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THE SPACE ELEVATOR DEVELOPMENT PROGRAM

Bradley C. Edwards
Carbon Designs, Inc., United States
brad_edwards@yahoo.com

ABSTRACT

For 40 years, the space elevator has been a concept in science fiction and appearing occasionally in technical journals. Versions of the space elevator concept have generally been megalithic in design. However, recent advances in technology and new designs for an initial space elevator have presented a much smaller and a more realistic version that has created a renewed interest in serious technical study. There are now over a dozen entities and hundreds of engineers and scientists with active research related to the space elevator. The activity includes conferences, engineering competitions, extensive media coverage, international collaborations, publications and private investment. These activities are rapidly expanding with the number of publications in 2004 nearly ten times the total for the prior forty years.

INTRODUCTION

The space elevator concept has been around for many years (Tower of Babel, Jack and the Beanstalk, Clarke's *Fountains of Paradise*, Robinson's *Red Mars*) and between 1960 and 1999 a few technical studies addressed the basics of the system (Moravec, 1977; Isaacs, 1966; Pearson, 1975; Smitherman, 2000). These studies addressed the oscillations inherit in the system, the taper requirements, and the general difficulties but did not cover most of the technical details of construction and operation.

In 2000, Edwards published a unique design for the space elevator and followed this publication with an overview engineering funded by NASA's Institute for Advanced Concepts (NIAC). The final report from the Phase I effort and book resulting from the Phase II effort (Edwards, 2003) outline the basics of a space elevator. These publications go through the basic ribbon design, the climber design, the deployment spacecraft, the power delivery system, challenges to the system, etc.

The basic design presented in the NIAC work has stressed simplicity – a single, small, static ribbon with mechanical climbers that ascend using conventional electric motors (figure 1). The design implements conventional technology with little or no development wherever possible. The design is easy to grasp and analyze and may present a reasonable first system though may not present the optimal final design for future generations of elevators. This initial effort completed with $570,000 in funding has been the catalyst for variant designs and additional studies.

The initial effort also generated a template for defining the challenges and where research and engineering were most critically needed. Some items such as the anchor station have been viewed as straightforward and understood in

