPS satellites, Van Allen Belt radiation.
Geostationary Orbit (GEO) [12]	35790km	Weather satellites, communication satellites.

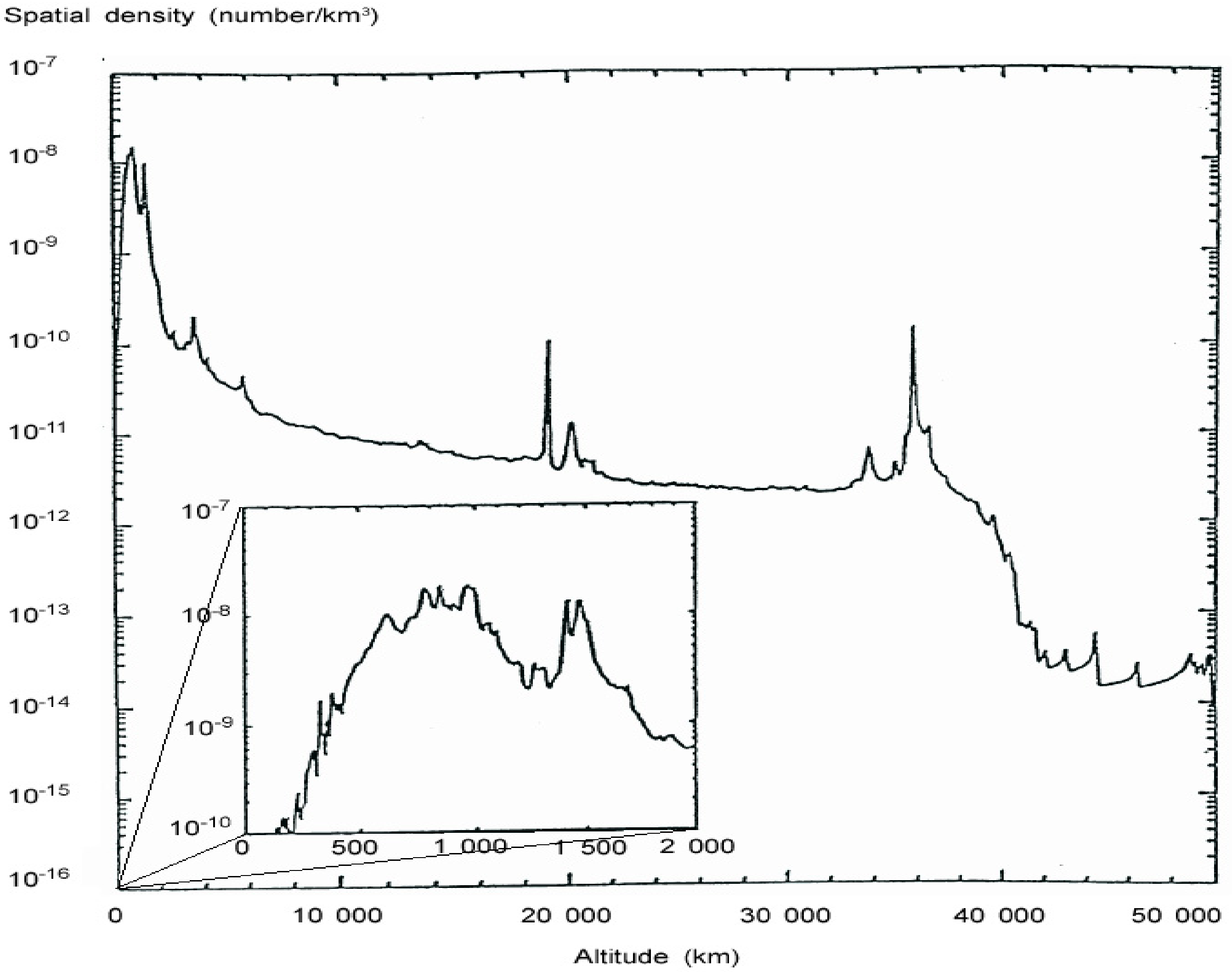
This table lists the types of orbits around the Earth. For each orbit, the altitude is given along with a list of objects that commonly occupy that orbit.

