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Space Elevators

Building a Permanent Bridge for Space Exploration and Economic Development

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SPACE ELEVATORS: BUILDING A PERMANENT BRIDGE FOR SPACE EXPLORATION AND ECONOMIC DEVELOPMENT

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Abstract

A space elevator is a physical connection from the surface of the Earth to a geo-stationary orbit above the Earth approximately 35,786km in altitude. Its center of mass is at the geo-stationary point such that it has a 24-hour orbit, and stays over the same point above the equator as the Earth rotates on its axis. The structure is utilized as a transportation and utility system for moving payloads, power, and gases between the surface of the Earth and space. It makes the physical connection from Earth to space in the same way a bridge connects two cities across a body of water (Fig. 1). The space elevator may be an important concept for the future development of space in the latter part of the 21st century. It has the potential to provide mass-transportation to space in the same way highways, railroads, power lines, and pipelines provide mass-transportation across the Earth's surface. The low energy requirements for moving payloads up and down the elevator make it one of only a few concepts that has the potential of lowering the cost to orbit to less than $10 per kilogram.

This paper will summarize the findings from a 1999 NASA workshop on Space Elevators held at the NASA Marshall Space Flight Center (MSFC). The workshop was sponsored by the Advanced Projects Office in the Flight Projects Directorate at MSFC, and was organized in cooperation with the Advanced Space Transportation Program at MSFC and the Advanced Concepts Office in the Office of Space Flight at NASA Headquarters. New concepts will be examined for space elevator construction and a number of issues will be discussed that has helped to bring the space elevator concept out of the realm of science fiction and into the realm of possibility. In conclusion, it appears that the space elevator concept may well be possible in the latter part of the 21st century if proper planning and technology development is emphasized to resolve key issues in the development of this advanced space infrastructure concept.

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1. History

The idea of building a tower from the surface of the Earth into space, the sky, or the heavens dates back to some of the very earliest known manuscripts in existence. The writings of Moses reference an earlier civilization that in about 2100 BC tried to build a tower to heaven out of brick and tar. About 1900 BC, Jacob had a dream about a staircase or ladder built up to heaven, commonly called Jacob's Ladder. The idea for building a structure from Earth into space, has been dreamed, invented, and reinvented, many times throughout modern civilization.

Today, the world's tallest structure is a stayed, television-transmitting tower near Fargo, North Dakota, USA, that stands 629 m high. The CN Tower in Toronto, Ontario Canada is the world's tallest building at 553 m in height. The world's tallest office building is the Petronas Towers in Kuala Lumpur that stand 452 m in height, about 10 m taller than the Sears Tower in Chicago, Illinois. The height of existing towers and buildings today are not limited by construction technology or by materials strength.

2. Key Findings

Several key findings were identified during the workshop that helped determine the overall feasibility of a space elevator as a possible future project instead of being pure science fiction. The key findings included:

1. The materials technology needed for space elevator construction is in the development

process in laboratories today. Continued research and development will likely produce the high-strength materials needed for efficient space elevator construction and for a wide variety of new and improved products.

2. The tallest structure today is 629 meters in height. Buildings and towers can be constructed many kilometers in height today using conventional construction materials and methods. These heights have not been attempted because there has not been a demonstrated need. Advanced materials and new construction methods could make it possible to construct towers tens and perhaps hundreds of kilometers in height.

3. A tether structure hanging down from GEO connected to a tall tower constructed up from the Earth, through most of the Earth's atmosphere, appears to be the most efficient and technically feasible method for space elevator construction.

4. Climatic conditions at the equatorial zone are very mild in comparison to more northern and southern latitudes, making construction along the equator ideal from a weather hazard standpoint. It is not physically possible for hurricanes and tornadoes to form at the equator.

5. The space elevator structure is inherently flexible and can be designed to avoid major hazards. Minor hits from asteroid debris are inevitable and will require standard repair procedures. A simple analogy is to think of the space elevator structure as a 36,000km long interstate, or railroad, that requires ongoing maintenance and repair.