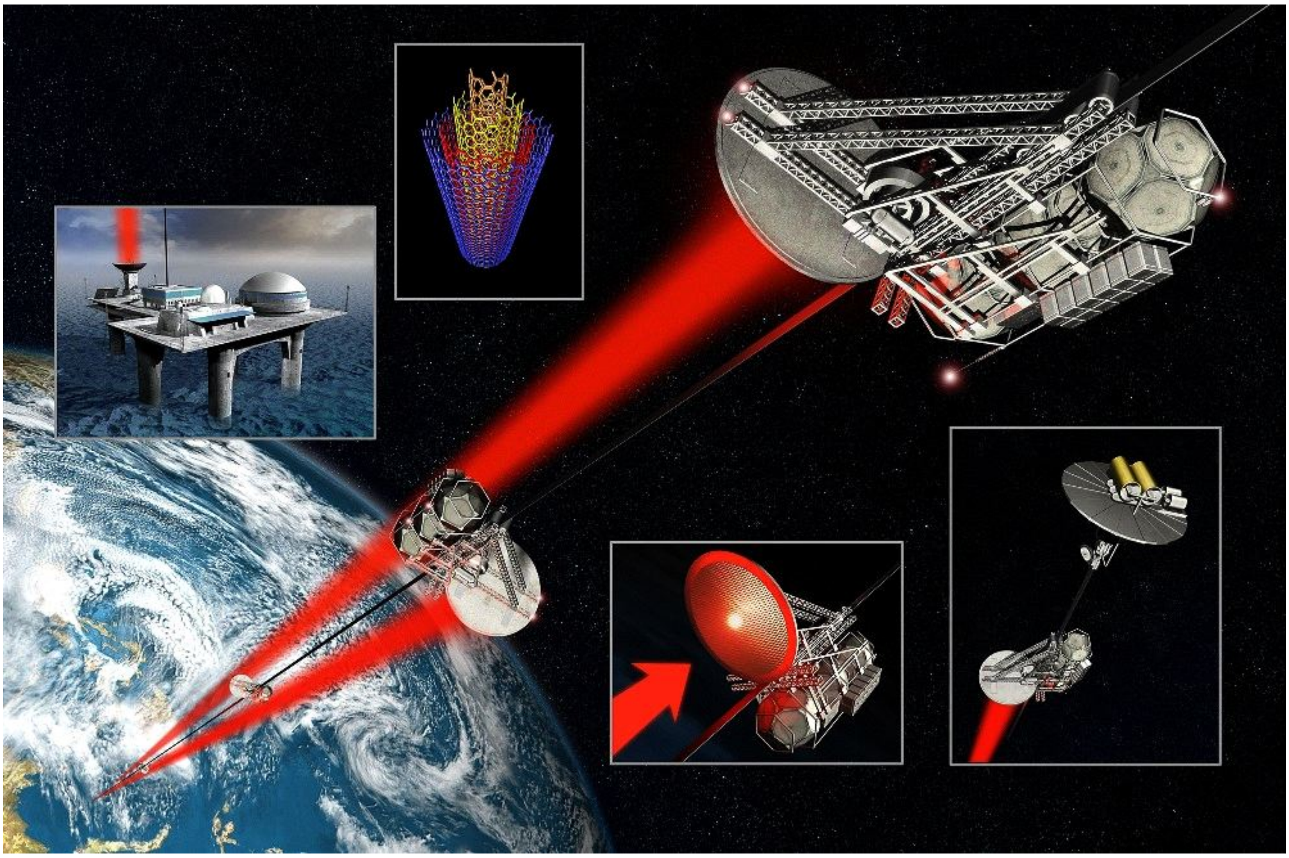

Figure 1: Illustration of the first space elevator illustrating the various components. Insets from left to right: anchor station with power beaming station, carbon nanotubes, underside of climber showing the power beaming component, the upper end of the elevator with the initial deployment spacecraft and climber as counterweights. (Image from Discover Magazine)

terms of current technology where as other components, such as the ribbon and system dynamics, are unique and considered challenges. By defining the challenges the problem has been broken down into pieces that can be investigated by individuals or groups. This accessibility of the problem has spawned growing interest in engineering and research communities. For example, in 2000, a search on the Internet for 'space elevator' would have produced several hundred links. The same search today will return over 150,000 links.

The primary technical hurdle for construction of the space elevator is the production of the high-strength material with a tensile strength of 100 GPa. At the current time, carbon nanotubes (CNTs) have been measured with tensile strengths of 200 GPa. CNTs have been spun into yarns of pure carbon nanotubes and have been implemented in composite fibers. The spun fibers are a new development (Li, 2004) though CNT composite fibers have been made with as high as 60% CNTs, strengths comparable to steel (5% CNTs by weight) and kilometers in length. The high-strength material being the primary hurdle to construction it has also become the focus of several efforts.

The ribbon design and deployment are being re-examined in terms of possibly building the ribbon by attaching full width segments end-to-end instead by of the baseline increasing the width by splicing additional ribbons onto an initial small ribbon.

The system dynamics has also become an active area of study due to its ease of entry. The dynamics that are now being investigated range from the smallest scale (individual fibers) to the largest (finite element modeling of the full 62,000 mile ribbon). Small-scale dynamics revolve around the degradation of the ribbon components at the individual fiber and interconnect level. Primarily this pertains to breakage of individual fibers in the ribbon and how the ribbon responds. Large-scale dynamics involve the oscillations, profile variations and how the ribbon generally responds as a system.

The climber, being a straightforward mechanical system, has also attracted interest in the form of engineering competitions and detailed design studies. The various designs now being considered include the baseline tread system, pinching rollers, and offset rollers. Few new designs for the power transmission have been presented.