Appendix 2: Carbon Nanotube Timeline

Year	Breakthrough
1991	Multi-walled carbon nanotubes discovered.
1993	Synthesis of single-walled carbon nanotubes.
1996	Single-walled nanotube ropes synthesized.
1998	Parallel, clean, straight MWNTs up to 2mm long.
2000	Testing of CNTs yields: • MWNT yield strengths: 11-63GPa. • CNT/PVC composite: 3.6GPa. • SWNT yield strengths: 13-52GPa.
2002	SWNT composites with polypropylene tensile strength: 1.03GPa.
2003	SWNT composites with PVC tensile strength: 1.8GPa.
2004	Electron-beam irradiation used to create inner-tube bonding between SWNTs.

This timeline represents important breakthroughs that have been made in the field of carbon nanotube technology since they were discovered in 1991. [40]

Appendix 3: Space Debris Spatial Density



This data plot indicates space debris density at varying altitudes above the surface of the Earth. This special density is of catalogued objects as of August 1997 [38].

Appendix 4: Table of Space Elevator and Carbon Nanotube Impacts

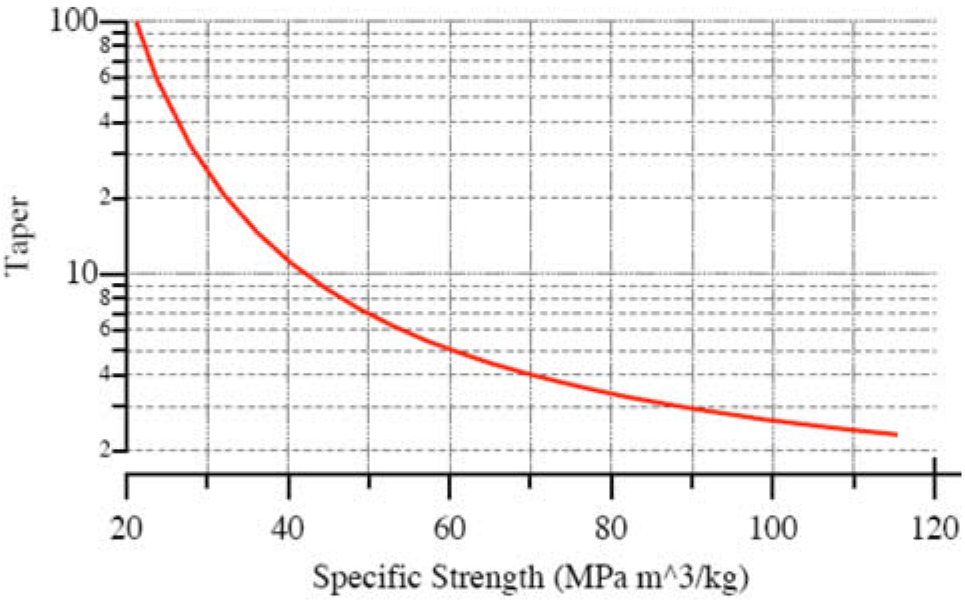
Category	Impact	Description	Rank (1-5)	Timeline	Reference
Space Travel	**Moon Exploration**	New ability to transfer material to and retrieve material from the moon.	**3**	15 years (entire infrastructure and transport system to and on the moon would need to be developed)	[37], [18], [32]
	Tourism	Public ability to travel into space, possible vacation facilities.	**3**	Long term (Not feasible within first 15 years, would take a few decades to gain popularity)	[34], [9]
	Planetary Missions	New ability to access planets and moons for exploration missions.	**4**	50 years (extensive development of exploration technology needed)	[32]
Scientific	**Radiation Research**	Research into prolonged human exposure to space radiation.	**5**	Immediate (can be done with current technology)	[10], [25]
	Global Climate Observation	New constellations of satellites could analyze global weather.	**2**	5 years (approximately same development time of GPS satellites)	[7]
	Space Debris Cleanup	Easy removal of space debris, safer for all satellites	**3**	Short term (Immediate if methods are developed before completion of space elevator)	[8], [15], [21]
Commercial	**Inexpensive Satellite Launch and Repair**	Reduced costs allow smaller companies and countries to expand and benefit economically.	**5**	Immediate (satellite launch will be available upon completion of elevator)	[8], [9], [15], [41]