3. A Space Elevator Concept

A baseline concept for a space elevator was created during the workshop to illustrate its purpose, scale, and complexity. The concept, as shown in Figure 1A, is envisioned to emerge from a platform at sea. The platform works like a seaport where cargo and passengers make their transfers from terrestrial transportation systems to the space elevator vehicles. A sea platform was selected because it illustrates that a remote location in international waters would be appropriate for a project of this scope that will probably require international cooperation and consensus to succeed. There was some discussion, without resolution, over whether the base would be fixed to the ocean floor or could actually float and move if needed. Figure 1B illustrates a concept for high-altitude support and control of the elevator tower through the use of inflatable platforms, which may also be useful during early construction phases.

From the top of the tower to the station at GEO is a long 36,000-km ride. The best concept for traveling this structure is an electromagnetic-propelled vehicle that can travel thousands of kilometers per hour. Figure 1C illustrates a concept for this vehicle, suspended in a track, with no moving parts (wheels) in contact with the elevator rails. Any other type of mechanical system would require traction wheels that would be much slower and cause considerable wear on the vehicle and the elevator structure. The vehicle is completely reusable, and returns to the base port on Earth, transferring passengers and cargo up and down the structure. At the GEO transfer station, Fig. 1D, passengers and cargo are transferred into the station or to outbound space transfer vehicles. This station is the center of mass for the total system, therefore large reels are present to adjust the location of the station, tension of the structure, and the counterbalance mass. An inflatable habitation structure is also present for living and working environments. Outbound vehicles can continue on the elevator track through the asteroid counterbalance mass, Fig. 1E, to the end of the structure at 47,000 km altitude. Launch to the Moon or other deep space destinations requires minimal energy because the rotation of the elevator acts like a sling beyond GEO to throw its payloads out of orbit.