With the increasing interest there has also been a healthy re-examination of the baseline design. Trade studies are beginning to examine the possibility of using a moving looped ribbon, oscillating ribbon, or sets of pulleys.

Due to the activity there has also been an increased need for a detailed overall systems engineering of the program. The efforts to date have been disjoint and independent. Efforts to coordinate the efforts will result in a more efficient development program.

To lay out the work in progress and how it is being addressed the space elevator development program can be discussed by a set of topics:
1. Research groups
2. Research activities
3. Public interest
4. Private interest
5. Complimentary development

RESEARCH GROUPS

INSTITUTE FOR SCIENTIFIC RESEARCH (ISR) / NASA'S MARSHALL SPACE FLIGHT CENTER (MSFC)

ISR/MSFC is slated to receive $2.485M for 2004 to conduct Pre-Phase A / Phase A engineering studies. This funding is a congressional appropriation that will be directed by NASA's Marshall Space Flight Center. The funding for the 2004 fiscal year arrived at ISR/MSFC for use in mid-August, 2004.

The ISR/MSFC development effort has six tasks:
1. Systems engineering
2. High strength materials
3. Ribbon dynamics
4. Ribbon design
5. Prototype climber
6. Distribution of Results

These tasks were selected as the most critical from either the program or technology development perspective.

TASK 1: SYSTEMS ENGINEERING

The interactions and interdependence of the various space elevator subsystems and driving factors have not been quantified in detail and compiled for easy access. ISR plans to bring together past work and current efforts into a database and attempt to illustrate the priority issues and the solutions. This framework for data archival and trade-off evaluation is important for effective management of a project with the size and complexity of the space elevator.

TASK 2: HIGH STRENGTH MATERIALS

ISR/MSFC will be putting a small fraction of their funds toward development and evaluation of high strength materials. Part of this will be to organize a CNT materials workshop which may happen in November, 2004, in Kentucky.

TASK 3: RIBBON DYNAMICS

ISR/MSFC has begun to compile the information on the drivers in the dynamics area. These include: atomic oxygen, debris, electric and magnetic fields, radiation, orbital dynamics, and thermal loads. Complete simulations are being developed to understand quantitatively how these drivers will affect the ribbon at the various scales. This work is in collaboration with David Lang (see below).

TASK 4: RIBBON DESIGN

Utilizing the results of the ribbon dynamics efforts, ISR/MSFC plans to build and test segments of ribbons with materials of varying strength and stiffness as well as ribbons with varying interconnects. The tests will be used to understand what issues will arise as higher-strength material is used. One of the main issues will be the recoil dynamics of broken fibers and where the stored energy goes. In conventional materials this is not a problem but at the tensions in the space elevator the stored energy could be released in ways that could cause more serious collateral damage. By testing and modeling the ribbons with increasing strength ISR/MSFC hopes to design a ribbon that readily handles the energy release.

TASK 5: PROTOTYPE CLIMBER

In this task ISR/MSFC plans to construct several small prototype climbers and begin quantifying the issues. The first two prototypes are under construction with different teams and different thrusts. The tracking and overall design issues are the first being addressed (see figure 2).

TASK 6: DISTRIBUTION OF RESULTS

ISR/MSFC started pushing to finish Pre-Phase A efforts and begin Phase A level work. The effort plans to distribute the results of work in the form of conferences, reviewed papers and access to the systems database being produced.

LOS ALAMOS NATIONAL LABORATORY

A set of of researchers at Los Alamos National Laboratory (LANL) has acquired internal funding for several basic studies and to support conference organization. These efforts at LANL are augmented by personal commitment extending beyond the standard work hours.

Several efforts are being pursued at LANL including: 1) the viability of solar power satellites using the space elevator, 2) the radiation environment and how it affects the operation of the space elevator, 3) dynamics of the system, and 4) overall applications of the space elevator.