Commercial	**Solar Satellites**	Solar arrays collect energy from the sun and beam the power to earth at competitive rate to fossil fuels	**4**	Immediate (pending assessment of related issues and technological refinement of solar arrays)	[9], [13]
Carbon Nanotubes	**CNT Field Emitters**	CNTs can be used as the field emitter in CRTs, vacuum tube lamps, and other display devices. They operate at room temperature and have long lifespan	**5**	Already implemented, 3-5 years before commercial product available	[5], [27], [41]
	CNT Nanowires	CNTs are one of the few materials known that form true nanowires; they have the potential for use in nano-scale electronic devices	**5**	15 years until direct application to a product, more R&D required	[5], [27]
	Nonvolatile Memory NRAM by Nantero	Semiconducting and Metallic CNTs placed in overlapping lattices form nonvolatile memory	**4**	Already 10GB prototype units by Nantero. 5 years before products hit the market as alternatives to hard drives	[5], [41]
	Nanoelectronic Components	A single CNT can function as a transistor or as a diode, enabling the	**5**	The impact of constructing such devices is extreme, but the technology needs at least another	[5]

Carbon Nanotubes		construction of nano-scale electronic devices		30 years of research	
	Conductive Garments	CNTs can be woven into garments to operate as GPS tracking and communication antennas, or for use as small wires fro conduction. A military “smart” garment is another possibility	**2**	The technology could be a reality in the next 10 years, and advancement is probably dependant upon commercial or military interest	[2]
	Robust tips for SPM	CNTs can deform considerably and recover fully. They also have a well defined tip, making them ideal for SPM	**2**	The technology is no more than 5 years away, but the impact it will have is relatively low	[5], [27]

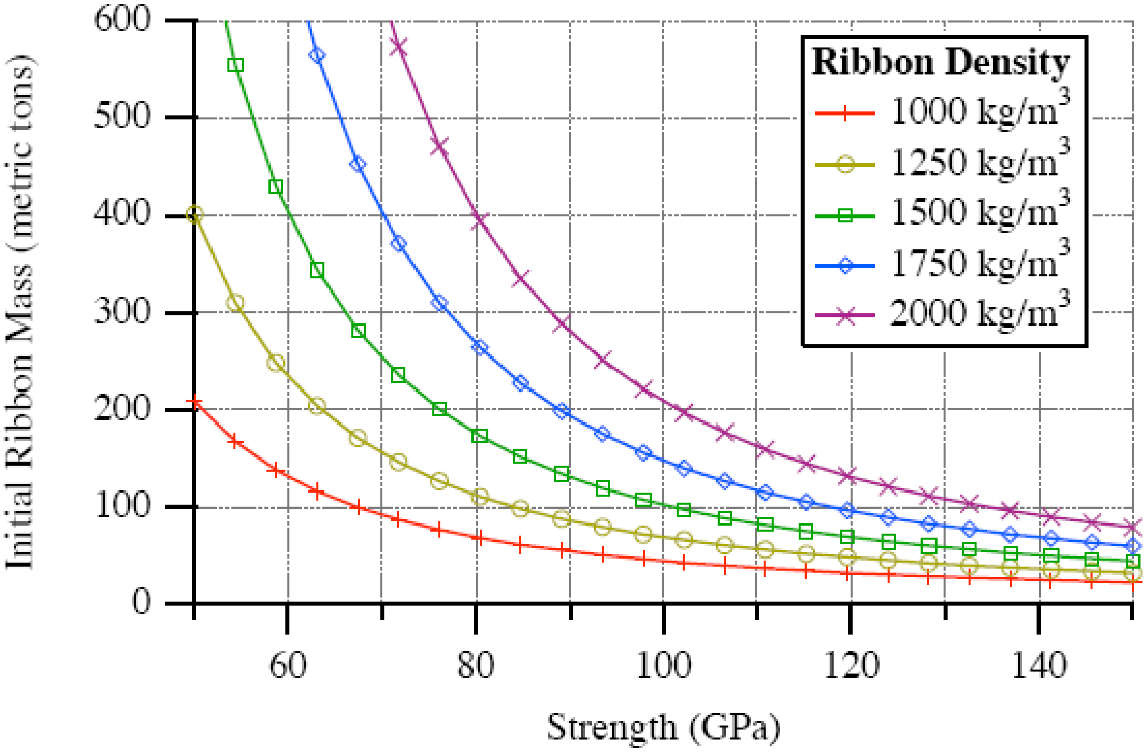
This table divides the implications studied in this report into four categories: Space Travel, Scientific, Commercial, and Carbon Nanotubes. Each impact is given a brief description that brings out its importance. The ranking system for each impact is on a scale of 1 to 5 with 5 being most important. This ranking system is based on how useful each impact would be if it were implemented, according to research done on each topic. References for this research can be found in the last column. Finally, each impact is also given a timescale that indicates how long it may be (after the space elevator is built) for that impact to be realized.