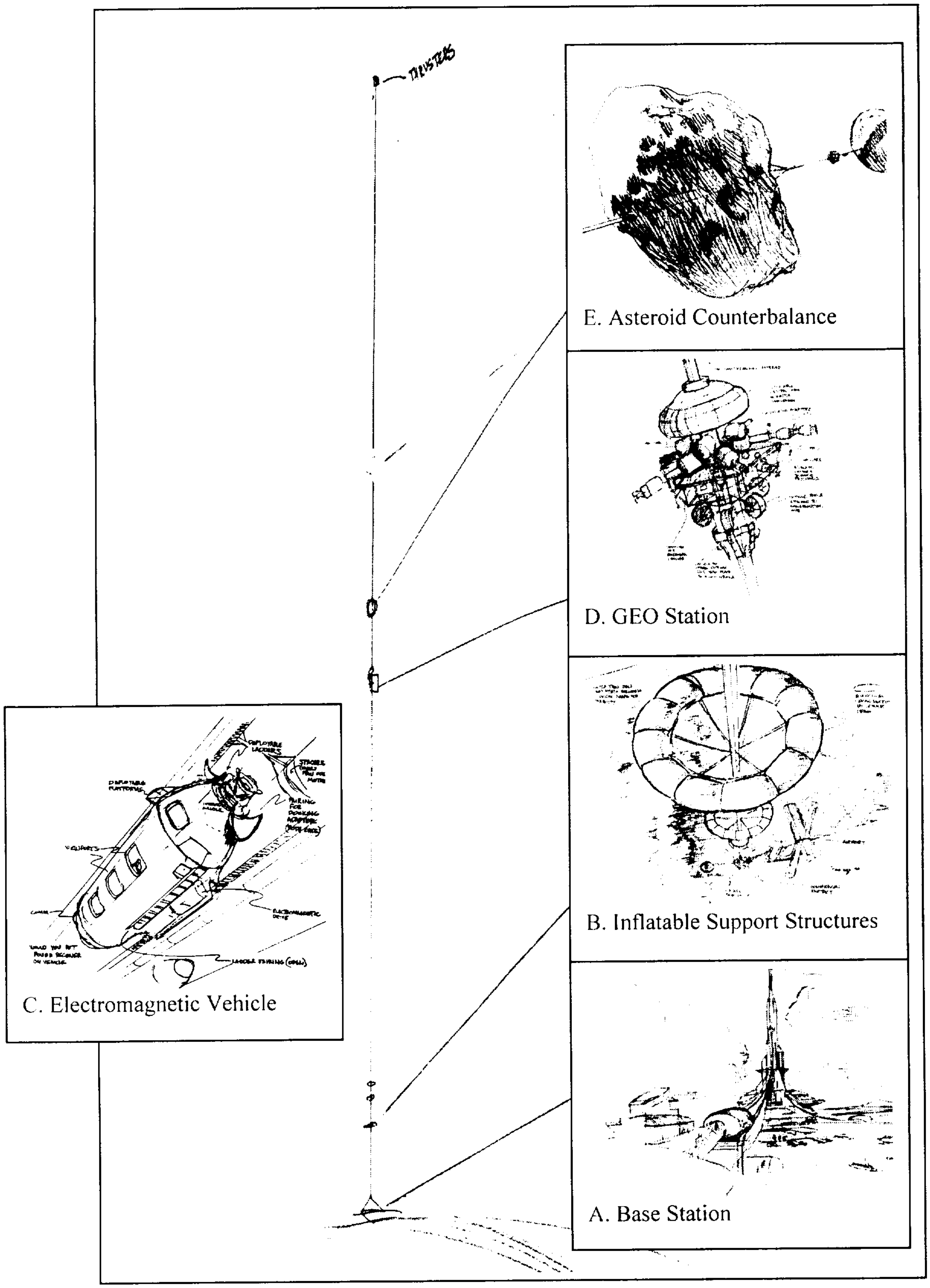


Figure 1. A Space Elevator Concept

4. Technology

The Earth to GEO space elevator is not feasible today, but could be an important concept for the future development of space in the latter part of the 21st century. The low energy requirements for moving payloads up and down the elevator could make it possible to achieve cost to orbit bellow 10 dollars per kilogram. This makes consideration of the technology paths required for space elevator construction very important today. Five primary technology thrusts were identified that are critical to the development of space elevators in the 21st century. The five technology areas are:

1. Materials: Develop advanced high strength materials like the graphite, alumina, and quartz whiskers that exhibit laboratory strengths over 20 G Pa. Continue development of the fullerene nanotube materials that exhibit strengths 100 times stronger than steel. Introduce these new lightweight, high-strength materials to the commercial, space and military markets for new and improved product developments.

2. Tension Structures: Continue development of space tether technologies for space transportation systems to gain experience in the deployment and control of long structures. Utilize higher strength materials, as they become available. Continue analysis on momentum exchange and LEO space elevator facilities for low cost in-space transfer to GEO.

3. Towers: Introduce lightweight composite structural materials to the general construction industry for the development of tall tower and building construction systems. Foster the development of multi-kilometer height towers for commercial applications (i.e., communications, science observatories, and launch platforms).

4. Electromagnetic Propulsion: Develop high-speed electromagnetic propulsion systems for mass transportation systems (Maglev), launch assist systems (Maglifter), and high velocity launch rails.

5. Space Infrastructure: Develop transportation, utility, and facility infrastructures to support space construction and space industrial development. Key components include highly reusable space launch systems, reusable in-space transportation, and space facility support from LEO to GEO.

As part of the workshop, these technologies were organized into technology demonstration roadmaps for input into NASA technology programs as well as the technology initiatives of other agencies and organizations. Technology demonstrations were identified for tethers, towers, and electromagnetic systems as being critical to a technology progression towards space elevator construction capabilities during the 21st century. Figure 2 illustrates one logical course of events over an indefinite period of time leading up to the full-scale development of Earth to GEO space elevators. The intent is to show that these technology demonstrations and developments can provide incremental benefits and are logical to pursue for their own merit in addition to their obvious relationship to future space elevator developments.

One of the most common misconceptions about the space elevator concept is the assertion that materials strong enough to span the 36,000-km height from the surface of the Earth to GEO are unavailable. But, it is theoretically possible to build a structure of this size out of any common structural material by simply increasing its thickness to compensate for the high tensile or compressive loads. The problem is that for most readily available construction materials it simply is not practical, due to the massive quantity and associated cost that would be involved. So finding the right material in combination with the right construction method is the key to success.

The problem with compression structures or tall towers is that failure is usually through buckling, and most materials are actually stronger in tension than in compression. So, the ideal structure will likely be a combination of a tall tower in compression connected to a tension structure. Many early engineering concepts for the Earth to GEO space elevator have assumed a requirement for a diamond-filament cable. Diamond was used because it exhibited the strongest tensile and compressive material strengths available at that time.