The LANL radiation studies have found that there will be operational challenges to transporting humans on the space elevator unless the climbers can move more quickly or be shielded. Solutions for this problem are being studied.

The LANL studies on solar power satellites have found that the space elevator could be used effectively to construct an economically competitive system for delivering clean energy for terrestrial uses.

Figure 2: Model of a complete climber system. The insert shows the details of the drive system.

OTHER GROUPS

Several other groups have begun research at various levels. These include Spaceward, X Tech, Liftport, MIT, and individuals.

RESEARCH ACTIVITIES

CONFERENCES

There have been three conferences dedicated to space elevator efforts. They occurred in August 2002: Seattle, September 2003: Santa Fe, and June 2004: Washington D.C. Each was 2-3 days with 70 to 100 participants. Dedicated sessions at larger international conferences have also begun to appear. The first of these sessions will be in Vancouver at the IAF/IAC 2004 conference, the second will be at the Space Exploration 2005 conference in Albuquerque in April 2005 and additional ones will occur at the IAC/IAF in 2005. In addition, the space elevator is becoming a regular topic presented at various technical conferences.

Publications

The number of published technical articles on the space elevator in the last year (~50) and in the coming year (~80) will be over ten times the total number of technical journal articles published previously on the subject. Many of these articles are in the proceedings of the 3rd Annual Space Elevator conference and available through the Institute for Scientific Research. Proceedings will also be published for the other large conferences mentioned above. In addition to published journal articles there are books in progress on the systems engineering of the space elevator, a updated version of the original *The Space Elevator*, and several general interest books on the development of the space elevator.

PUBLIC INTEREST

General public interest in the space elevator has also grown dramatically. In the last couple years the space elevator has appeared as a prominent article thousands of times around the world. Initially the space elevator appeared in technically-oriented publications (Ad Astra, Tech TV, Science News, Space.com). Recently, the space elevator has appeared in more general interest or business media (Wall Street Journal, New York Times, Inc., Fox News).

Articles on the space elevator have appeared in:

- CNN Live
- Fox News
- BBC
- Inc.
- Space.Com
- MSNBC
- Tech TV
- Seattle Times
- Science News (cover)
- New York Times
- Ad Astra (cover)
- Wall Street Journal
- Wired Magazine
- Canadian National Post
- Discover (cover)
- The Tonight Show

Another indication of public interest is the distribution on the Internet. As stated above the the number of links found in a Google search of ‘space elevator’ has increased from under two hundred in 1999 to over 150,000 today. Part of this increase is likely due to improvements in the search engine. Public interest can also be seen in the number of message boards now operating with specific discussions on the space elevator. These include National Space Society, Yahoo, Slash.dot, Space.com, and Liftport.

The large space advocacy groups are also taking an interest in the space elevator. The National Space Society has come out and stated definitively that they strongly support the development of a space elevator and will do whatever they can to make it happen.

The space elevator concept has also been the center of several art exhibits in Europe (Utopia Station), considered for documentaries and is now a component of the movie script, *The Ark*, by Alan Chan.

Educational interests

With the growing research interest in the space elevator there has been an increase in the number of students (K-12, college, graduate) that are actively getting involved in space elevator related activities. These activities are unorganized and involved students conducting research reports on the space elevator, science fair activities, and thesis work related to various subsystems.

PRIVATELY FUNDED EFFORTS

CARBON DESIGNS, INC.

Carbon Designs is a privately funded research entity to develop high-strength materials. The first round of funding is expected to begin in September 2004. The initial efforts will be directed at advancing the current state-of-the-art in materials to achieve materials with tensile strengths of between 30Gpa and 50Gpa in 2005. Follow-on funding is expected to increase this strength in the second year. The commercial focus of this effort will allow for continued funding prior to implementation of the material in the space elevator. Carbon Designs was co-founded by the author.