Appendix 5: Taper Ratio, Material Properties, and Factor of Safety



Assuming a factor of safety of 2.0, this graph illustrates the taper ratio versus ribbon tensile specific strength. Included in this calculation is the additional weight of a 1,000 kg lifter. [1]

Another interesting calculation which can be made is the approximation of the amount of material needed to construct the space elevator cable, dependent on the final density of the material(s) used in its' construction. The graph on the next page details these approximations.



In this graph, we see projections of the cable mass as a function of cable tensile strength. Once again, this assumes a factor of safety of 2.0, and a 1000kg lifter mass.

If we continue to assume an initial mass of 1000kg for a lifter, and a material strength of 130GPa (the value assumed in the NIAC Phase I report), an initial ribbon mass of 44.7 metric tons is required. This closely agrees with the NIAC report estimates of 40.3 tons (although the NIAC report assumes a lifter mass of 900kg). With current launch technology, it would require only four Atlas-V Heavy launches to begin construction of the space elevator cable, even if we consider a material with 90GPa strength [1]. A detailed derivation of the calculations used for these graphs can be found at the following URL: http://www.liftport.com/papers/2005Nov_LP-Ribbon_Mass.pdf.

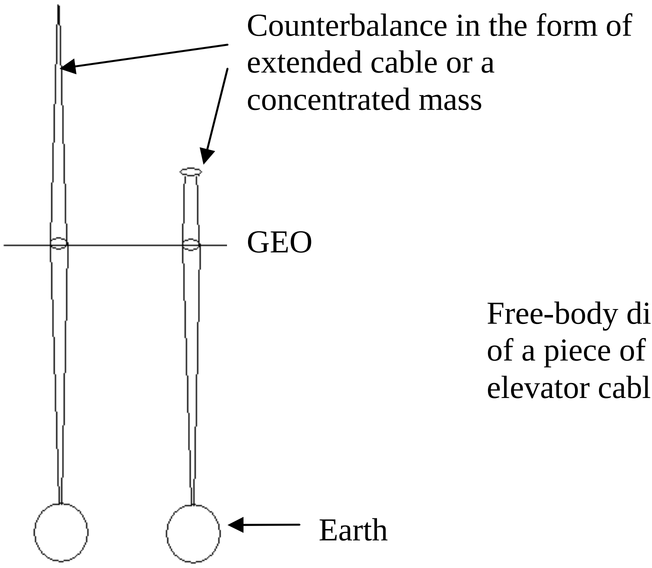
Appendix 6: Properties of Carbon Nanotubes, Kevlar, and Stee

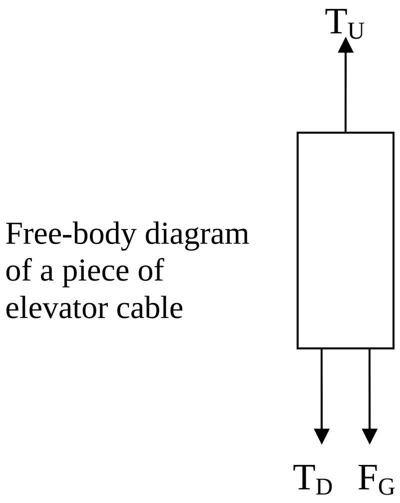
Material	Tensile Strength (GPa)	Density (kg/m^3)	Elastic Modulus (GPa)	Taper Ratio
CNT	300	1300	1000	1.5
Steel	1.2	7900	210	1.7×10^{33}
Kevlar	3.6	1440	83-186	2.6×10^{8}

This table displays various properties of carbon nanotubes, steel, and Kevlar. From this table, we see how the various material properties influence the taper ratio needed for the space elevator.