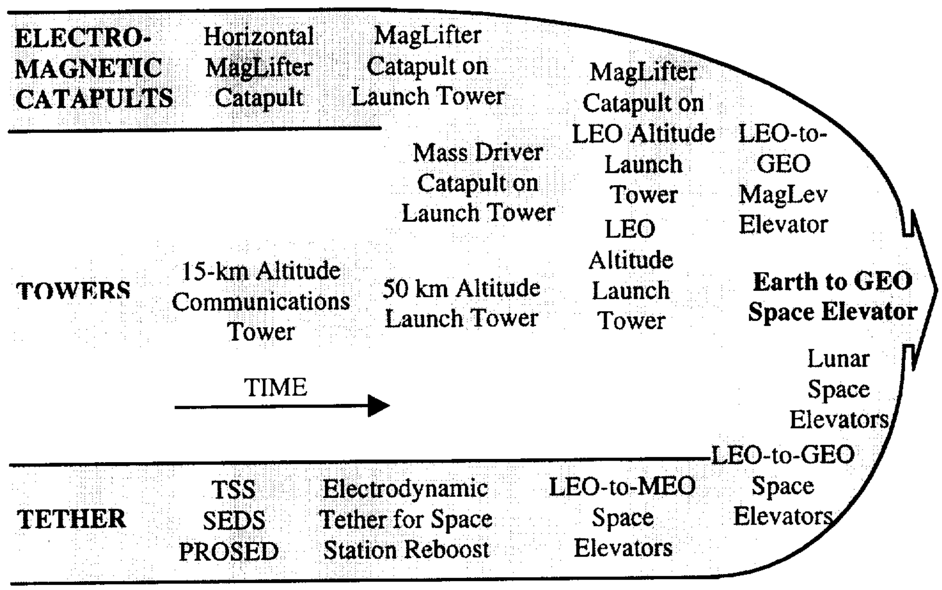
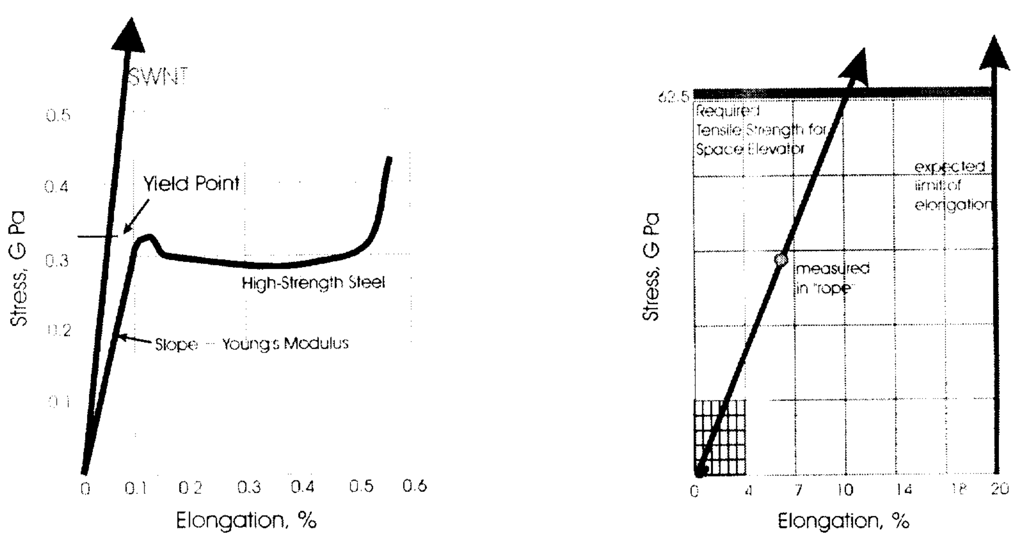


Figure 2. Technology Demonstration Roadmap (see also Fig. 4)

4.1 Materials

The lightest and strongest materials readily available today are the graphite epoxy composite materials that are commonly used in aerospace applications: but, the material strengths required for space elevator development appear to be far more demanding. Continued development of a new material known as carbon nanotubes that has exhibited laboratory strengths 100 times stronger than steel with only a fraction of the weight will be important (see Fig. 3). At present, production of carbon nanotubes is very expensive and limited in quantity. However, there are numerous commercial applications for carbon nanotube materials in existing markets, and potentially many new applications that cannot be envisioned today. Space elevator materials strength requirements is thought to be about 62.5 G Pa. Carbon Nanotubes have measured strengths in excess of 20 G Pa with theoretical strengths in excess of the 62.5 G Pa needed.