SPACEWARD / ELEVATOR: 2010

Spaceward, a recently initiated non-profit organization off-shoot of Gizmonics, is dedicated to producing the Elevator: 2010 climber competition. To be held in June, 2005, the competition will pit university and individual efforts against each other in a speed (>1m/s over 100m vertical altitude) and carrying capacity (~100 kg climbers) competition with the winner receiving prizes in the tens of thousands of dollars. The competition is expected to demonstrate the viability of the climbing and laser power beaming components.

Spaceward also supports research activities on specific engineering aspects of the space elevator including ribbon and deployment scenarios.

MARC BOUCHER / SPACEREF

Marc Boucher, founder of SpaceRef, constructed a website dedicated to the space elevator at www.spaceelevator.com. This site has space elevator resources and news.

LIFTPORT

A private group working to toward the realization of a space elevator. Liftport hosts a site with news and resources on space elevator activities. Liftport states on their website that they are collecting funds and will be supporting high-strength material development efforts.

INDIVIDUALS

David Lang has been conducting dynamics modeling of the space elevator using a customized version of the GTOSS simulation code. GTOSS is a finite element analysis code that has been utilized in conventional space tether modeling and has demonstrated accuracy in that situation. The customized version of GTOSS for the space elevator simulation has a larger set of finite elements and works in both dynamic and static situations. Lang has used the code to illustrate the oscillation and failure modes of the elevator and the required impulses to induce each.

Pete Swan has been working to lay out the systems engineering aspects of the space elevator. He has begun defining the overall structure and architectures required for a project like the space elevator.

Roger Gilbertson, The Robot Store, has worked to implement a small climber competition at the Robotics Society of America meeting. This climber competition has had three successful years of operation and produced small climbers that work at a scaled down level of what is required in the real system (see figure 3).

Figure 3: Climber built by Jack Buffington that won the 2004 ribbon climbing competition of the Robotics Society of America. The climber is shown with its photovoltaic arrays folded up. During ascent the arrays fold down.

Andrew Price and Blaise Glassend both support websites with space elevator information and efforts. Each has also been conducting research in specific areas of the space elevator in terms of deployment and dynamics.

COMPLIMENTARY DEVELOPMENT

The space elevator system utilizes a diverse set of technologies so advancements in related fields can greatly benefit the space elevator effort. The baseline design for the space elevator attempts to maximize the use of these off-the-shelf technologies. Several of the recent advancements are illustrated below.

New laser designs

The baseline space elevator design has a laser power beaming system to deliver power from Earth to the climbers. Recent advancements in lasers may simplify this system. The solid-state laser being developed at Boeing (Vetrovec, 2004.) uses a disk of active material to produce high continuous power (figure 4). A single 1 kW laser has been produced and tested with excellent results (figure 5) and current proposals plan to construct a 100kW laser by combining individual modules (figure 6). The wallplug efficiency is 30% and the operating wavelengths are in the 800 to 1000 nm range.

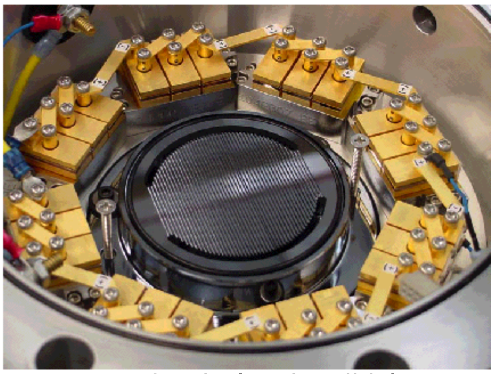

Figure 4: Image of a single 1 kW disk laser module. (Vetrovec, 2004).

Figure 5: Image of a 1kW disk laser during operation (Vetrovec, 2004).