Appendix 7: Analysis of Space Elevator Taper Ratio

As mentioned, the space elevator cable will need to have a tapered shape in order to uniformly distribute the enormous loads throughout it. Figure 3 shows this variation in shape.





The free-body diagram on the right shows the forces acting on a small element of cable. From the figure, there exist three forces on any element of the cable: T_U is the upward force due to the section of cable above the element; T_D is a downward pull from the section of cable attached below it; and F_G is the weight of the element due to the Earth's gravitational attraction, the magnitude of which is dependent on the distance of the element from the surface of the earth.

Recall now that geostationary orbit (GEO) is an orbit height above the surface of the earth where the imaginary outward centrifugal force due to an object's rotation about the Earth balances the inward gravitational force on the object. Likewise, the element of cable at GEO has an inward gravitational force F_G which is balanced by the outward force arising from the cable's rotation. For the element of the cable at GEO, the downward tension from the cable below it is then balanced by the upward tension from the cable above it.

Below GEO, the gravitational force increases and exceeds the outward centrifugal force. In order to maintain the equilibrium of the element, the upward tension T_U must exceed T_D. The result of this interaction of forces below GEO is that that the tension force in the cable increases exponentially as one moves from the surface of the earth to GEO. The result is that the element at GEO experiences a tremendous tension force – one much greater than the force in the cable at Earth. The cable can therefore be engineered to possess a constant internal force per unit area (stress) which a known material like carbon nanotubes can support. To do this, the cable must be constructed with a cross-sectional area which increases at a rate similar to the increasing tension force in the cable. The result is a cable which begins narrow at the Earth's surface and gets progressively wider towards GEO. The ratio of the cross-sectional area at GEO to that at Earth is known as the taper ratio. With regard to the space elevator, a cable made of other materials like steel or Kevlar would have an enormous taper ratio – 1.7×10^{33}:1 and 2.6×10^{8}:1, respectively. Carbon nanotubes allow a taper ratio of 1.5:1, and are literally the only objects in the world capable of such strength. Their discovery is perhaps the most important technological advance in the construction of the space elevator.

With that said, discussion of the physics of the space elevator can continue on to examine an element above GEO. For an element in this position, the free body diagram in

Figure 3 remains valid. However, the force of gravity becomes increasingly less as one rises above GEO while the centrifugal force increases. To maintain equilibrium, T_D must exceed T_U. Detailed calculation of the interaction of these forces results in a tension force in the cable which decreases as one rises beyond GEO. The cable taper above GEO would therefore begin wide and terminate narrow. This segment of cable above GEO provides the enormous T_U required by the section of cable below GEO, and can be thought of as the counterweight for the gravitational effects on the cable below GEO.

In light of this, engineers can design counterweight solutions besides the long length of cable above GEO to provide the balancing T_U. A shorter length of cable can be used in connection with a large point load beyond GEO. Both of these are shown in Figure 3. Another design consideration is the launch of spacecraft from the end of the elevator. The further out the cable/counterweight extends, the greater velocity the elevator can impart on spacecraft to “slingshot” them to their destination. This fact will most certainly be balanced with the cost per length of cable before a design is finalized.

Glossary

Buckyball - The molecule C_{60}, consisting of 60 carbon atoms arranged on the surface of a sphere in a manner identical to the vertices of the pentagons and hexagons on a soccer ball. Buckyball is a contraction of “buckminsterfullerene”, named for R. Buckminster Fuller, the creator of geodesic domes. The three allotropic forms of pure carbon are diamond, graphite and buckyball.