Strength comparison of carbon nanotubes (SWNT) with steel

Space Elevator requirements in comparison with theoretical strength of carbon nanotubes

Figure 3. Space Elevator Materials Strength

4.2 Tension Structures

The second technology area is in the continued development of tension structures for space applications. This includes a LEO space elevator as an intermediate version of the Earth to GEO space elevator concept, and appears to be feasible today using existing high-strength materials and space technology. It works by placing the system's midpoint station, and center of gravity, in a relatively low-Earth orbit and extending one cable down so that it points toward the center of the Earth and a second cable up so that it points away form the Earth. The bottom end of the lower cable hangs down to just above the Earth's atmosphere such that a future sub-orbital space plane transferring a payload up from the Earth's surface would require less change in velocity. A payload delivered to the lower end is then lifted to the upper end and released into a GEO transfer orbit. The overall length of a LEO space elevator from the bottom end of its lower cable to the top end of its upper cable is anywhere from 2,000 to 4,000 km, depending on the amount of launch vehicle ΔV reduction desired. If a resonant orbit is used, the lower end of the system will pass within range of most of the world's major airports twice a day on a fixed schedule. Periodic re-boost of the LEO space elevator will be required to compensate for the drag of the lower end in the upper atmosphere and the capture and transfer of payloads to higher levels on the elevator structure. A variety of Earth orbiting and Lunar space elevator structures are illustrated in Figure 4.

4.3 Towers

The third technology area is in the continued development of tall towers for Earth applications. This requires the introduction of lightweight composite structural materials to the general construction industry for the development of tall tower and building construction systems. However, one of the most fundamental problems with high-strength materials is that they are typically stronger in tension than in compression. Therefore what is needed is a way to convert tensile strength into compressive strength.

By converting tensile strength into compressive strength with a pressurized shell, PBO fibers can be used to build towers many times taller than would otherwise be possible. The tower would be constructed in segments with bulkheads to keep the pressurized gas from migrating to the bottom of the tower. A problem with a tower of this height is failure through buckling. Although the PBO fiber materials in combination with a pressurized system can likely handle the compressive loads, some type of active stabilization system would be required to keep the tower vertical. Today, many tall buildings include active control systems to control movement from high winds and earthquakes.

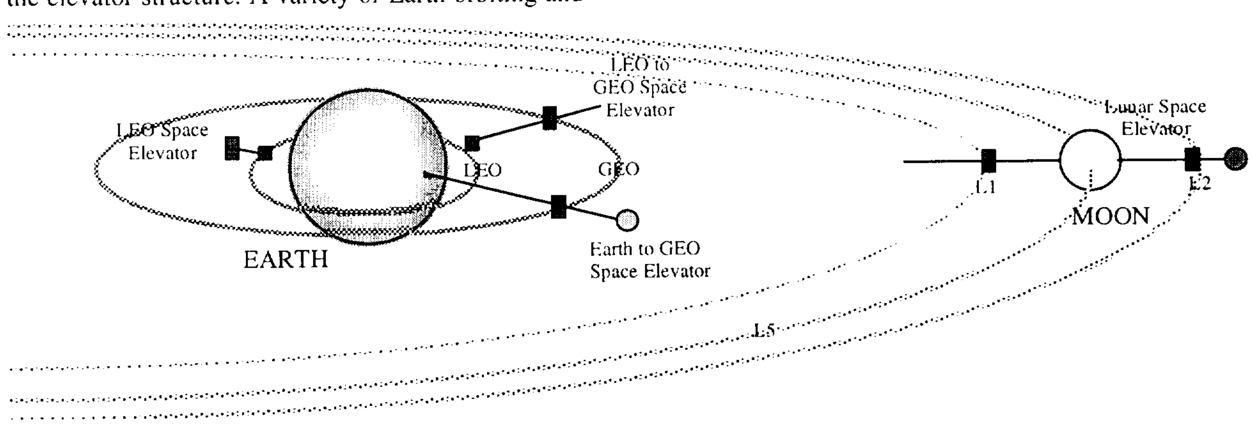


Figure 4. Earth Orbiting And Lunar Space Elevator Concepts.

4.4 Electromagnetic Propulsion

The purpose for exploring electromagnetic technology for the elevator is to develop a means by which vehicles can climb up and down the elevator without contacting the structure or guide rails. This would be very low maintenance on both the vehicles and the structure, and potentially very fast. High-speed systems in the thousands of kilometers per hour are desirable due to the great length to be traveled in space. Energy is used during the initial lift and acceleration phase up the elevator. With an electromagnetic system there is the potential that electrical energy could be recovered in the braking phase to slow the vehicle down.