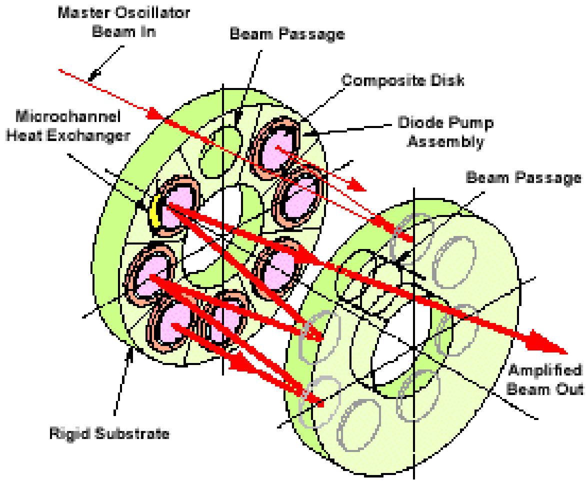

Figure 6: Illustration of multiple 1kW disk laser modules combined into a single large laser (Vetrovec, 2004).

Carbon nanotubes

The National Nanotechnology Initiative (NNI) was created to speed up development of a number of nanoscale related technologies. The 2004 funding level for NNI is $990M and spread across a dozen federal agencies. One of the technologies being pursued under the NNI is carbon nanotube composites. The programs that are part of the NNI include the Small Business Technology Transfer (STTR), Small Business Innovative Research (SBIR) and Advanced Technology Program. Funding levels in these programs range from $600,000 to $2 million spread out over two years or longer. These levels are insufficient to move large developments forward. With the current composite market at $40 billion annually it is more likely that the carbon nanotube composites will be developed independently for golf clubs, tennis racquets, and aerospace rather than in the NNI or for the space elevator.

Recent reports on health issues related to CNTs have been published. These reports include several animal-based studies and individual reports from a worker at a nanotube production facility. Some initial reports indicate serious health hazards while others indicate that the risks are minimal. This is a critical issue for the composite industry so it is expected that the number and accuracy of these studies are expected to increase in the coming years and clarify the health issues related to CNTs.

Applications Technology

NASA's exploration program is driving toward a sustained presence in space with a station on the moon and men on Mars. The required technology developments for this program including habitat modules will benefit the space elevator in terms of allowing rapid development of space and producing detailed estimates of cost and complexity of commercializing space. The disconnect between the NASA effort and what will be needed in applications using the space elevator is in the much more expensive construction required for rocket based systems.

TRENDS AND UNIQUE ASPECTS OF THE SPACE ELEVATOR DEVELOPMENT

One of the unique aspects of the space elevator is the speed at which it has gone from being considered a strictly science fiction concept or distant possibility (1999) to a concept seriously considered for near-term construction (2004). Most of this change has occurred since completion of the NIAC study and release of the book, *The Space Elevator*, in early 2003. This rapid change is a result of clarifying the engineering arguments for construction of the space elevator.

However, the construction of a space elevator is a large program and will require a much larger effort than what currently exists. Estimated costs for construction are around $10 billion for the first space elevator and a fraction of this for subsequent systems. Development costs for the space elevator should then be expected to be around 5% to 10% of the final cost or $500 million to $1 billion. The other aspect of this is the schedule for development. The engineering of integrating the components and conducting the required tests will take years. The effort will need to grow considerably in the near future for the space elevator to be built in the next 15 years.

Future work on the space elevator could go in several directions. Private organizations are currently pushing development with the only public funding coming through a congressional appropriation (ISR/MSFC). This disparate level of interest is in spite of many more briefings to government agencies than to private organizations. Governmental briefings have included perhaps a dozen at NASA headquarters and various NASA centers, DARPA, Air Force Research Laboratory, Air Force Space Missile Center, NRO, NSA, Rayburn House Office Building and personal invitations to the space elevator conferences. In addition, proposals in response to NASA's Exploration Systems Broad Area Announcement for examining a space elevator based exploration program were not selected for funding.

CONCLUSIONS

Recent developments in the design of a viable space elevator have led to a dramatic increase in the amount of activity and research conducted in this area. The number of researchers investigating the space elevator has grown from a handful in 1999 to hundreds today at many institutions. The activity includes dedicated conferences, publications, media coverage, and private investment.

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