Carbon Nanotube - Carbon nanotubes are cylindrical arrangements of carbon molecules with properties that make them potentially useful in extremely small scale electronic and mechanical applications. They exhibit unusual strength and unique electrical properties

Carbon Nanotube Ropes (CNT Ropes) - A grouping of Single Walled Carbon Nanotubes. Single-wall nanotubes can be thought of as the fundamental cylindrical structure, and these form the building blocks of both multi-wall nanotubes and the ordered arrays of single-wall nanotubes called ropes.

Composites - Composite materials (or composites for short) are engineering materials made from two or more components, a fiber and a matrix.

Disruptive Technology - A new technological development that eventually overturns the existing dominant technology in the market, despite the fact that the new technology is both radically different from the leading technology and that it often initially performs worse than the leading technology according to existing measures of performance.

Elastic Modulus - Young's modulus (also known as the modulus of elasticity or elastic modulus) is a measure of the stiffness of a given material. It is defined as the limit for small strains of the rate of change of stress with strain. Elastic modulus is measured in units of GPa.

Elasticity - Elasticity is a measure of how a solid object moves and deforms in response to external stress.

Fusion - A process where nuclei collide so fast they stick together and emit a great deal of energy.

Geostationary Orbit (GEO) - A circular orbit at 35786 km above Earth's surface, and in the same plane as the equator. In this configuration, a spacecraft’s orbital velocity is matched to the rotational velocity of the planet; a spacecraft appears to hang motionless above one position over the planet's surface. A geostationary orbit is a special type of geosynchronous orbit.

GPa - Gigapascals is a unit of pressure which can be used to express the strength of a material. It is 10^9N/m^2 or 1.5x10^5psi. This means that a 1 inch square cable of a material with a tensile strength of 1 GPa could lift a 150,000 pound load.

Interferometry - A technique in widespread use to dramatically improve the resolution of telescopes, especially radio telescopes. Several telescopes observe the object simultaneously, and a computer analyzes how the signals interfere with each other. A computer analyzes the signals from them to produce an image with a much better resolution than would have been possible with either telescope individually.

Low Earth Orbit (LEO) - A Low Earth Orbit (LEO) is an orbit that usually ranges from 600 to 2000 km in altitude above the surface of the Earth.

Maria - a relatively dark-colored and smooth region on the surface of the Moon.

Matrix - in a fiber reinforced composite, the matrix is the material in which the fiber is embedded, the material that the fiber reinforces.

Medium Earth Orbit (MEO) – A type of orbit that typically falls in the range of altitudes of 9,000 - 15,000 kilometers (km) above the surface of the Earth.

Multi Walled Carbon Nanotubes (MWNT) - Multi Walled Carbon Nanotubes are a type of Carbon Nanotube whose walls can be composed of multiple layers.

Regolith - The unconsolidated residual material that resides on the solid surface of the Moon.

Single Walled Carbon Nanotubes (SWNT) - Single Walled Carbon Nanotubes are a type of Carbon Nanotube whose walls are one layer thick.

Solar Array (Solar Power Satellite, SPS) - A large collection of panels in orbit around the earth that would transmit power to earth for consumers.

Space Debris - Fragments from space missions and satellites that are in orbit around the earth.

Stiffness - Stiffness is the resistance of an elastic body to deflection by an applied force.

Strain - Strain is the geometrical expression of deformation caused by the action of stress on a physical body.

Stress - Stress is the internal distribution of forces within a body that balance and react to the loads applied to it.

Taper - The gradual change in thickness or width of an object from one end to another.

Taper ratio - The taper ratio as we use it in this manuscript refers to the ratio of the cross-sectional area of the space elevator cable at geostationary to the cross-sectional area of the cable at the Earth end.

Tensile Strength - The tensile strength of a material is the maximum amount of tensile stress that it can be subjected to before it breaks.

Tensile Stress - Tensile stress (or tension) is the stress state leading to expansion (volume and/or length of a material tends to increase). In the uniaxial manner of tension, tensile stress is induced by pulling forces across a bar, specimen etc. Tensile stress is the opposite of compressive stress.

Tension - Tension is a force on a body directed to produce strain (extension)

Van Allen Belt - The Van Allen radiation belt is a torus of energetic charged particles around Earth, trapped by Earth's magnetic field. When the belts "overload", particles strike the upper atmosphere and fluoresce, causing the polar aurora.

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