There are several intermediate steps that can be taken toward reaching this level of technology. These have been grouped into low-g and high-g systems. Low-g systems are for human-rated vehicles that have accelerations up to ≈3-g (3 Earth gravity levels). Two concepts for use of electromagnetic propulsion in low-g systems are the MagLev for magnetically levitated train systems, and the MagLifter for magnetic lift to provide launch assist for space launch vehicles. High-g systems are for nonhuman payloads that can survive high accelerations in the hundreds and thousands of gees. Two concepts for high-g propulsion systems are the rail gun and the mass driver (or coil gun). It is not yet evident which of the electromagnetic systems would be best suited for the space elevator or exactly how any of them could be integrated into a space elevator structure that needs to be as light as possible.

4.5 Space Infrastructure

Today, our progress in space development is restricted to single projects of limited scope in LEO. Significant expansion of space infrastructure will be necessary to create the economic base and the construction capabilities needed for major developments beyond LEO. A mature space transportation system from Earth to GEO will be needed to facilitate space elevator construction. These transportation systems should not be built exclusively for space elevator construction. The space elevator concept will only be successful if it is done in support of a growing economy in space where people are actively working to make this new frontier their home. The transportation systems must also be multipurpose and highly reusable to support frequent flights comparable to today's airplane.

Transportation support facilities from Earth to GEO would include space stations and servicing platforms to support a growing economy in space. In support of the vehicles, stations, and platforms, a network of propellant production, delivery, and storage systems will be needed. It is likely that human activities on orbit will include tourism and permanent residency in new space station-type facilities called space business parks before space elevator developments can be supported economically.

Solar-powered systems in space are in common use today on the *ISS* and most Earth-orbiting satellites. There is an abundance of solar energy available, and technology work is in progress to improve the performance of these systems. Advances in the development of solar cell films may make it possible for the surface of the space elevator to become a solar collector. The first Earth to GEO tether structure used to make the initial connection could be used as a direct power line. Initially, power would be delivered up the elevator for construction support at GEO, and later power would be delivered down the elevator to ground utility systems from solar power satellites stationed in GEO.

Developments at the Moon and asteroids could have an important role to play in the overall plan to develop and demonstrate the technology for a space elevator. Development of space resources for materials and propellants will likely play an important role in overall space development as well as support development of the space elevator. Of particular interest is the concept for utilizing an asteroid as a counterweight for the space elevator and mining its resources to produce some of its construction materials.

The interesting thing about the space elevator concept and space development in general is that the opportunity is here to chart a course for expansion that is no longer limited to the physical constraints of Earth resources. Through development of these technologies and infrastructures there will be many new benefits, products, and services that cannot possibly be envisioned at this time from an Earth perspective.

5. Safety Issues

Major issues related to the space elevator concept tended to focus on either environmental or safety concerns. The environmental issues dealt primarily with the effects the natural environment on Earth and in space would have on the space elevator system. Some of these concerns led to safety issues for people traveling on the elevator as well as for others on

Earth and in space in the event of a catastrophic failure.

The single greatest safety concern identified centered on the hazards caused by potential collisions between the elevator structure and other objects in orbit. Cleanup of orbital debris was identified as a high priority that needed to be done to protect all future spacecraft. Small debris materials <1 mm in diameter are numerous and can cause erosion of spacecraft surfaces. The real problem is with debris and incoming meteoroids in the 1 mm to 10 cm size. They are difficult to track with current technology and can cause significant damage to spacecraft systems. Space debris and meteoroids 1 mm to 10 cm in diameter are thought to be many times greater in number than the known tracked objects.

6. Conclusion

The massive size and complexity of the space elevator concept is often cited as making such a system impossible to conceive except in the realm of science fiction. More detailed analysis of the system indicates that it is indeed very complex, but it is comparable to other Earth-based infrastructures that have been built over many years. Many benefits were identified that supported the pursuit of space elevator technology, most of which centered on the potential for low-cost mass transportation capabilities to space. However, there are many questions and problems to be resolved before space elevators can be considered economically feasible. The space elevator is not a near-term project, but can now be considered a good potential project for the latter part of the 21st century.

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